# 12. The Science of Energy: Chaps 1-4

- Cultural history of thermodynamics ("science of energy"): 1840's-1880's.
- *Main characters*: North British (Scottish) natural philosophers:
  - William Thomson (Lord Kelvin)
  - James Prescott Joule
  - Macquorn Rankine
  - Peter Guthrie Tait
  - James Clerk Maxwell



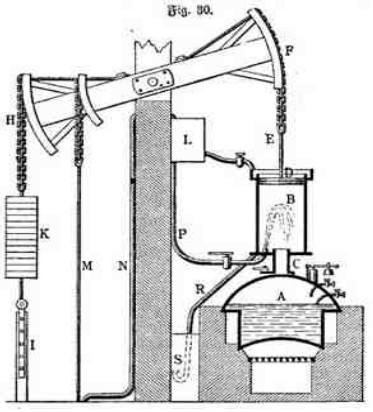


- *Key concept at stake*: ***ENERGY!***

- *Related concepts:* heat, work, entropy.
  - Conservation law: Can energy be created/destroyed? Heat? Work?
  - "2nd Law of Thermodynamics": The entropy of a closed system increases.
    - Empirical observation or cosmological hypothesis?
    - Reducible to mechanics or intrinsically probabilitistic?

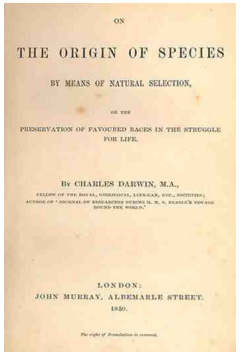
- *Claim*: "Energy physics was not the inevitable consequence of the 'discovery' of a principle of energy conservation in mid-century, but the product of a 'North British' group concerned with the radical reform of physical science and with the rapid enhancement of its scientific credibility." (Smith, pg. 2.)

- *Historically contingent cultural factors*:




  - *Economic/Industrial*:
    - How to build a maximally efficient steam engine?
    - *heat engine* = any device that produces mechanical work from heat.

  - *Religious*:
    - Christian faith in creation *vs.* Darwinian materialism.
    - Democratic Presbyterianism *vs.* elitist Anglicanism.
    - Moderate *vs.* Evangelical Presbytarianism.

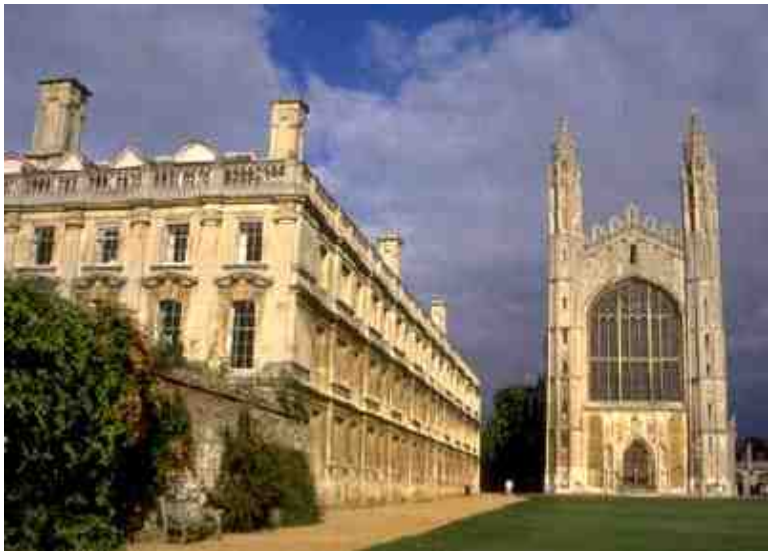

ON
THE ORIGIN OF SPECIES
BY MEANS OF NATURAL SELECTION,
OR THE
PRESERVATION OF FAVOURED RACES IN THE STRUGGLE FOR LIFE.
By CHARLES DARWIN, M.A.,
LONDON:
JOHN MURRAY, ALBEMARLE STREET.
1859.

*Origin of Species* 1859

  - *Professional*:
    - How to increase professional and public credibility?
    - How to attract more tuition-paying students to classes?

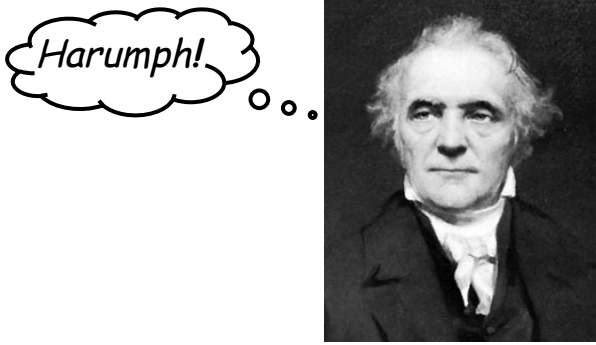
# 1. Religious Context: 1840's Scotland.

- Scottish Presbyterianism *vs.* English Anglicanism.
  - Institutionalized at leading universities (Glasgow, Edinburgh, Oxford, Cambridge).



  - Structural differences:
    - Presbyterianism: No bishops, autonomy in electing leaders, clergy from working/agrarian classes (open access to academia).
    - Anglicanism: Hierarchical structure, clergy from landed gentry (those with wealth, hence access to Oxford/Cambridge).

- *Disruption of 1843*
  - Evangelical Presbyterians split from moderates and form "Free Church of Scotland", and concomitantly "free" universities.
  - Moderates fear for their tuition-paying students!

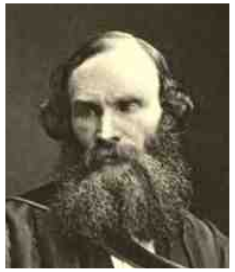



*Thomas Chalmers*

- *Chalmer's "Presbyterian economy"*
  - Nature = decay and dissolution.
  - *Downward process of gift-giving*: Humans receive finite natural and spiritual gifts from God ("gifts of grace").
  - *Transformative process of gift-exchange*: Good Presbyterians accept gifts and seek to turn them to useful effect. "Maximization of virtues of useful work and minimization of vices of idleness and waste."

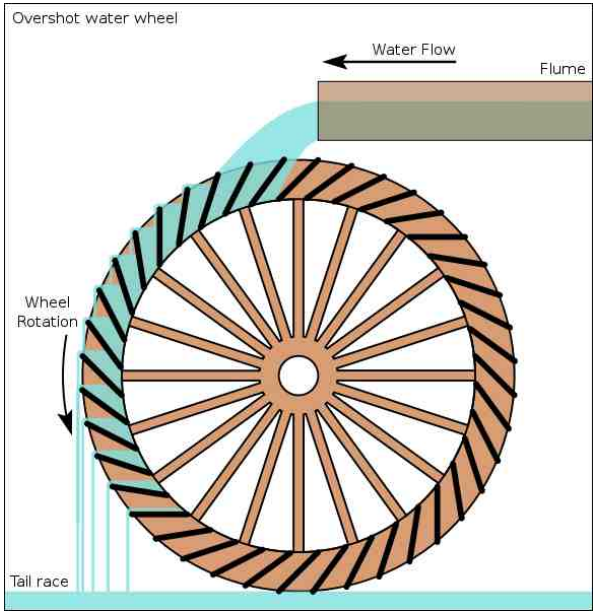
- 1840's-50's: Reformers seek to re-assert their cultural credibility. "North British" scientifists of energy fill this role.

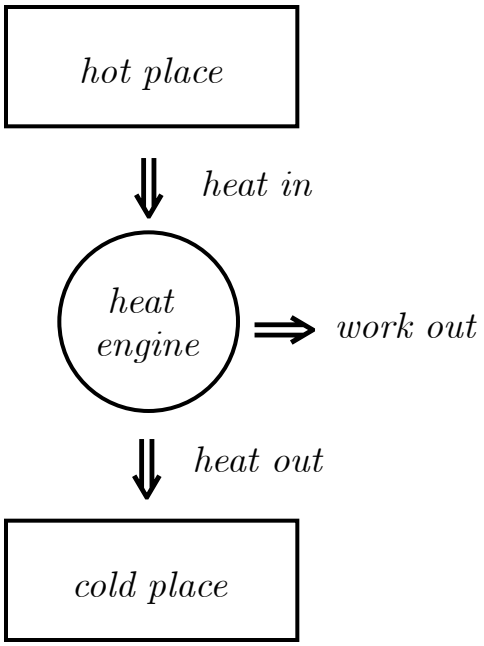
# 2. Thomsons, Water-wheels, and Heat Engines.



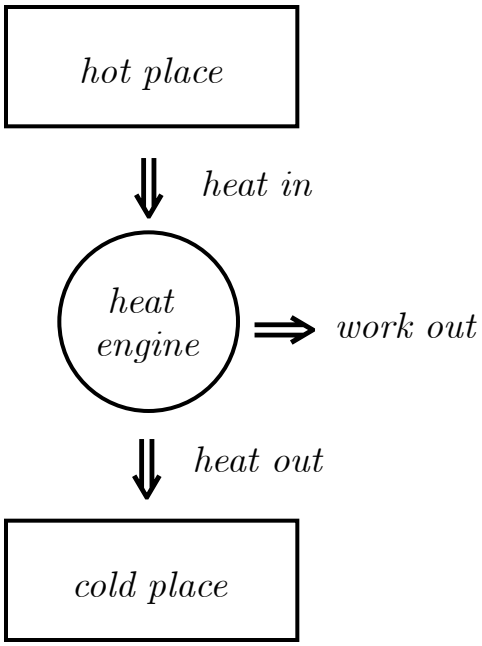
*Big Brother*

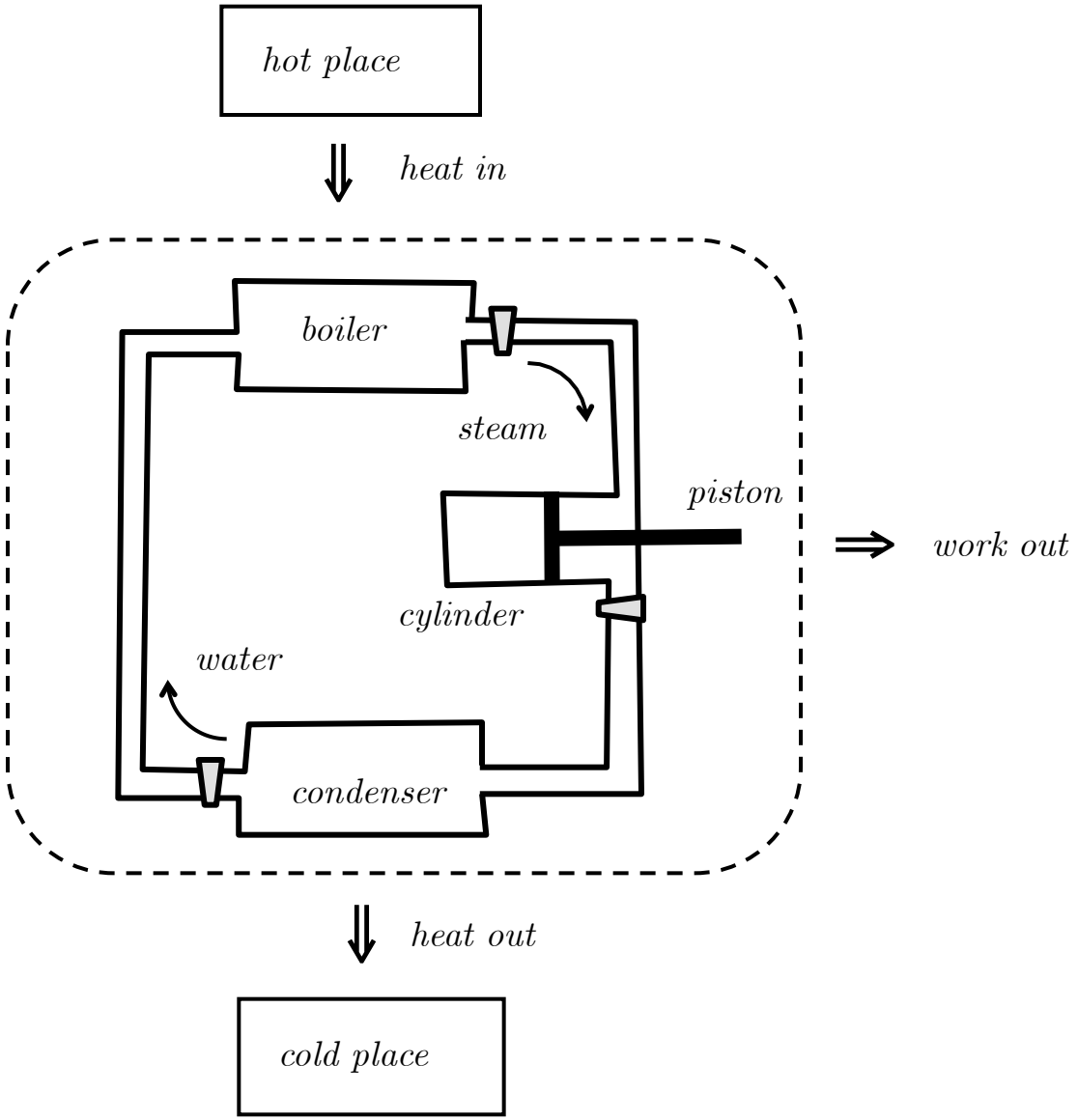
- James Thomson: 1841-42 engineering class at Glasgow.
- How to maximize the useful work obtainable from a given fall of water and minimize the waste?
- Reads Clapeyron (1834) "Memoir on the Motive Power of Heat".
  - Development of Carnot's (1824) "Reflections on the Motive Power of Fire".
- *Idea*: Treat heat in analogy with water as a substance that produces mechanical effect (work) when it "falls" from a hot place to a cold place.



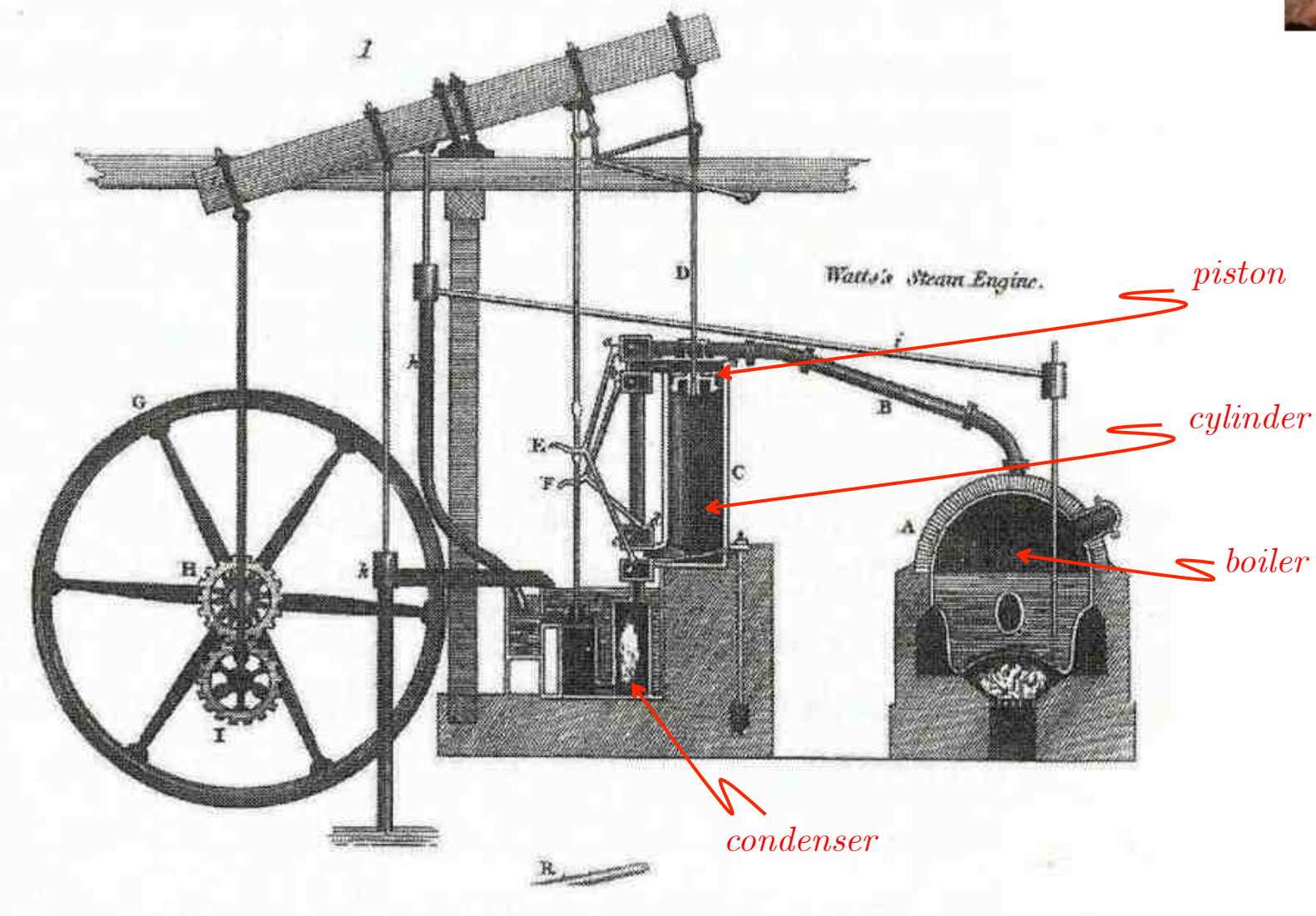



- Heat engine of economical interest: Steam engine!



- James Watt (1765): Improvement in efficiency of Newcomen steam engine (addition of external condenser).

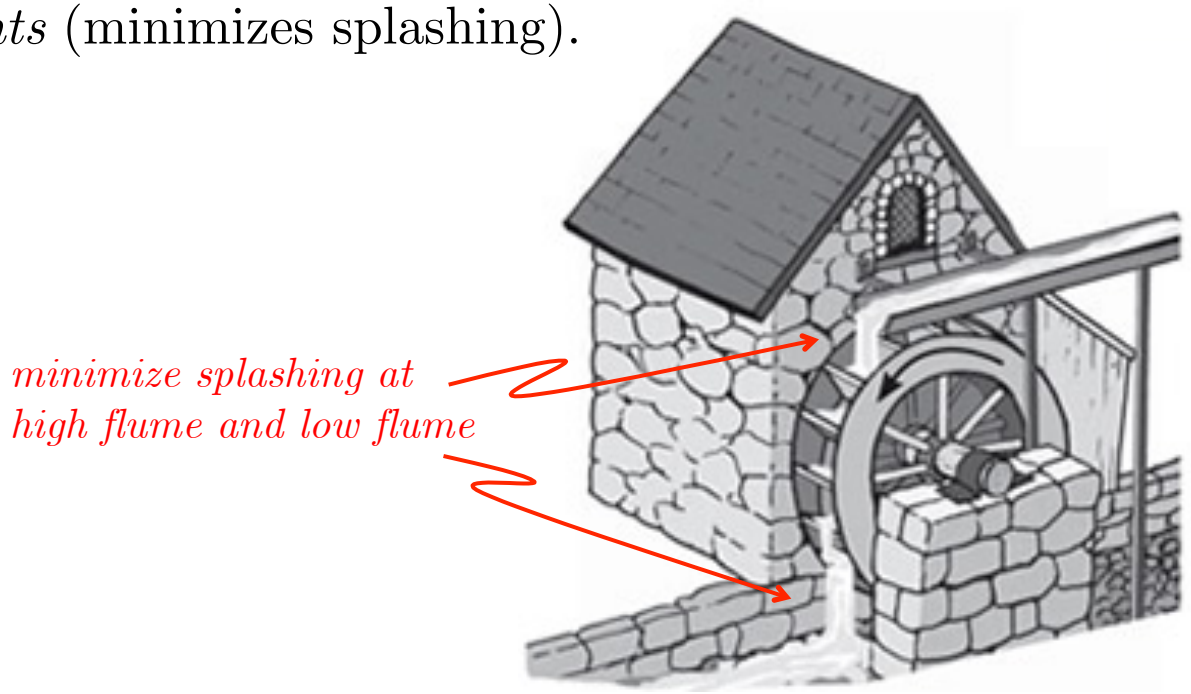


- *Important question*: What is the *maximally efficient* heat engine (*i.e.*, maximizes work output while minimizing waste)?

- Carnot (1824): Maximum efficiency is obtained when heat-flow between hot place and engine, and engine and cold place, occurs at *equal temperatures*.

*Sadi Carnot*

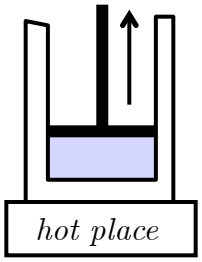
- *Analogy with water-wheel:* Maximum efficiency obtained when water-flow between stream and water-wheel occurs at *equal heights* (minimizes splashing).

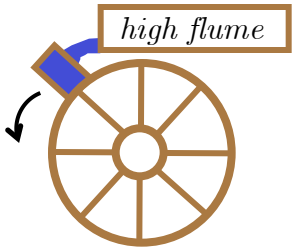


***Carnot Cycle*** = One complete cycle of a maximally efficient heat engine.

Step 1 (isothermal expansion):

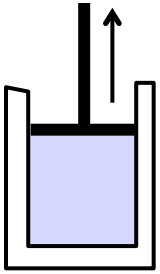
*Heat absorbed at constant temp.*
Gas in piston expands, doing work.
(Pressure drops, volume increases.)

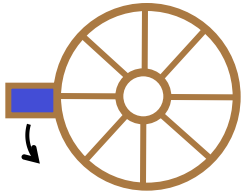



Step 2 (adiabatic expansion):

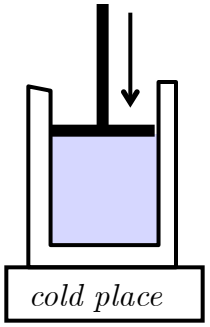
Hot place removed. Gas expands at constant heat, decreasing temp.
(Pressure drops, volume increases.)

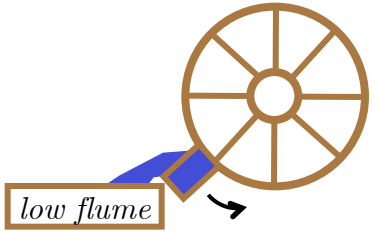




Step 3 (isothermal contraction):

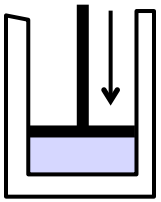
*Heat shed at constant temp.* Gas contracts. (Pressure increases, volume contracts.)

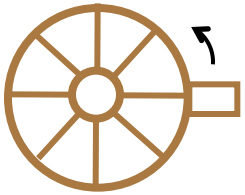


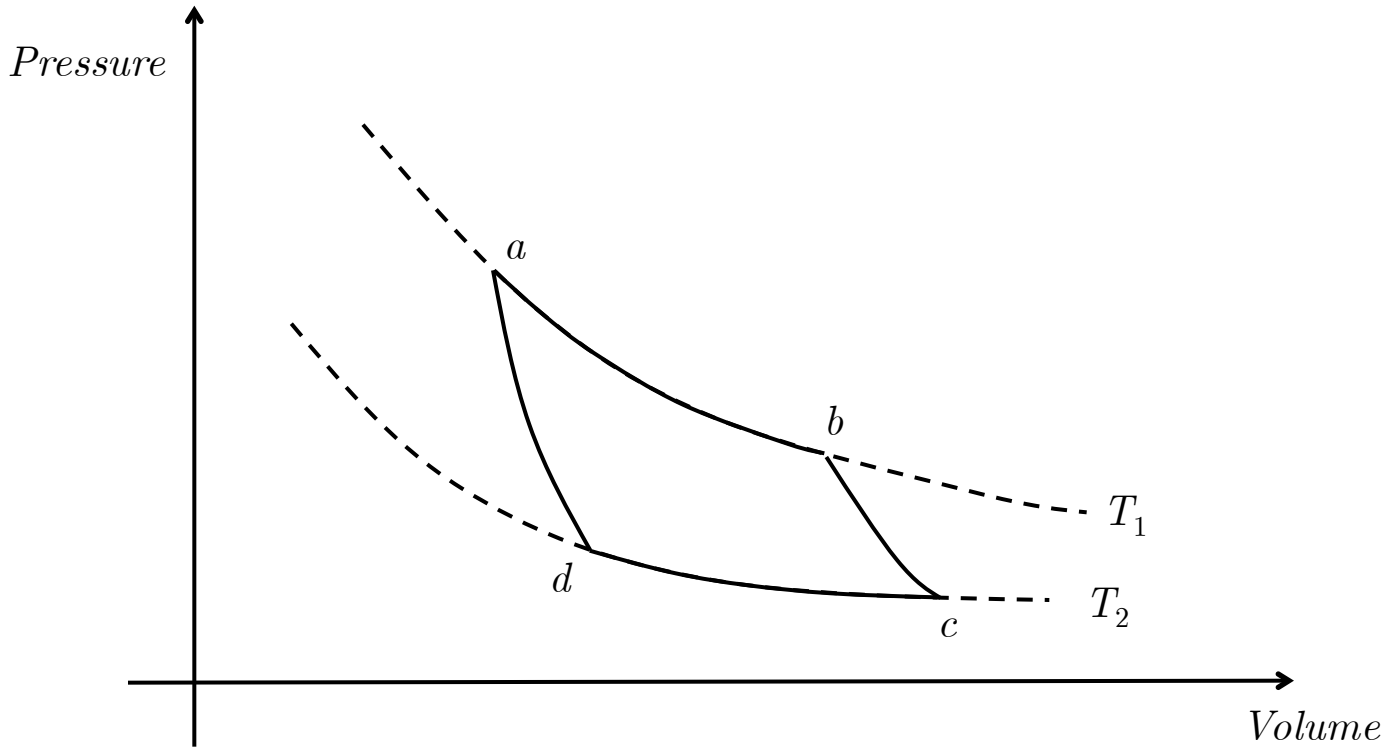

Step 4 (adiabatic contraction):

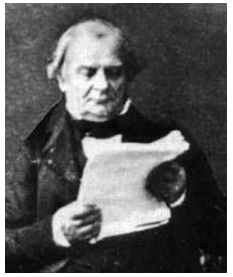
Cold place removed. Gas contracts at constant heat, raising temperature.
(Pressure increases, volume contracts.)





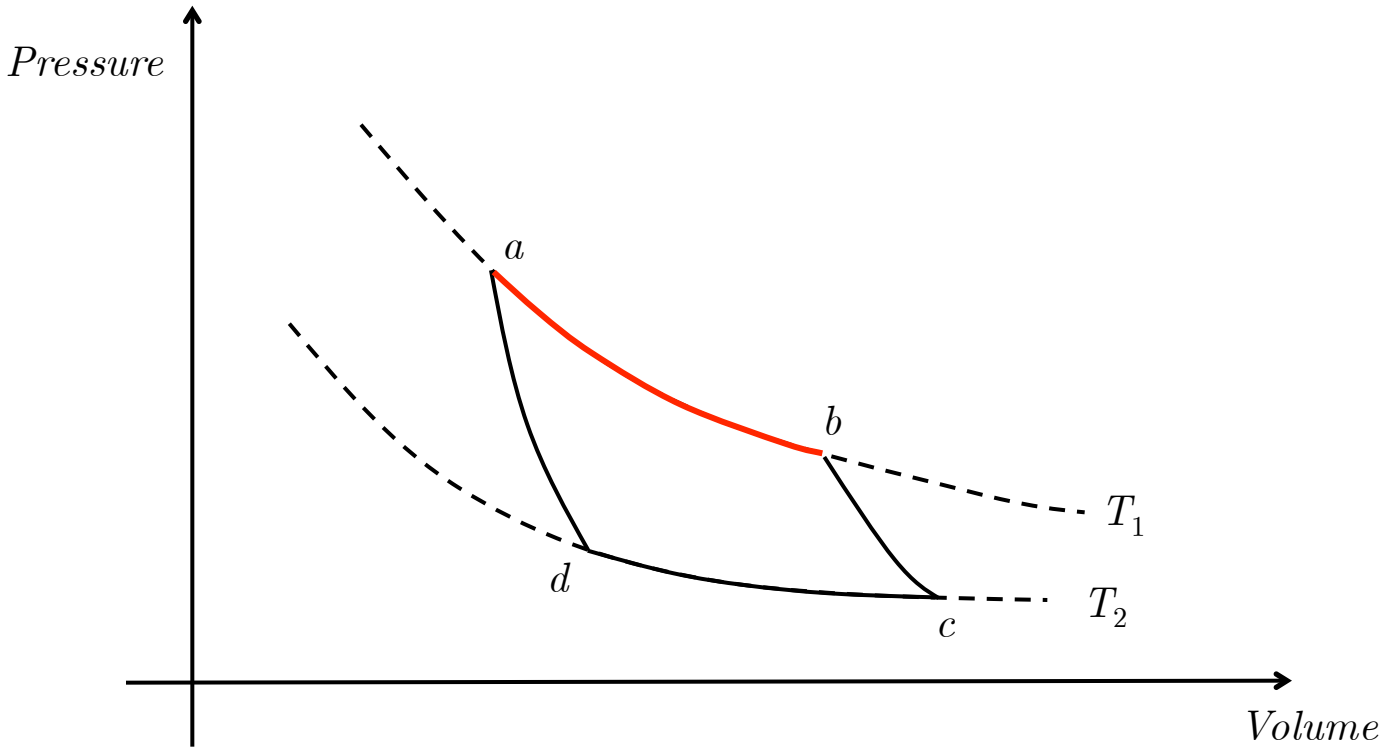
- Only possible in ideal "reversible" heat engine; never in a real one.
- Analysis indicates efficiency (work done/heat input) only depends on the *temperature* of the hot and cold place; *not* on the working fluid.

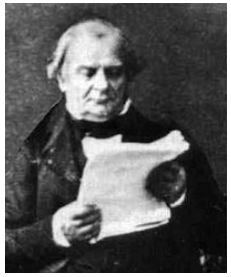


*Emile Clapeyron*
*1834 "Memoir on the*
*Motive Power of Heat"*

- Only possible in ideal "reversible" heat engine; never in a real one.
- Analysis indicates efficiency (work done/heat input) only depends on the *temperature* of the hot and cold place; *not* on the working fluid.

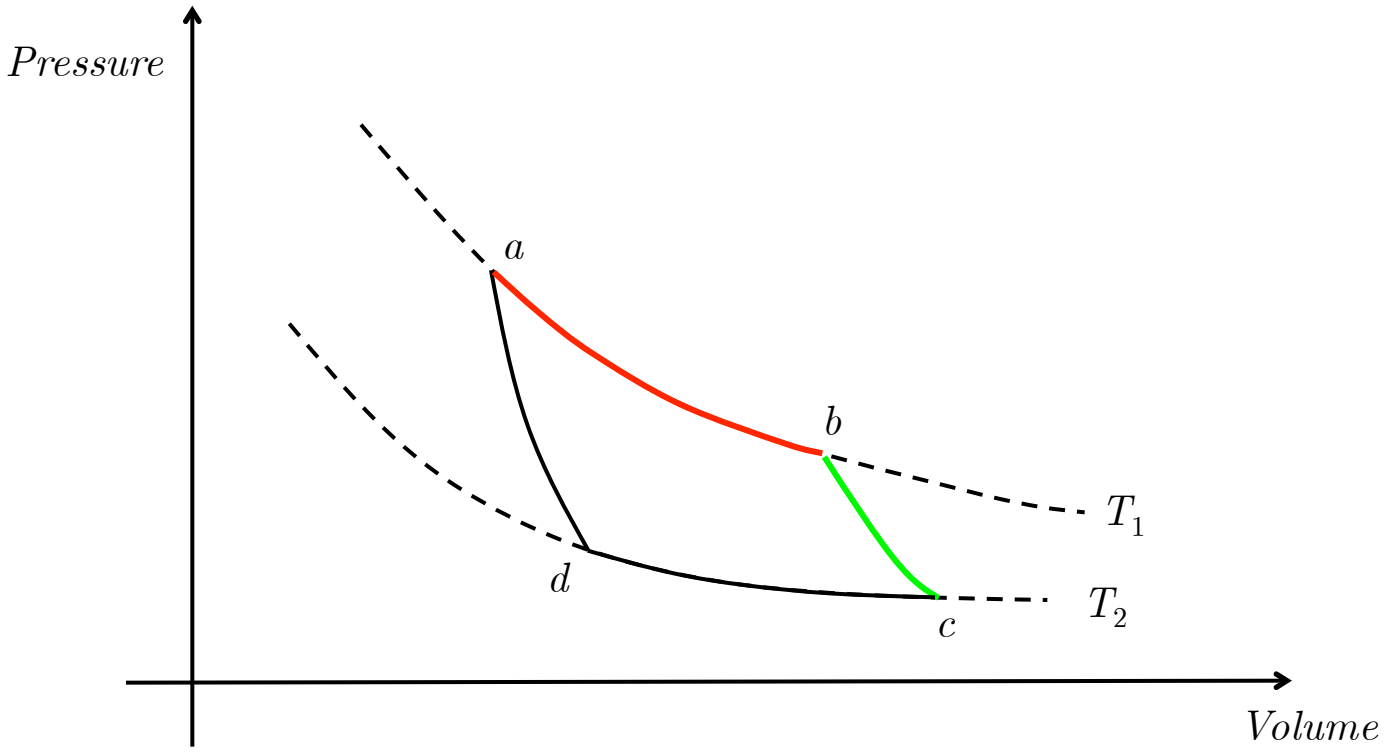


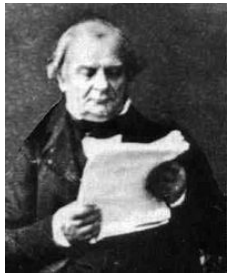



*Emile Clapeyron*
*1834 "Memoir on the Motive Power of Heat"*

- Step 1: $a$ to $b$ ($P$ drops, $V$ expands at const. temp. $T_1$).

- Only possible in ideal "reversible" heat engine; never in a real one.
- Analysis indicates efficiency (work done/heat input) only depends on the *temperature* of the hot and cold place; *not* on the working fluid.

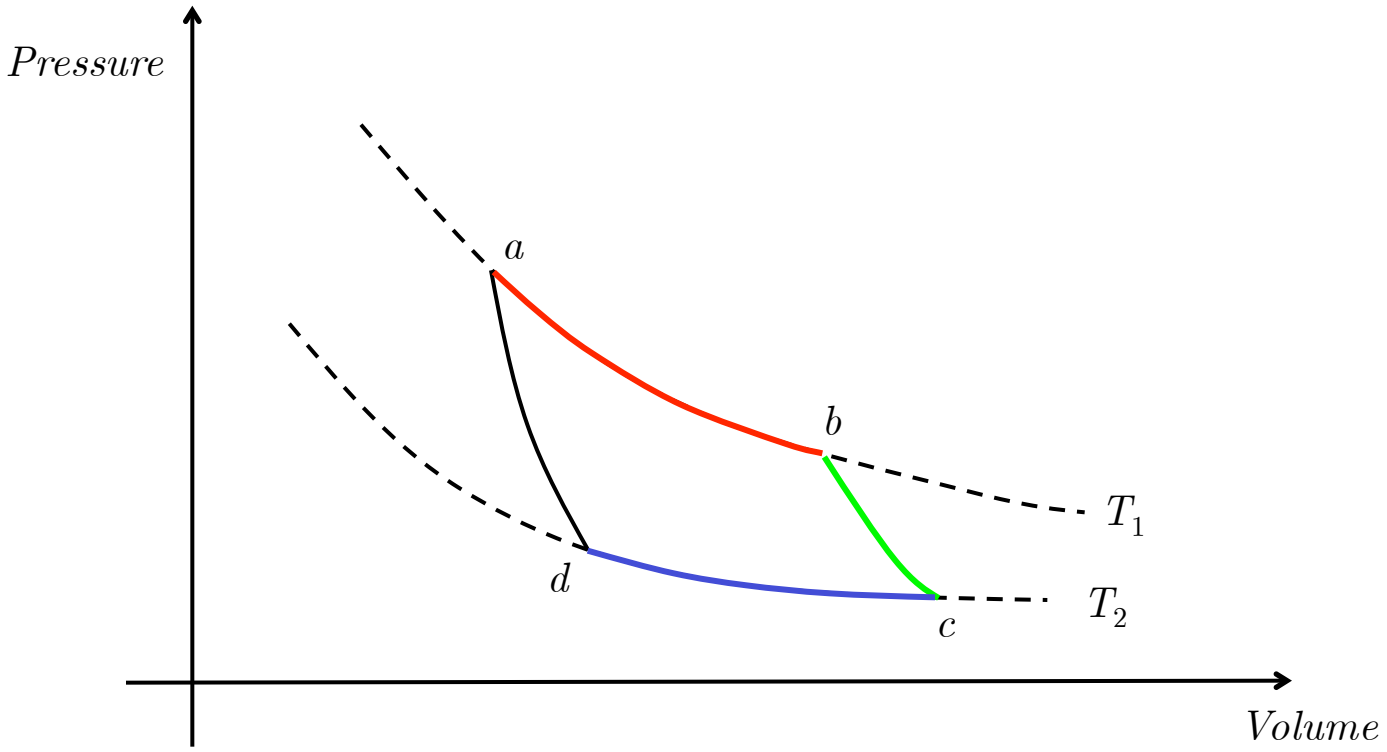


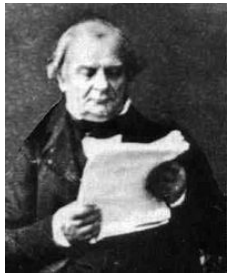



*Emile Clapeyron*
*1834 "Memoir on the*
*Motive Power of Heat"*

- Step 1: $a$ to $b$ ($P$ drops, $V$ expands at const. temp. $T_1$).
- Step 2: $b$ to $c$ ($P$ drops, $V$ expands, temp drops from $T_1$ to $T_2$ at const. heat).

- Only possible in ideal "reversible" heat engine; never in a real one.
- Analysis indicates efficiency (work done/heat input) only depends on the *temperature* of the hot and cold place; *not* on the working fluid.

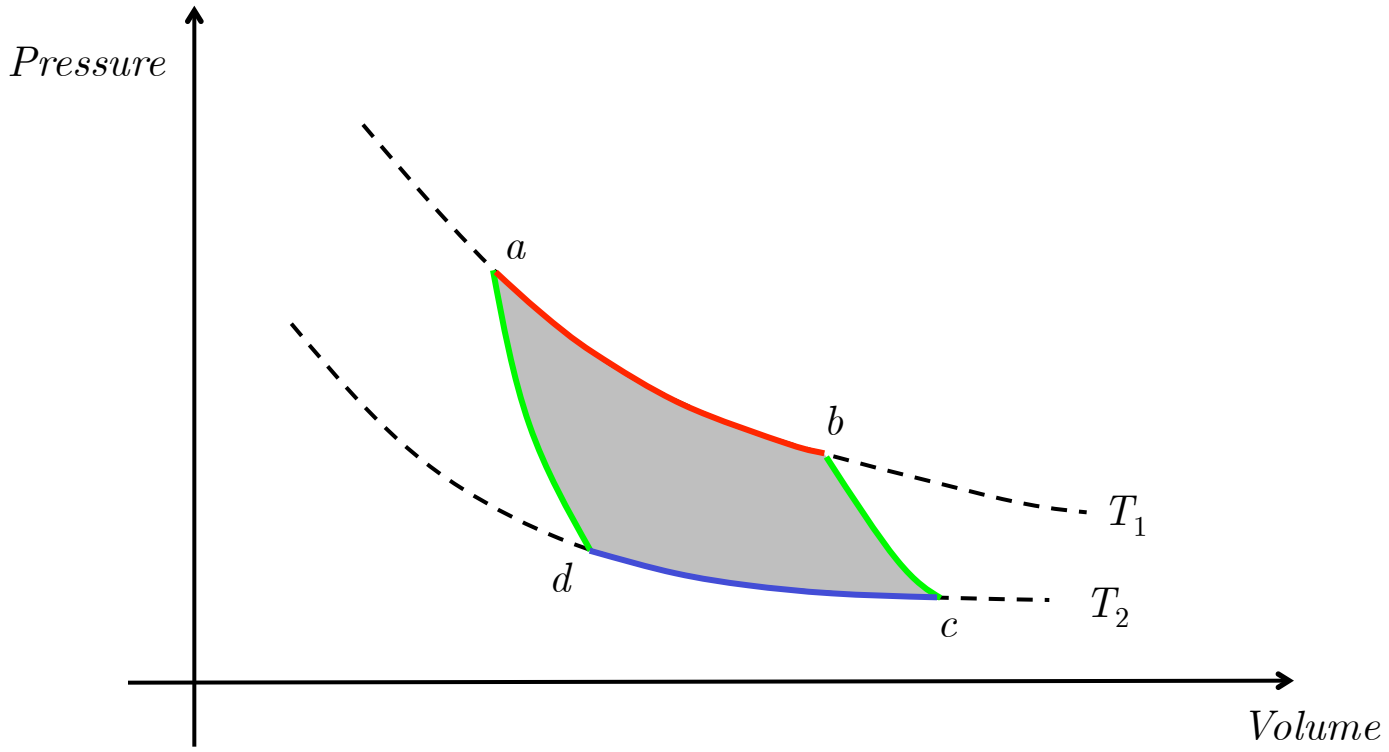


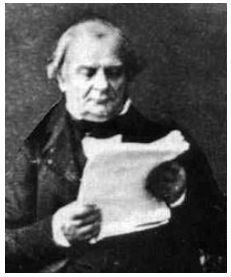



*Emile Clapeyron*
*1834 "Memoir on the Motive Power of Heat"*

- Step 1: $a$ to $b$ ($P$ drops, $V$ expands at const. temp. $T_1$).
- Step 2: $b$ to $c$ ($P$ drops, $V$ expands, temp drops from $T_1$ to $T_2$ at const. heat).
- Step 3: $c$ to $d$ ($P$ increases, $V$ contracts at const. temp. $T_2$).

- Only possible in ideal "reversible" heat engine; never in a real one.
- Analysis indicates efficiency (work done/heat input) only depends on the *temperature* of the hot and cold place; *not* on the working fluid.



*Emile Clapeyron*
*1834 "Memoir on the Motive Power of Heat"*

- Step 1: $a$ to $b$ ($P$ drops, $V$ expands at const. temp. $T_1$).
- Step 2: $b$ to $c$ ($P$ drops, $V$ expands, temp drops from $T_1$ to $T_2$ at const. heat).
- Step 3: $c$ to $d$ ($P$ increases, $V$ contracts at const. temp. $T_2$).
- Step 4: $d$ to $a$ ($P$ increases, $V$ contracts, temp raises from $T_2$ to $T_1$ at const. heat).
- Total work done = Area $abcd$ = a function only of $T_1$ and $T_2$!

***Thomson brothers appropriate Clapeyron/Carnot theory:***

(1) William Thomson and absolute temperature scale:

- Carnot/Claperyron result:

$$efficiency = \frac{work\ done}{heat\ in} = f(temp)$$

- Suggests an "absolute" temperature scale can be defined without respect to working fluid.
  - Mercury thermometer temperature scale depends on properties of mercury.
  - Air thermometer temperature scale depends on properties of air.
  - <u>*Thomson's suggestion*</u>:

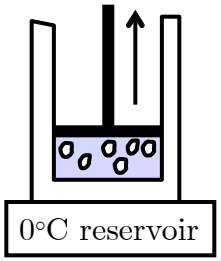
    "... a unit of heat descending from a body $A$ at the temperature $T°$ of this [absolute] scale, to a body B at the temperature $(T - 1)°$, would give out the same [work], whatever be the number $T$."
  - No dependence of Thomson's absolute temperature scale on properties of working substance. (Now called the "Kelvin" scale.)

(2) James Thomson and melting point of ice:

- *Observation*: Water expands on freezing.
- *Question*: Can this expansion process be used in a Carnot Cycle?
- *Standard Carnot Cycle*: Generates work by "fall" of heat from *hot* place to *cold* place.
  - Absorbtion of heat from hot place expands gas to drive piston and do work.
  - Discharging of heat to cold place contracts gas back to initial state.
- Suppose we use water/ice slurry as working substance? Then:
  - Discharging heat will create ice and expansion can then be used to drive piston and do work.
  - Absorbing heat will melt ice and contraction will bring slurry back to initial state.
- *Concern*: Could this process generate work for free without "moving" heat from a hot place to a cold place?
- A "perpetual motion machine"?

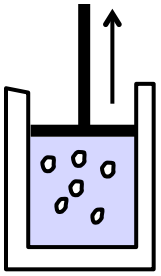
Step 1:

*One unit of heat spontaneously shed at constant temp.* Slurry in piston expands, doing work.



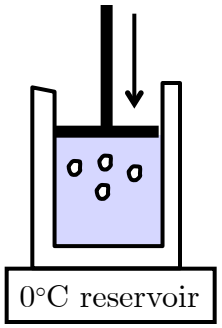

Step 2:

Reservoir removed. Slurry expands at constant heat.



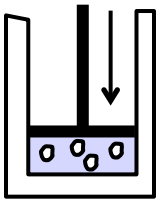
Step 3:

*One unit of heat spontaneously absorbed at constant temp.* Slurry contracts. (*No* work done on piston!)




Step 4 (adiabatic contraction):

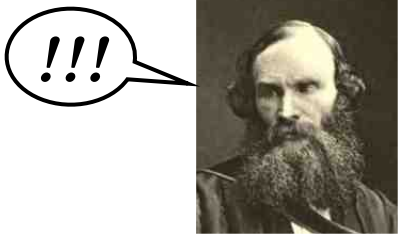
Reservoir removed. Slurry contracts at constant heat back to initial state.



Result:

*Work done without net gain/loss of heat!*

- James Thomson (1849): This cannot be!






*Big Brother*

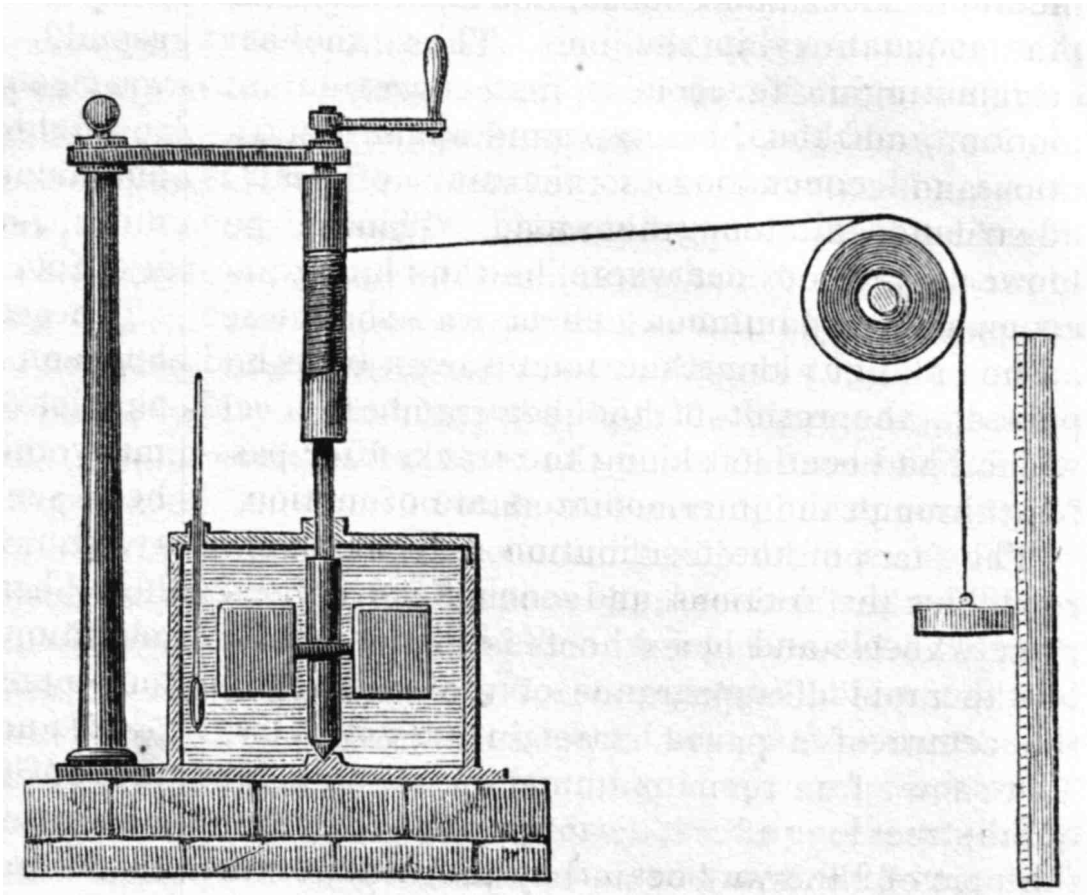
- *Prediction*: The melting point of ice *drops* when pressure is applied.
- *Then*: At Step 4, the pressure on the slurry will cause some of the ice to melt (it's melting point will be below 0°C while it will be at 0°C).
- *And*: The melting ice will cool the slurry below 0°C.
- *Thus*: To get Step 1 going again, we need to *add* work to the slurry to extract heat from it. No work from nothing!
- 1850: William Thomson confirms prediction!
- Ice skaters rejoice.

*Little Brother*

# 3. Joule and Interconvertibility of Heat and Work

- *Big Question*: What is the nature of heat?
- *Carnot/Clapeyron:* Implicitly adopt a substance theory of heat.
  - Heat is a substance (like water) called *caloric* that "falls" from hot places to cold places and in the process generates work.
  - *And*: *Like water, no heat is lost during this process.*
- *But*: Falling caloric should develop *vis viva* ($1/2mv^2$) which is lost at the "lower" cold place.
- *And*: "Believing that the power to destroy belongs to the Creator alone, I entirely coincide with Roget and Faraday in the opinion that any theory which, when carried out, demands the annihilation of force, is necessarily erroneous." (Joule 1845.)
- *Suppose*: Heat can be converted into work (unlike water!). Then a portion of the "falling" heat gets converted into work and the remainder, less than the initial amount, ends up in the cold place.
- *Moreover*: Suppose heat isn't a substance like water. Suppose it's something different...

- "[If] we consider heat not as a substance, but as a state of vibration, there appears to be no reason why it should not be induced by an action of a simply mechanical character." (Joule 1843.)
- Paddle wheel experiment (1845): Paddle wheel rotating in container of water (doing work) generates heat!
- *Claim*: Heat and work are interconvertible: Work can be converted into heat *and* heat can be converted into work.
- *The mechanical equivalent of heat:* "When the temperature of a pound of water is increased by one degree of Fahrenheit's scale, an amount of *vis viva* is communicated to it equal to that acquired by a weight of 890 pounds after falling from the altitude of one foot." (Joule 1845.)



## *Joule and Credibility*

- "... Joule gradually fashioned for himself a career, not as ingenious inventor of new forms of motive power, not as member of an elite professoriate, and not as a popular practitioner of electrical science, but as a 'gentlemanly specialist', that is, a scientific practitioner of independent means... whose expertise had been gained within a fairly specialized branch of science and whose credibility had been acquired within the ethos of gentlemanly scientific societies and institutions." (Smith, pg. 55.)
- Fails to initially publish in leading academic journals.
- 1847: Catches attention of Thomson.
- Priority dispute with Julius Robert Mayer.
  - Mayer (1842). Heat is a "force" that is equivalent to work: "The sinking of a mercury column by which a gas is compressed is equivalent to the quantity of heat set free by the compression."
  - Joule: Mayer first proposed concept, but I experimentally verified it.
  - Smith Claim: Mayer employs concept of "kraft" ("force") distinct from eventual concept of "energy".