# MEEN 5110/4110: Alternative Energy


## Lecture 02

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# Thermodynamic Fundamentals of Energy

Daily experience gives us what “energy” is, but the term “energy” is difficult to adequately define.

The great paradox: <u>Energy</u> is the capacity for doing <u>work</u>, and <u>work</u> is any mode of <u>energy</u> transfer (other than heat) capable of changing the state of a system.

Energy is conserved. The total energy in the universe is constant.

Energy can be transformed from one state to another, but it cannot be created or destroyed.

Manifestations of energy with the potential to perform work include chemical potential, electrical potential, mechanical potential, and thermal potential.

# Thermodynamic Fundamentals of Energy

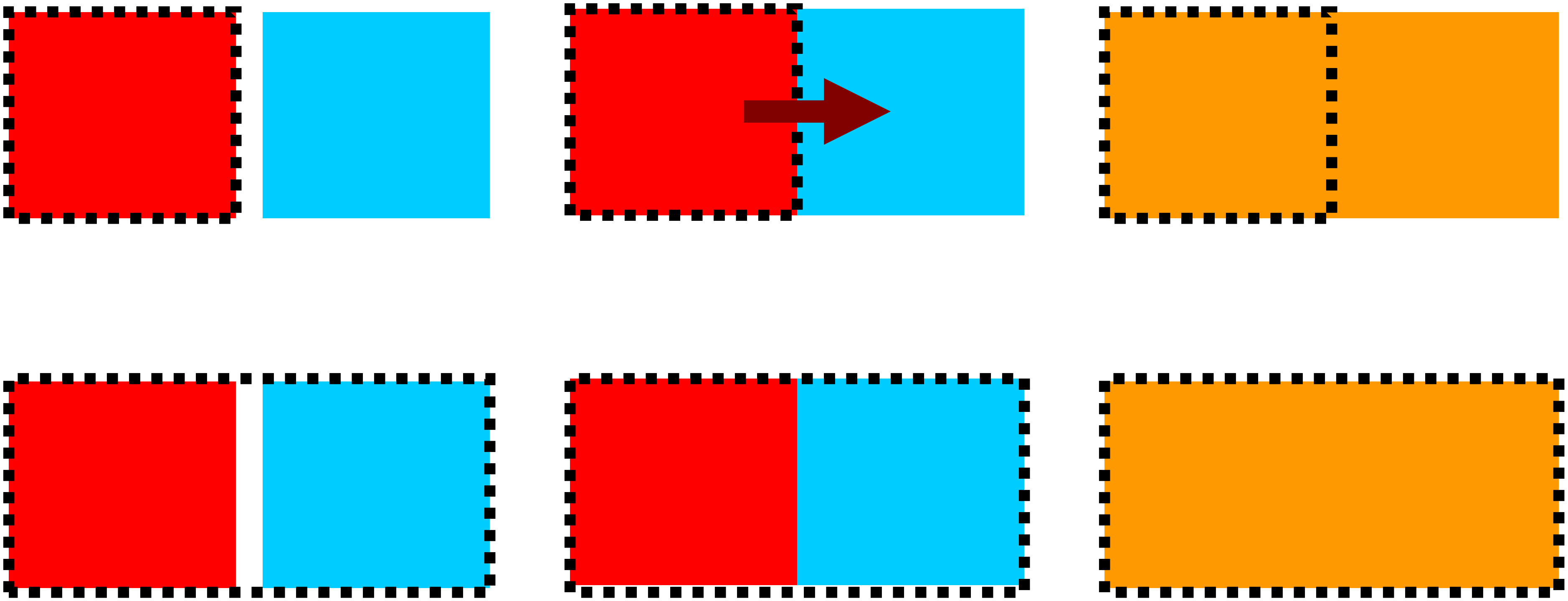
A “thermodynamic system” is any arbitrarily-defined chuck of the universe.

By defining a system, we must set the boundaries of that system. System boundary selection **is critical** to following energy flows correctly.

Energy flows into and out of a system by crossing the arbitrarily-defined system boundaries.

# Thermodynamic Fundamentals of Energy

Qualitative example showing importance of system boundary selection.



Although both processes are identical, the total energy of the top system has changed while the total energy of the bottom system remains fixed.

# Thermodynamic Fundamentals of Energy

Heat is a special form of energy that also contains entropy.

MIT Professor Seth Lloyd put is best: entropy represents the number of bits of information registered by atoms in a system. Processes that increase the complexity of a system increase its information content, and hence increase its entropy.

While the complexity (entropy) of a system can be reduced, this local entropy reduction can only occur at the expense of an increase in complexity (entropy) in the environment surrounding the system.

The magnitude of entropy increase in the environment always exceeds the magnitude of entropy decrease in the local system.

Thus, while the energy content of the universe is conserved, the entropy content of the universe continues to increase.

# Thermodynamic Fundamentals of Energy

Qualitative example showing how entropy decease in a local system increases entropy in the surrounding environment.



When a computer is off, it is not organizing information, and it is in thermal equilibrium with the environment. When turned on, the computer organizes information (reduces entropy). The local entropy reduction in the computer results in an environmental entropy increase as the computers heat up the room.

# Thermodynamic Fundamentals of Energy

Entropy is the thermodynamic property that prevents the same energy from being re-used over and over again.

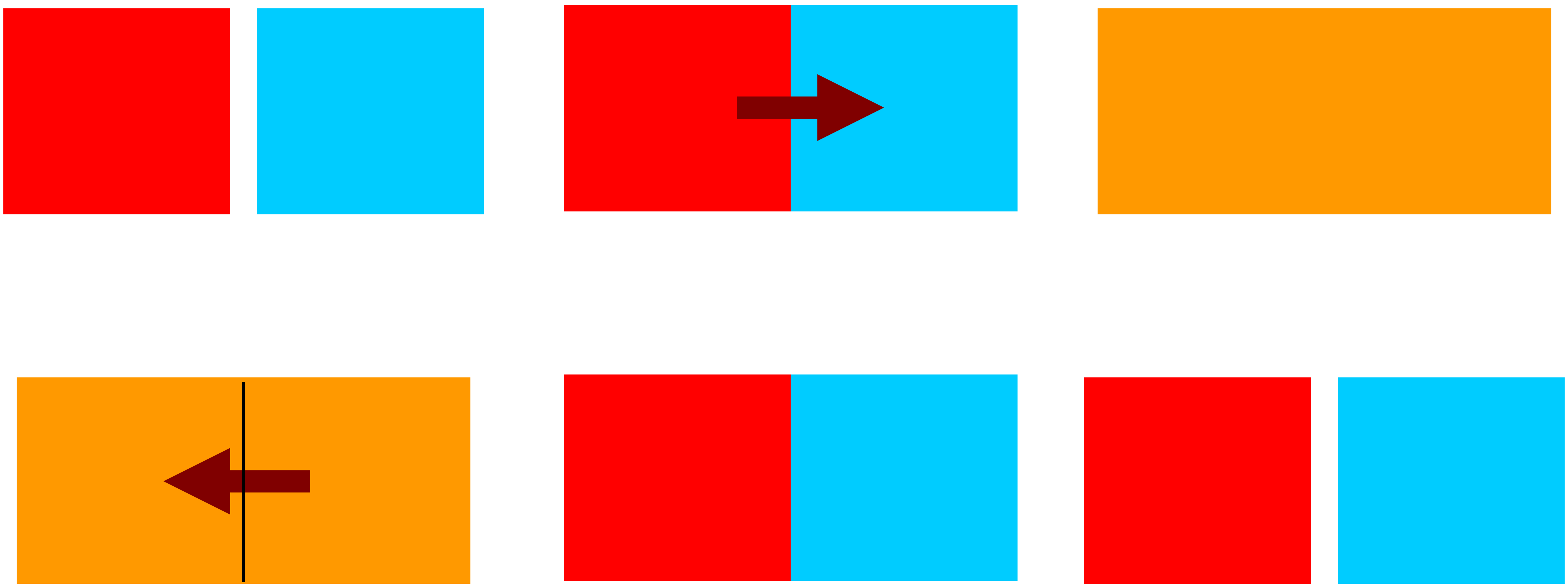
For our purposes, entropy is a thermodynamic variable of state that can be loosely thought of as the “quality” of a reservoir of heat.

Entropy also controls the direction of thermodynamic processes.

These processes naturally run the direction that increases entropy. This directionality is loosely referred to as the “thermodynamic arrow of time”.

# Thermodynamic Fundamentals of Energy

Qualitative example showing directionality of process due to entropy



The top process, two blocks of dissimilar temperature equilibrating, is a familiar process. Never would two blocks at equal temperature spontaneously grow hot and cold respectively

# Thermodynamic Fundamentals of Energy

Entropy is generated by processes that add disorder (information) to a system; for example: temperature gradients, friction, and mixing. These disorder-adding processes are called <u>irreversible processes</u>.

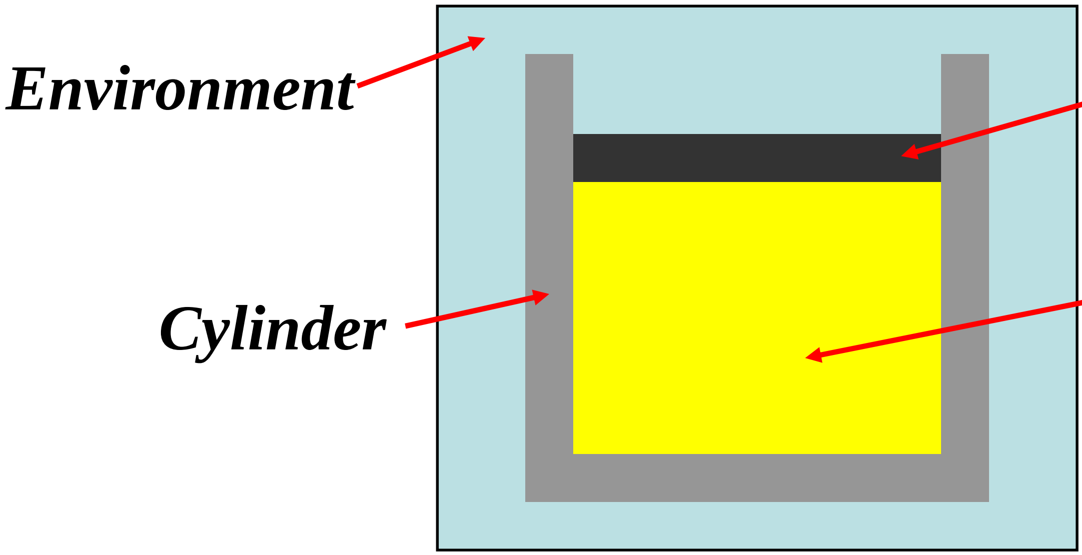
Since the entropy of a system cannot be reduced without creating even more entropy elsewhere, the term "irreversible process" literally means that the system and its surroundings cannot be restored to the same thermodynamic state once an irreversible process has occurred.

All real thermodynamic processes generate entropy, but we define a hypothetical "reversible process" as system undergoing a change of state that generates no entropy. A system and its surroundings undergoing a reversible process can be restored to their original state if the process is simply run in reverse.

# Thermodynamic Fundamentals of Energy

A “Closed System” is a system defined such that none of the matter within the system boundaries can cross the system boundary or interact directly with the environment.

An excellent example of a closed system is a frictionless piston-cylinder filled with ideal gas.

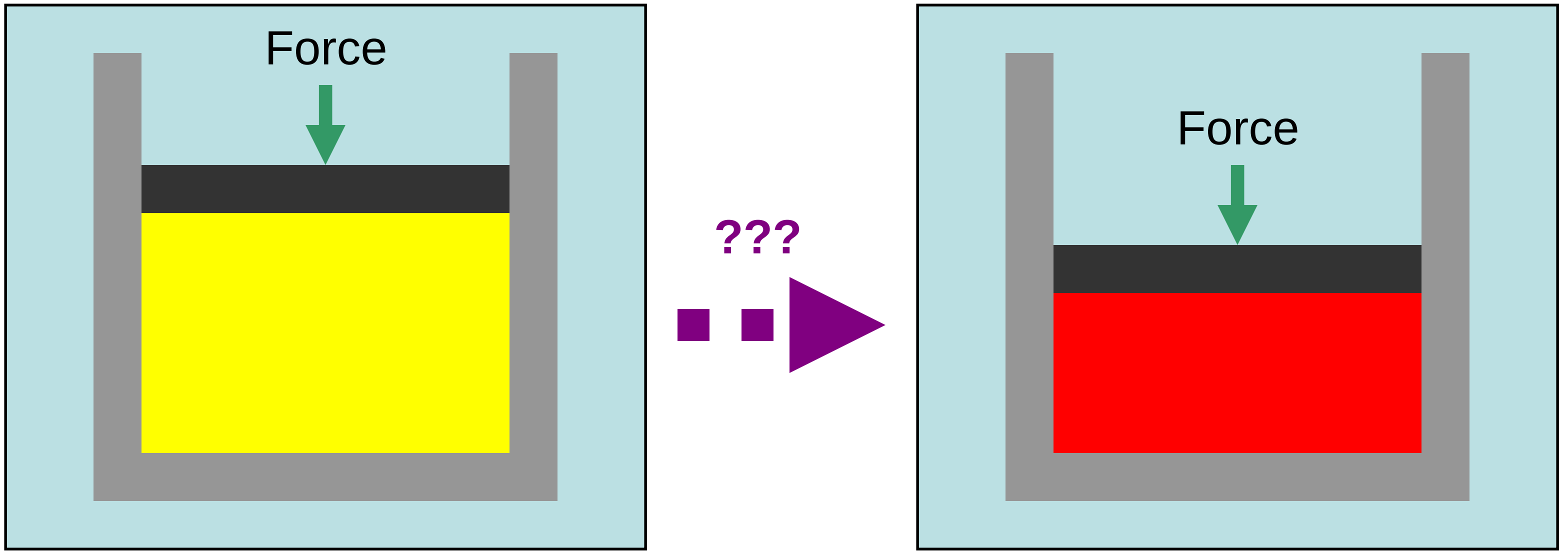



If the system boundary is the piston-cylinder, the ideal gas can independently exchange both work and heat with the environment.

# Thermodynamic Fundamentals of Energy

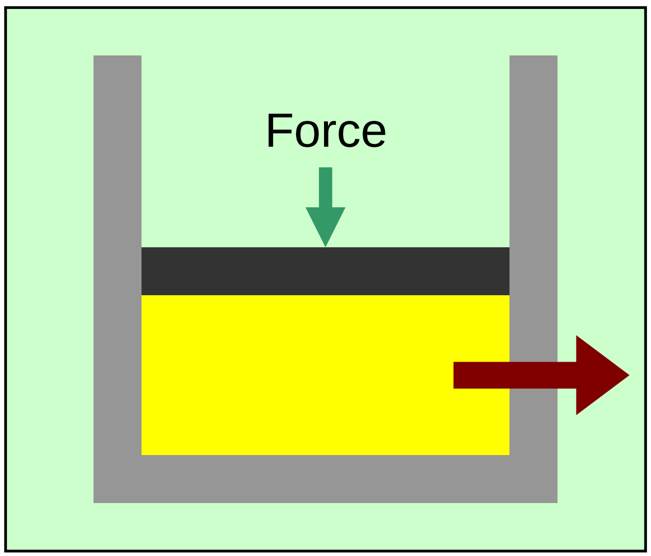
Depending on the specific parameters set, ideal gas inside a piston-cylinder is an excellent conceptual tool for thermodynamic thought experiments.

For example, if the piston is compressed, what happens to the temperature of the ideal gas inside?

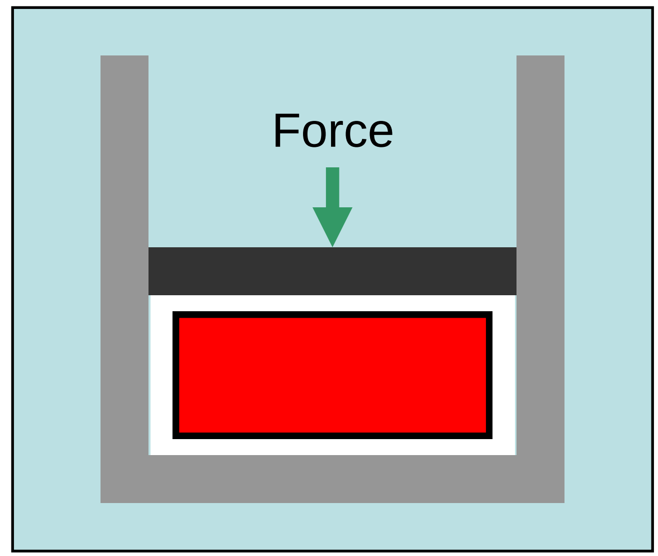


# Thermodynamic Fundamentals of Energy

The result depends on at least two factors: 1) whether the application of force was reversible/irreversible and 2) whether the walls of the container were adiabatic [insulated against transmission of heat].




Isothermal Compression



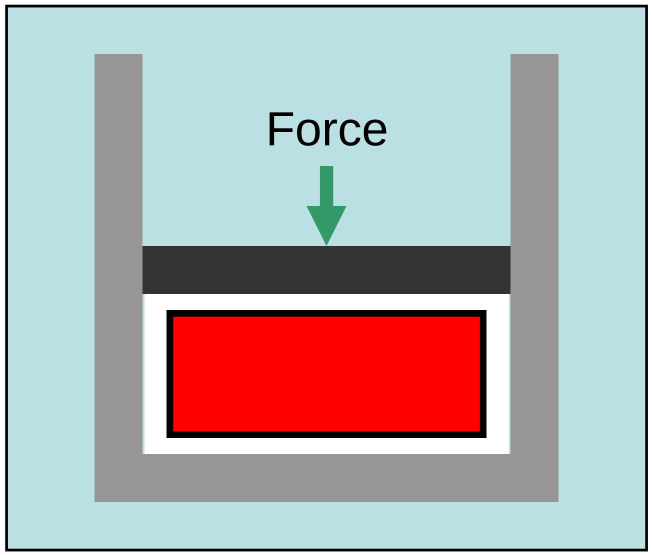

Adiabatic Compression

# Thermodynamic Fundamentals of Energy

Consider the energy transfer occurring in an adiabatic compression

The Equation of State for an ideal gas is $\Delta U = mC_p \Delta T$ where U is the internal energy of the gas, m is its mass, $C_p$ is its specific heat, and T is its temperature.

The amount of work done on (energy transferred to) the system by the surroundings is F x d, where F is the force and d is the distance traversed by the piston.



Adiabatic Compression

This energy transfer process induces a temperature increase in the gas.

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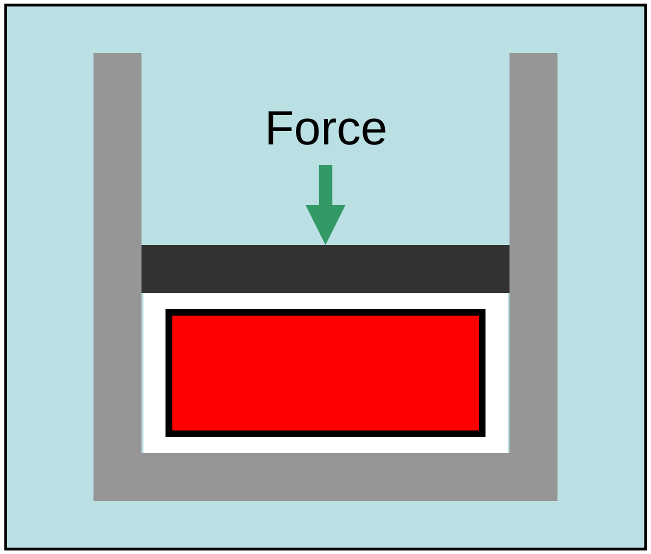

Adiabatic Compression

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# Thermodynamic Fundamentals of Energy

Work done to compress a volume of gas is often referred to a PV work because the environment has to push the closed system out of the way.

$$W_{PV} = \int_{V_o}^{V_f} P(V)\,dV$$

Any other kind of work done to or by the system is referred to as "shaft work", $W_{SH}$, in reference to the turning shaft of a turbine.

Despite the mechanical reference, shaft work includes electrical work, chemical work, and essentially all energy processes that are not PV work.

# Thermodynamic Fundamentals of Energy

An “Open System” is a system defined such matter can flow freely across the system boundaries, carrying energy and entropy along with it.

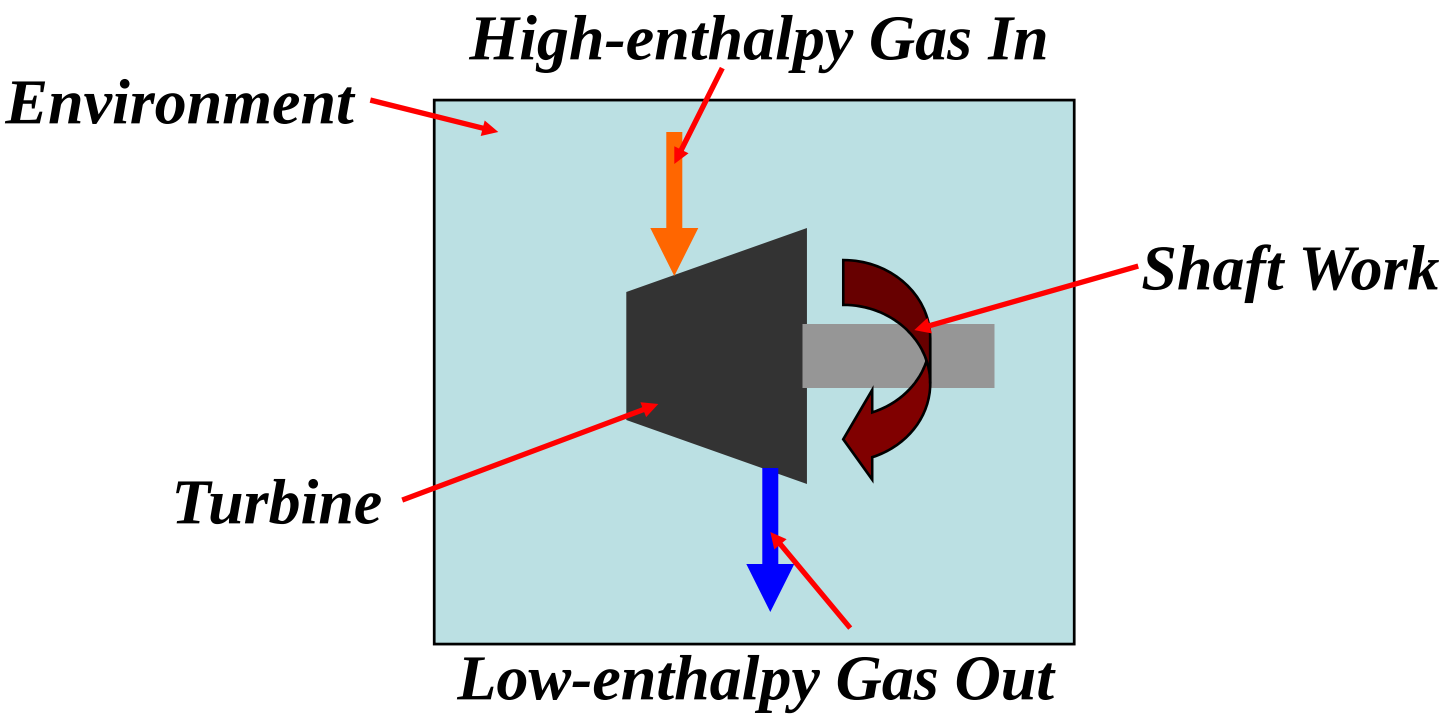
For open systems, it is convenient to define a thermodynamic state variable called “enthalpy”, H, which represents the sum of internal energy plus PV work.

$$H = U + PV$$

where P is most often taken as the pressure within the system.

# Thermodynamic Fundamentals of Energy

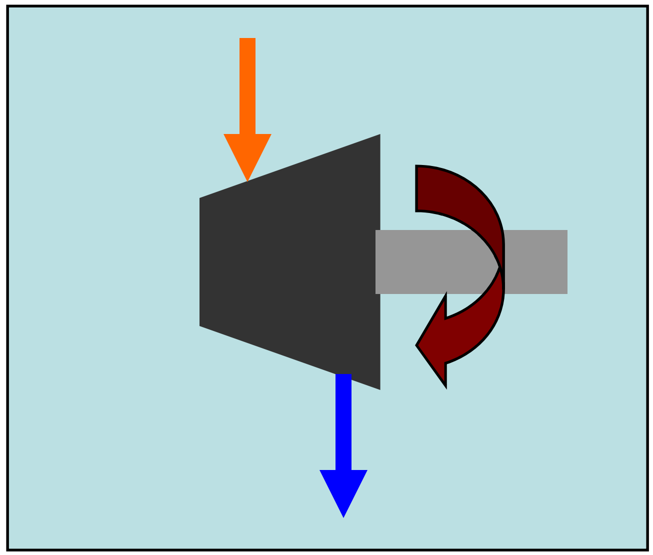
An excellent example of an open system is a frictionless, lossless gas turbine performing shaft work with ideal gas running through it.




If the system boundary is the gas turbine, this system can extract enthalpy from the ideal gas to generate shaft work. <u>Work extraction processes do not extract entropy.</u>

# Thermodynamic Fundamentals of Energy

Provided the gas turbine is well-insulated [adiabatic], the change in enthalpy of the ideal gas between the inlet and the outlet converts to shaft work.



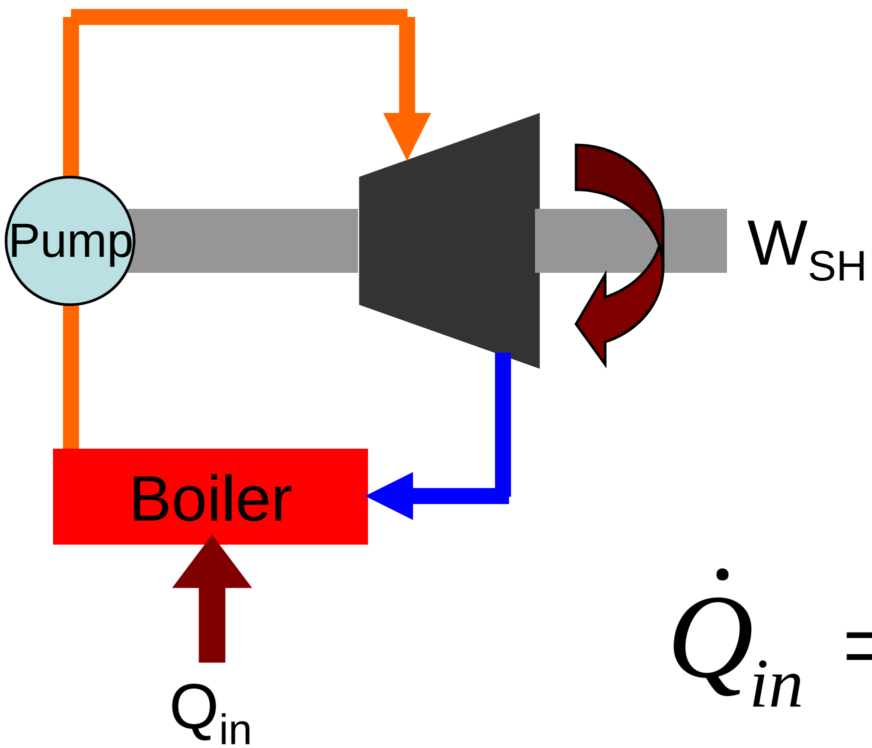
$$W_{SH} = H_{out} - H_{in}$$

Note that while there is still enthalpy (energy) in the outlet stream, it would be difficult to extract more useful work because the enthalpy (energy) is of low quality, in other words it is high in entropy.

# Thermodynamic Fundamentals of Energy

Thermodynamic cycles can be either closed or open systems, but the hallmark of these cycles is that the working fluid must go through a complete thermodynamic cycle with each traverse of the system.

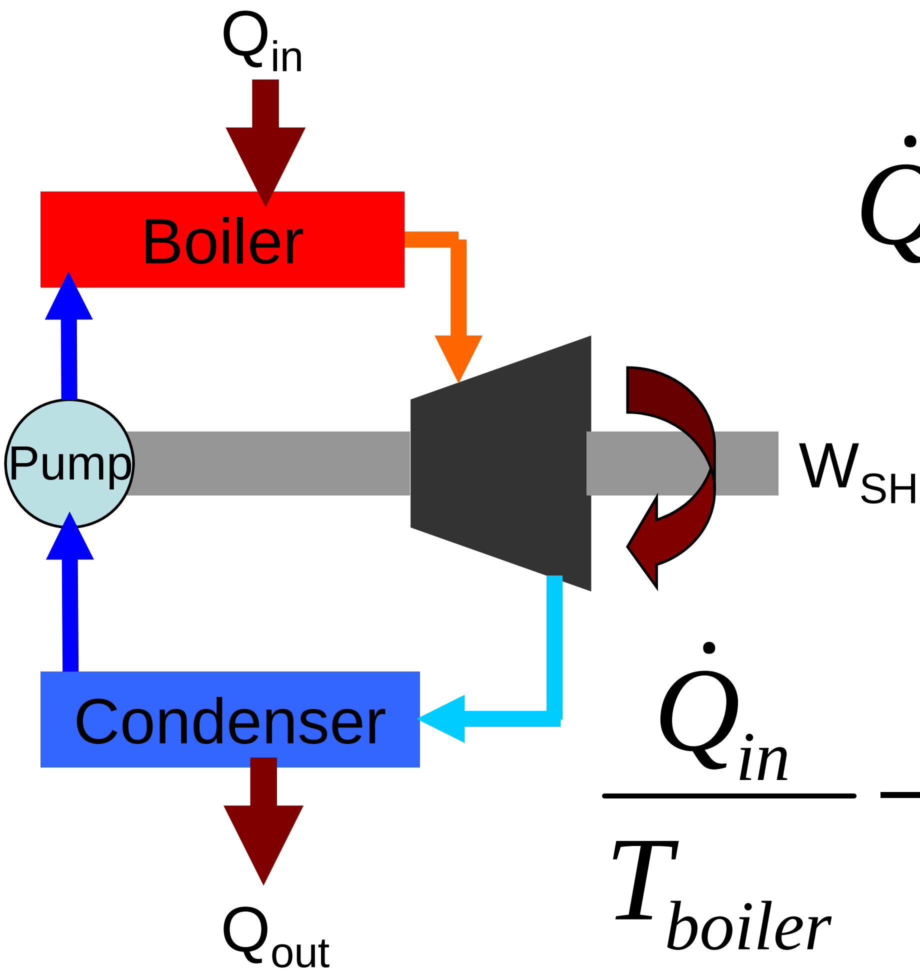
Is there something wrong with this cycle?




$$\dot{Q}_{in} = \dot{W}_{SH}$$

# Thermodynamic Fundamentals of Energy

There must be a mechanism to reject entropy from a cycle to return the working fluid to its original thermodynamic state on each traverse of the system.




$$\dot{Q}_{in} - \dot{Q}_{out} = \dot{W}_{SH}$$

$$\frac{\dot{Q}_{in}}{T_{boiler}} - \frac{\dot{Q}_{out}}{T_{cond}} = \Delta\dot{S}_{cycle} = 0$$