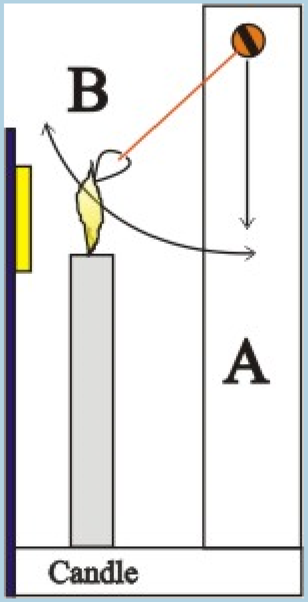
Curie Temperature

Neil McGlohon & Nathan Beck (2012)

Tim Corbly & Richard Mihelic (2013)

The Curie Point

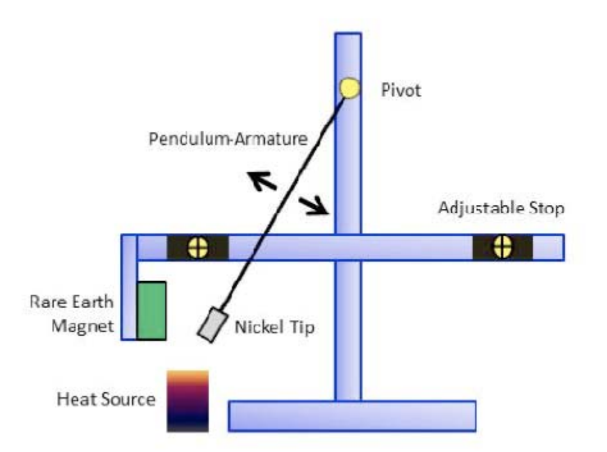
- Curie point, also called Curie Temperature, temperature at which certain magnetic materials undergo a sharp change in their magnetic properties.
- This temperature is named for the French physicist Pierre Curie, who in 1895 discovered the laws that relate some magnetic properties to change in temperature.
- At low temperatures, magnetic dipoles are aligned. Above the curie point, random thermal motions nudge dipoles out of alignment.



An example of a curie pendulum which utilizes the effects of heat on a ferromagnetic substance’s magnetization. The motion is periodic and follows the heating/cooling process of the swinging bob.

Curie Pendulum

- The heat engine uses a principle of magnetism discovered by Curie. He studied the effects of temperature on magnetism.
- Ferromagnetism covers the field of normal magnetism that people typically associate with magnets. All normal magnets and the material that are attracted to magnets are ferromagnetic materials.
- Pierre Curie discovered that ferromagnetic materials have a critical temperature at which the material loses their ferromagnetic behavior. This is known as its Curie Point.
- Once the material reaches the Curie Point, it will lose some of its magnetic properties until it cools away from the heat source and regains its magnetic properties. It is then pulled into the heat source again by the engine magnet to cycle through again.



The heat source could be a flame or even a light depending on the material of the bob.

Heat Engines

- A heat engine transfers energy from a hot reservoir to a cold reservoir, converting some of it into mechanical work.
- No engine operating between two heat reservoirs can be more efficient than a Carnot engine operating between the same reservoirs.
- Examples of heat engines:
  - Curie point
  - Stirling Engine
  - Steam engine
  - Elastic engine

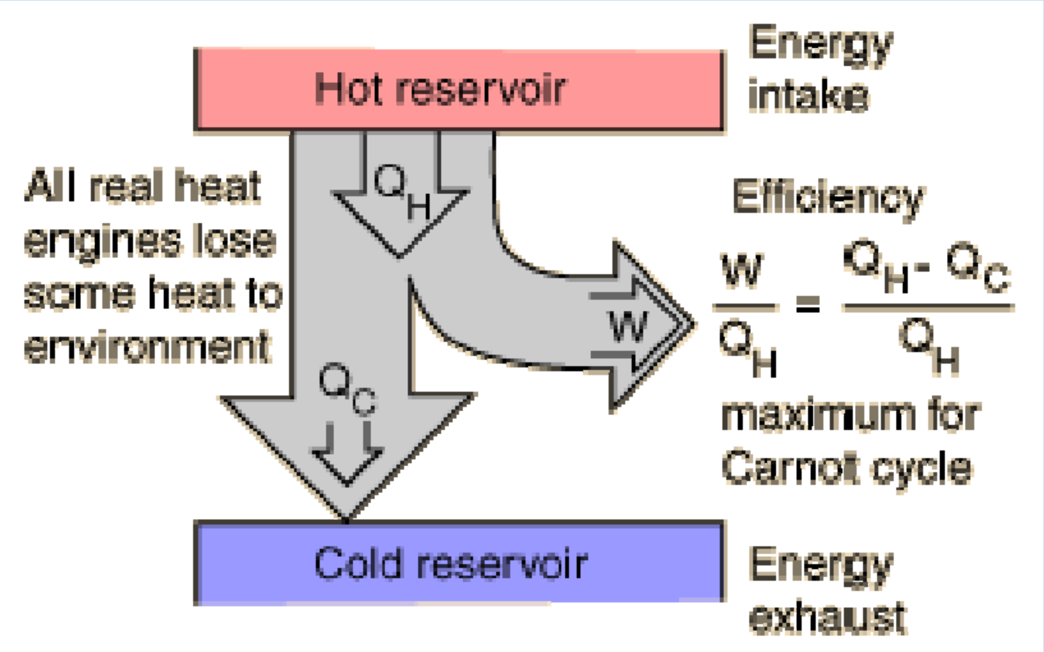
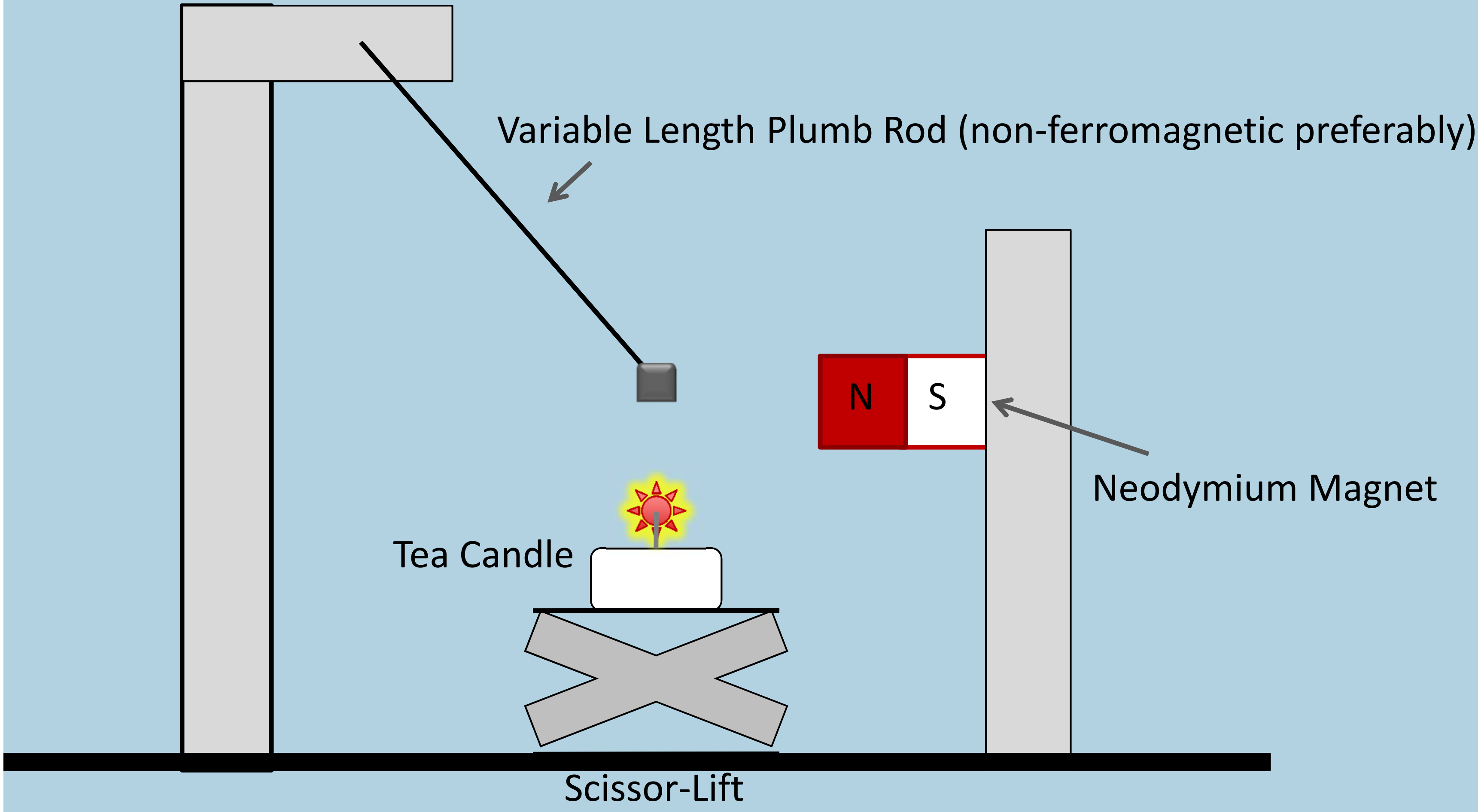
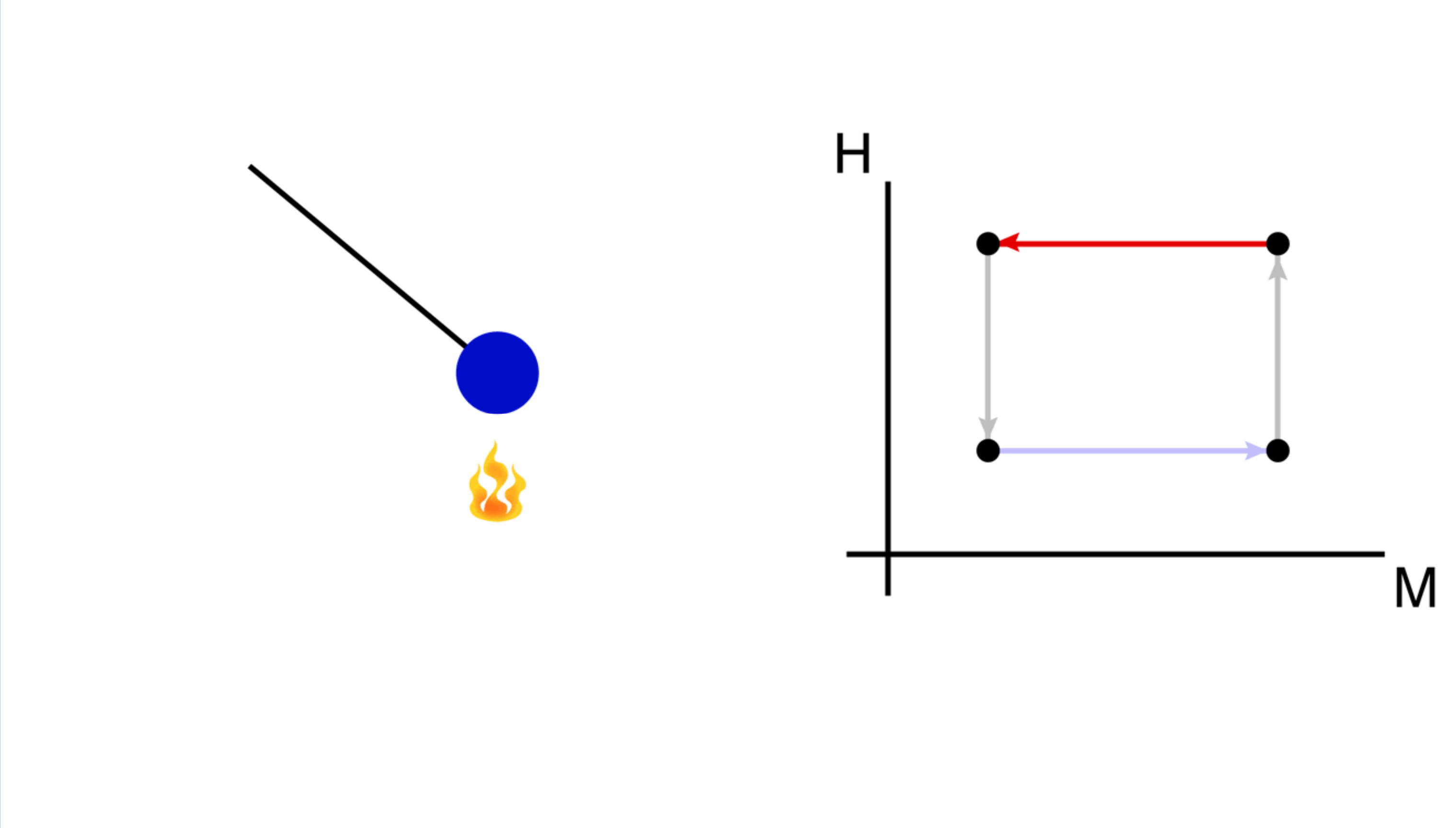


Diagram of Apparatus

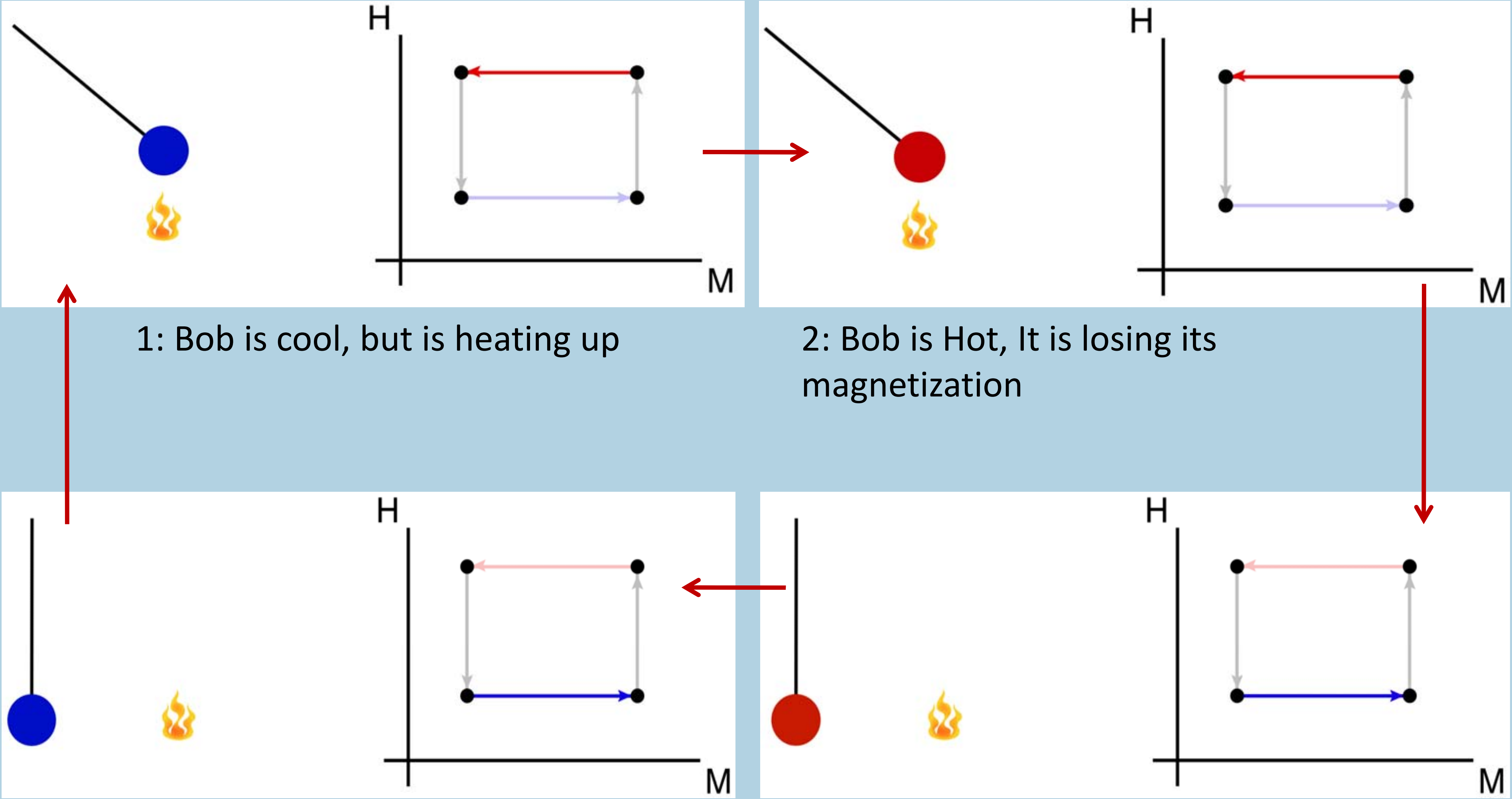


How it works!



H: magnetic field intensity
M: magnetization

How it works!



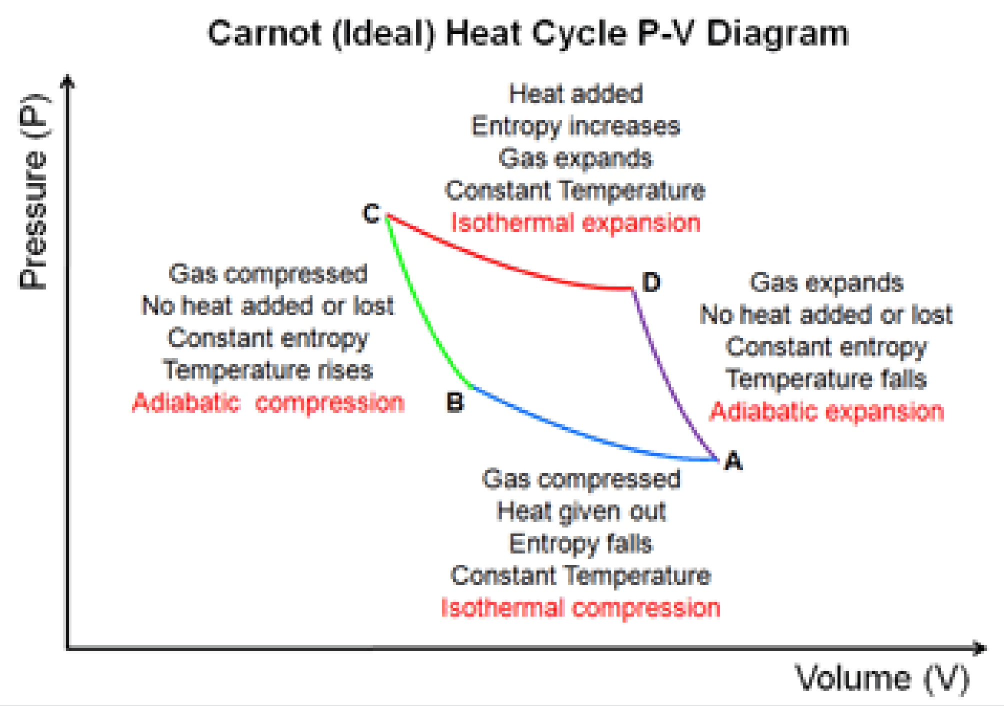
1: Bob is cool, but is heating up

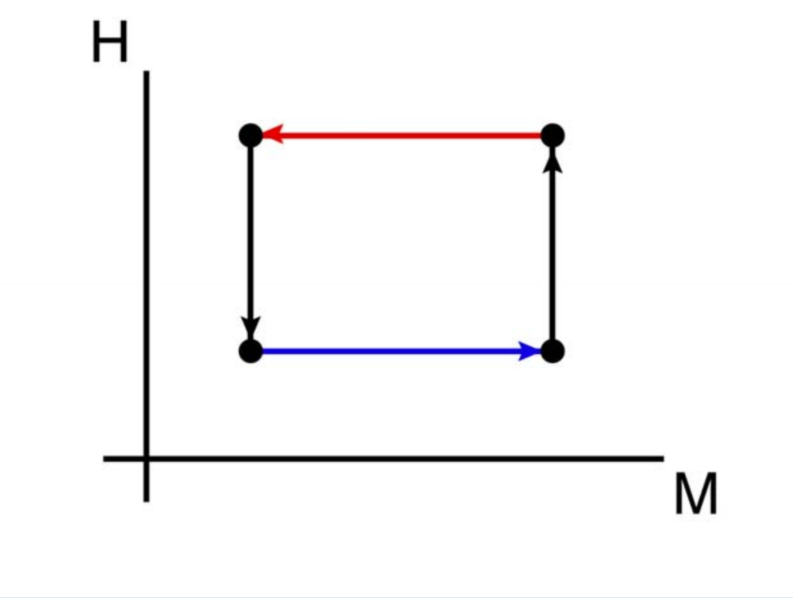
2: Bob is Hot, It is losing its magnetization

4: Bob is cool, regaining its magnetization

3: Bob is Hot, but is cooling down

Carnot Cycle PV Diagram

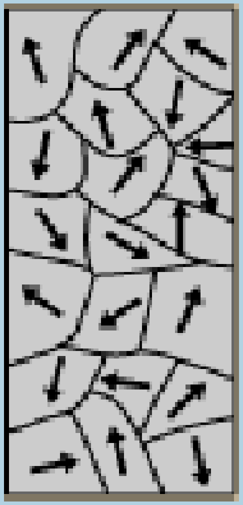




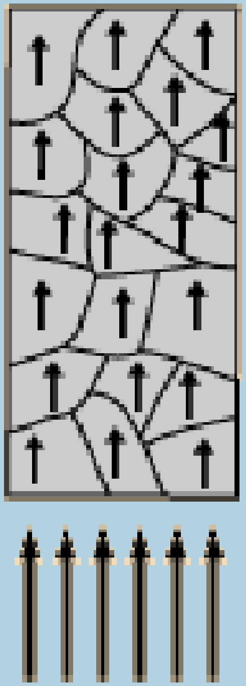
Our heat engine is not exactly a Carnot cycle, however there are similarities between it and our HM diagram.

Paramagnetism vs. Ferromagnetism

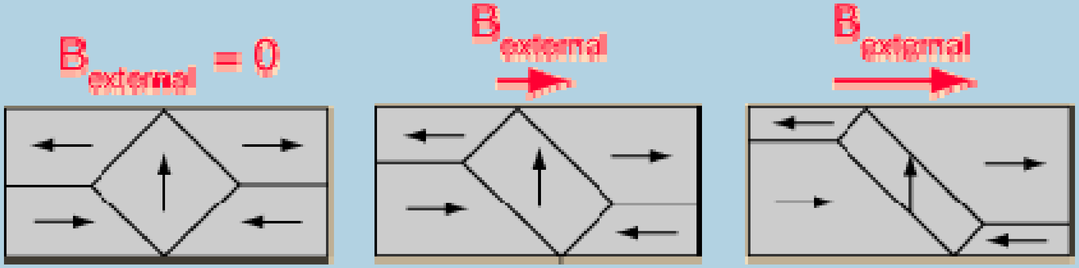
- Materials are made up of magnetic domains, which contain atomic dipoles coupled together in some direction.
- Typically, these domains are aligned in random directions, and so there is no overall magnetic direction.
- In the presence of a magnetic field, domains parallel to the field grow while others shrink.
- Paramagnetic materials have a positive magnetic susceptibility. Ferromagnetic materials have a strong positive susceptibility.
- Ferromagnetic materials can remain magnetized after the external field is removed.



In bulk material the domains usually cancel, leaving the material unmagnetized.



Externally applied magnetic field.

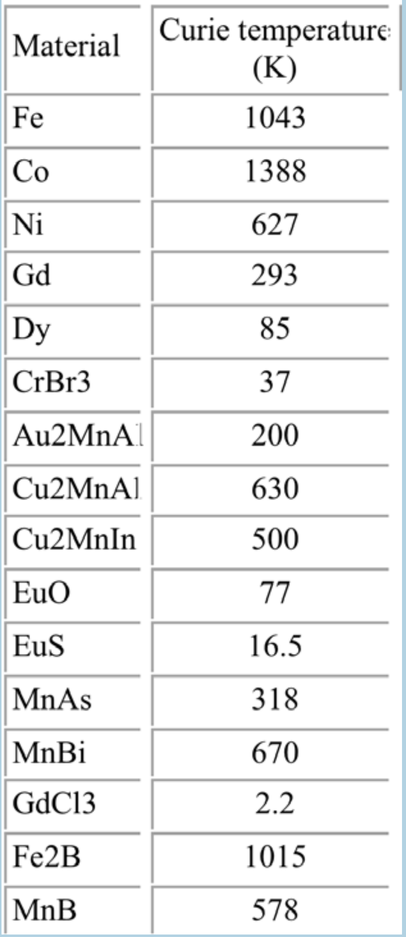


No external field

Weak applied field

Strong applied field

The Curie Point



Material	Curie temperature (K)
Fe	1043
Co	1388
Ni	627
Gd	293
Dy	85
CrBr3	37
Au2MnAl	200
Cu2MnAl	630
Cu2MnIn	500
EuO	77
EuS	16.5
MnAs	318
MnBi	670
GdCl3	2.2
Fe2B	1015
MnB	578

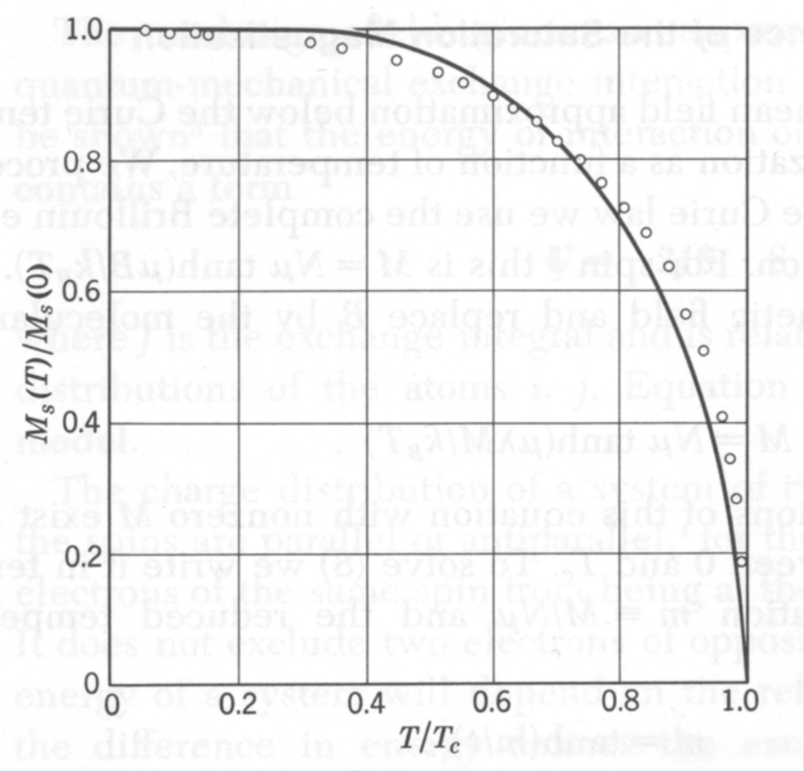
Nickel’s curie point is 627 K, this is equivalent to around 354 degrees Celsius. This make it optimal for a flame based Curie Pendulum.

Gadolinium has a Curie Temperature of 293 K. This is equivalent to around 20 degrees Celsius. This makes for a good material in a light based Curie Pendulum.

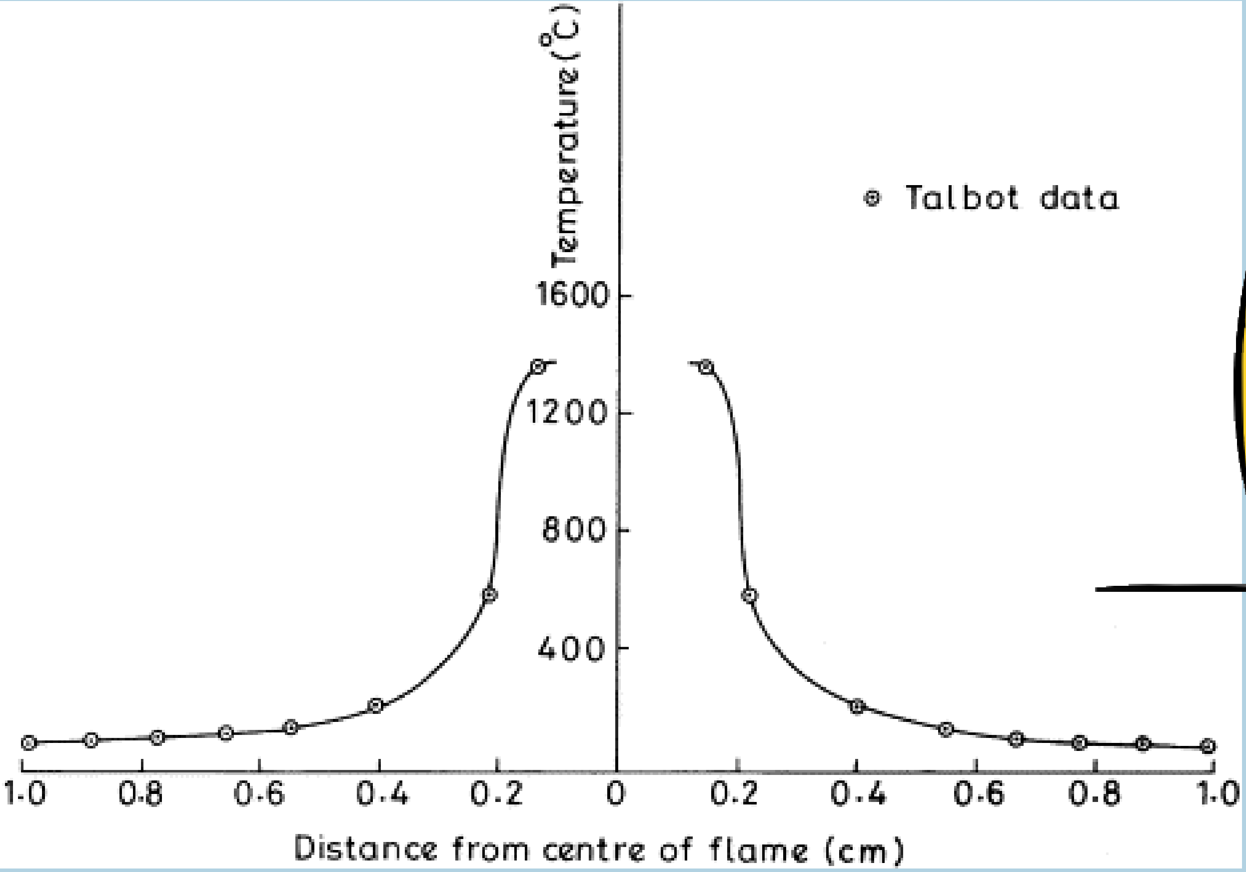
Data from F. Keffer, Handbuch der Physik, 18, pt. 2, New York: Springer-Verlag, 1966 and P. Heller, Rep. Progr. Phys., 30, (pt II), 731 (1967)

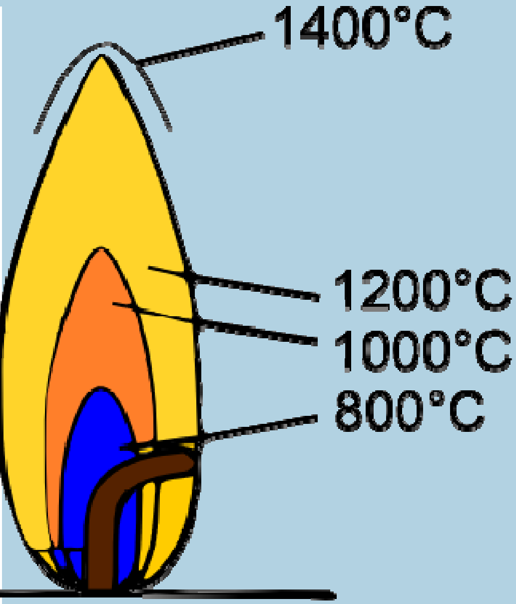
Temperatures of Interest

- Nickel has a Curie Temperature of 627K.
- We expect the bob to follow an oscillatory path that orbits the curie point with a period under 10 seconds (from observation of examples).



Candle Temperature Profile

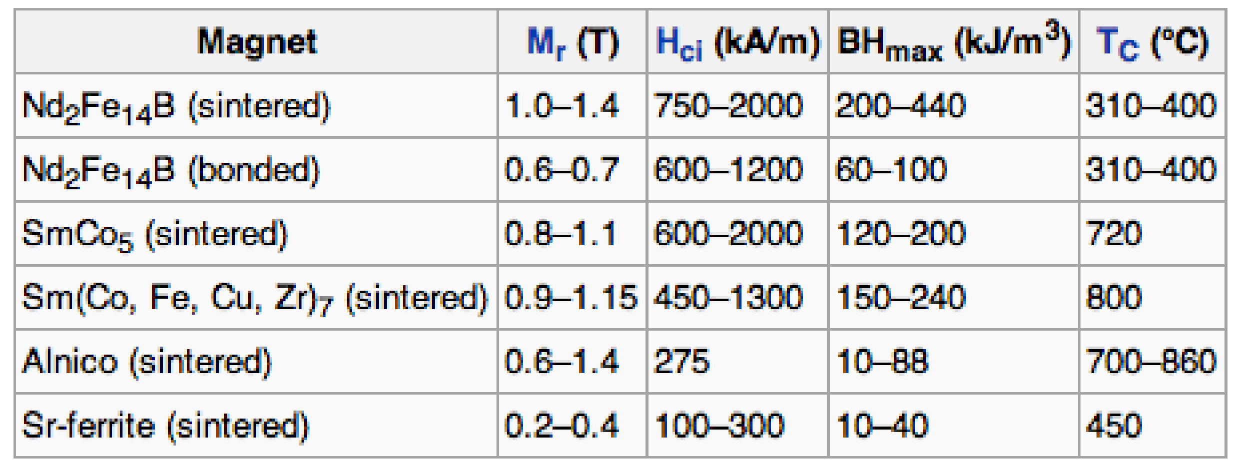




Horizontal distance from flame:
Source: http://www.sciencedirect.com/science/article/pii/S0143816699000378

Neodymium Magnets

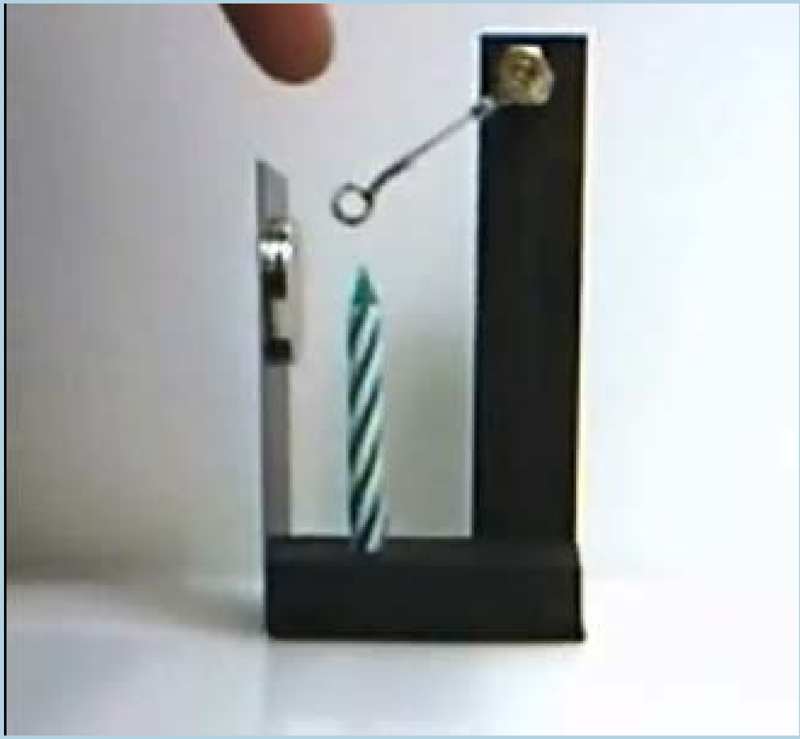
Could we damage the magnet itself with the flame?



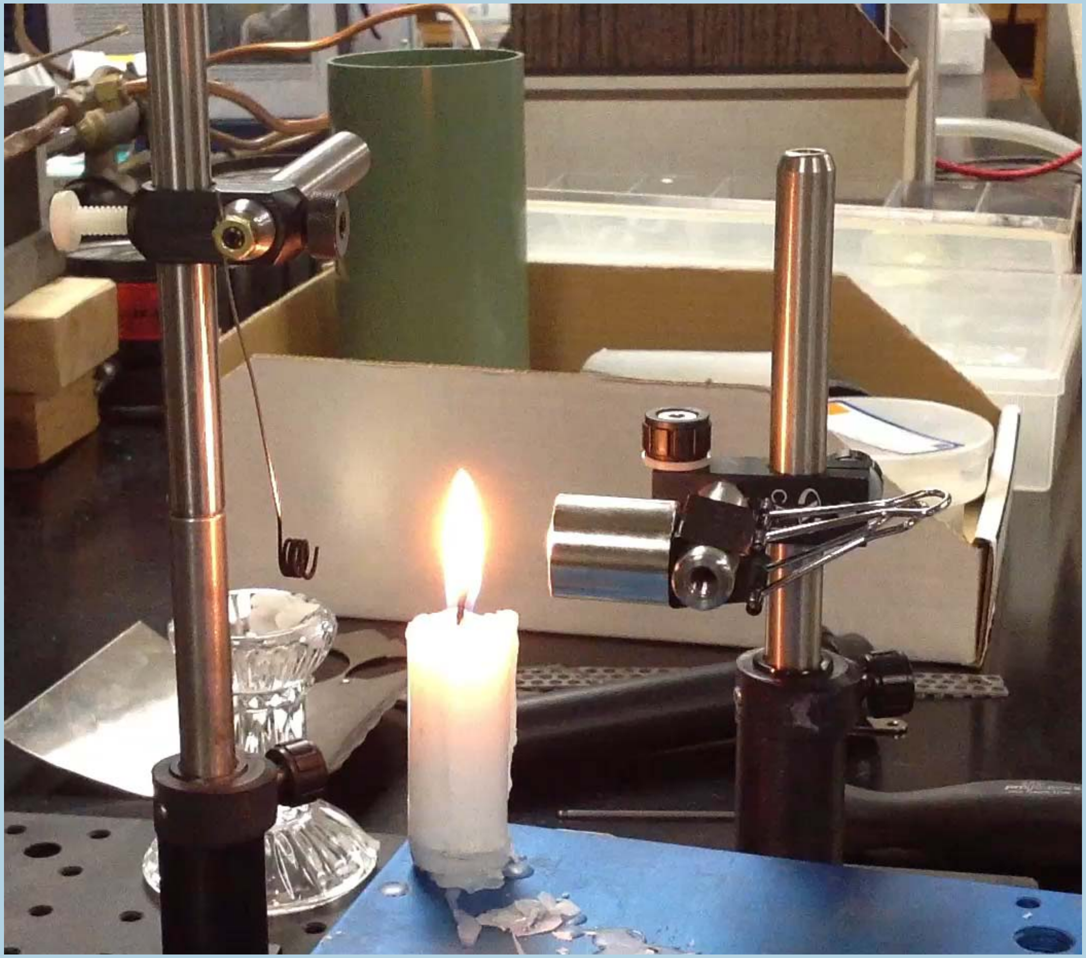
Magnet	M_r (T)	H_{ci} (kA/m)	BH_{max} (kJ/m^3)	T_C (°C)
$Nd_2Fe_{14}B$ (sintered)	1.0–1.4	750–2000	200–440	310–400
$Nd_2Fe_{14}B$ (bonded)	0.6–0.7	600–1200	60–100	310–400
$SmCo_5$ (sintered)	0.8–1.1	600–2000	120–200	720
Sm(Co, Fe, Cu, Zr)$_7$ (sintered)	0.9–1.15	450–1300	150–240	800
Alnico (sintered)	0.6–1.4	275	10–88	700–860
Sr-ferrite (sintered)	0.2–0.4	100–300	10–40	450

We could, if the magnet crosses its Curie point, it will permanently lose its magnetization. But from the flame profile in the previous slide the magnet is kept at a safe enough horizontal distance to avoid damage. The magnet stayed cool enough to touch throughout the experiment.

Example of Basic Apparatus

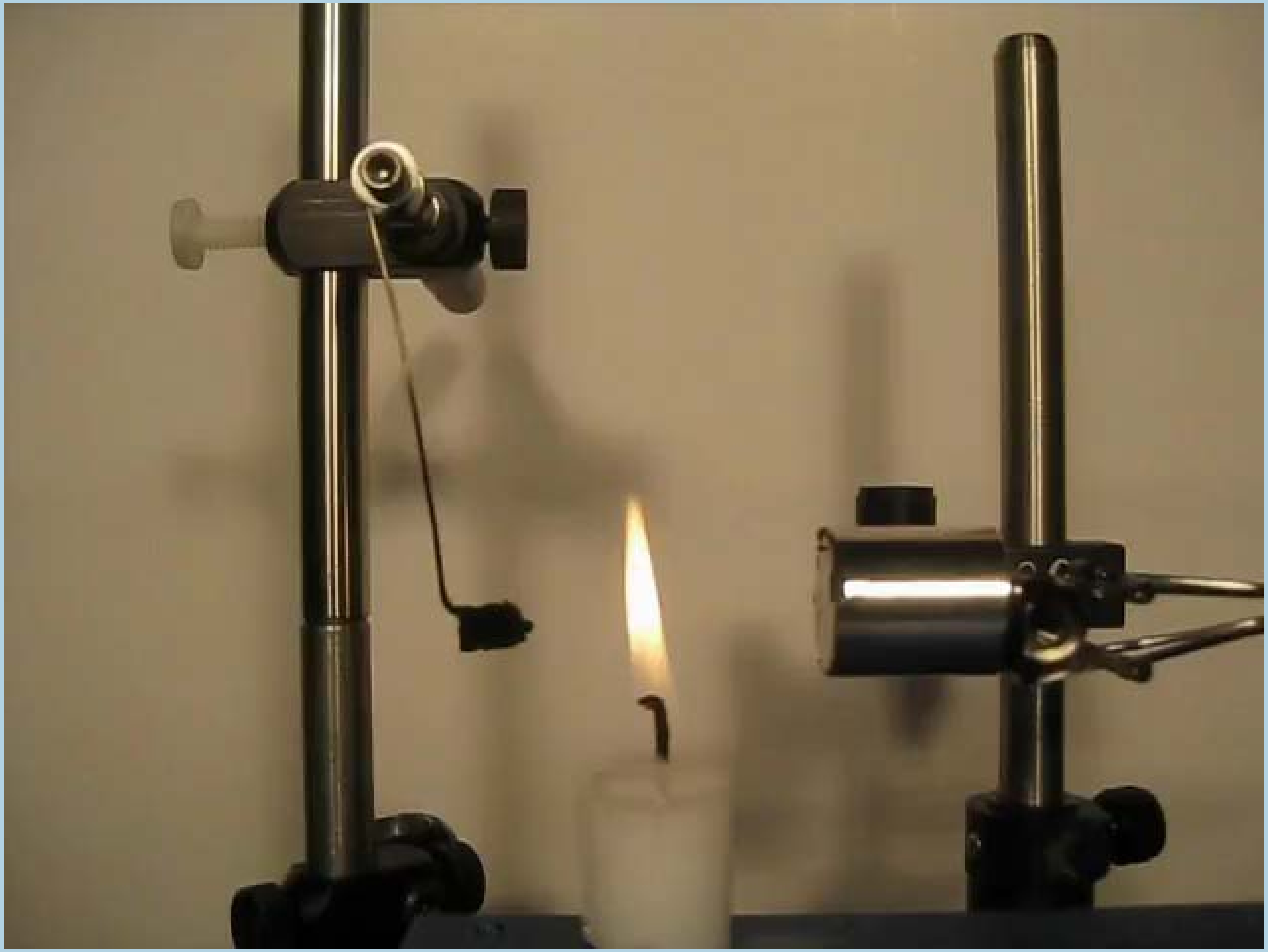


Mark I



Period of about 7 seconds.

Mark II



Period of about 5 seconds.

Stefan-Boltzmann Law - Cooling

- Energy radiated by a blackbody radiator per second per unit area is proportional to the fourth power of the absolute temperature and is given by the Stefan-Boltzemann Law:

$$\frac{P}{A} = \sigma T^4$$

- But not every radiator is ideal – in which case the proportionality constant for emissivity is introduced:

  (ideal radiator: $e = 1$)

$$\frac{P}{A} = e\sigma T^4$$

Stefan-Boltzmann Law - Cooling

- If the hot object is radiating energy to its cooler surroundings at temperature T_s then the total energy radiated is:

$$P = e\sigma A(T^4 - T_s^4)$$

- Our concern with this is the candle soot that builds up on the pendulum bob could affect the emissivity of the nickel and change the properties of the system over time.

Data - Magnetic Field

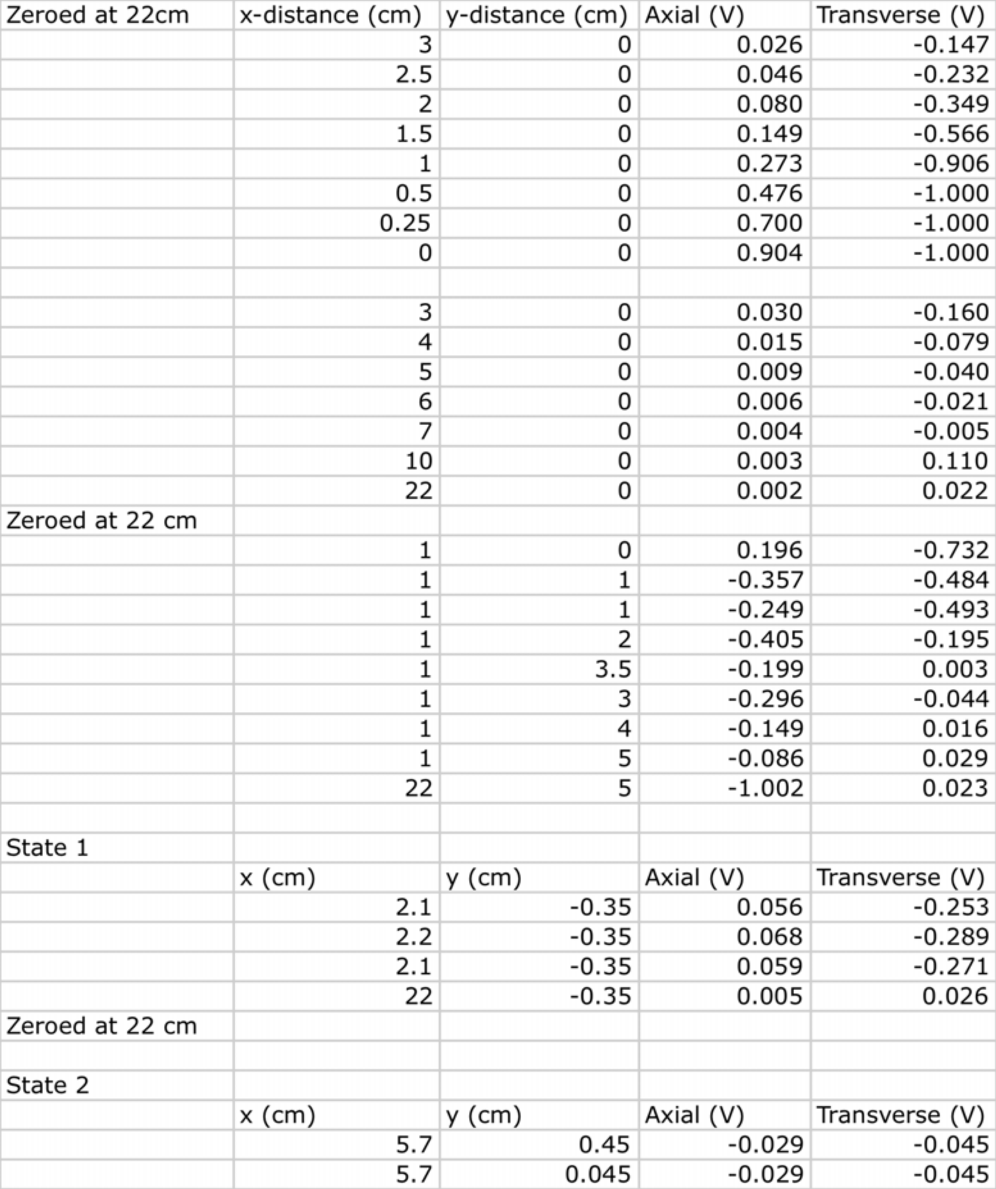
Measurements with a magnetic field probe, output a voltage corresponding to two different sweet spots that measured the Axial and Transverse potential at a given point.

X distance: Horizontal distance from edge of magnet. Positive away.

Y distance: vertical distance from center of magnet. Positive down.

State 1, the position of the bob when it is at its maximum magnetic field amplitude.

State 2, the position of the bob after it falls from the magnet.



Zeroed at 22cm	x-distance (cm)	y-distance (cm)	Axial (V)	Transverse (V)
	3	0	0.026	-0.147
	2.5	0	0.046	-0.232
	2	0	0.080	-0.349
	1.5	0	0.149	-0.566
	1	0	0.273	-0.906
	0.5	0	0.476	-1.000
	0.25	0	0.700	-1.000
	0	0	0.904	-1.000
	3	0	0.030	-0.160
	4	0	0.015	-0.079
	5	0	0.009	-0.040
	6	0	0.006	-0.021
	7	0	0.004	-0.005
	10	0	0.003	0.110
	22	0	0.002	0.022
Zeroed at 22 cm				
	1	0	0.196	-0.732
	1	1	-0.357	-0.484
	1	1	-0.249	-0.493
	1	2	-0.405	-0.195
	1	3.5	-0.199	0.003
	1	3	-0.296	-0.044
	1	4	-0.149	0.016
	1	5	-0.086	0.029
	22	5	-1.002	0.023
State 1				
	x (cm)	y (cm)	Axial (V)	Transverse (V)
	2.1	-0.35	0.056	-0.253
	2.2	-0.35	0.068	-0.289
	2.1	-0.35	0.059	-0.271
	22	-0.35	0.005	0.026
Zeroed at 22 cm				
State 2				
	x (cm)	y (cm)	Axial (V)	Transverse (V)
	5.7	0.45	-0.029	-0.045
	5.7	0.045	-0.029	-0.045

Missing Data - Temperature

- Optimally we would have spot welded a thermocouple to the bob to measure its **temperature** at the different spots. This would allow us to have a definitive number for the amount of work we have harvested from the candle.

Possible issues:

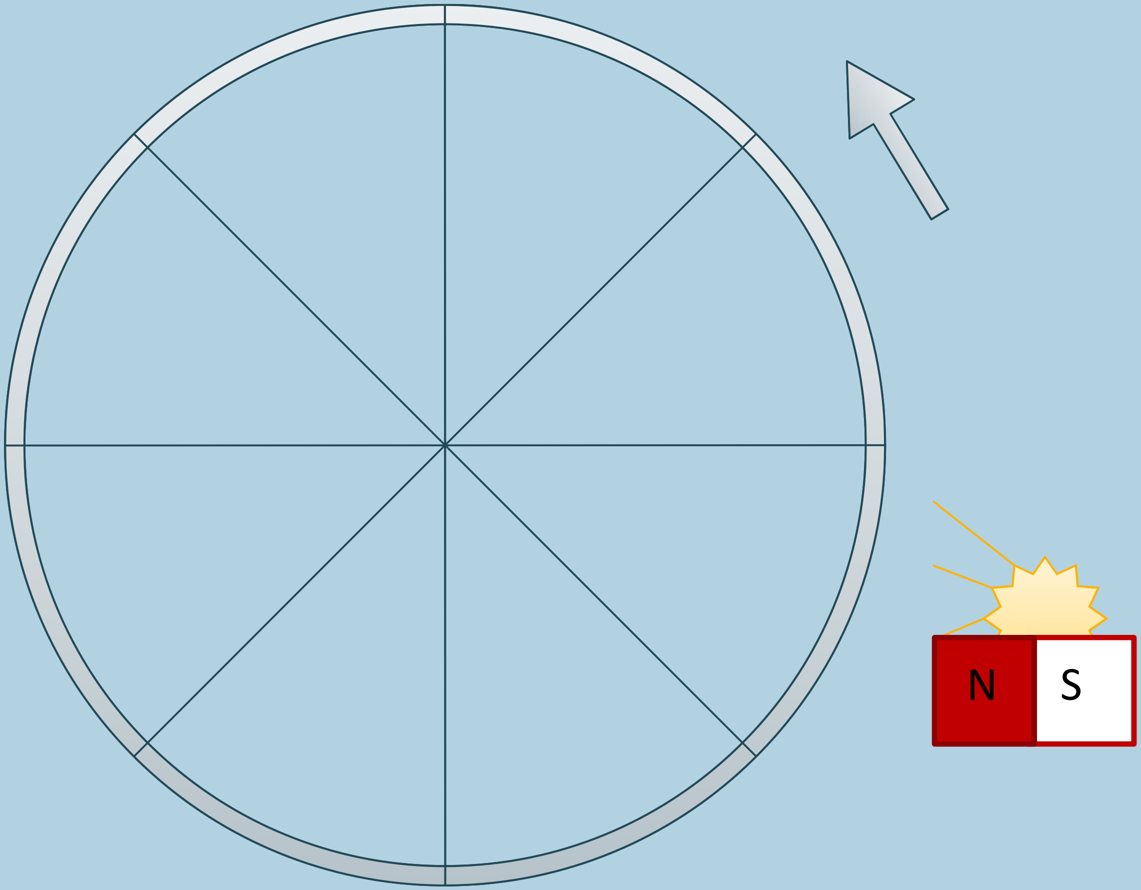
- The thermocouple is not without mass, this could affect how the bob interacts with the magnet, change the period, etc.
- The Thermocouple may be ferromagnetic itself and have a different curie point than that of the bob, this could alter how the magnet interacts with the bob as well.

Thoughts – How can we benefit?

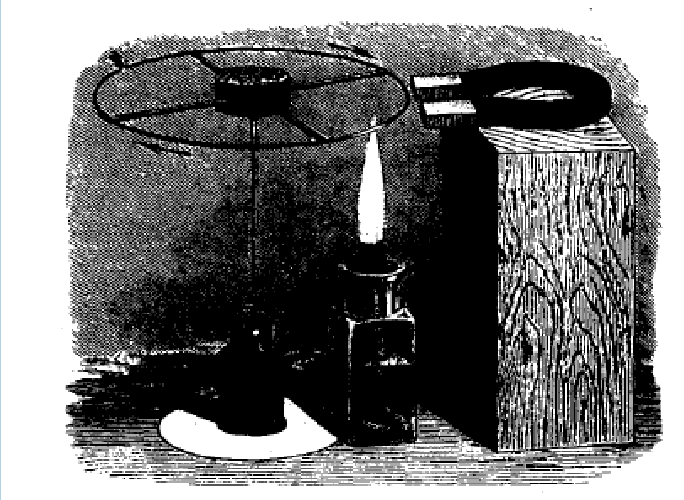
- Hopes:
  - To make a more efficient heat engine.
  - Optimally we would have a ferromagnetic pendulum bob with a non-ferromagnetic, non-conducting swing rod.
  - Use a Ratchet system to take energy out
- Concerns:
  - The soot from the candle can effect the cooling and heating rate of the bob.
  - The candle flame is not stable
  - The current pendulum rod is both conducting and ferromagnetic.
  - Due to the geometry of the bob, there are two nodes that it can stably reside in. For the most part during operation, it prefers the lower of the two, which is optimal.

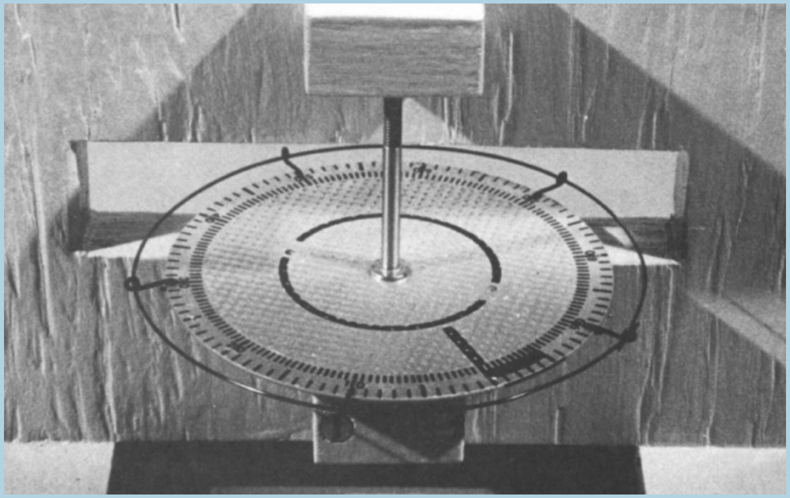
Possible Improvements

- Mark III – Rotary Curie Engine

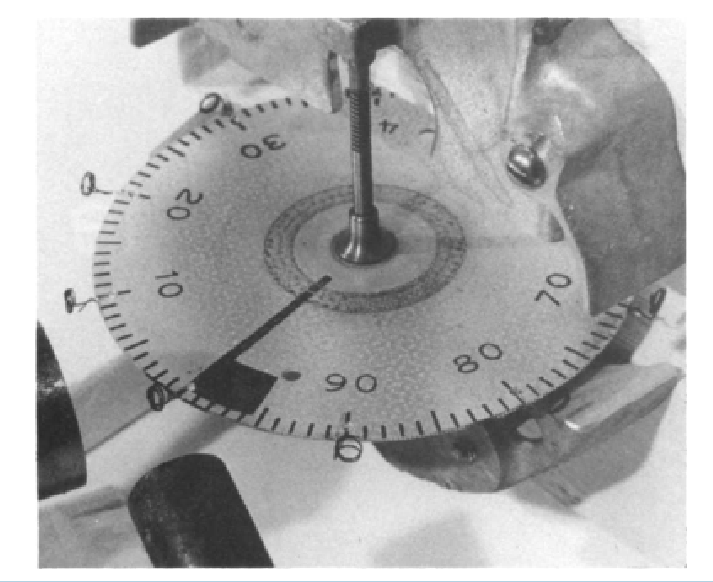


Examples of Rotary Type



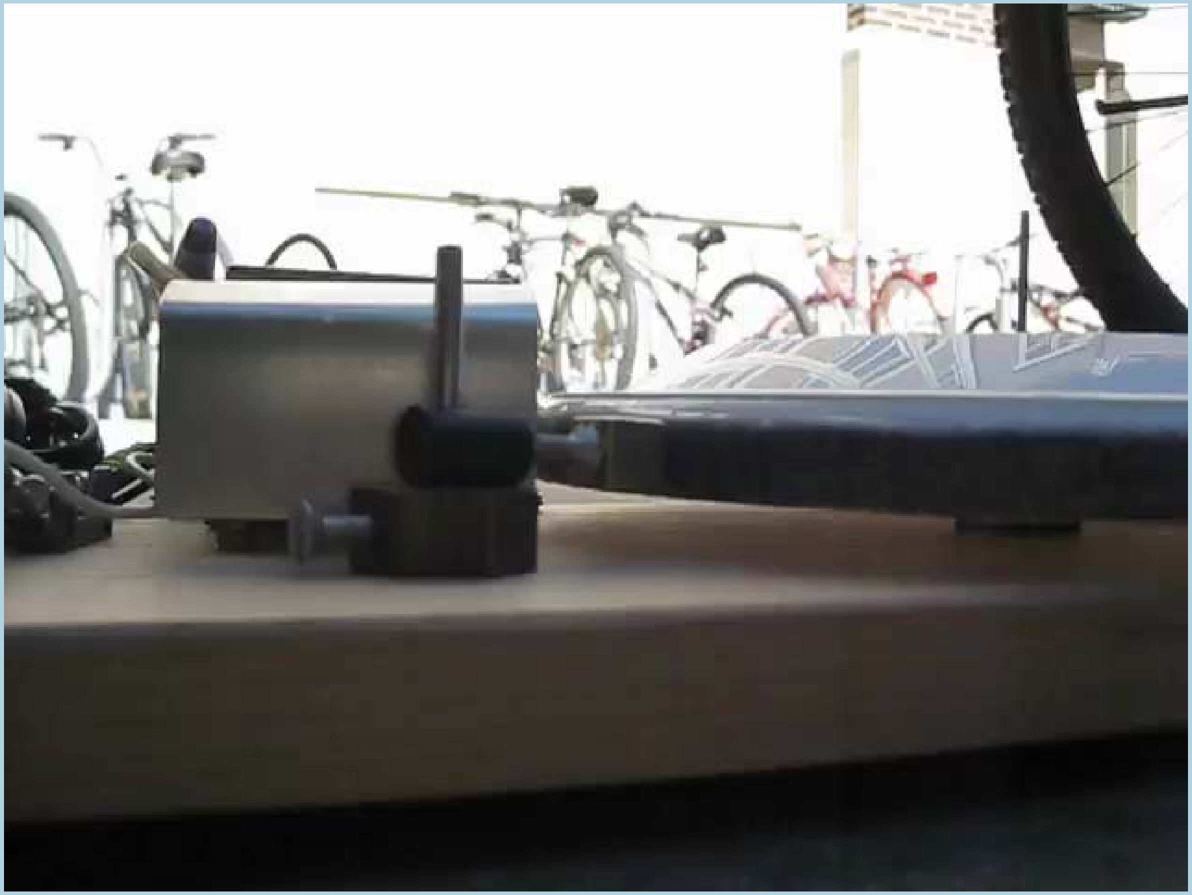


Aluminum disk with a continuous nickel loop



Aluminum disk with individual nickel loops

Example of Rotary Curie Engine



The period of this engine was approximately 1 rotation every 5 seconds at an average of 16°C outside temperature. The temperature between the disk and light fluctuated between 65°C and 85°C and the temperature next to the light was about 90°C.

Sources:

- http://scitoys.com/scitoys/scitoys/magnets/magnets.html#curie_effect
- http://dx.doi.org/10.1119/1.14959
- http://www.imagesco.com/articles/heatengine/HeatEngine.html
- http://www.sciencedirect.com/science/article/pii/S0143816699000378
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- http://www.doitpoms.ac.uk/tlplib/ferromagnetic/curie-weiss.php
- http://www.sciencedirect.com/science/article/pii/S0304885308011487