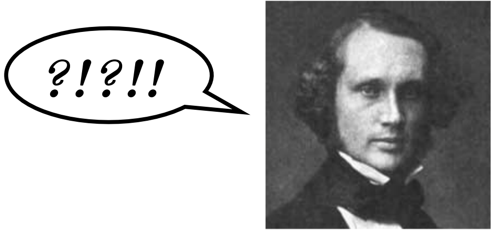
13. The Science of Energy: Chaps 5-7



1. William Thomson's Dilemma

- How to reconcile Joule with Carnot.

- *Conflicting Claims:*

  - *Carnot*: Work produced by heat engines requires the fall of heat from hot place to cold place.
  - *Joule*: Heat can be converted into work -- no "fall" required.

- *Thomson's Conflicting Sympathies*:
  - Pro-Carnot: Absolute temp scale, melting point of ice.
  - Pro-Joule: Paddle wheel explains fluid friction.

- *Key Assumption of Thomson and Carnot:*

  Any gain or loss of heat depends *only* on the initial and final states of a body, and not on the path between these states.

- This makes trouble for Joule's interconvertibility thesis:

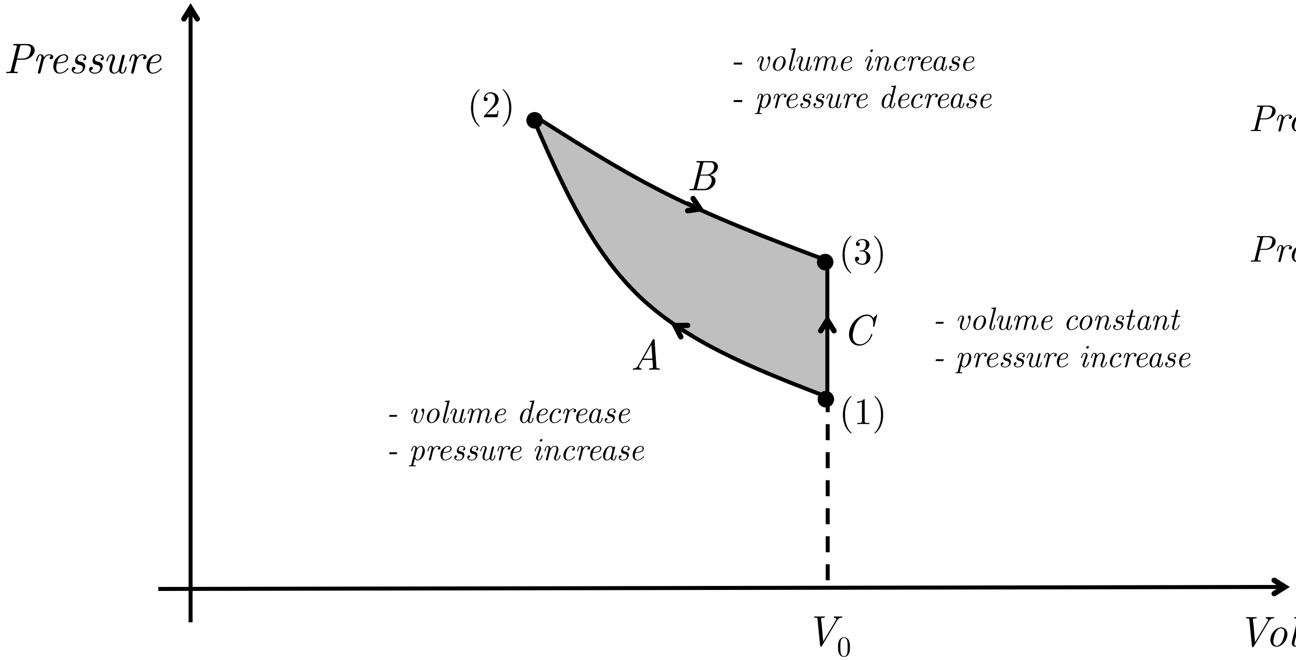
- Thomson's Thought Experiment (1848):

  Process #1: (Reversible compression and expansion producing work.)

  - Path A: *Piston of cool air with volume V_0 in initial state (1) is compressed so that temp rises to that of sea. Piston then plunged into sea.*
  - Path B: *Under const temp, volume of air expands back to V_0 and pressure drops. Final state (3): greater temp/pressure, same volume as (1).* ***Work done.***

  Process #2: (Irreversible conduction producing no work.)

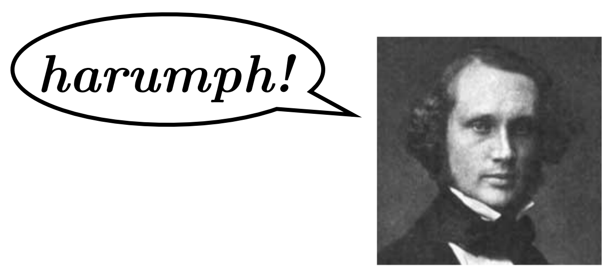
  - Path C: *Piston of cool air with volume V_0 in initial state (1) is plunged directly into sea. Temp rises via conduction to final state (3).* ***No work done.***



Process #1: Work done = area enclosed by ABC.

Process #2: No work done.

- *Upshot*: Two distinct processes that produce the *same* change of state. But only process #1 produces work. What happened to the work in process #2?
- Big mystery *if*:
  (a) Same amount of heat is involved in both processes, *and*
  (b) Work cannot be created/destroyed, *and*
  (c) Heat and work are interconvertible.
- Joule's response: Reject (a)! Allow that the amount of heat associated with a process depends *not* on the initial and final states, but on the *path taken* between these states.
- Thomson is unpersuaded!



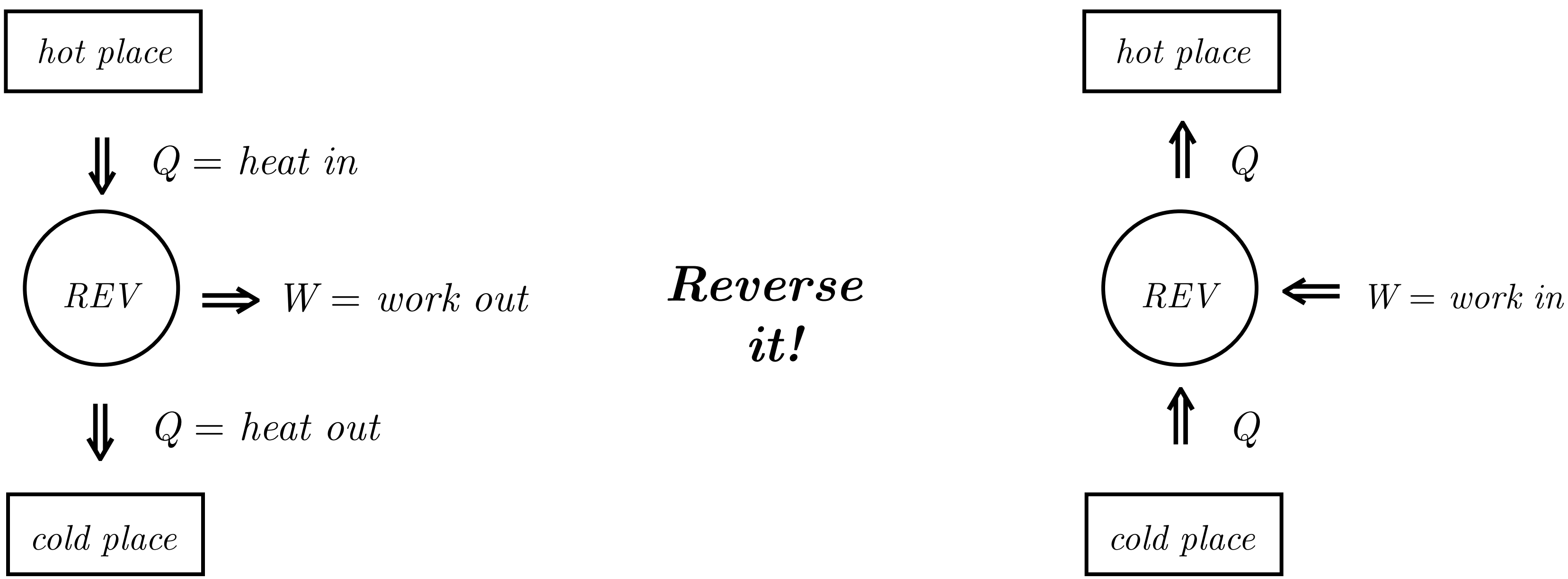
2. Thomson's (1849) "An Account of Carnot's Theory"

- *Carnot's "Fundamental Principle"*: No heat is lost in the operation of a heat engine (recall water analogy).

- *Concept of a "perfect thermo-dynamic engine"*:

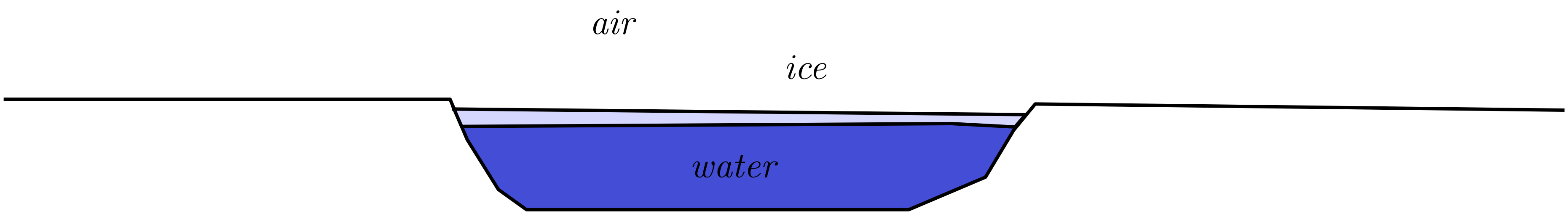
> "A perfect thermo-dynamic engine is such that, whatever amount of mechanical effect it can derive from a certain thermal agency; if an equal amount be spent in working it backwards, an equal reverse thermal effect will be produced."

- Call this a *reversible* heat engine.



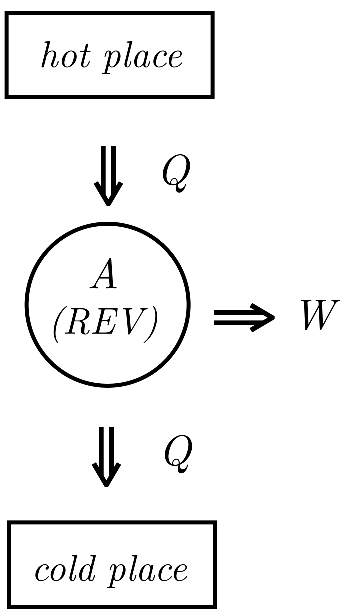
Aside: Reversible vs irreversible processes

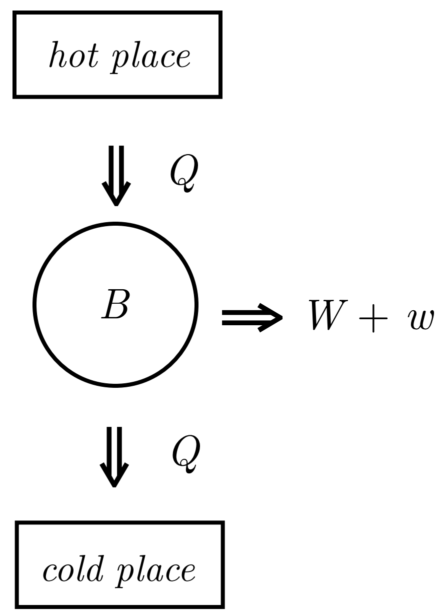
- A reversible process is a process minutely away from equilibrium.
- *Practical Check*: To determine if a process is reversible, record it on video and run video backwards. If the backwards video represents something that's physically possible, then the process is reversible.
- *Example:* Consider a frozen pond at $32°F$.



- Process I: Air warms minutely. Ice melts slowly.
  - Reversible! (Video check!)
  - Reverse of Process I: Ice forms slowly. Air cools minutely.
- Process II: Air is heated quickly to $75°F$. Ice melts rapidly.
  - Irreversible!
  - Backward video: Ice forms rapidly in $75°F$ weather causing air temperature to plummet!

- *Carnot Claim #1:* The maximum efficiency of *any* heat engine is equal to that of a reversible engine operating between the same hot and cold places.
- *Proof*:
  - Suppose we have a reversible engine A that produces work W.
  - Suppose there is a more efficient engine B between the same hot and cold places (B uses the same heat as A and produces more work).
  - Now reverse A and hook it up to B.





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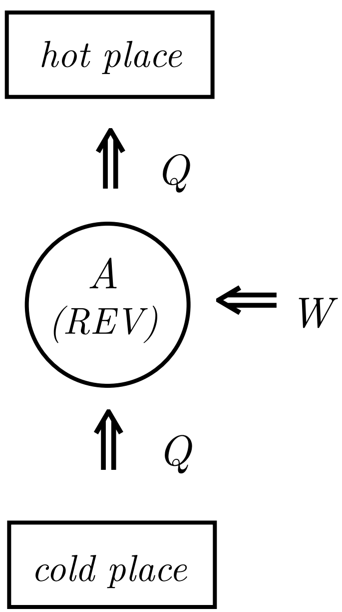

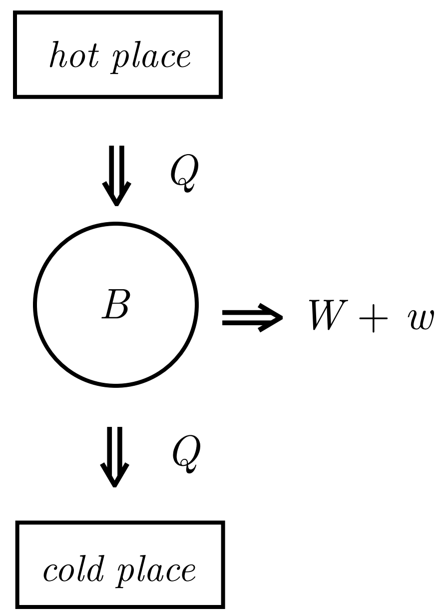

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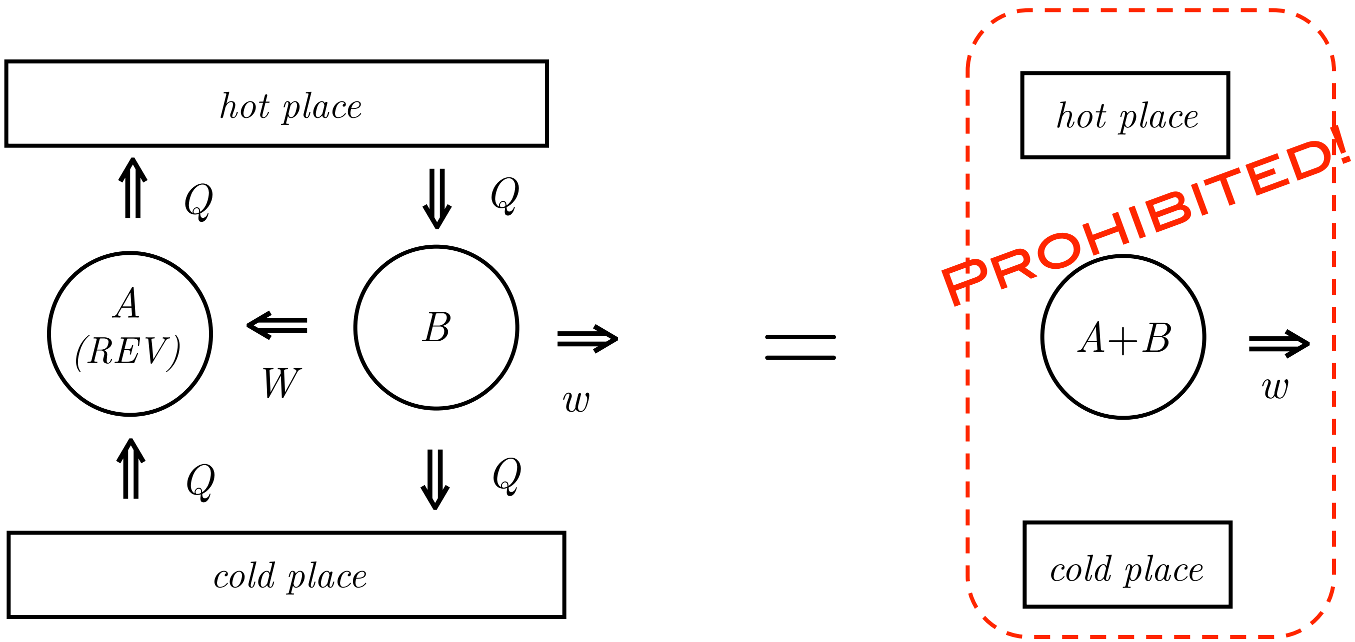
  - Now reverse A and hook it up to B.
  - Engine $(A+B)$ does work w for free (no net fall of heat required)! But, sez Carnot, this is impossible: a perpetual motion machine!



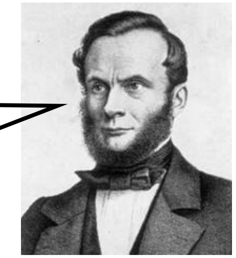
- *Smith's Analysis:*
  - Carnot rejects the existence of perpetual motion machines based on empirical evidence (French enlightenment ideals).
  - Thomson and Joule reject creation/destruction of *vis-viva* (work) based on appeals to God (Christian metaphysical ideals).
  - Thomson's concept of a perfect thermodynamic engine reflects Presbyterian imperatives:
    - standard of perfection (reversible ideal engines) to which humans can only strive and aspire
    - imperfections (irreversible real engines) lie with humans

3. Clausius Reforms Carnot

(1850) "On the Moving Force of Heat"

- *1st Maxim (Joule's equivalence of work and heat)*:

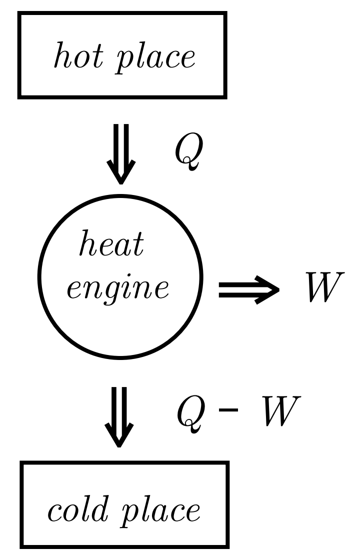
> "In all cases where work is produced by heat, a quantity of heat proportional to the work done is expended; and inversely, by the expenditure of a like quantity of work, the same amount of heat may be produced."



Rudolph Clausius

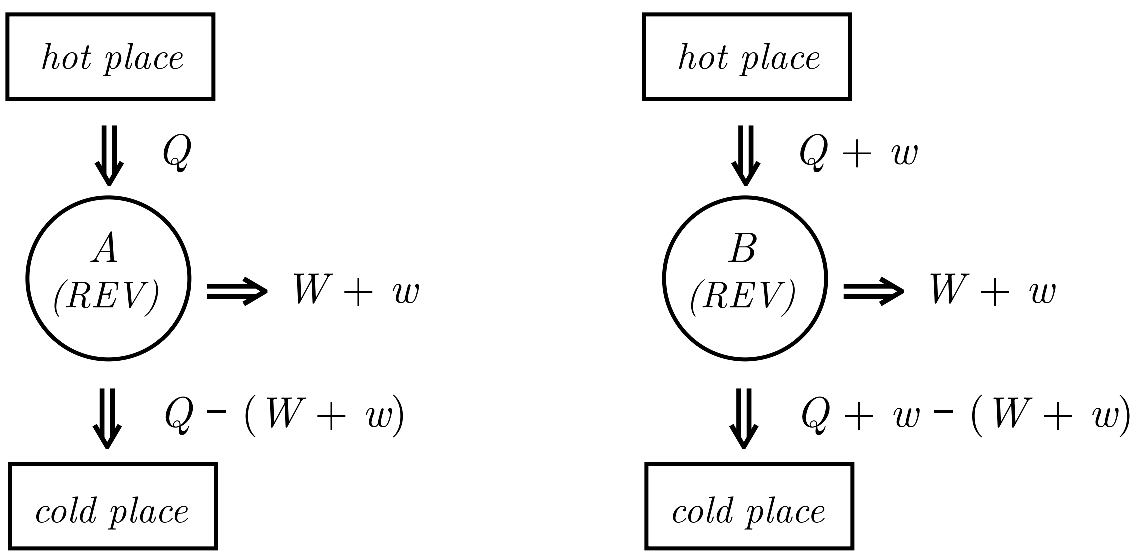
- *Carnot's Assumption:* In a heat engine, work is produced by the transmission of heat from a hot place to a cold place, *with no loss/gain of heat as a result.*
- *Clausius*: Accepts first clause as *2nd Maxim*, but rejects second clause.

- *Consequences:*
  - Allows that the amount of heat associated with a process depends on the path taken and *not* on the initial and final states.
  - If Q_{in} is the heat falling from the hot place, and W is the work produced, then the heat expended to the cold place is $Q_{out} = Q_{in} - W$.



- <u>*Carnot Claim #2:*</u> In an ideal (*i.e.*, reversible) heat engine, the work produced depends only on the quantity of heat transmitted (*i.e.*, the temperature of the hot and cold places), and not on the working fluid.

- <u>*Clausius' Proof:*</u>
  - Suppose A and B are reversible engines operating between the same hot and cold places, and A is more efficient (in the sense that B requires more heat to produce the same amount of work that A produces).
  - Reverse B and hook it up to A.



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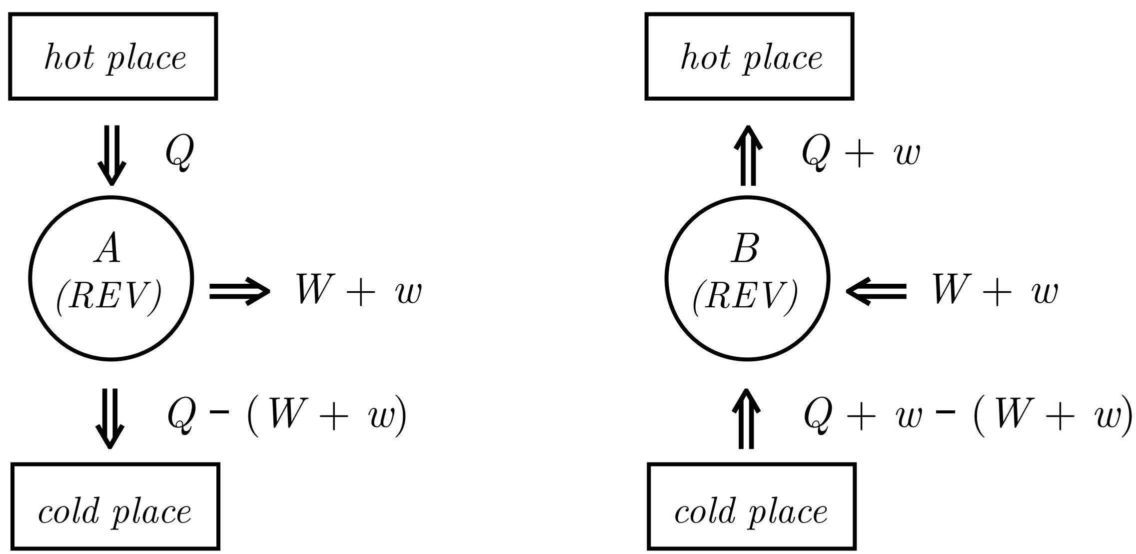

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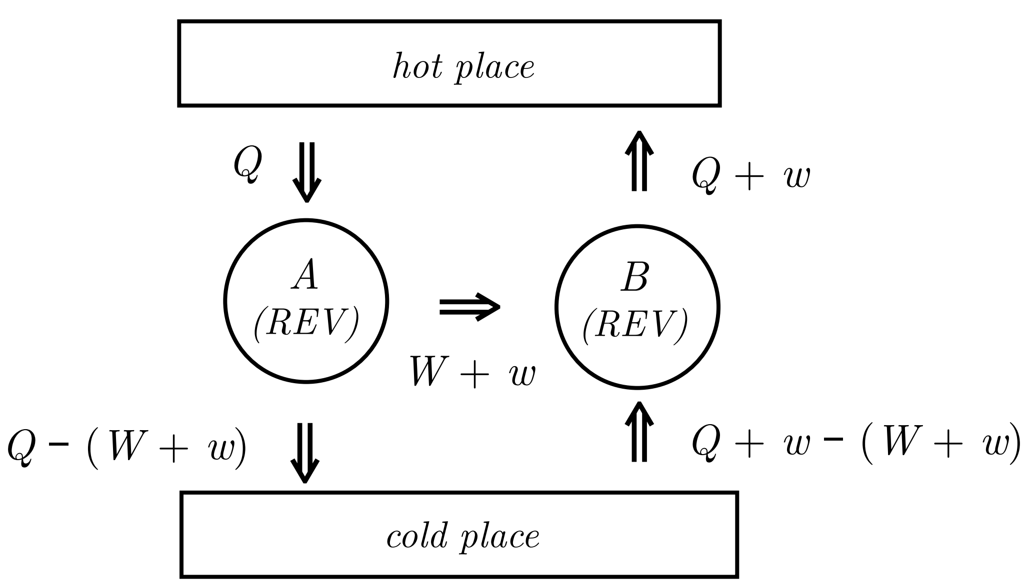
  - Engine (A+B) takes an amount of heat w from a cold place to a hot place with no work input!



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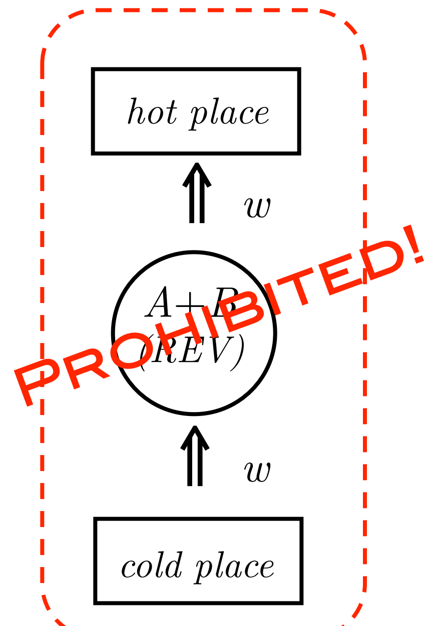
  - Engine $(A+B)$ takes an amount of heat w from a cold place to a hot place with no work input!
  - Clausius: This is impossible!

"[Heat] everywhere exhibits the tendancy to annul differences of temperature, and therefore to pass from a warmer body to a colder one."



3. Thomson's (1851-55) "The Dynamical Theory of Heat"

- *Prop. 1 (Joule):*

"When equal quantities of mechanical effect are produced by any means whatever from purely thermal sources, or lost in purely thermal effects, equal quantities of heat are put out of existence or are generated."

- Officially converts to Joule! But what happens to work during conduction or friction?

- *Prop. 2 (Carnot & Clausius):*

"If an engine be such that, when it is worked backwards, the physical and mechanical agencies in every part of its motions are all reversed, it produces as much mechanical effect as can be produced by any thermodynamic engine, with the same temperature of source and refrigerator, from a given quantity of heat."

- *In other words (Carnot Claim #1):* The most efficient heat engine for any given hot and cold places is a reversible heat engine.

- Thomson now seeks a theological and cosmological foundation for Prop. 2 (isn't satisfied with Carnot's or Clausius' reasoning).

- *Thomson on conduction and friction:*

"The fact is, it may I believe be demonstrated the work is lost to man irrecoverably; but not lost in the material world. ... Although no destruction of energy can take place in the material world without an act of power possessed only by the supreme ruler, yet transformations take place which remove irrecoverably from the control of man sources of power which, if the opportunity of turning them to his own account had been made use of, might have been rendered available."

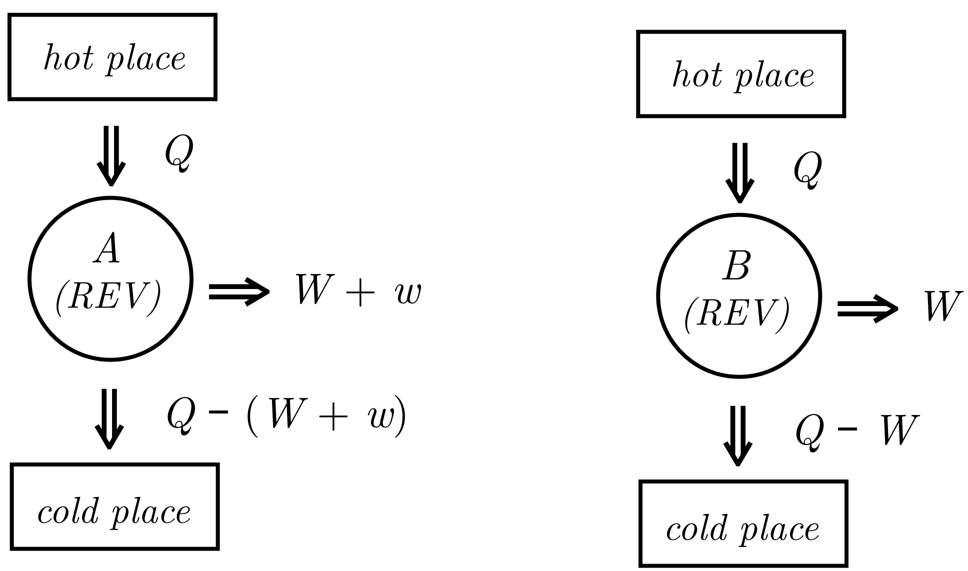
- *Smith's gloss:* God has ordained for nature two basic laws of energy: its conservation and its progressive transformation.

- *Thomson:* "Everything in the physical world is progressive."
- *Smith's gloss:* Reflects a Presbyterian economy of nature.
  - Energy = gift from God.
  - Only God can restore it.
  - Humans can transform it and distribute it, but in doing so lose some of it.

- *Thomson now claims:*

- *In other words:* No heat engine can produce as its sole effect the complete conversion of heat to work (there must be "exhaust" heat).

- *Thomson's Proof of Prop. 2*:
  - Let A and B be reversible engines with same hot and cold places, and let A be more efficient (in the sense that A produces more work than B for the same heat in).
  - Reverse B and hook it up to A.



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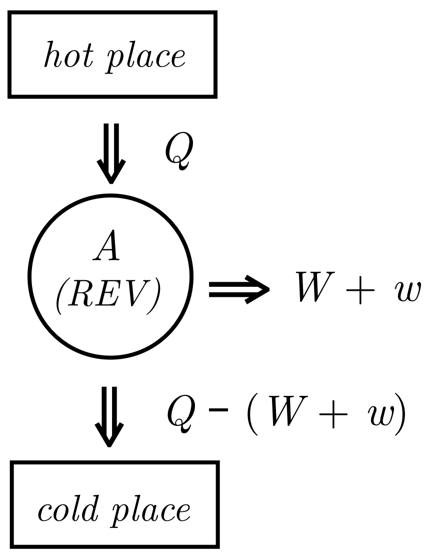

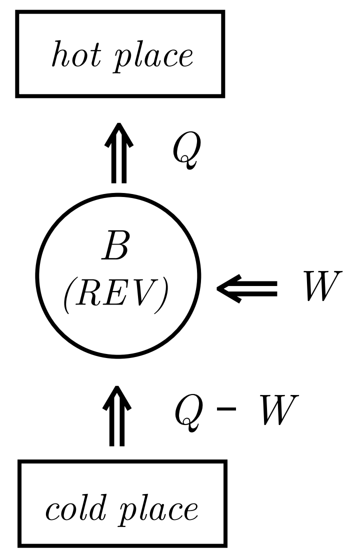

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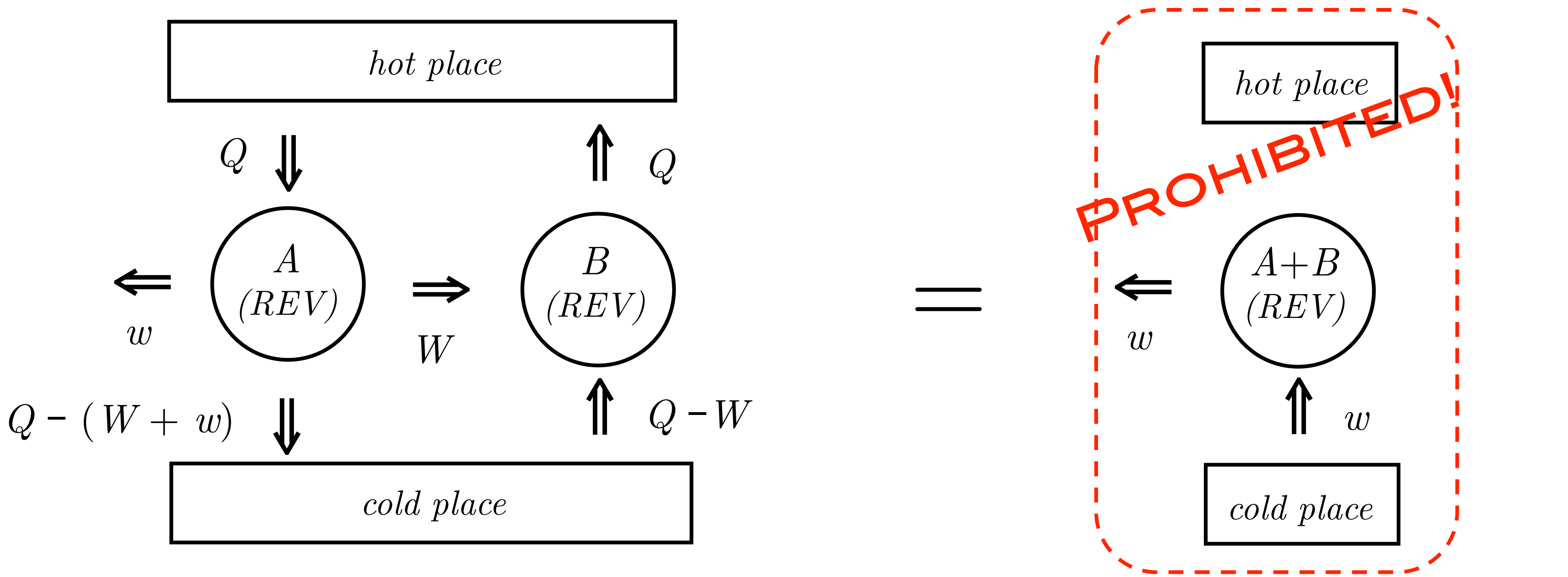
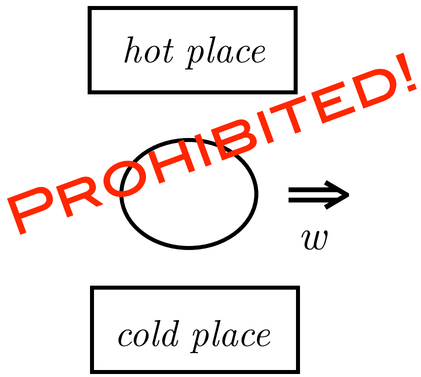
  - Let A and B be reversible engines with same hot and cold places, and let A be more efficient (in the sense that A produces more work than B for the same heat in).
  - Reverse B and hook it up to A.
  - Engine $(A{+}B)$ converts heat to work with no exhaust.

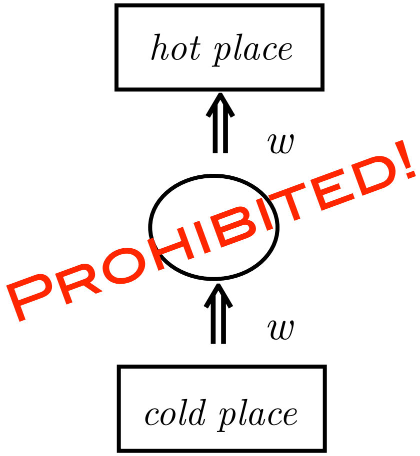


Three types of prohibited heat engines

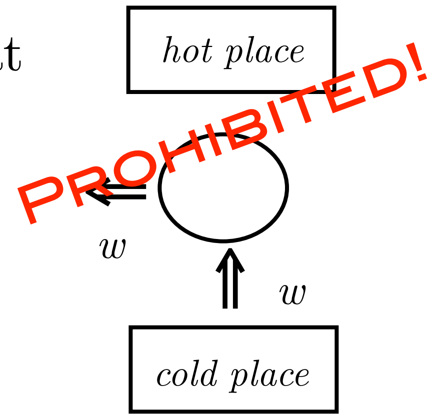
(a) *Carnot*: Work done without fall of heat (perpetual motion machine):



(b) *Clausius*: Heat transfer from cold to hot place with no work input:



(c) *Thomson*: Conversion of heat to work with no exhaust:



- *Aside*: Prohibitions on (b) and (c) are known today as the Clausius and Kelvin forms of the 2nd Law, respectively.

4. Helmholtz, "Kraft", and Conservation of Energy

Herman von Helmholtz

- *Helmholtz (1847) "On the Conservation of Force":*
  - force ("kraft") = cause of motion
  - *vis viva* = measure of force
  - All causes of motion reduce to attractive/repulsive forces that depend on distances between point sources of matter.
  - Conservation of force extends to all forces in nature.
- *Thomson (1852):* Appropriates Helmholtz's ideas in terms of "conservation of mechanical energy".
  - Mechanical energy is measured by its effect (work).
  - The *intensity* of energy is represented by force (a potential gradient).

"We may consequently regard it as certain that, neither by natural agencies of inanimate matter, nor by the operations arbitrarily efected by animated Creatures, can there be any change produced in the amount of mechanical energy in the Universe."

  - Rankine (1853) rephrases this as "The law of the conservation of energy".

Cultural significance of new "energy physics"

- British Association for the Advancement of Science (BAAS) meetings establish credibility of energy physics.
- Serves as unifying doctrine for BAAS members to rival Laplacian physics.
- Serves as patriotic and economic (steam engine technology) motivation for younger, entrepreneurial generation of BAAS members.