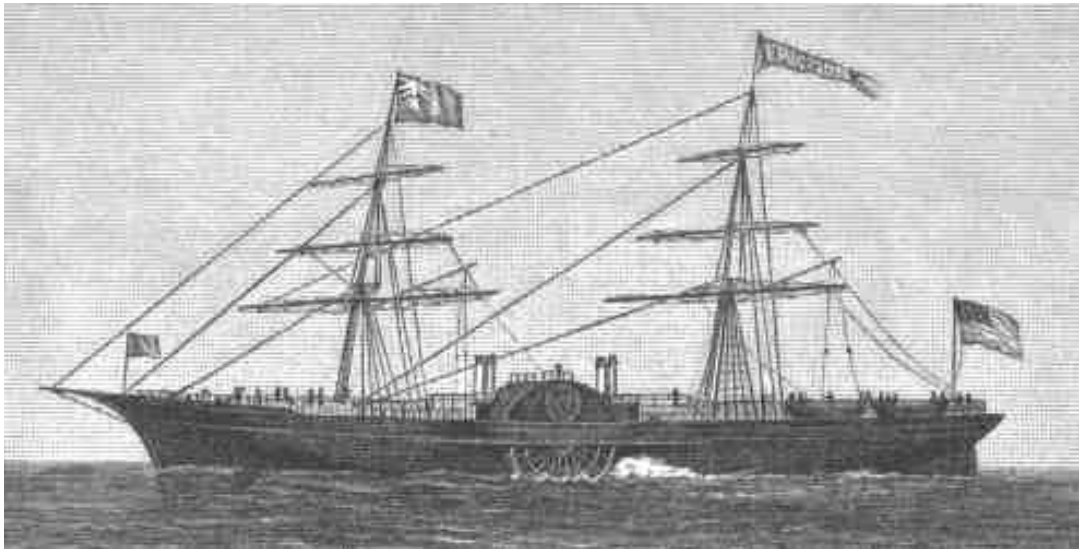
14. The Science of Energy: Chaps 8-11

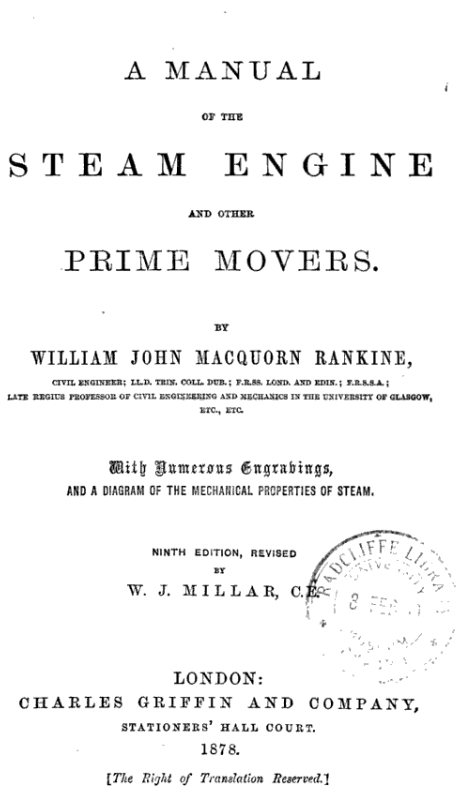
1. Consolidation

- Macquorn Rankine: 1855 appointed Glasgow chair of Civil Engineering and Mechanics.
- Practical applications of new theory of thermodynamics:
  - air-engines: larger "fall" of heat and no exploding steam boilers!
  - 1854: Launch of air-engined-powered *Ericsson* (flounders in a gale!).



(I) Rankine's consolidation of the new theory

- 1854. Address to BAAS annual meeting.
- 1857. Article in Nichol's *Cyclopaedia of the Physical Sciences*: "Heat, Theory of the Mechanical Action of, or Thermodynamics".
- 1859. Engineering textbook: *Manual of the Steam Engine and Other Prime Movers.*



A MANUAL

OF THE

STEAM ENGINE

AND OTHER

PRIME MOVERS.

BY

WILLIAM JOHN MACQUORN RANKINE,

CIVIL ENGINEER; LL.D. TRIN. COLL. DUB.; F.R.SS. LOND. AND EDIN.; F.R.S.S.A.;
LATE REGIUS PROFESSOR OF CIVIL ENGINEERING AND MECHANICS IN THE UNIVERSITY OF GLASGOW,
ETC., ETC.

With Numerous Engravings,
AND A DIAGRAM OF THE MECHANICAL PROPERTIES OF STEAM.

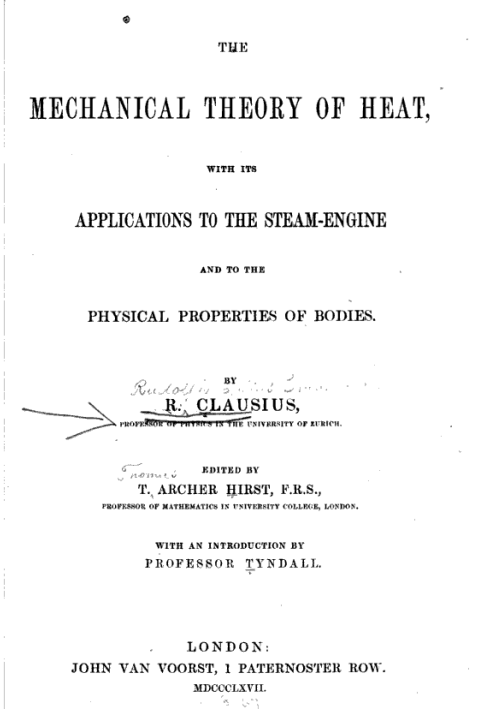
NINTH EDITION, REVISED
BY
W. J. MILLAR, C.E.

LONDON:
CHARLES GRIFFIN AND COMPANY,
STATIONERS' HALL COURT.
1878.
[*The Right of Translation Reserved.*]

- Introduces the term "thermodynamics".
- Reformulates the theory in terms of two "laws":
  - First Law: "The law of the mutual convertibility of heat and mechanical power".
  - Second Law: "The law of the efficiency of thermodynamic engines".
- Describes "energy" as "the capacity to perform work".

(II) Clausius' quantification of the 2nd Law

- 1854. "On a modified form of the second fundamental theorem in the mechanical theory of heat".
- 1865. *The Mechanical Theory of Heat.*


THE

MECHANICAL THEORY OF HEAT,

WITH ITS

APPLICATIONS TO THE STEAM-ENGINE

AND TO THE

PHYSICAL PROPERTIES OF BODIES.

BY

R. CLAUSIUS,

EDITED BY

T. ARCHER HIRST, F.R.S.,

WITH AN INTRODUCTION BY

PROFESSOR TYNDALL.

LONDON:

JOHN VAN VOORST, 1 PATERNOSTER ROW.

MDCCCLXVII.

- <u>*Clausius' "Fundamental Principle":*</u>

"Heat can never pass from a colder to a warmer body without some other change, connected therewith, occuring at the same time."

- <u>*Clausius' 2nd Law ("theorem")*</u>: The sum of all transformations occuring in a circular process must be less than (irreversible) or equal to (reversible) zero.
  - Let δQ represent an infinitesimal (very, very small) heat transformation.
  - <u>*But*</u>: Heat transformations are *path dependent*!
  - <u>*However*</u>: $\delta Q/T$ is *path-independent*, $T =$ absolute temp.
  - Clausius' 2nd Law is then given by (Clausius' Inequality): $\oint \frac{\delta Q}{T} \leq 0.$

- For a *reversible* process, let $dS = \delta Q_R / T$. Call S "entropy":

"... I propose to call the magnitude S the *entropy* of the body... I have intentionally formed the word *entropy* so as to be as similar as possible to the word *energy*; for the two magnitudes to be denoted by these words are so nearly allied in their physical meanings, that a certain similarity in designation appears to be desirable."

- Clausius' inequality then entails $S_{final} - S_{initial} = \int dS \geq 0$.

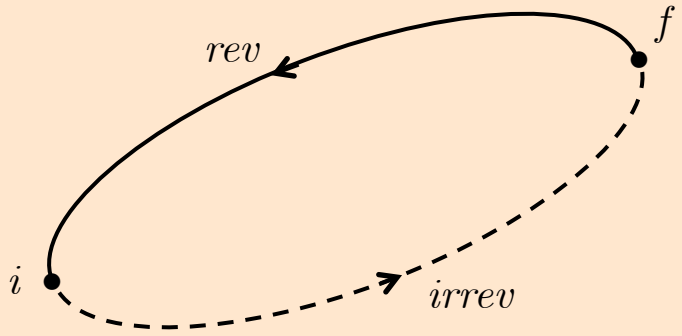
- <u>*What this means*</u>: For a closed system undergoing an energy transformation, the entropy of the final state is greater than the entropy of the initial state.

"... [W]e may express in the following manner the fundamental laws of the universe which correspond to the two fundamental theorems of the mechanical theory of heat:

1. *The energy of the universe is constant.*
2. *The entropy of the universe tends to a maximum.*"

How Clausius' Inequality entails $\Delta S \geq 0$

- *Consider*:



  - Irreversible cycle consisting of an irreversible process from equilibrium state i to equilibrium state f, followed by a reversible process from f back to i.

- Clausius' inequality is $\oint \frac{\delta Q}{T} = \int_{irrev} \frac{\delta Q}{T} + \int_{rev} \frac{\delta Q_R}{T} \leq 0.$

- *Thus*: $\int_{irrev} \frac{\delta Q}{T} \leq -\int_{rev} \frac{\delta Q_R}{T} = \int_{rev} \frac{\delta Q_R}{T} = S_f - S_i = \Delta S.$

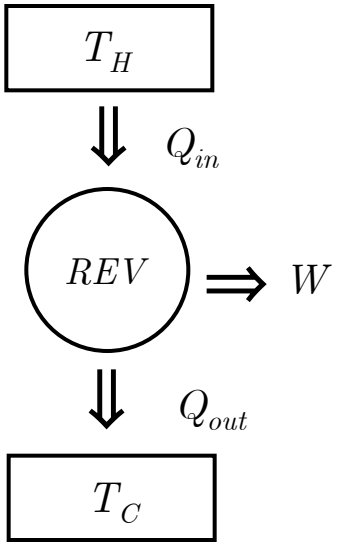
- *So:* $\Delta S \geq \int_{irrev} \frac{\delta Q}{T}.$

- *Now:* For a thermally isolated system, $\delta Q = 0$, so: $\boxed{\Delta S \geq 0}$

- *In words:* *The entropy of a thermally isolated system increases in any irreversible process and is unalterted in a reversible process.*

Derivation of Clausius' inequality from his Fundamental Principle

- *Recall*: Clausius' Fundamental Principle entails that the efficiency of a reversible heat engine is a function *only* of the temperatures of the hot and cold places.

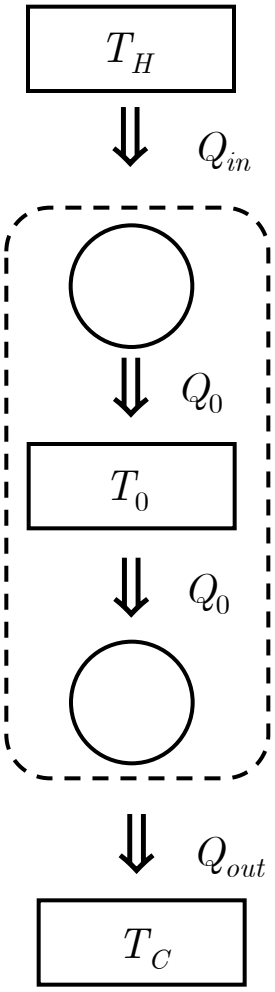


$$Q_{out} = Q_{in} - W$$

$$Efficiency = \frac{W}{Q_{in}} = 1 - \frac{Q_{out}}{Q_{in}} = F(T_H, T_C)$$

In particular: $\dfrac{Q_{out}}{Q_{in}} = f(T_H, T_C)$

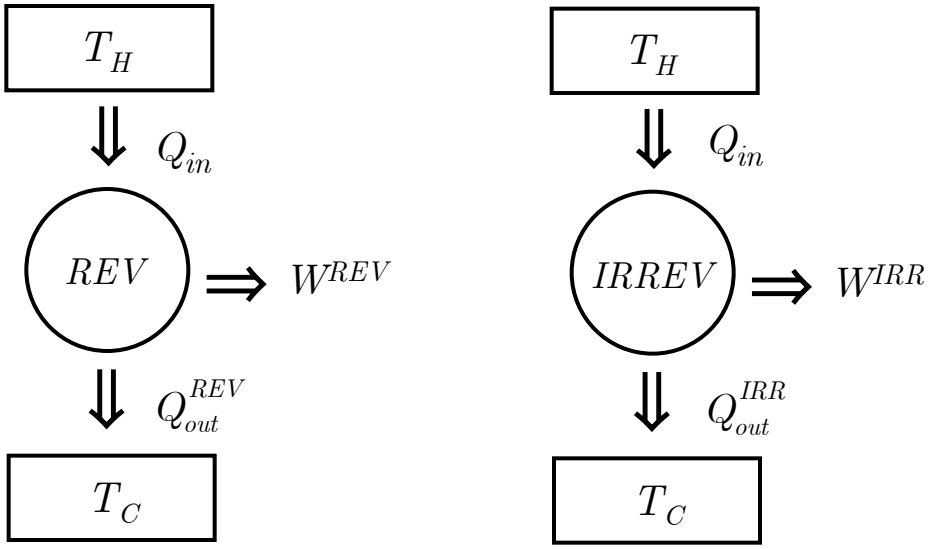
- Consider a multi-stage *reversible* heat engine:



- <u>*Note*</u>: $\dfrac{Q_{out}}{Q_{in}} = \dfrac{Q_{out}}{Q_0}\dfrac{Q_0}{Q_{in}}$, for any (non-zero) Q_0.
- <u>*So*</u>: $f(T_C, T_H) = f(T_C, T_0) f(T_0, T_H)$.
- <u>*Note:*</u> $f(T_H, T_H) = Q_{in}/Q_{in} = 1 = f(T_H, T_0) f(T_0, T_H)$.
- <u>*So*</u>: $f(T_0, T_H) = \dfrac{1}{f(T_H, T_0)}$.
- <u>*Thus*</u>: $\dfrac{Q_{out}}{Q_{in}} = f(T_C, T_H) = \dfrac{f(T_C, T_0)}{f(T_H, T_0)} = \dfrac{f(T_C)}{f(T_H)}$

  $= \dfrac{T_C}{T_H}$, *for abs. temp. scale.*
- <u>*Or*</u>: $\dfrac{Q_{in}}{T_H} - \dfrac{Q_{out}}{T_C} = \oint \dfrac{\delta Q}{T} = 0.$
- <u>*Thus*</u>: $\oint \dfrac{\delta Q^{REV}}{T} = 0.$

- *Now recall*: The maximum efficiency of any heat engine is equal to that of a reversible engine operating between the same hot and cold places.
- *Consider*: Reversible and irreversible engines operating between the same hot and cold places and receiving the same Q_{in}.



$$Q_{out} = Q_{in} - W$$

$$Efficiency = \frac{W}{Q_{in}}$$

- $W^{REV} > W^{IRR}$ so $Q_{out}^{IRR} > Q_{out}^{REV}$.
- *Thus*: $\oint \frac{dQ^{IRR}}{T} = \frac{Q_{in}}{T_H} - \frac{Q_{out}^{IRR}}{T_C} < \frac{Q_{in}}{T_H} - \frac{Q_{out}^{REV}}{T_C} = 0.$
- *Thus in general*: $\oint \frac{dQ}{T} \leq 0.$

- *So:*

2nd Law (Clausius Version)

There can be no cyclic process whose sole effect is the transfer of heat from a cold place to a hot place.

$\Updownarrow$

2nd Law (Thomson Version)

There can be no cyclic process whose sole effect is the extraction of heat from a source and the performance of an equivalent amount of heat.

$\Rightarrow$

Carnot's Claim #2

In a reversible cyclic process, the work produced depends only on the temperature of the hot and cold places, and not on the working fluid.

$\Rightarrow$

Clausius' Inequality

The sum of all heat transformations in a cyclic process, divided by the temperature, must be less than or equal to zero:

$$\oint \frac{\delta Q}{T} \leq 0.$$

$\Rightarrow$

2nd Law (Entropy Version)

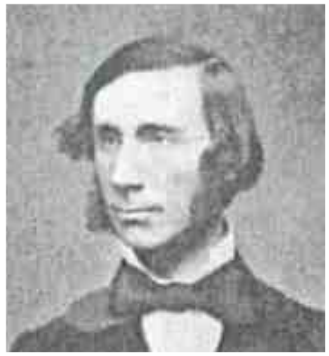
The entropy of a thermally isolated system increases in any irreversible process and is unalterted in a reversible process:

$$\Delta S \geq 0.$$

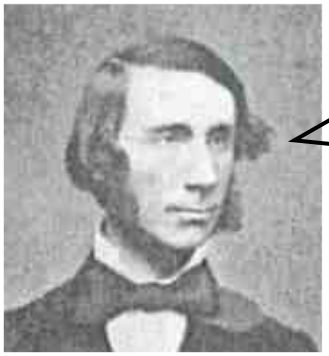
2. The Tait-Tyndall Debate

- In this corner.... Peter Guthrie Tait
  - Chair of Natural Philosophy at Edingburgh (1860).
  - Advocate of North British energy physics.
  - Member of North British Presbytarian milieu.

- In that corner... John Tyndall
  - Chair of Natural Philosophy at the Royal Institution, London (1853) (successor to Faraday).
  - Advocate of German-influenced energy physics (Helmholtz, Clausius, Mayer).
  - Advocate of Darwinian naturalism.



- Smith: "A contest for scientific authority."
  - Scottish Presbytarianism *vs.* British Anglicanism.
  - Christian creationism *vs.* Darwinian naturalism.
  - North British institutions *vs.* British Metropolitan instutitions.

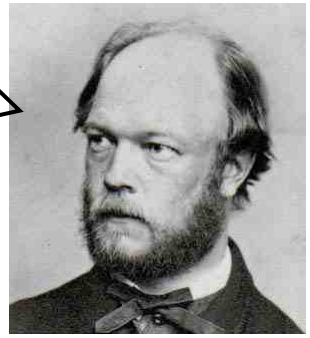


(1862 Lecture "On Force")

- Mayer is to be credited with equivalence of work and heat (not Joule).
- Helmholtz and Clausius are to be credited with constructing the new mechanical theory of heat.

(1862 popular essay "Energy" co-written with Thomson)

- New energy physics is based on conservation of *energy*, not to be confused with German "force".
- Cosmology of energy physics is that of creation and decay, *not* gradual (Darwinian) evolution.
- History of mechanical equivalent of heat runs through Joule back to Davy, Rumford, Locke (and *not* through Mayer).



3. Thomson and Tait's *Treatise on Natural Philosophy*

- First edition published in 1867. The Official Textbook of the new paradigm.
- Attempts to establish energy physics as a *Newtonian doctrine*.

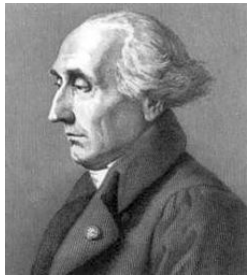
Principles in Statics:

Jean D'Alembert

(a) *D'Alembert's Principle (1743):* The sum of applied forces minus actual forces on a system in equilibrium is zero.

(b) *Principle of Virtual Velocities:* The sum of forces of a system of bodies in equilibrium multiplied by their respective virtual displacements is zero.

Lagrangian Formulation of Newtonian Mechanics:



Joseph Louie Lagrange

- *Lagrange-D'Alembert Principle (1788):* The sum of applied forces minus actual forces along a virtual displacement of a system is zero.
- Lagrange now derives Newton's Laws: *dynamics from statics*.
- Conservation of *vis viva* is not fundamental but derivative and only applicable for certain problems.

T & T':

T *T'*

- Make conservation of energy *fundamental*: Associate it with Newton's 3rd Law.
- Derive Principle of Virtual Velocities from conservation of energy: *statics from dynamics*.
- Relegate notion of *force* to a derived concept.
- Replace search for causes in nature (*i.e.*, forces) with:

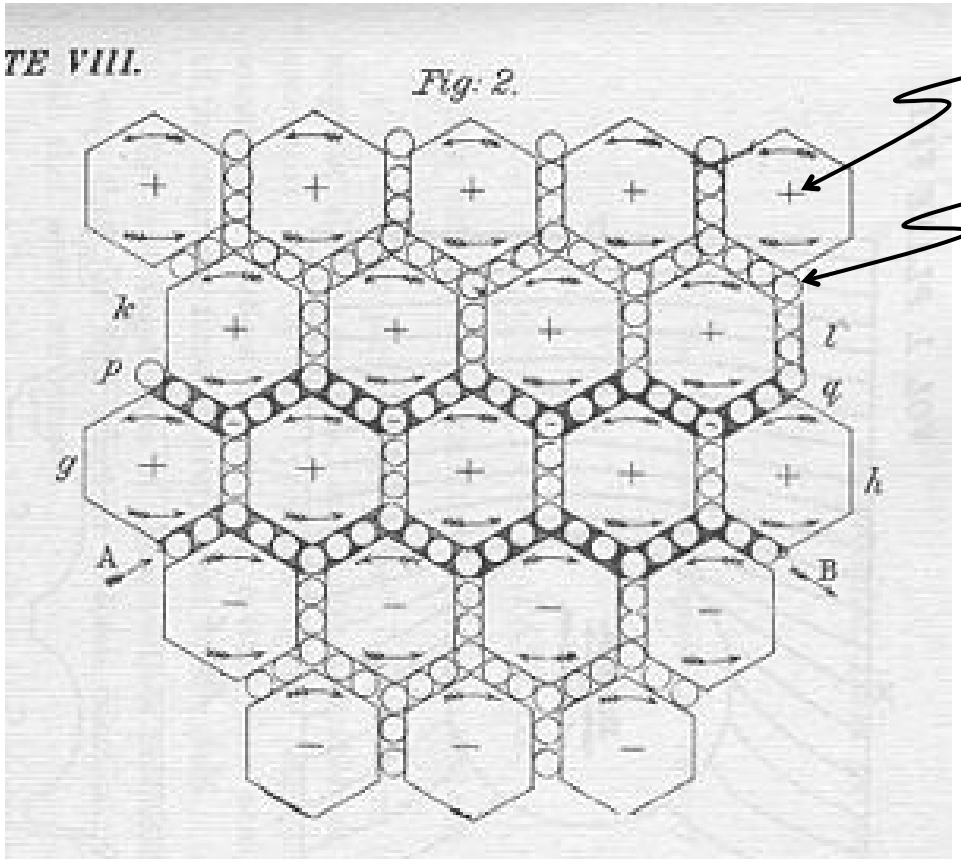
Principle of Least Action (Lagrange):

Energy transformations in nature minimize the action between states.

- Action = The rate of production of kinetic energy (the rate of working of an engine). (T & T')

4. Maxwell's Theory of Electromagnetism

- ***Molecular vortex theory of electromagnetism:***
  - 1861-62. "On Physical Lines of Force".



motion of vortices = magnetism

motion of idle wheels = electricity

- "Somewhat awkward" and of "provisional and temporary character".
- *Smith*: Concerned to offer a *possible* explanation in terms of a continuous mechanism in opposition to action-at-a-distance force models.

"... built up to shew that the phenomena are such as can be explanined by mechanism. The nature of this mechanism is to the true mechanism what an orrery is to the Solar System."

orrery

Key Features:

(a) Existence of "displacement currents".

- Conductor = "a porous membrane which opposes more or less resistance to the passage of a fluid".
- Dielectric = "an elastic membrane that is impervious to the fluid, but transmits the pressure of the fluid on one side to that of the other."
- Variations of pressure on a dielectric produce "displacement" currents.

"We cannot help regarding the phenomena as those of an elastic body, yielding to a pressure, and recovering its form when the pressure is removed."

(b) Theoretically derived velocity of transverse oscillations of magnetic medium agrees with experimentally measured velocity of light!

"We can scarcely avoid the inference that light consists in the transverse undulations of the same medium which is the cause of electric and magnetic phenomena."

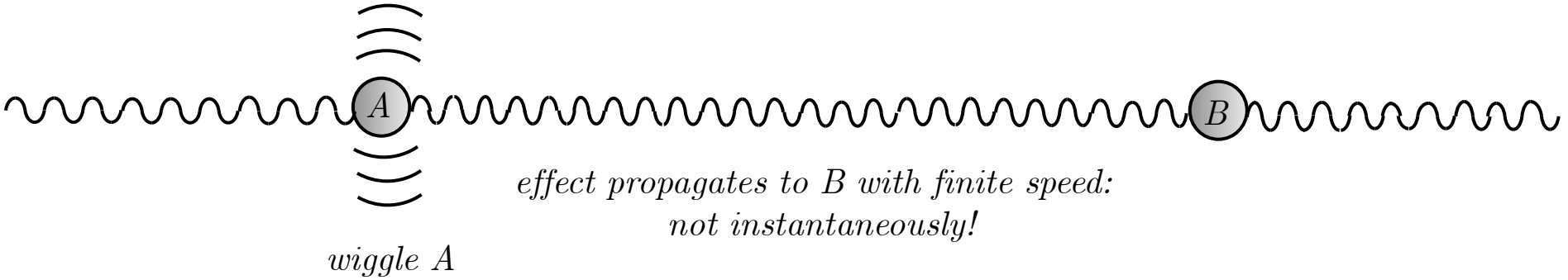
- ***Concept of electromagnetic field:***

- 1865: "A Dynamical Theory of the Electromagnetic Field"

"That part of space which contains and surrounds bodies in electric or magnetic conditions."

- EM field mediates the influences that electromagnetic bodies have on each other:

"... [T]he motion of one part communicates motion to the parts in its neighborhood... [T]his communication is not instantaneous but progressive..."



- *Smith gloss*: The etherial medium is the means by which energy is transmitted between bodies.

"In speaking of the energy of the field... I wish to be understood literally... Where does it reside?... On our theory it resides in the electromagnetic field, in the space surrounding the electrified and magnetic bodies, as well as in those bodies themselves..."

- *Smith gloss*: "The tactic here was to embed what was potentially an exceedingly hypothetical assumption, that of the existence of an ethereal medium, in the frameworks of contemporary science ranging from the (by now) highly credible undulatory theory of light to the much more recent energy cosmology." (pg. 231.)