Kinetics, Thermodynamics, & The Stirling Engine

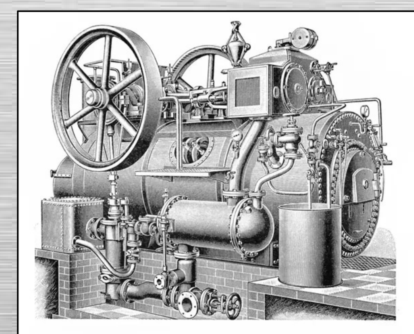
By Le Kang

Today's Goals

- Types of energy
- Functionality of an heat engine
- Theoretical maximum efficiency
- Fermi-style calculation of actual efficiency
- How the Stirling engine works
- Stirling versus other engine types

What is an Engine?

- A device that converts a form of energy to useful energy



What is an Engine?

- A device that converts a form of energy to useful energy

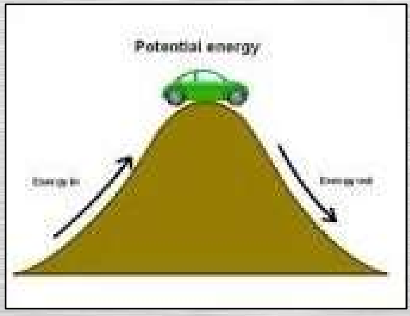
- What are some forms of energy?

What is an Engine?

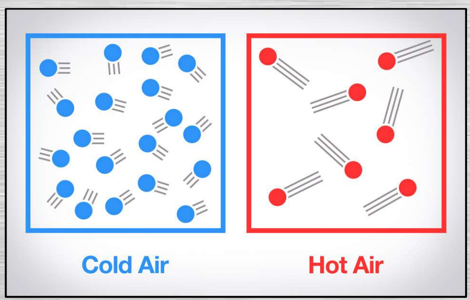
- A device that converts a form of energy to useful energy
- What are some forms of energy?
- What is useful energy?

Some Form of Energies

- Gravitational potential energy

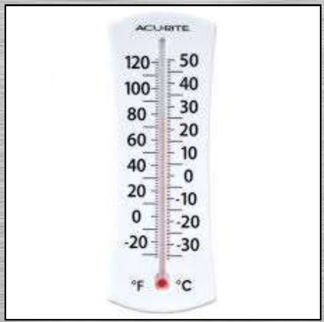


- Kinetic energy



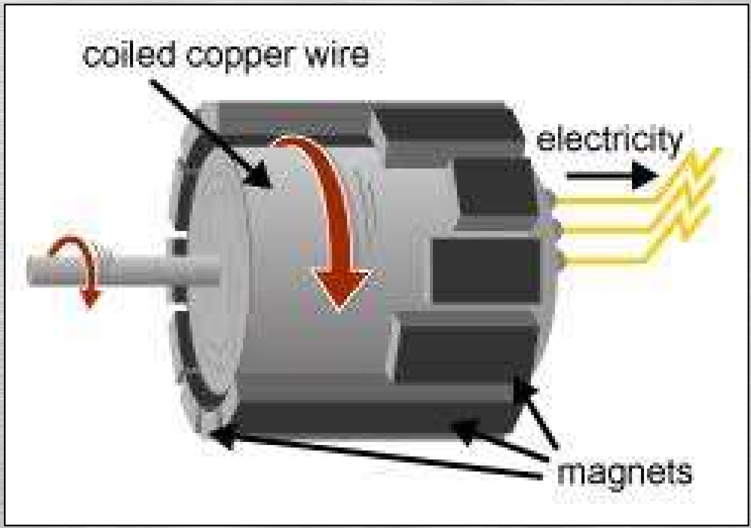
- Chemical energy

- Thermal Energy (heat, Q)



Useful Energies

- Mechanical energy (energy available to do work)



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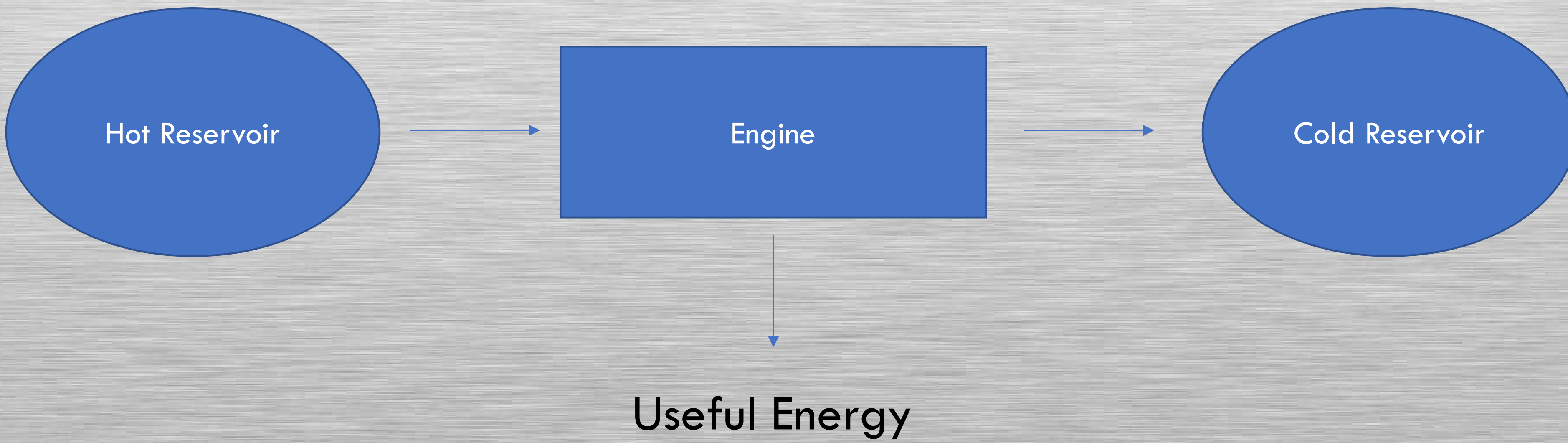
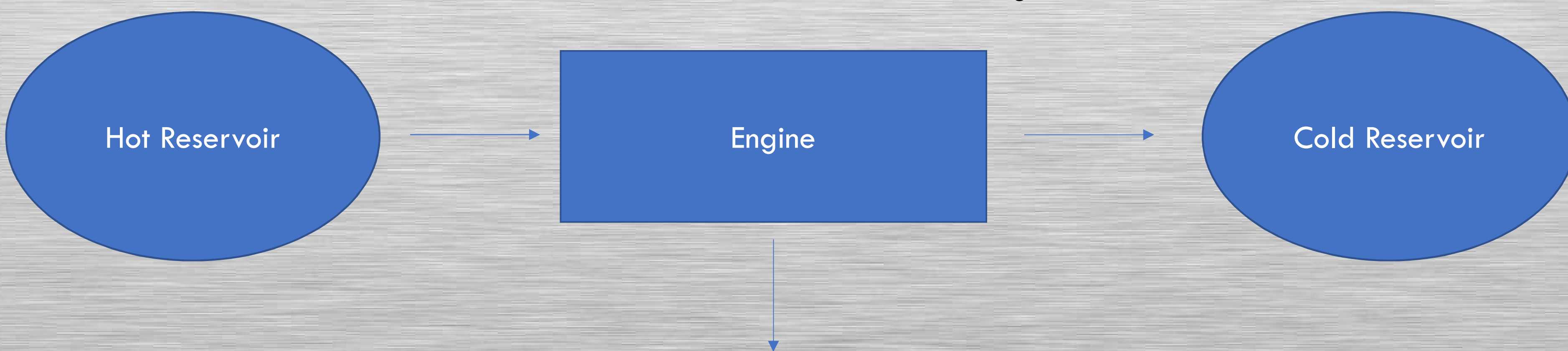


Theoretical Maximum Efficiency

$$\text{Efficiency} = \frac{Benefit}{Cost}$$

Q_H = Energy in

Q_c = Waste Energy



W = Useful Energy

Theoretical Maximum Efficiency

$$\text{Efficiency} = \frac{W}{Q_H}$$

Q_H = Energy in

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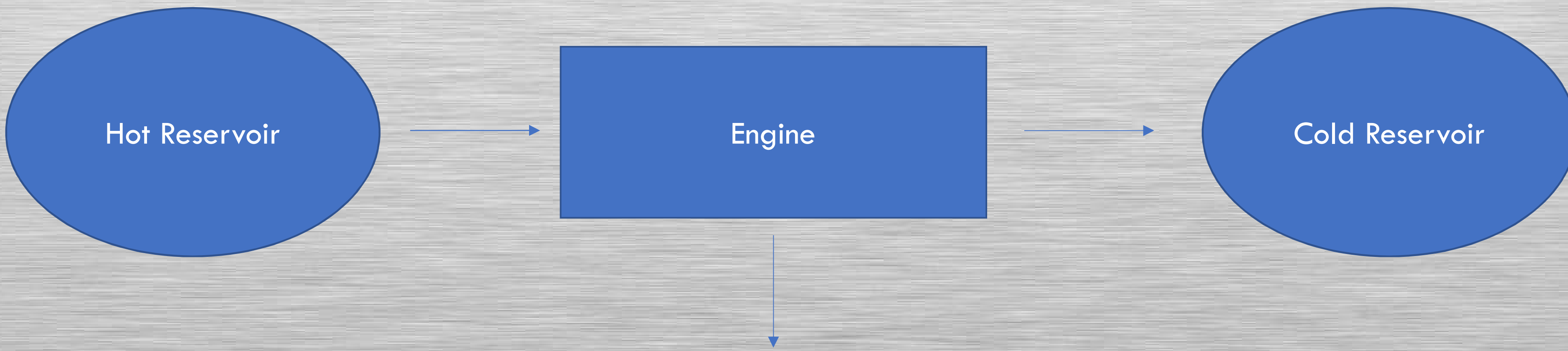


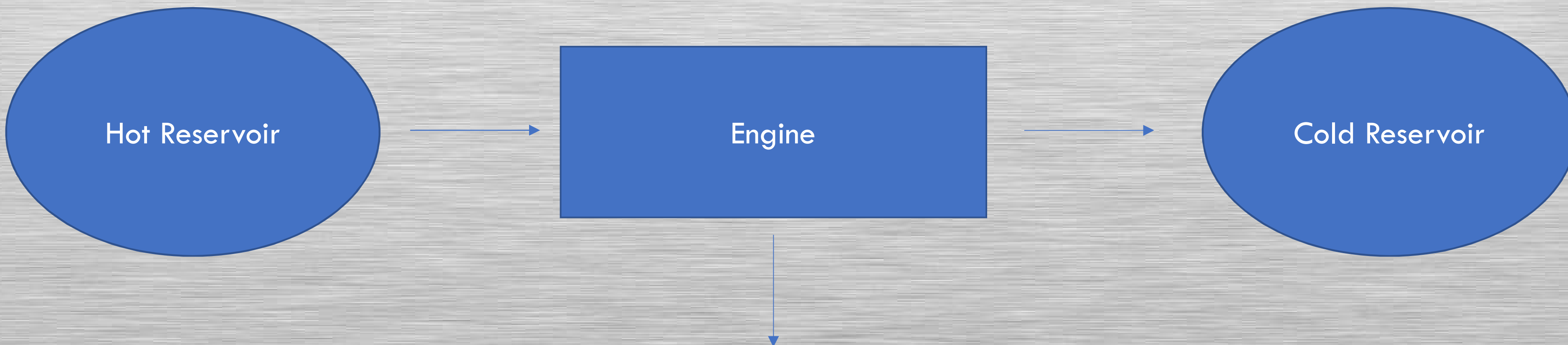
W = Useful Energy

Theoretical Maximum Efficiency

$$\text{Efficiency} = \frac{Q_H - Q_C}{Q_H}$$

Q_H = Energy in

Q_c = Waste Energy



W = Useful Energy

Theoretical Maximum Efficiency

$$\text{Efficiency} = 1 - \frac{Q_C}{Q_H}$$

Q_H = Energy in

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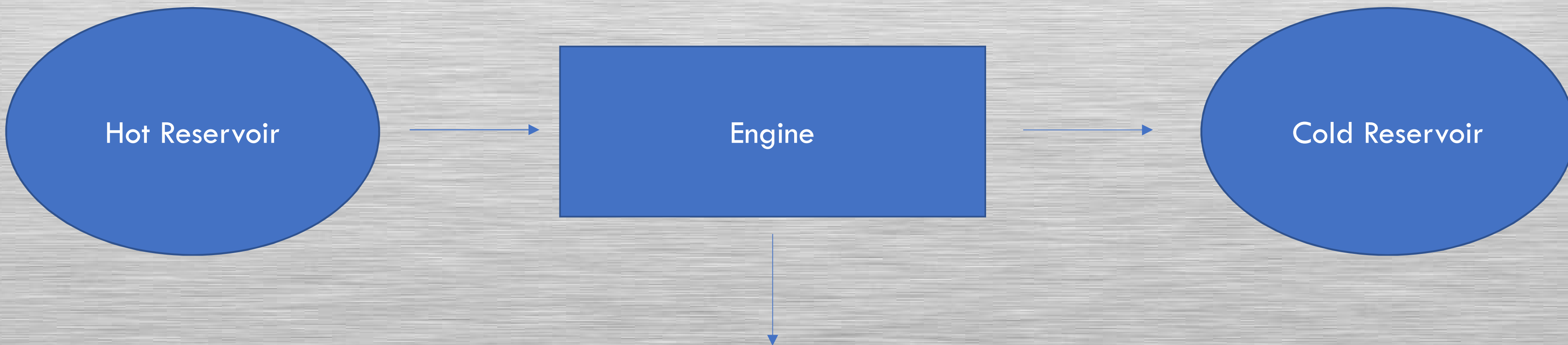
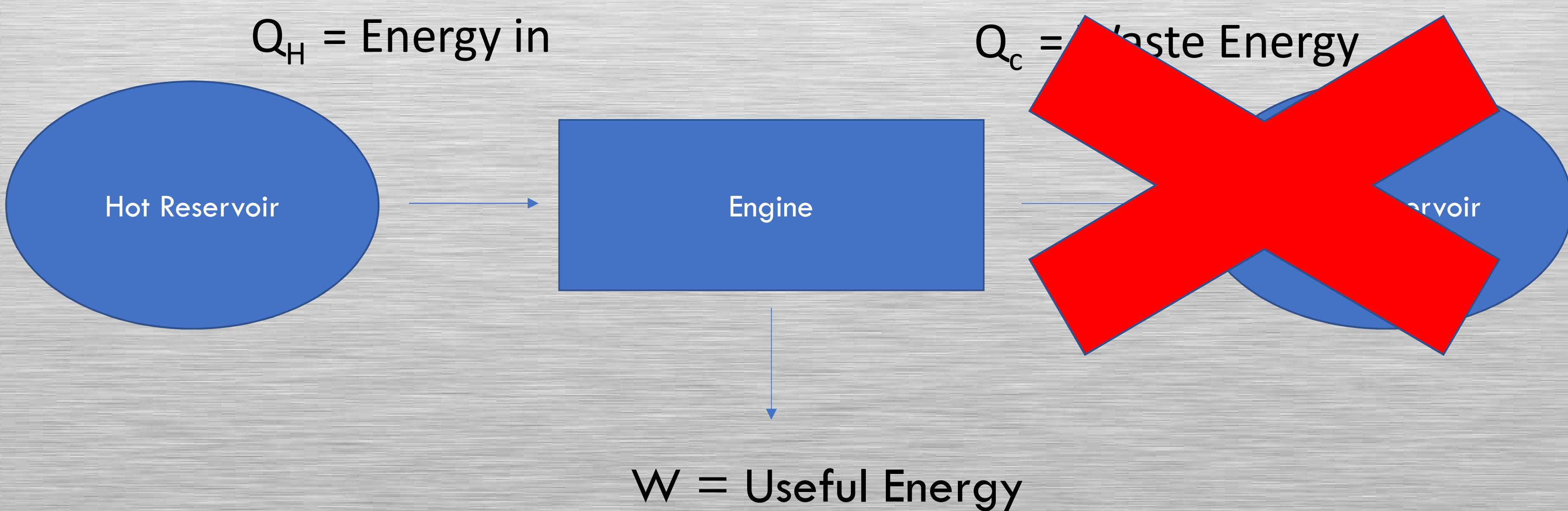


W = Useful Energy

Theoretical Maximum Efficiency

$$\text{Efficiency} = 1 - \frac{Q_C}{Q_H} = 1\ ?$$



Theoretical Maximum Efficiency

$$\text{Efficiency} = 1 - \frac{Q_C}{Q_H} \neq 1$$

- Entropy (S)
- The entropy of the engine plus its surroundings can never decrease

$$\Delta Q = T \times \Delta S$$

*Temperature in Kelvin
Kelvin = Celsius + 273

Theoretical Maximum Efficiency

$$\text{Efficiency} = 1 - \frac{Q_C}{Q_H}$$

$Q_H = T_H \times S$

$Q_C = T_C \times S$

Theoretical Maximum Efficiency

$$\text{Efficiency} = 1 - \frac{Q_C}{Q_H}$$

$Q_H = T_H \text{ x } S$

$Q_C = T_C \text{ x } S$

$$\text{Efficiency} = 1 - \frac{T_C \text{ x } S}{T_H \text{ x } S}$$

$$\text{Efficiency} = 1 - \frac{T_C}{T_H}$$

*Temperature in Kelvin

Theoretical Maximum Efficiency

$$\text{Efficiency} = 1 - \frac{T_C}{T_H}$$

Known as Carnot's Theorem

- Nicolas Léonard Sadi Carnot (1796 – 1832)
- Discovered in 1824 when he was 28
- Carnot is coined "Father of thermodynamics"

Represents the maximum possible efficiency of any heat engine

Theoretical Maximum Efficiency

$$\text{Efficiency} = 1 - \frac{T_C}{T_H}$$

T_H = 1000 Kelvin (727 Celsius)

T_C = 100 Kelvin (-173 Celsius)

Efficiency = ?

Theoretical Maximum Efficiency

$$\text{Efficiency} = 1 - \frac{T_C}{T_H}$$

T_H = 1000 Kelvin (727 Celsius)

T_C = 100 Kelvin (-173 Celsius)

Efficiency = 0.9 = 90%

Theoretical Maximum Efficiency

$$\text{Efficiency} = 1 - \frac{T_C}{T_H}$$

T_H = 1000 Kelvin (727 Celsius)

T_C = 100 Kelvin (-173 Celsius)

Efficiency = 0.9 = 90%

$T_H \approx$ 353 Kelvin (80 Celsius)

$T_C \approx$ 296 Kelvin (23 Celsius)

Efficiency = ?

Theoretical Maximum Efficiency

$$\text{Efficiency} = 1 - \frac{T_C}{T_H}$$

T_H = 1000 Kelvin (727 Celsius)

T_C = 100 Kelvin (-173 Celsius)

Efficiency = 0.9 = 90%

$T_H \approx$ 353 Kelvin

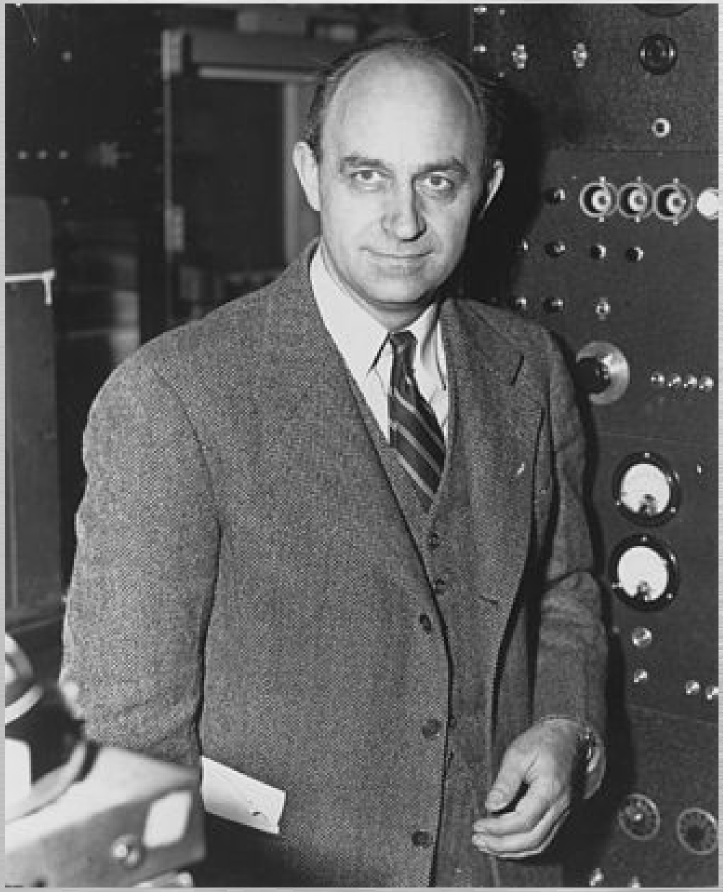
$T_C \approx$ 296 Kelvin

Efficiency $\approx$ 0.84

Theory Versus Real Life

- Theoretical maximum efficiency = 0.84 = 84%
- Realistic efficiency is much lower due to energy losses in friction (heat), vibration (sound), etc
- Real gasoline engine ≈ 0.25 = 25%
- Real steam engine ≈ 0.2 = 20%
- Real diesel engine ≈ 0.35 = 35%

Fermi Approximations



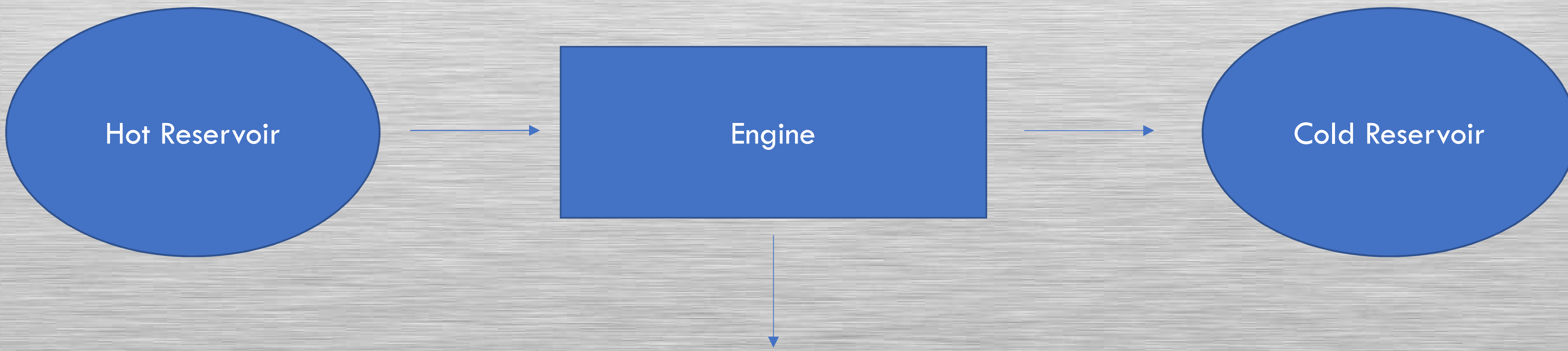
- Named after physicist Enrico Fermi
- Originated from Fermi’s quick estimate of strength of atomic bomb tested in 1945
- Very common method for physicists
- Finding accurate answers with little data (making educated guesses)

Fermi Approximation of Real Efficiency

3. Efficiency = $\frac{W}{Q_H}$

1. Q_H = Energy in

Q_c = Waste Energy



2. W = Useful Energy

Fermi Approximation of Real Efficiency

1. Calculate energy available to the engine

Fermi Approximation of Real Efficiency

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$$Q = m \times C \times \Delta T$$

C = specific heat capacity of water = 4.18 J g^{-1} K^{-1}

m = mass of water

ΔT = temperature change in Kelvin or Celsius

Fermi Approximation of Real Efficiency

1. Calculate energy available to the engine

$$Q = m \times C \times \Delta T$$

Mass of water = 100 g (100 ml)

$C = 4.18\ J\ g^{-1}\ K^{-1}$

ΔT = ?

ΔTime = ?

Energy supplied per second = ?

Fermi Approximation of Real Efficiency

2. Calculate energy used by the engine

Fermi Approximation of Real Efficiency

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$$KE_{rotational} = m \times \pi^2 \times R^2 \times f^2$$

m = mass of rotational part of engine

R = radius of wheel

f = frequency of rotation in revolutions per second

Fermi Approximation of Real Efficiency

2. Calculate energy used by the engine

$$KE_{rotational} = m \times \pi^2 \times R^2 \times f^2$$

Mass of rotational part of engine = 200 g = 0.2 kg

Radius of wheel = 4.5 cm = 0.045 m

Frequency of rotation = ?

$KE_{rotational}$ = ?

Number of revolutions it takes to stop from 200 revs per min = 8 revolutions

Energy per revolution = ?

Energy used per second = ?

Fermi Approximation of Real Efficiency

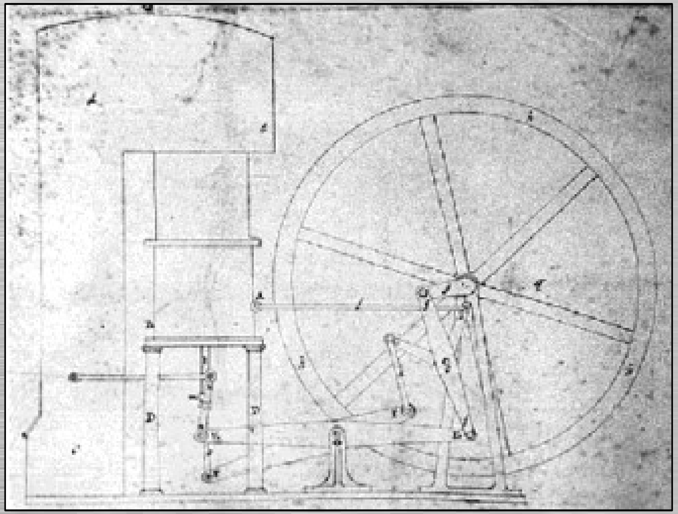
3. Calculate the real efficiency

$$\text{Efficiency} = \frac{Benefit}{Cost}$$

Theoretical maximum efficiency = 84%

Stirling Engine

- Dr. Robert Stirling (1790 – 1878)
- Invented in 1816
- Created for a safer alternative to steam engines



Why Stirling Engine?

- Silent operation
- No fossil fuels required
- Abundance of heat sources
- Abundance of working fluid (air or hydrogen gas)
- Very Eco-friendly (no waste products)
- Easy maintenance
- Price
- Lack of variation of power once built
- Low power to weight ratio (heavy & bulky)

Displacer-type Stirling Engine

[How does it work?]

Steam Engine

- Very powerful
- Requires high pressure – can be very unsafe
- Requires combustion of fuel for heat
- Heavy, bulky, and loud
- Takes a long time to start
- Not Eco-friendly
- Low efficiency

Gasoline & Diesel Engines

- High power to weight ratio (light & compact)
- Can be started immediately
- High efficiency
- Relatively safe
- Loud
- Requires combustion of fuel
- Not Eco-friendly

Future of Stirling engines

- Reduction of pollution
- Silent generation of electricity in the background
- Use with solar panels
- Space travel

Questions?