Title: The smallest possible thermal machines and the foundations of thermodynamics

Date: May 18, 2011 02:00 PM

URL: http://www.pirsa.org/11050009

Abstract: In my talk I raise the question of the fundamental limits to the size of thermal machines - refrigerators, heat pumps and work producing engines - and I will present the smallest possible ones. I will also discuss the issue of a possible complementarity between size and efficiency and show that even the smallest machines could be maximally efficient. Finally I will present a new point of view over what is work and what do thermal machines actually do.

The smallest possible thermal machines and the foundations of thermodynamics

Sandu Popescu

Motivation

Quantum effects in biology?

Motivation

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Biological systems are open, driven systems far from equilibrium

Motivation

Quantum effects in biology?

Biological systems are open, driven systems far from equilibrium

Could biological molecules act as refrigerators?

How to construct very small thermal machines?

Small = A few qubits or something like that.

What are the smallest possible thermal machines?

What are the smallest possible thermal machines?

Self contained:

What are the smallest possible thermal machines?

Self contained: No external source of work

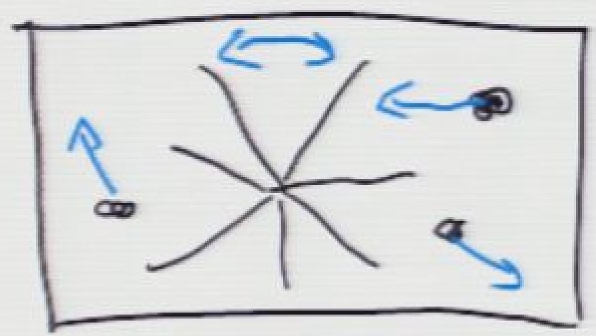
What are the smallest possible thermal machines?

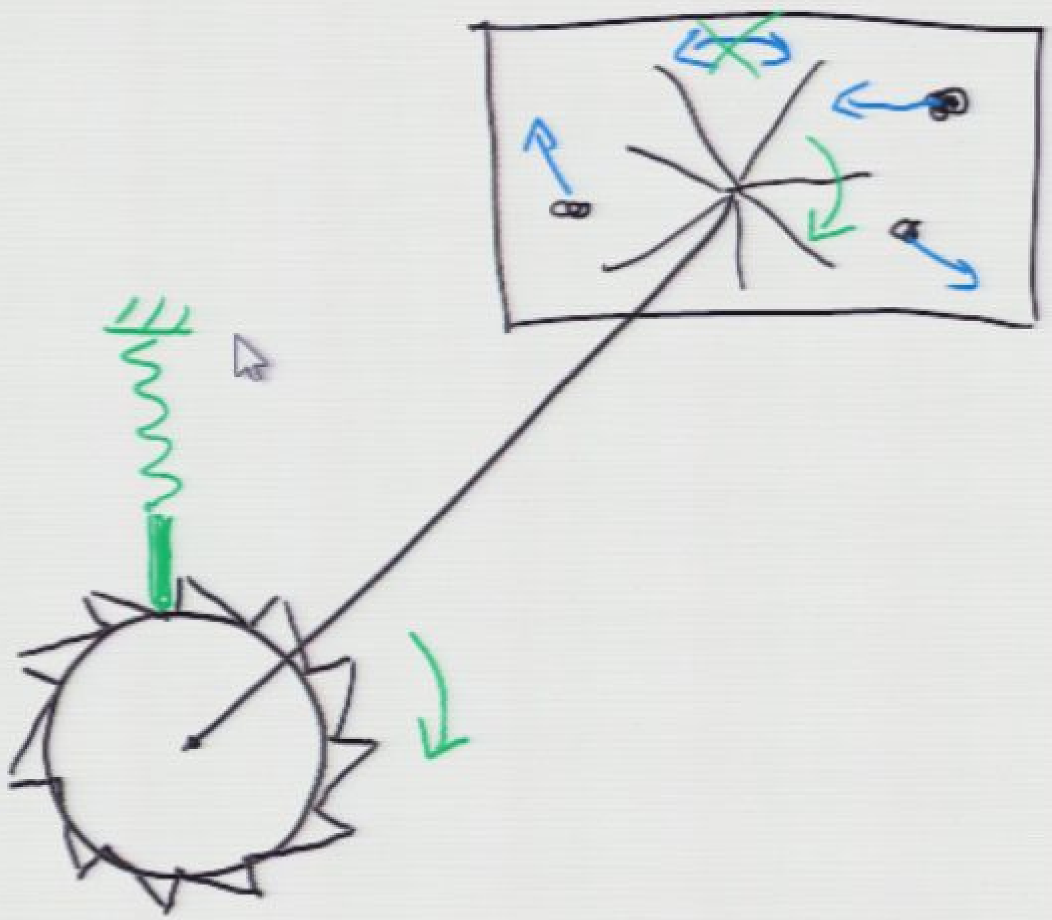
Self contained: No external source of work

No pre-determined unitary transformations

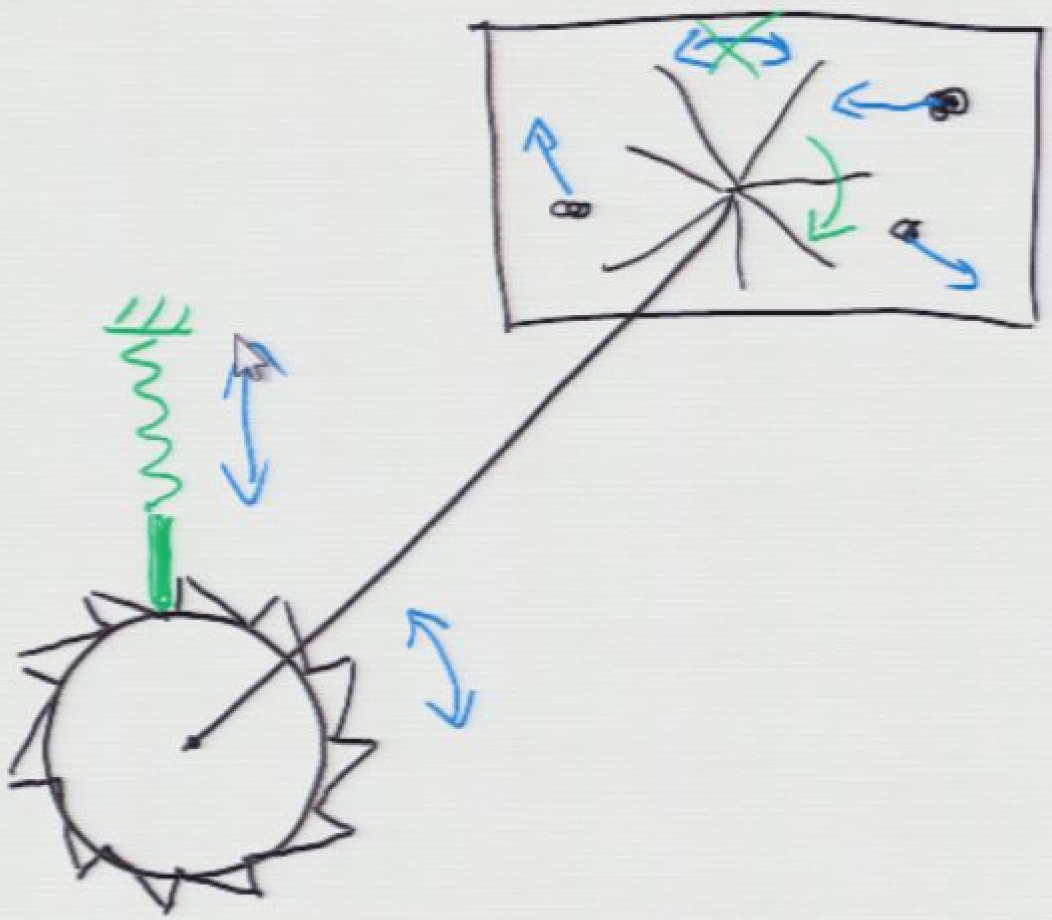
- How to construct very small thermal machines?
- What is the minimal size of a thermal machine?
- How well do they work?
- Is there a complementarity size-efficiency?

Feynman's Example

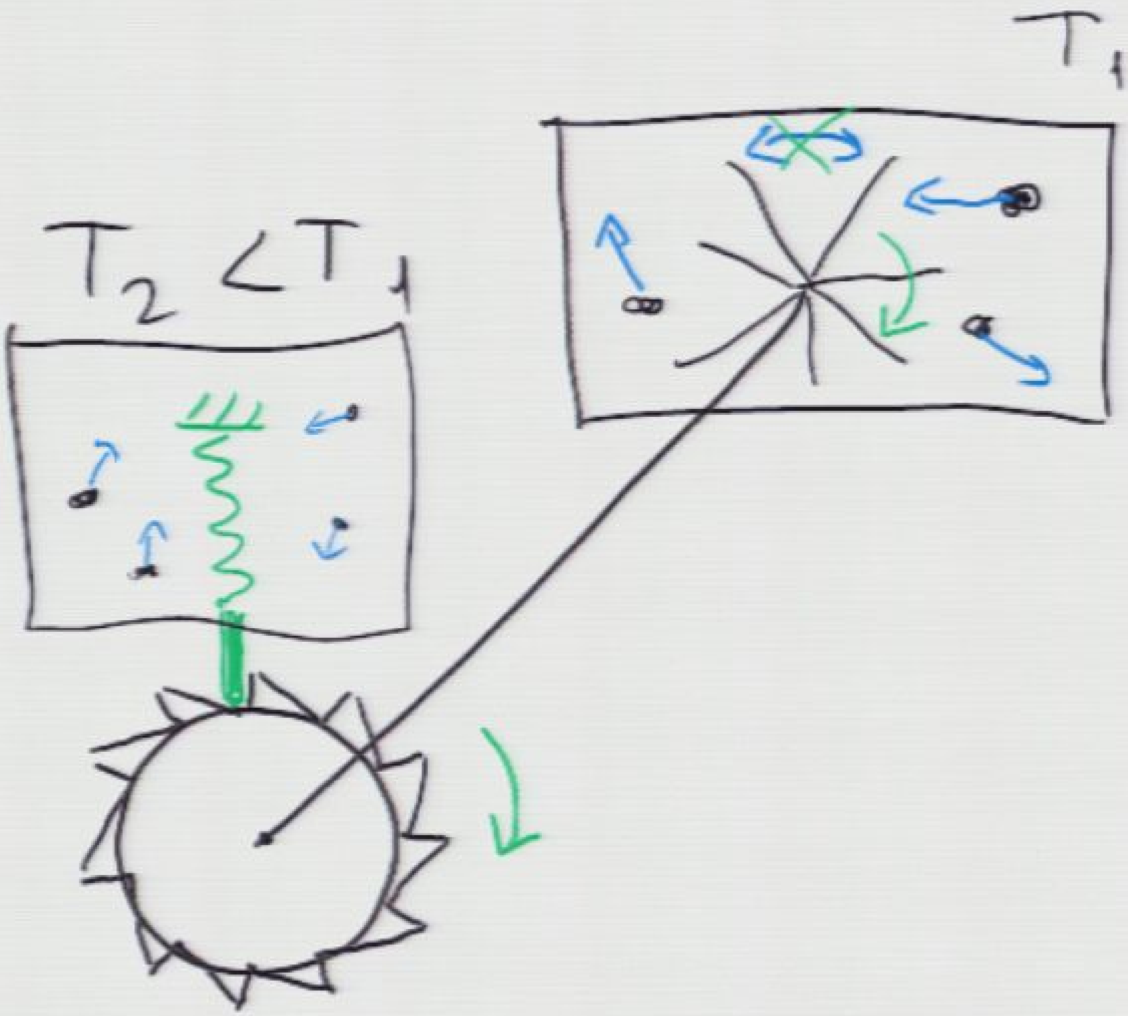




Problem



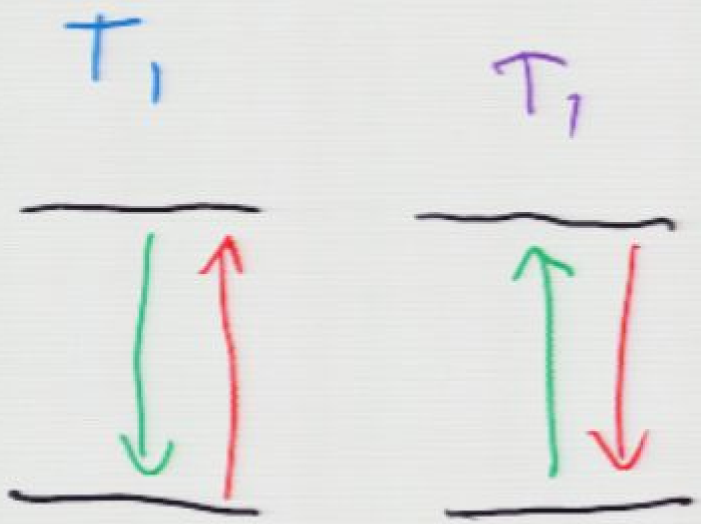
Solution



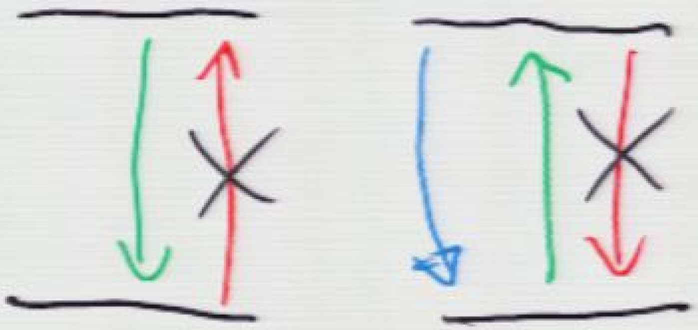
The smallest possible refrigerator

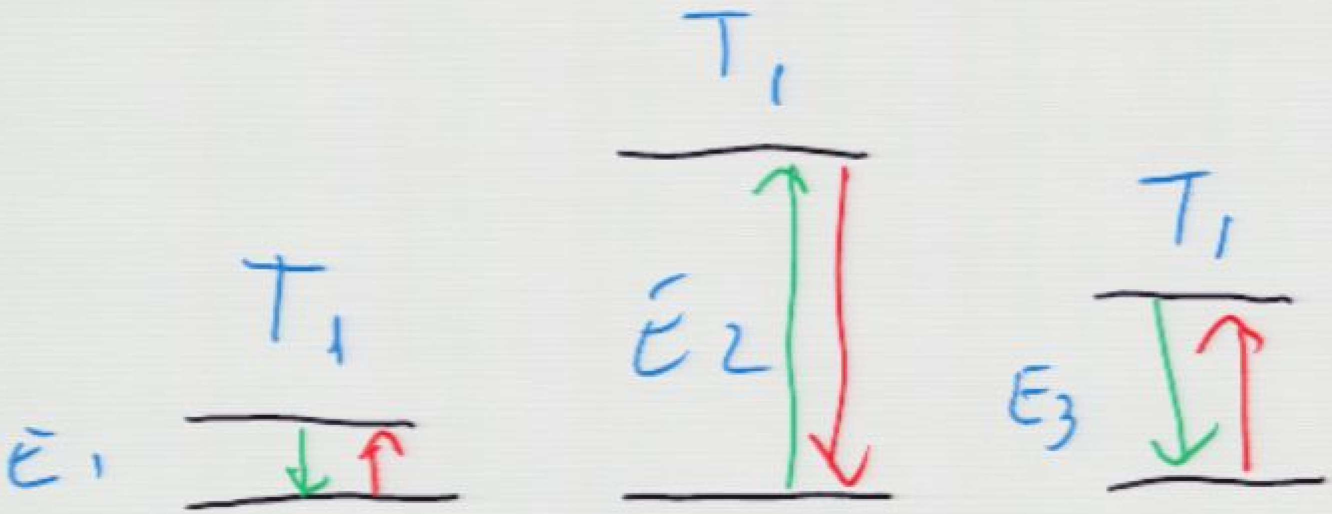
T_1

T_1 T_1

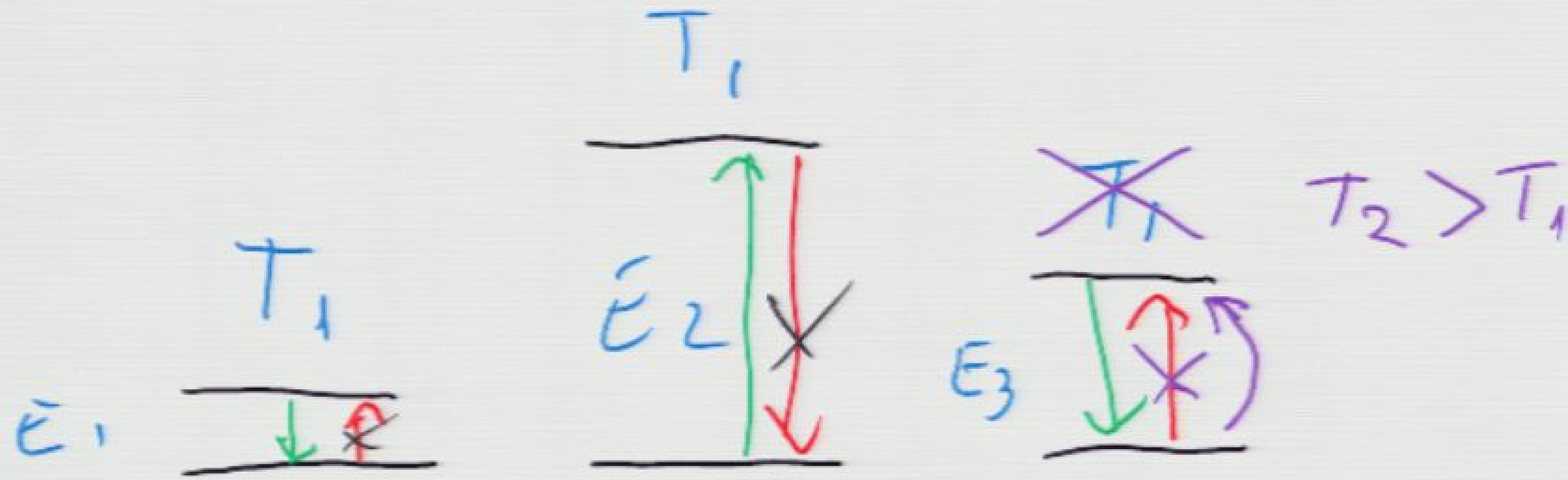

T_1
T_1

T_1 $\qquad$ $\cancel{T_1}$ $\quad$ $T_2 < T_1$

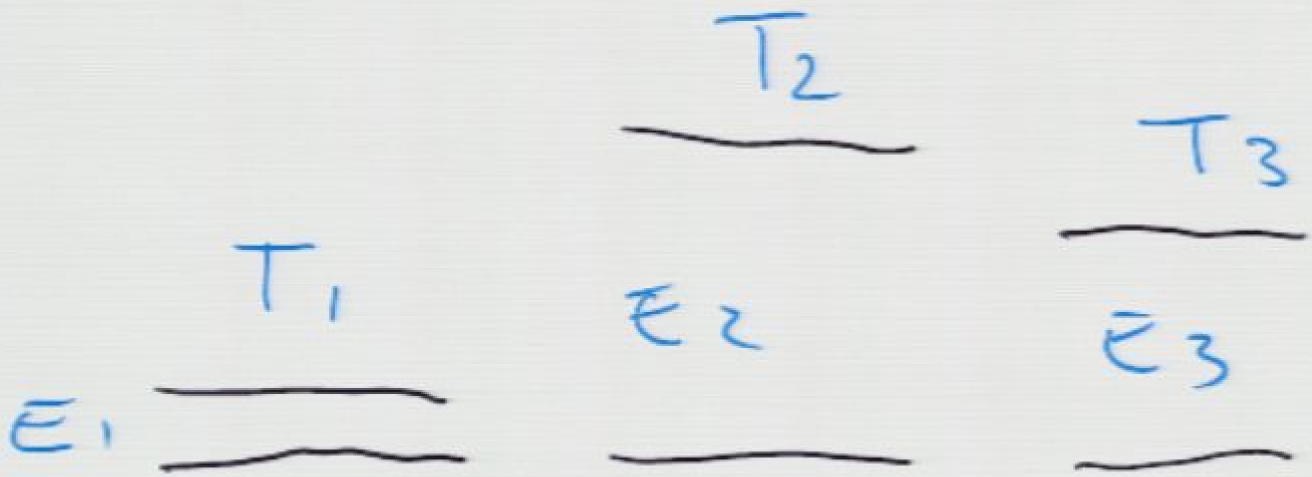




$$E_1 + E_3 = E_2$$

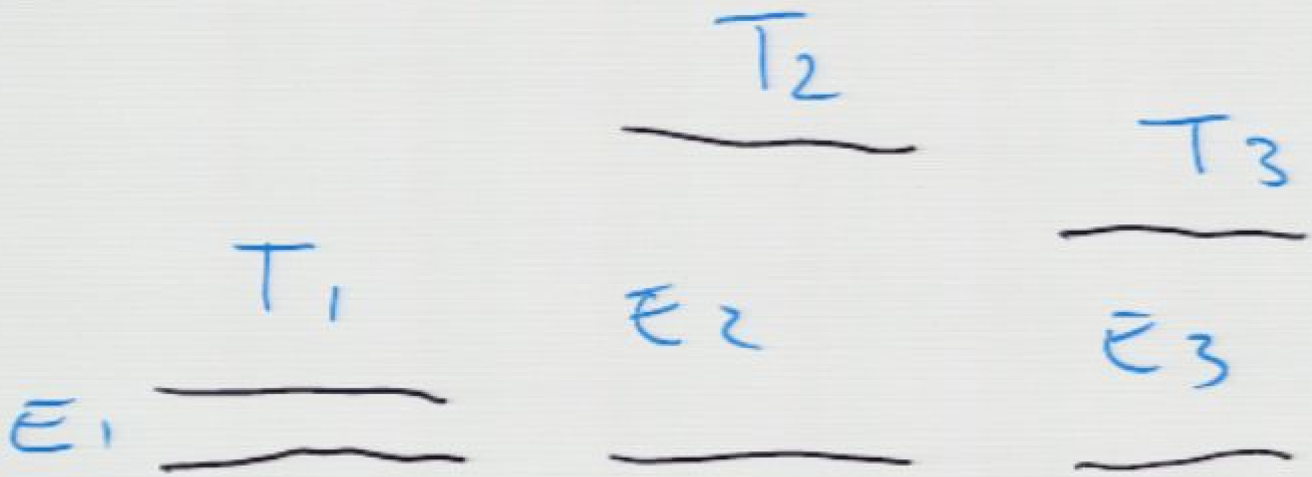


$$E_1 + E_3 = E_2$$



$$E_1 + E_3 = E_2 \qquad T_1 < T_2 < T_3$$

$$|101\rangle \rightleftarrows |010\rangle$$



$$E_1 + E_3 = E_2 \qquad T_1 < T_2 < T_3$$

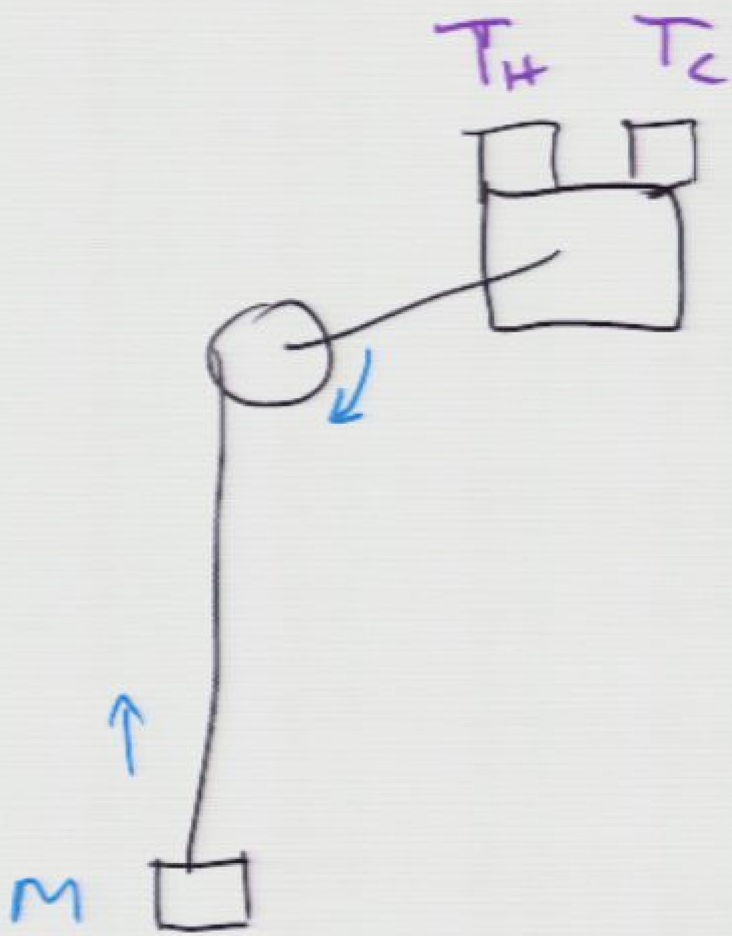
$$e^{-\frac{E_1}{kT_1}}\, e^{-\frac{E_3}{kT_3}} > e^{-\frac{E_2}{kT_2}}$$

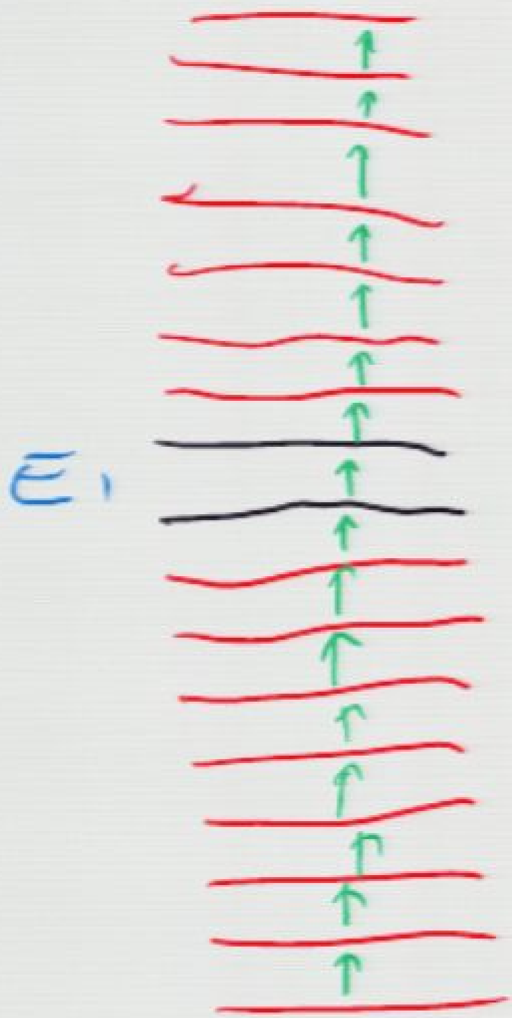
Smallest possible heat engine

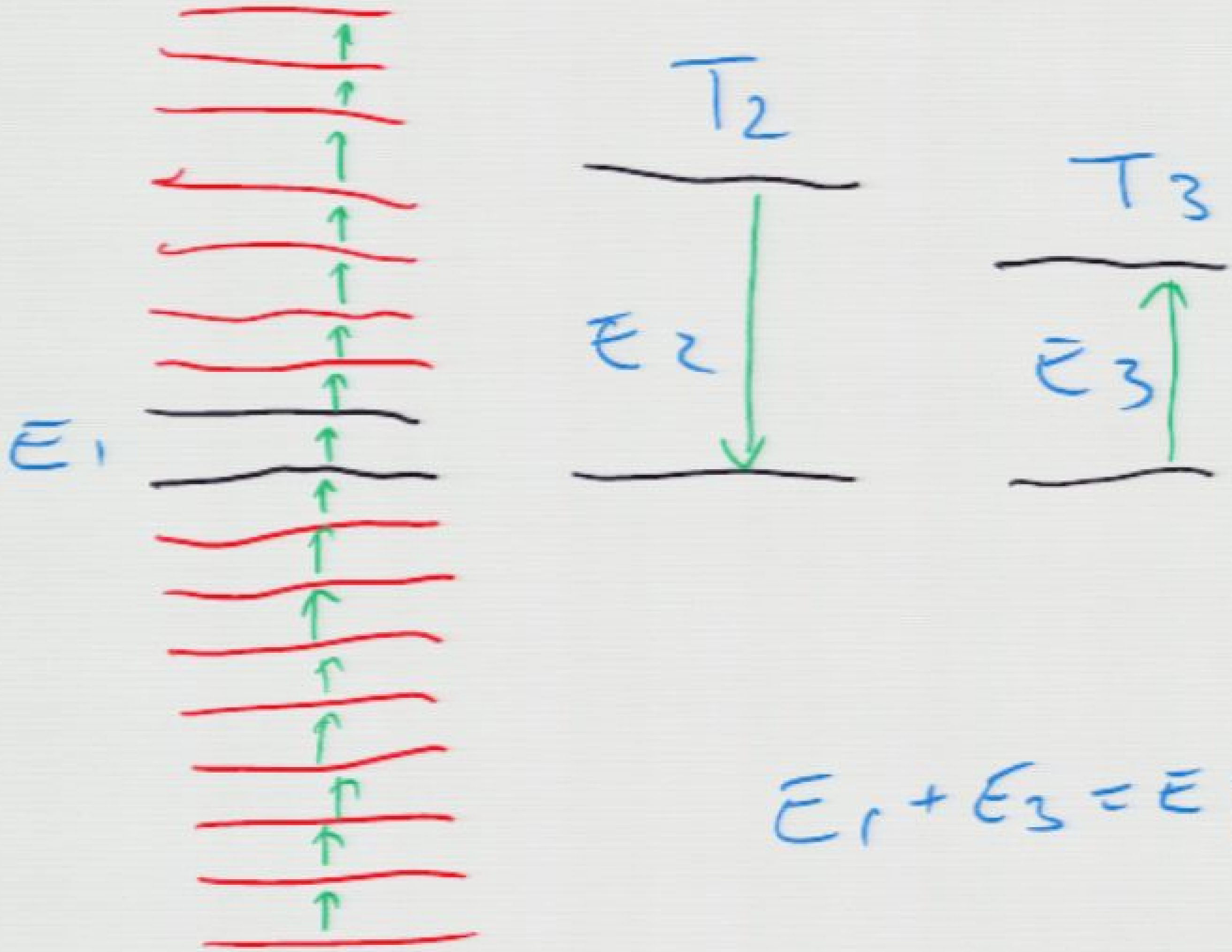
Smallest possible heat engine

What is work?

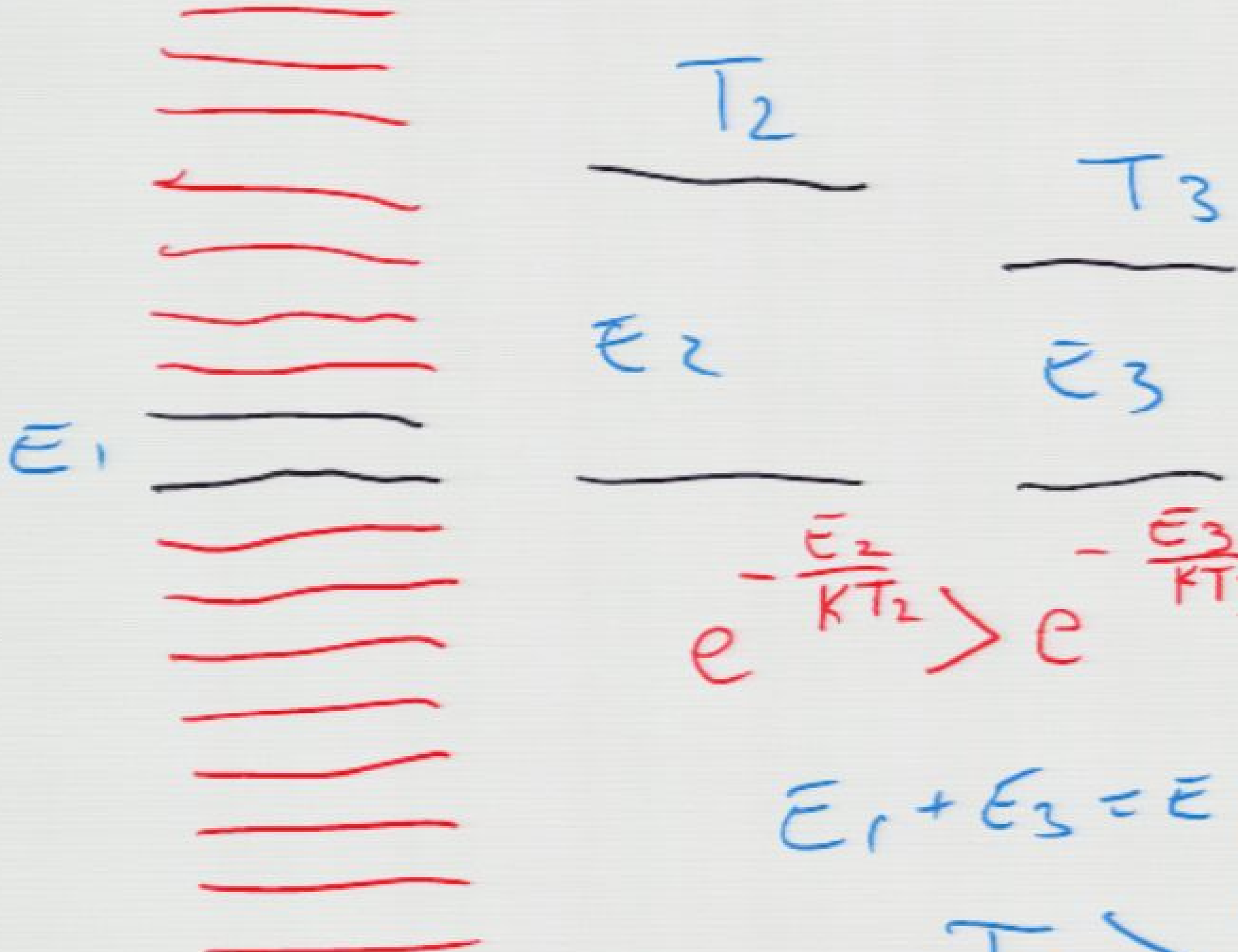
Smallest possible heat engine




E,



$$E_1 + E_3 = E_2$$

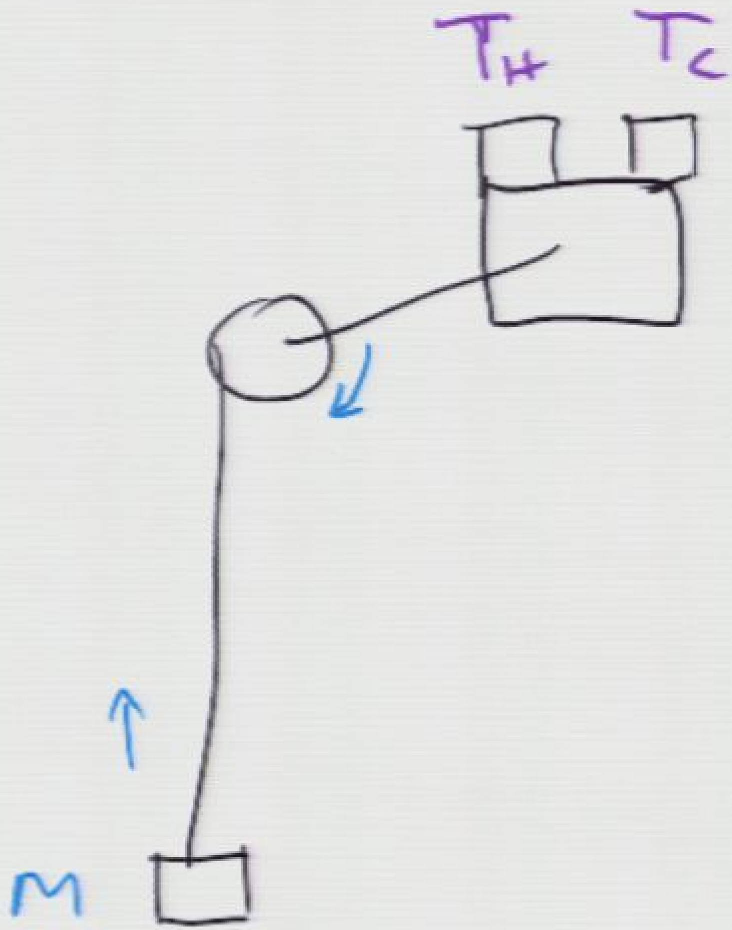


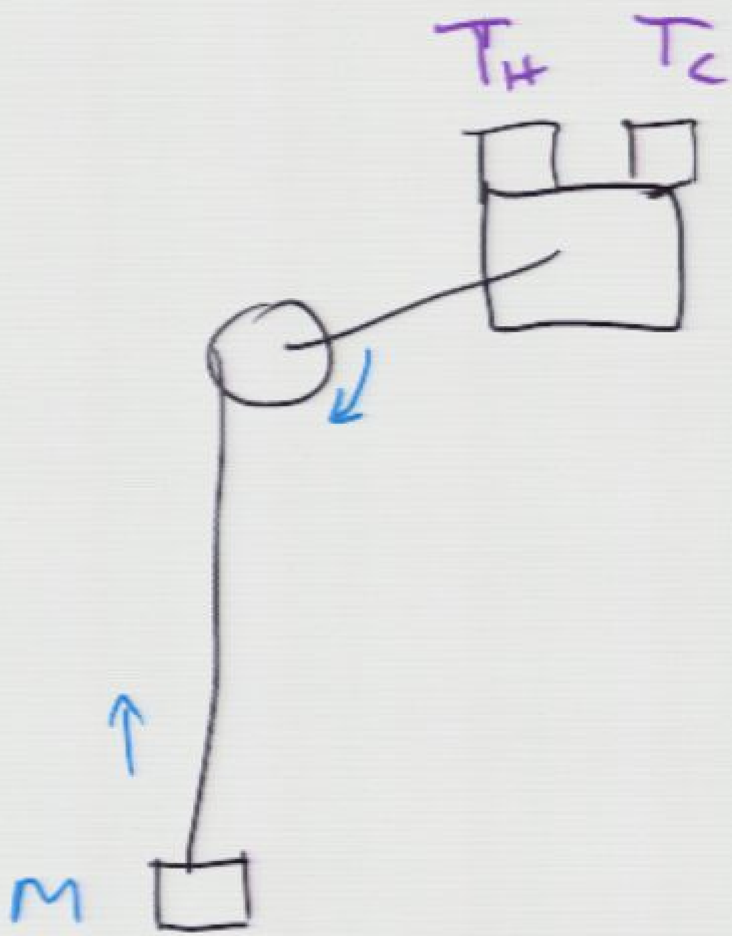
$$e^{-\frac{E_2}{kT_2}} > e^{-\frac{E_3}{kT_3}}$$

$$E_1 + E_3 = E_2$$

$$T_2 > T_3$$

Efficiency of the smallest machines


T_H
T_C
M



W

Q_H Q_c

$$\frac{W}{Q_H} = 1 - \frac{T_c}{T_H}$$

Efficiency of the smallest machines

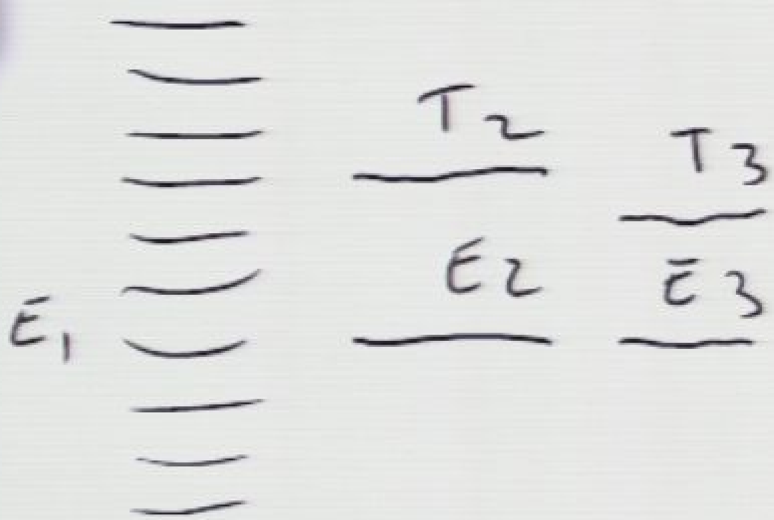
Is there a size-efficiency complementarity?

Efficiency of the smallest machines

Is there a size-efficiency complementarity?

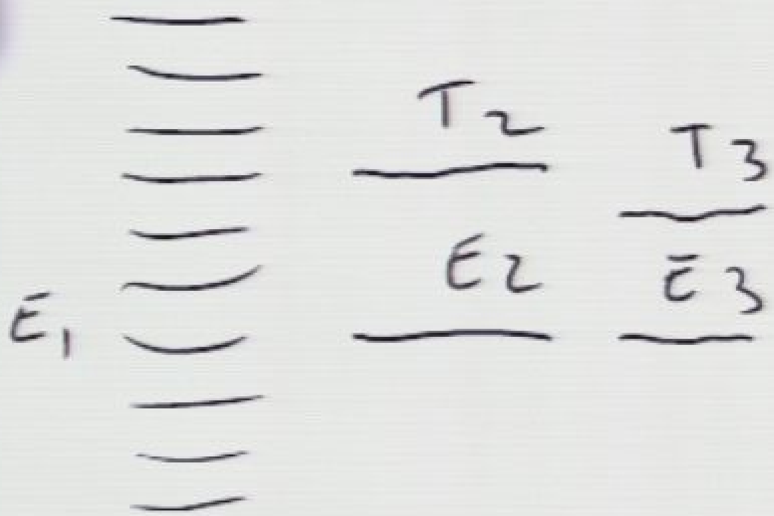
NO

Reaching Carnot efficiency



$$E_1 + E_3 = E_2$$

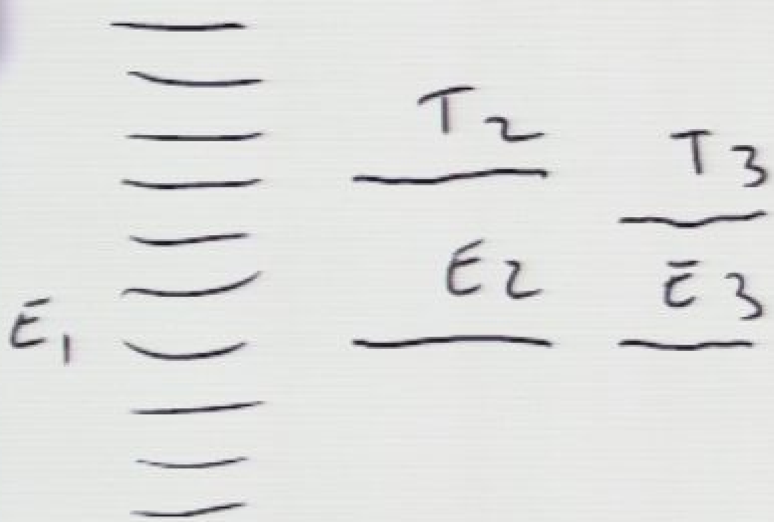
Reaching Carnot efficiency



$$E_1 + E_3 = E_2$$

$$e^{-\frac{E_3}{kT_3}} = e^{-\frac{E_2}{kT_2}}$$

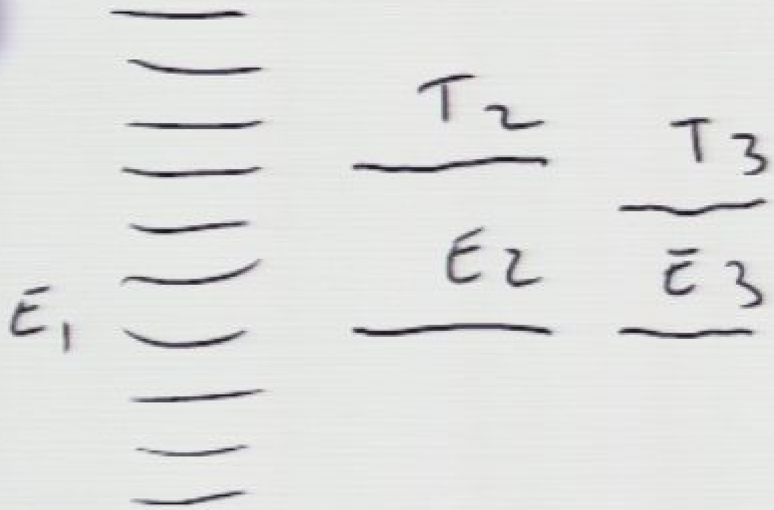
Reaching Carnot efficiency



$$E_1 + E_3 = E_2$$

$$\frac{E_3}{T_3} = \frac{E_2}{T_2}$$

Reaching Carnot efficiency

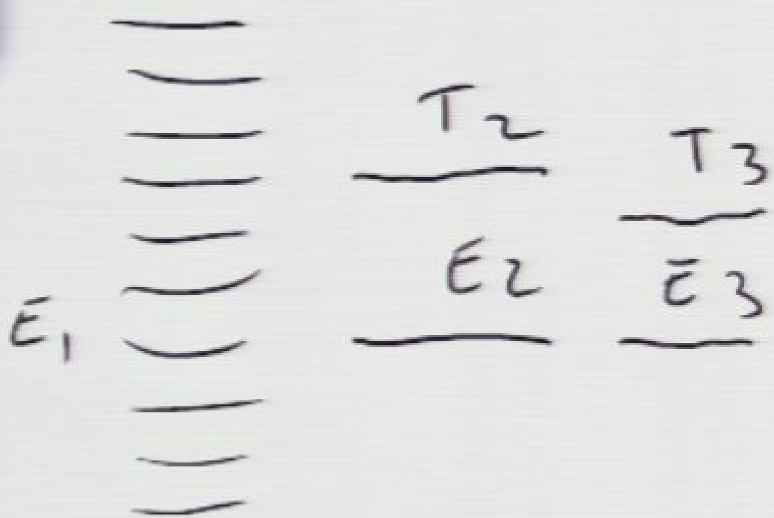


$$E_1 + E_3 = E_2$$

$$\frac{E_3}{T_3} = \frac{E_2}{T_2}$$

$$W : Q_2 : Q_3 = E_1 : E_2 : E_3$$

Reaching Carnot efficiency



$$E_1 + E_3 = E_2$$

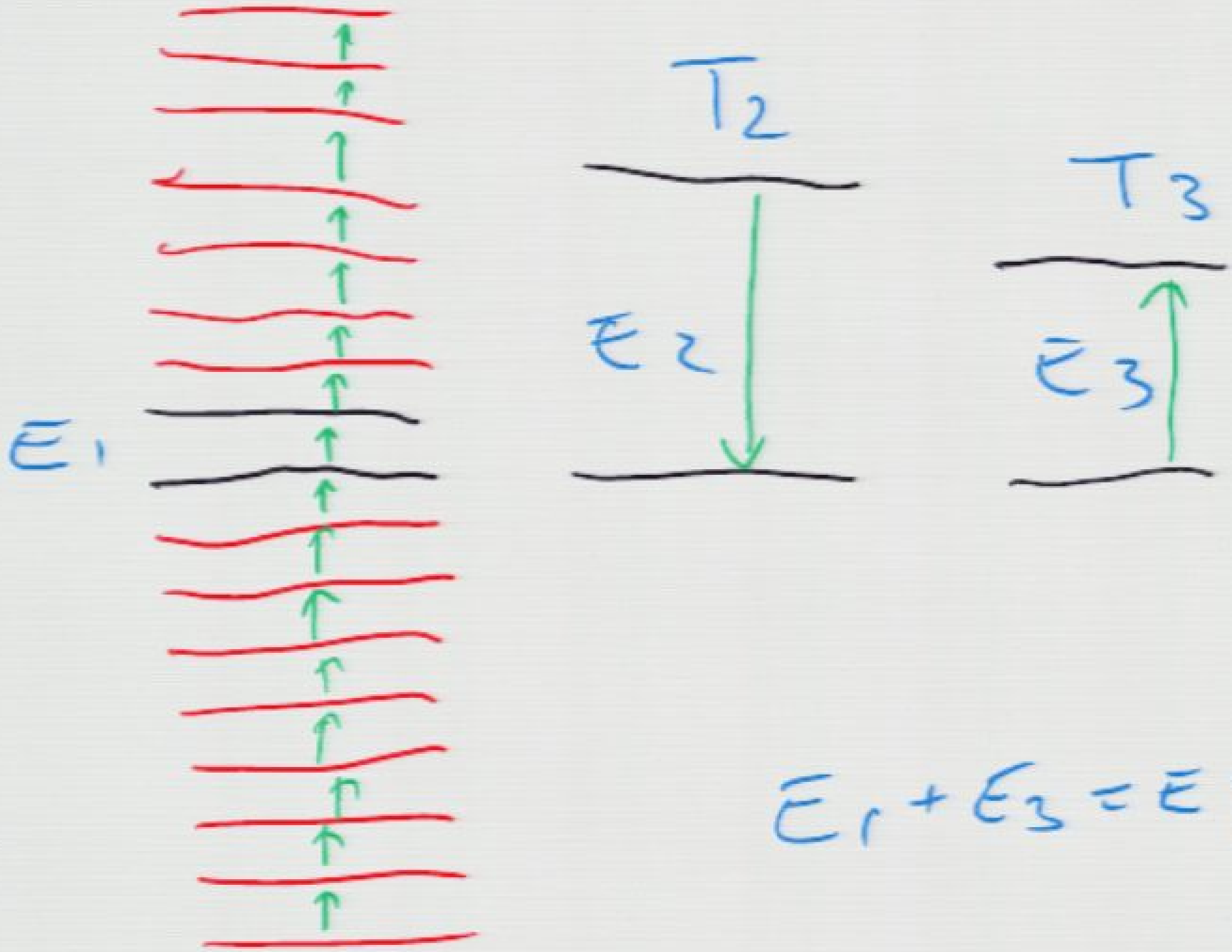
$$\frac{E_3}{T_3} = \frac{E_2}{T_2}$$

$$W : Q_2 : Q_3 = E_1 : E_2 : E_3$$

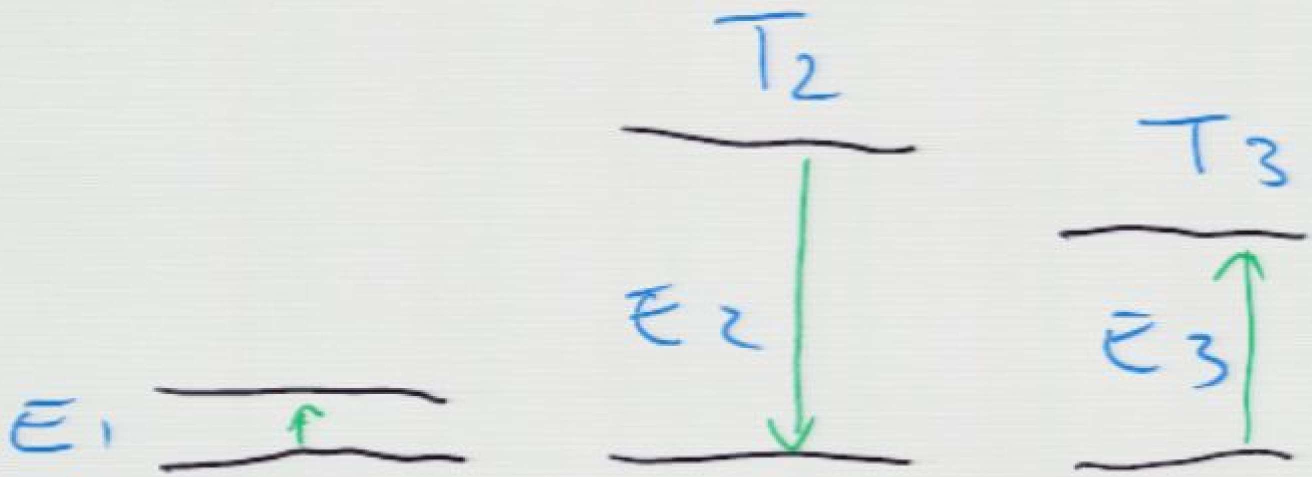
$$\frac{Q_2 - W}{T_3} = \frac{Q_2}{T_2}$$

$$\boxed{\frac{W}{Q_2} = 1 - \frac{T_3}{T_2}}$$

What is work? II

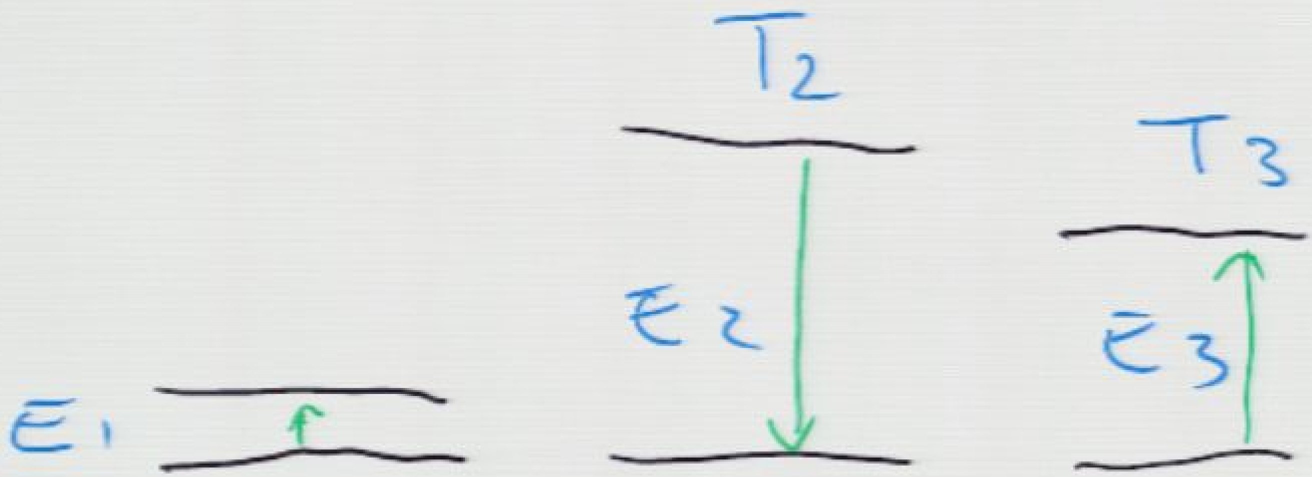


$$E_1 + E_3 = E_2$$



$$E_1 + E_3 = E_2$$

Work is producing population inversion



$$E_1 + E_3 = E_2$$

What do thermal machines do?

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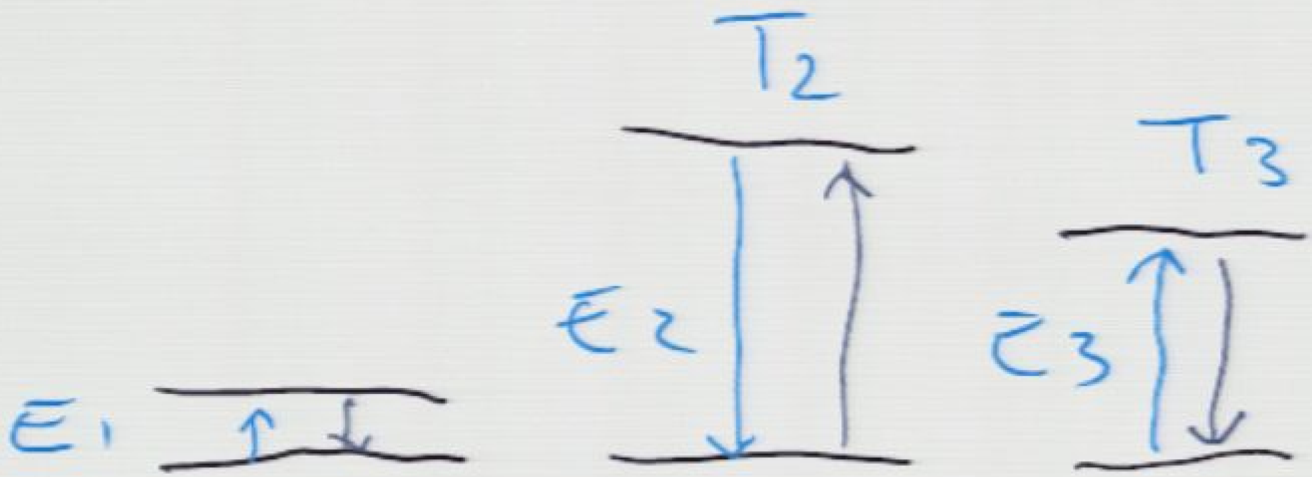
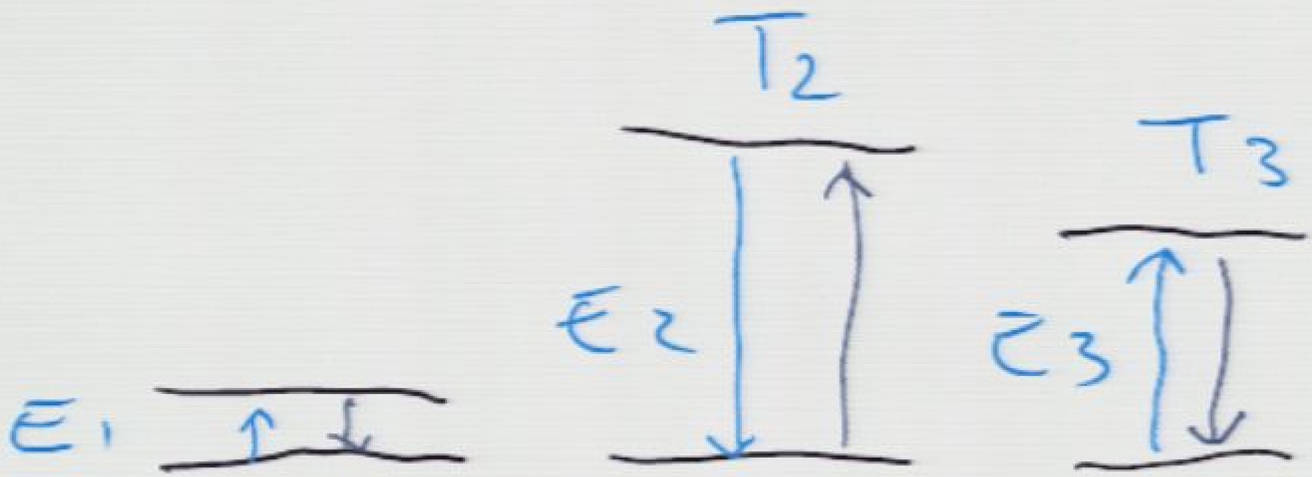


$$E_1 + E_3 = E_2$$

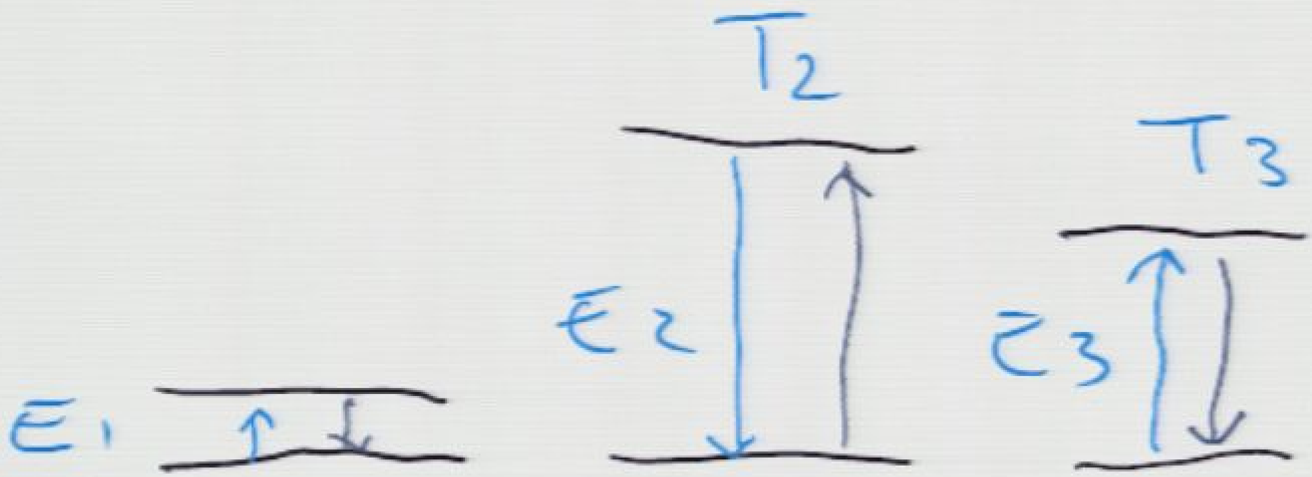
What do thermal machines do?



$E_1 + E_3 = E_2$

$$|g\rangle|e\rangle|g\rangle \rightleftarrows |e\rangle|g\rangle|e\rangle$$

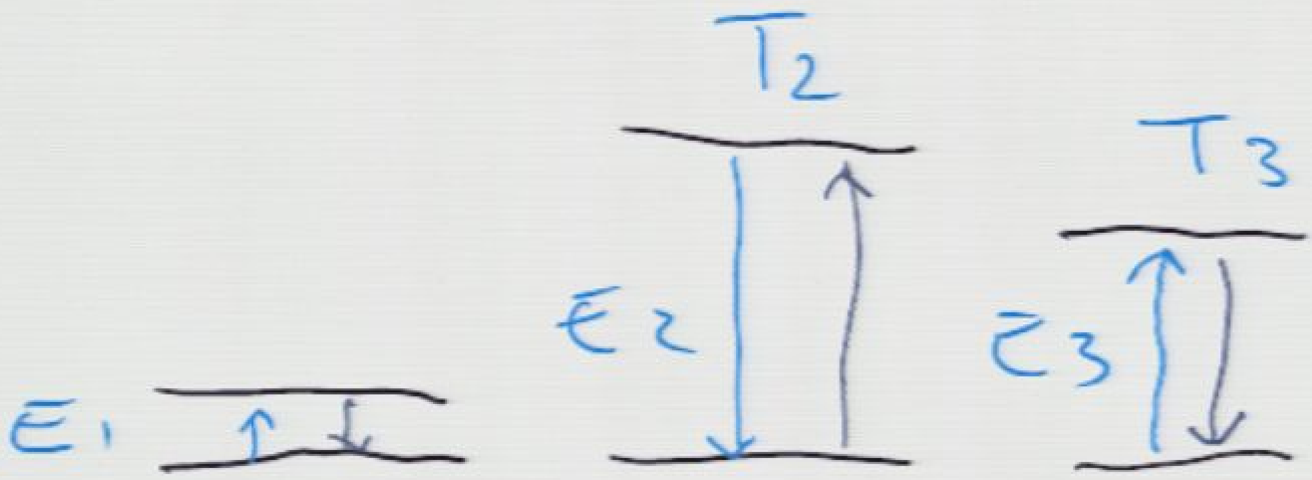
What do thermal machines do?



$$E_1 + E_3 = E_2$$

$$|g\rangle|e\rangle|g\rangle \rightleftharpoons |e\rangle|g\rangle|e\rangle$$

What do thermal machines do?



$$E_1 + E_3 = E_2$$

$$|g\rangle|e\rangle|g\rangle \rightleftharpoons |e\rangle|g\rangle|e\rangle$$

$$|g\rangle|E\rangle \rightleftharpoons |e\rangle|G\rangle$$

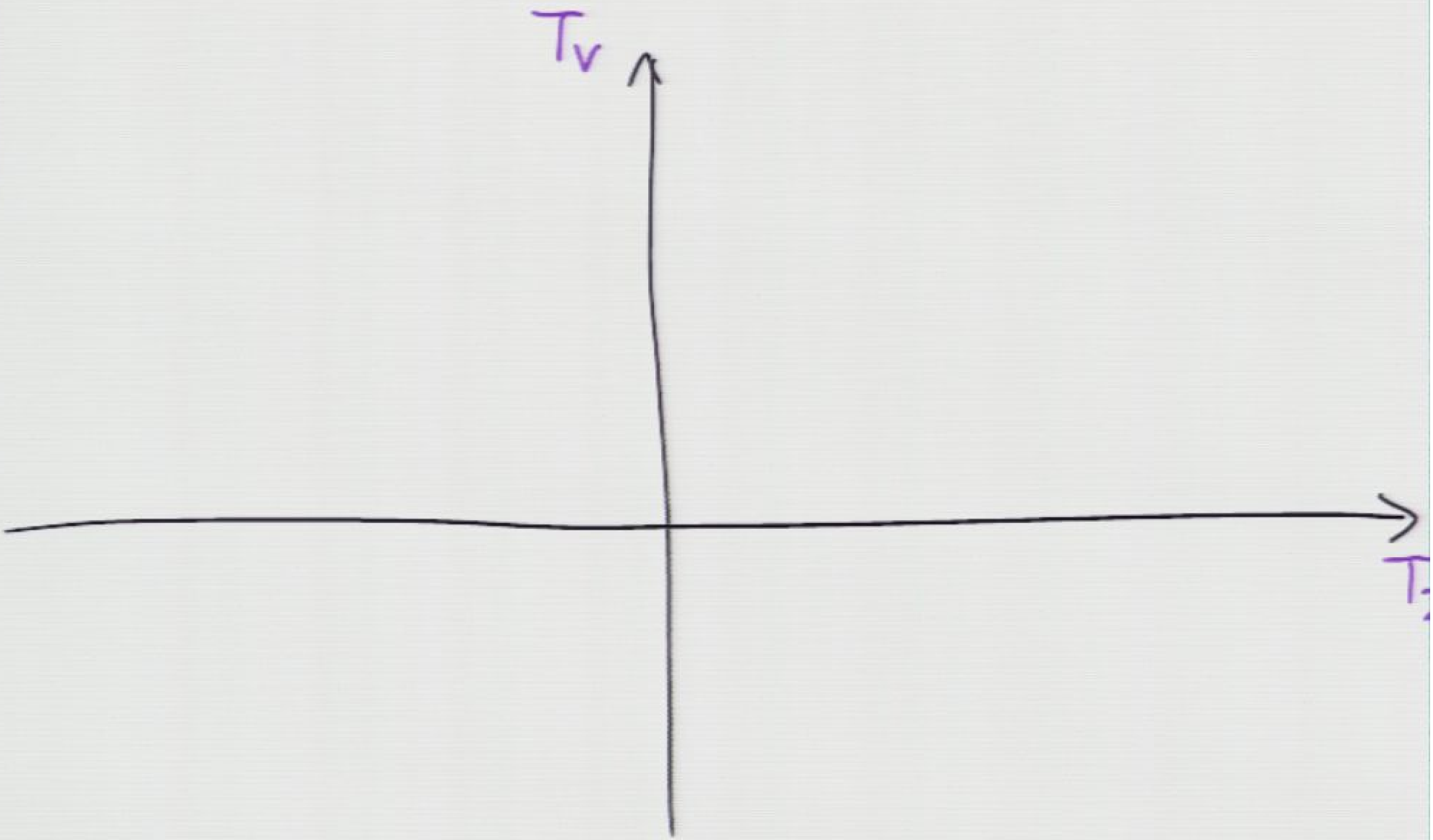
Virtual Q-bit

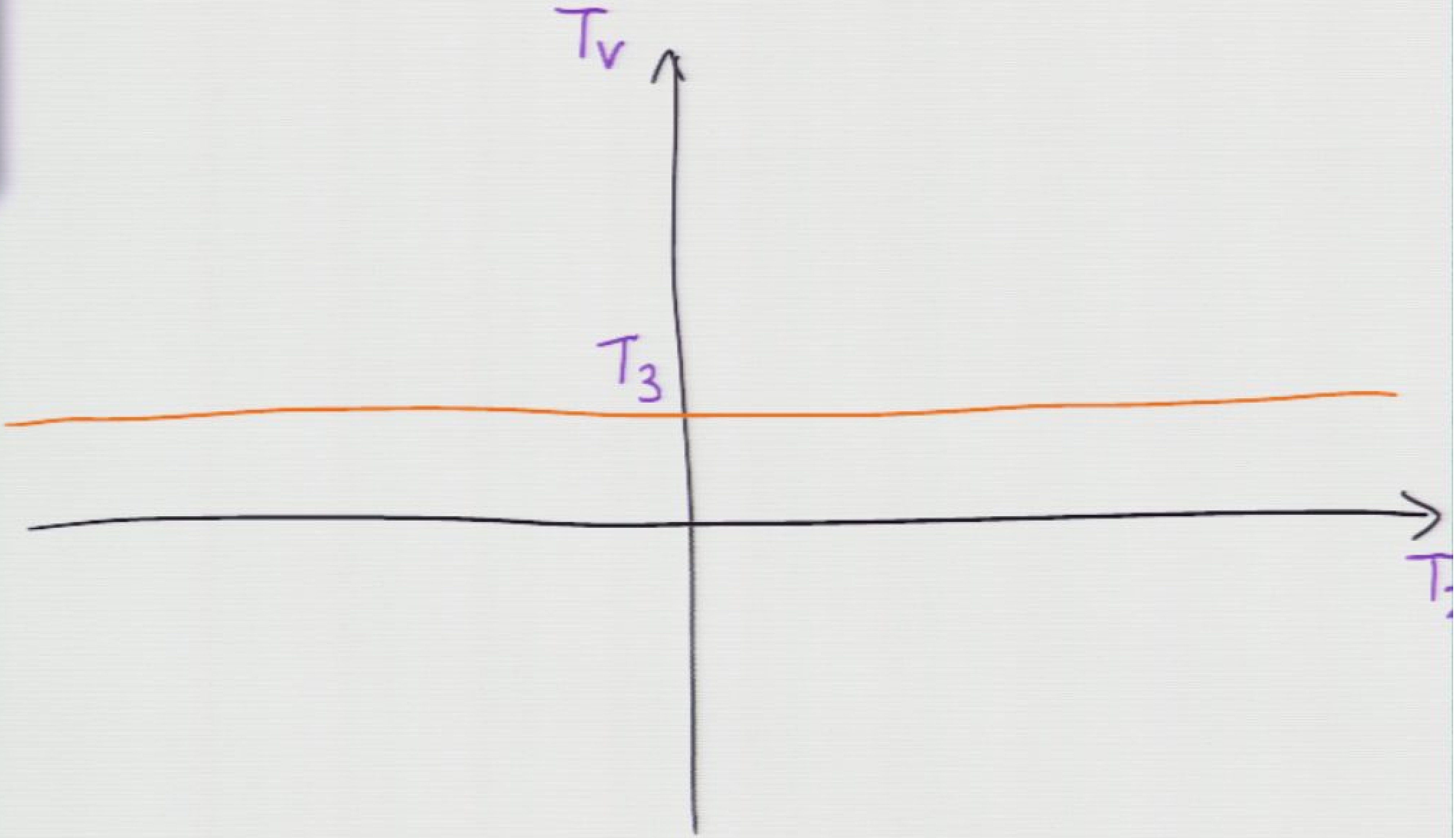
Virtual Q-bit

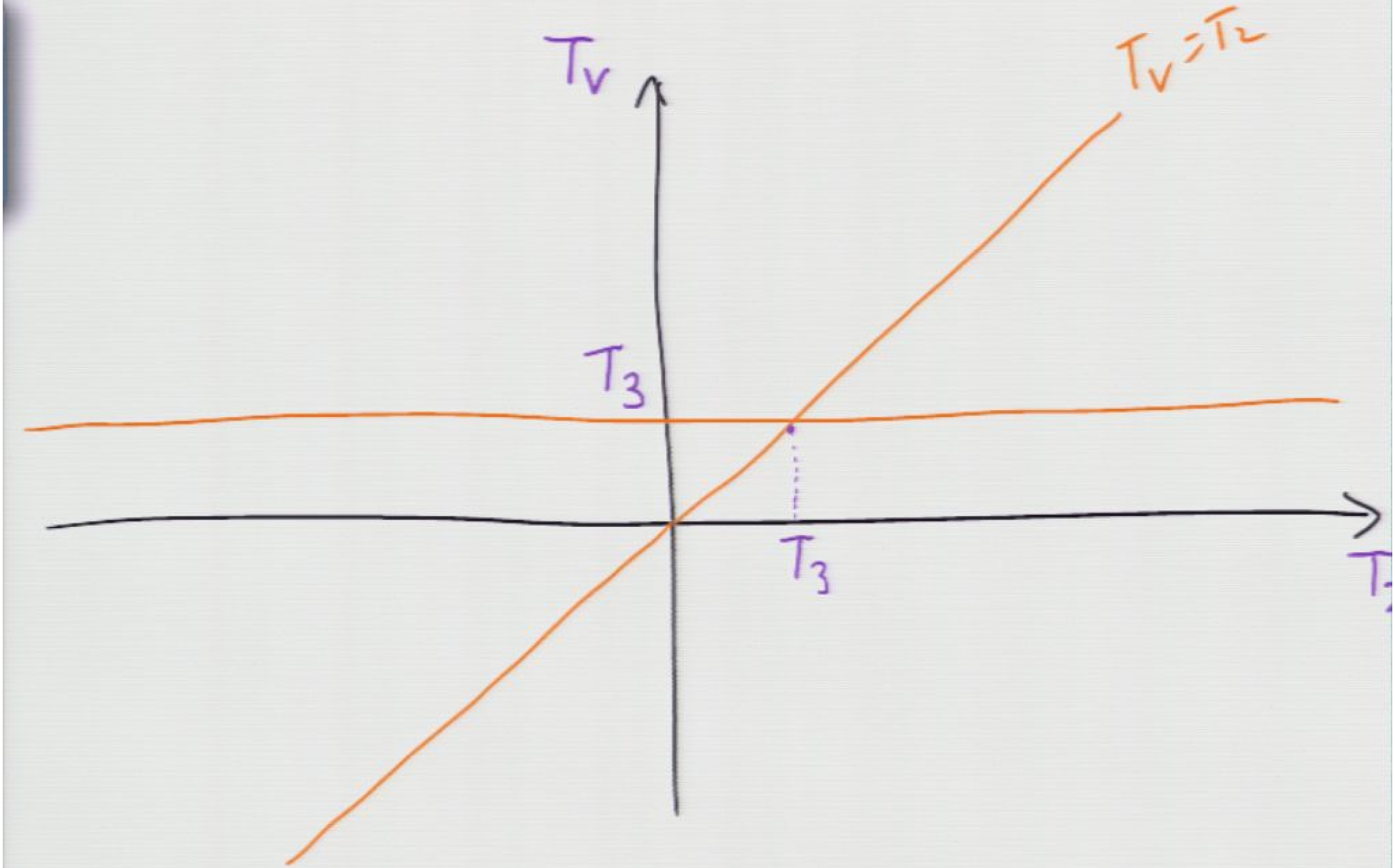
E_1

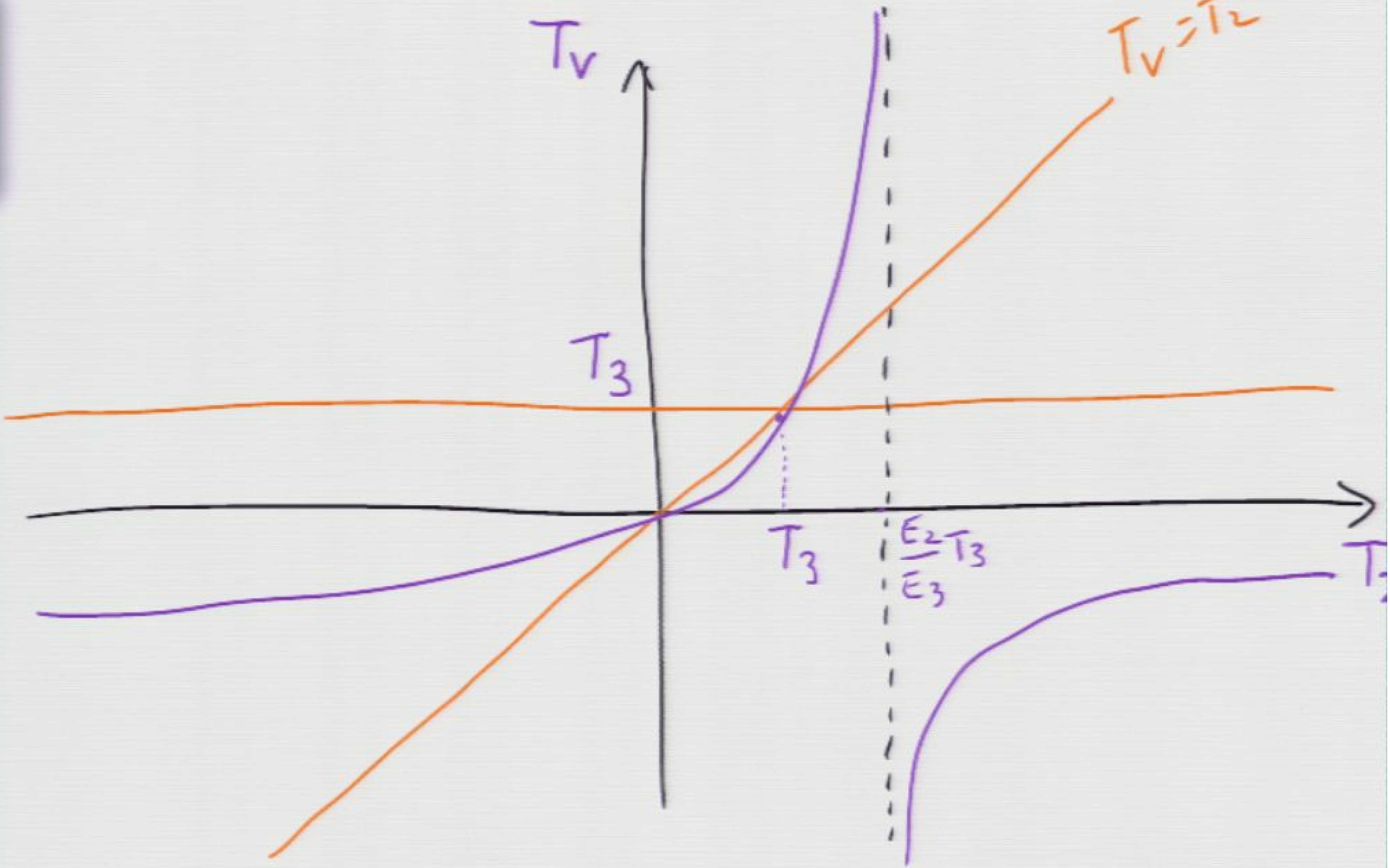
E_1

$$\boxed{T_v = \frac{E_2 - E_3}{\frac{E_2}{T_2} - \frac{E_3}{T_3}}}$$

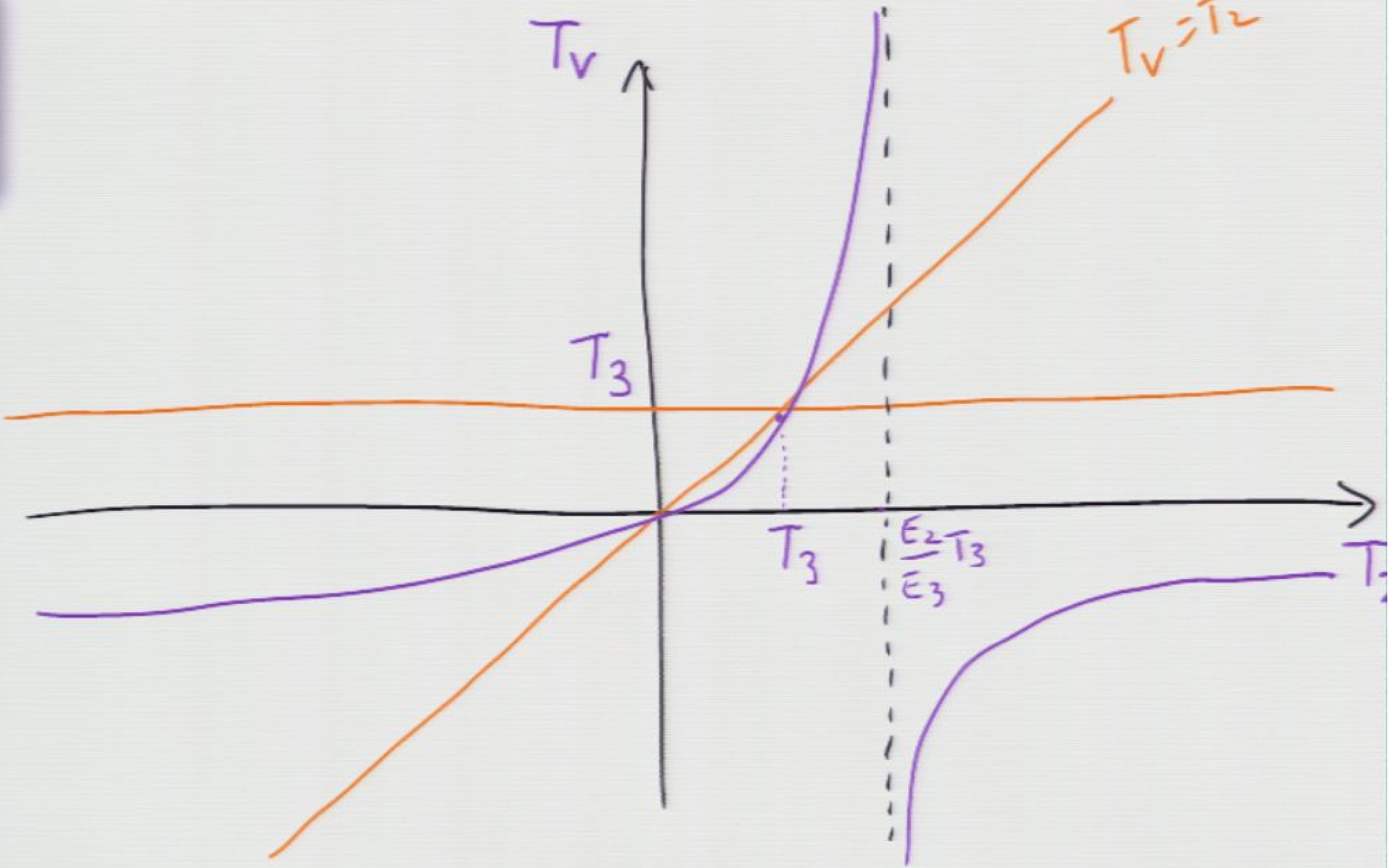

T_V


T_v
T_3

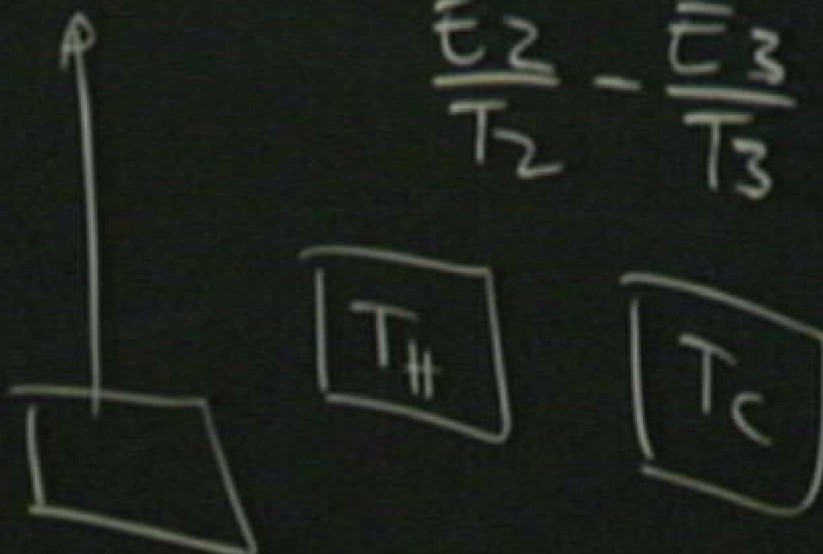

T_v
$T_v = T_2$
T_3
T_3

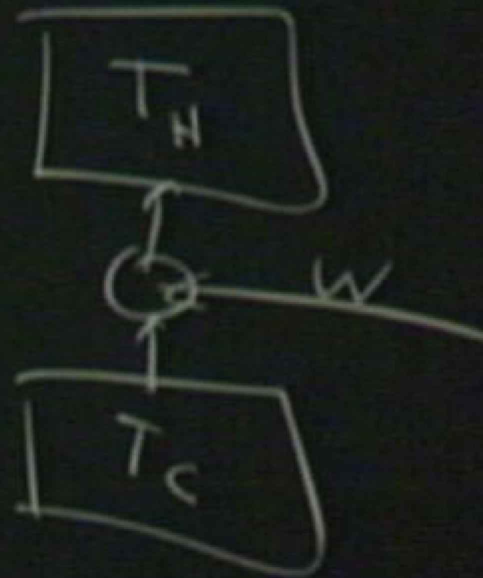

T_v
$T_v = T_2$
T_3
T_3
$\frac{E_2}{E_3} T_3$
T_2

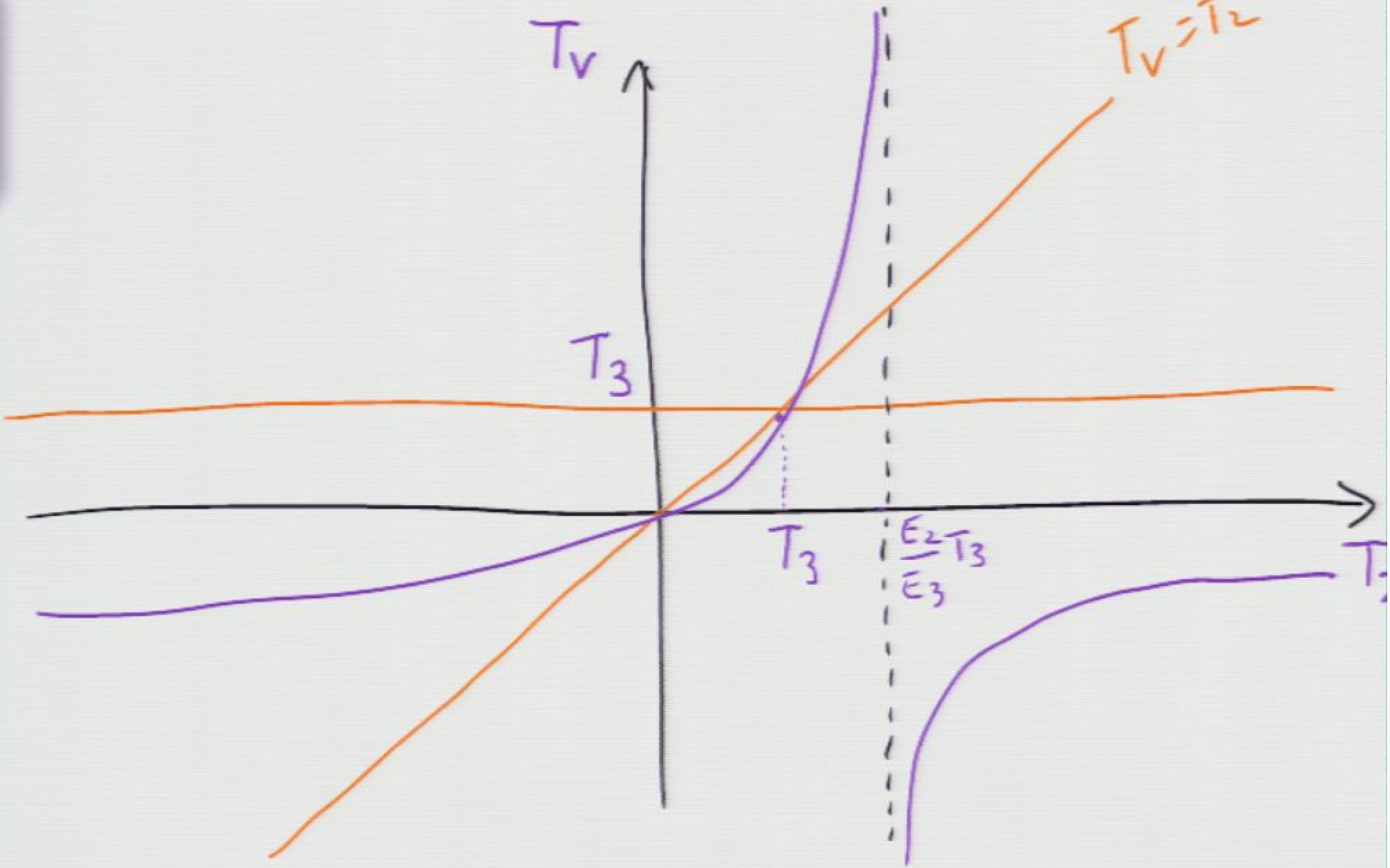
$$T_V = \frac{E_2 - E_3}{\frac{E_2}{T_2} - \frac{E_3}{T_3}}$$


T_v
$T_v = T_2$
T_3
T_3
$\frac{\epsilon_2}{\epsilon_3} T_3$
T_2

$$T_V = \frac{E_2 - E_3}{\frac{E_2}{T_2} - \frac{E_3}{T_3}}$$



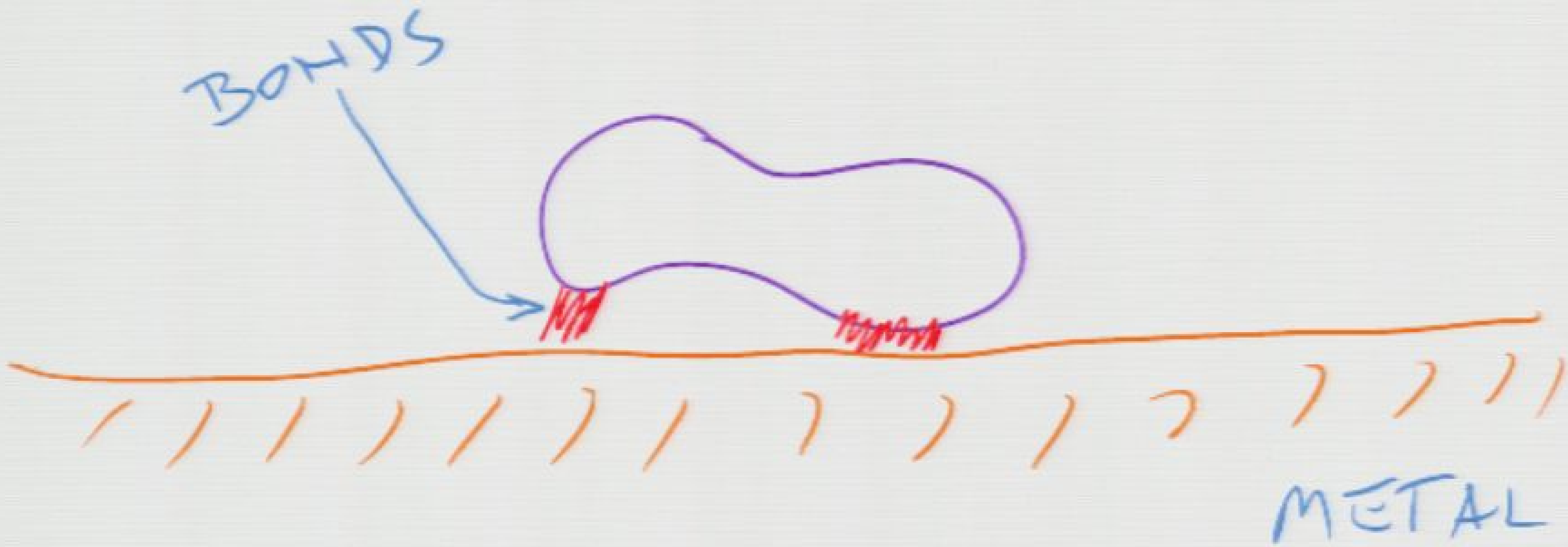




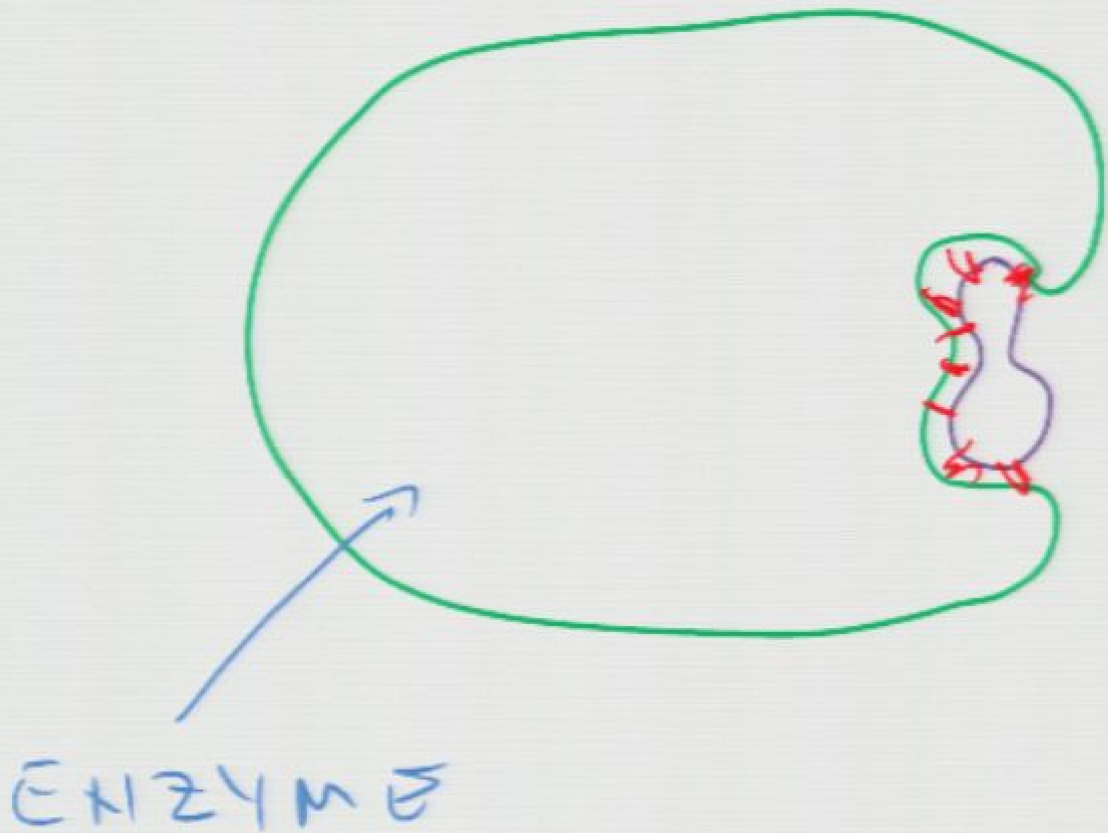
T_v
$T_v = T_2$
T_3
T_3
$\frac{\epsilon_2}{\epsilon_3} T_3$
T_2

Catalysis

Catalysis



Much better catalysis: Enzymes



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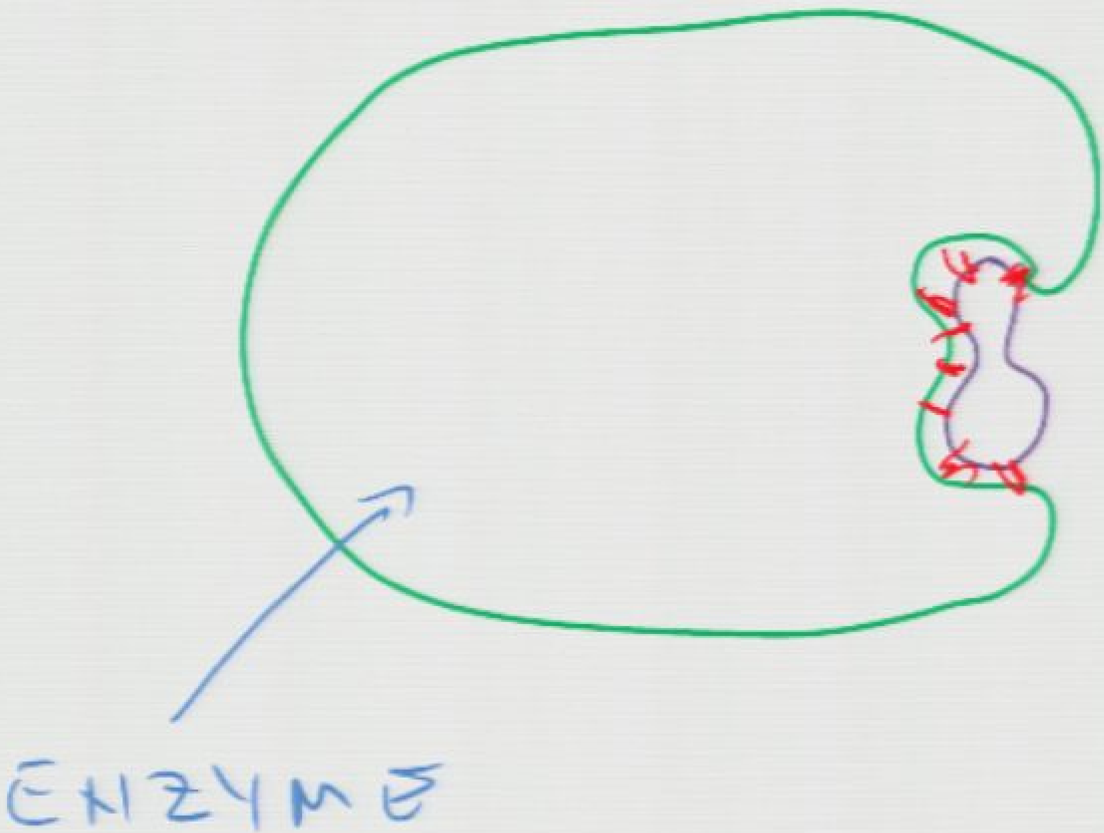
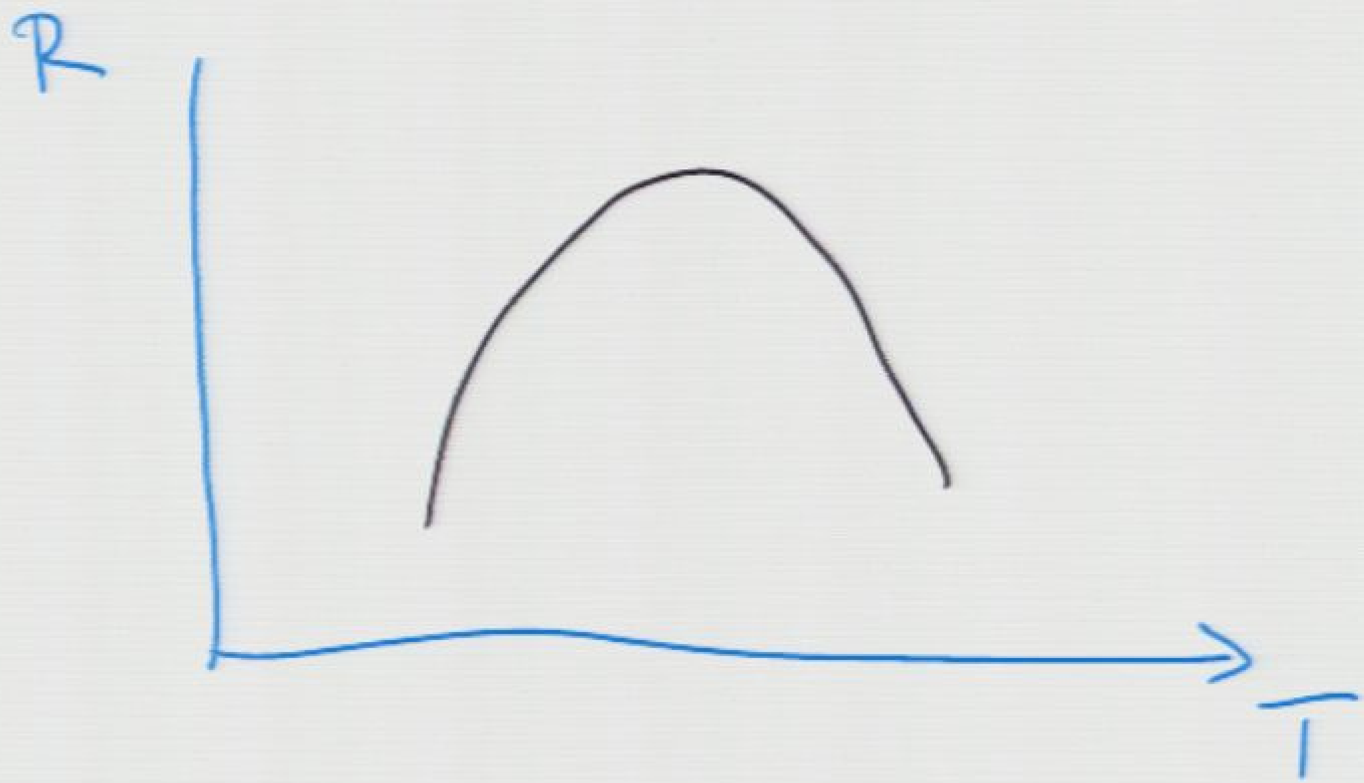
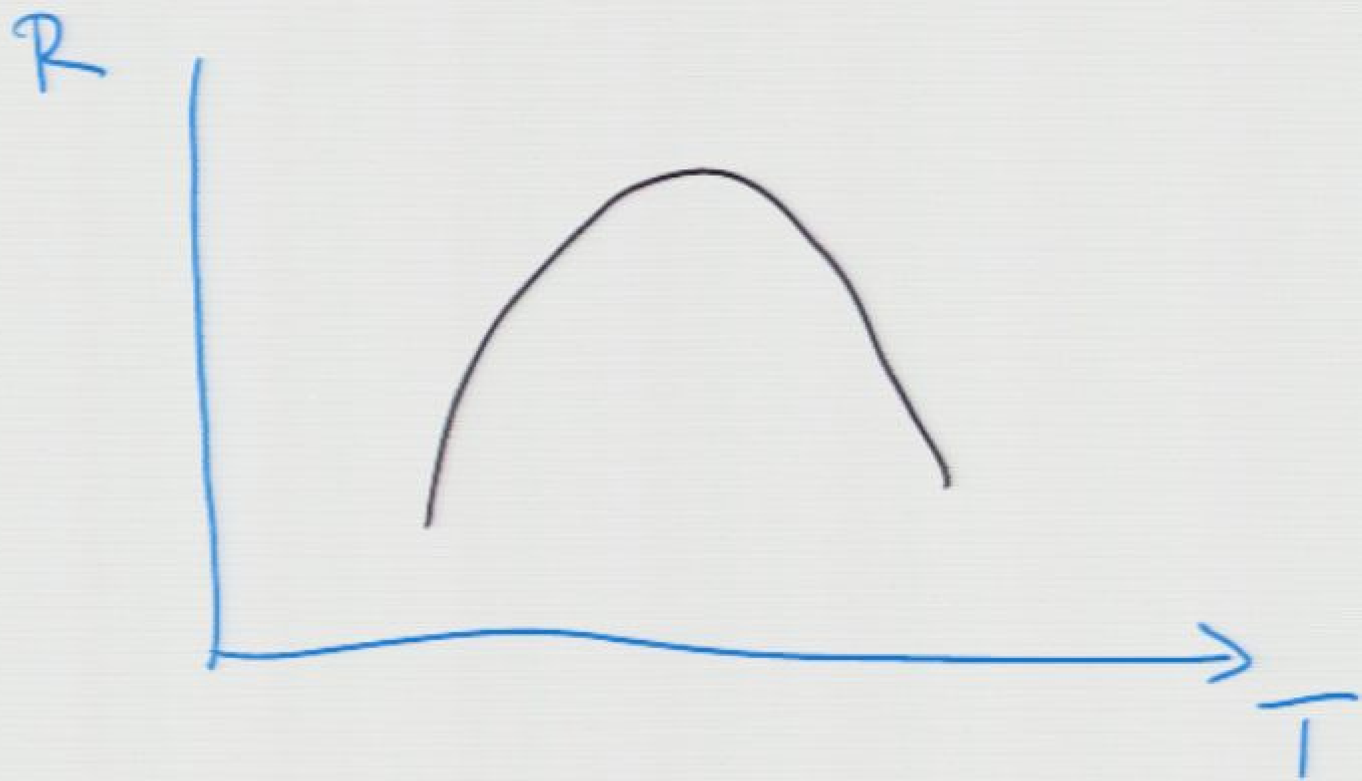
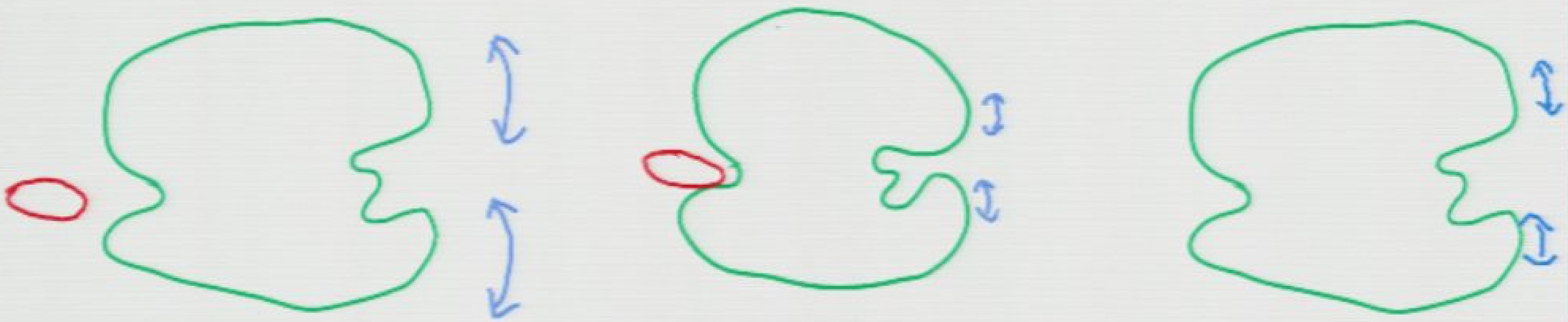


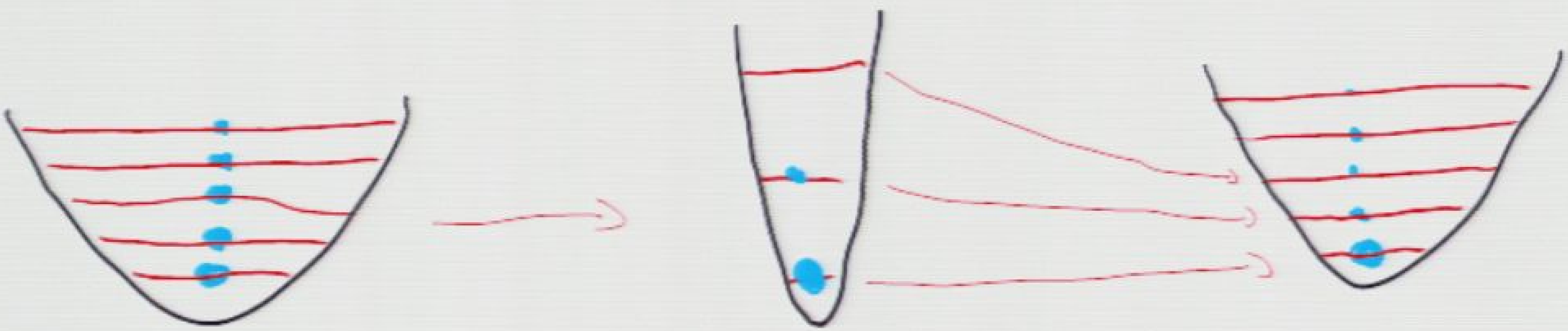
Reaction rate vs Temperature



Reaction rate vs Temperature







Reaction rate vs Temperature