Total cost of operating an information engine

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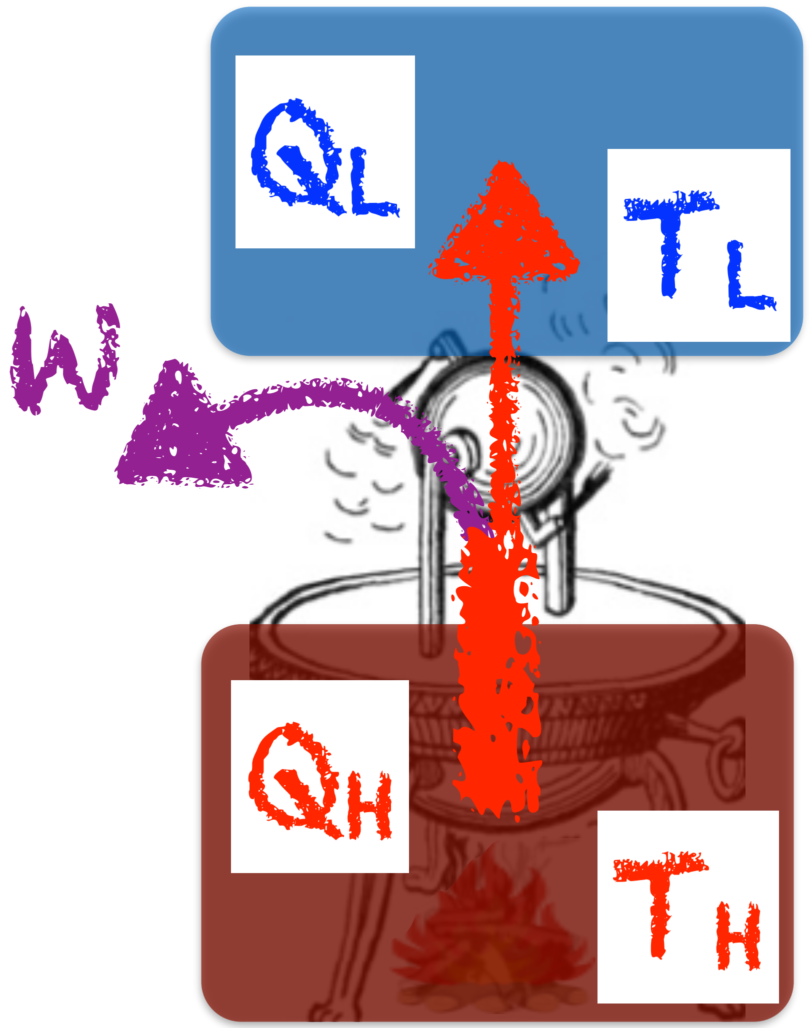
Chulan Kwon (Myongji Univ.)
Hyunggyu Park (KIAS)

30/10/2015, NESP 2015, ICTS

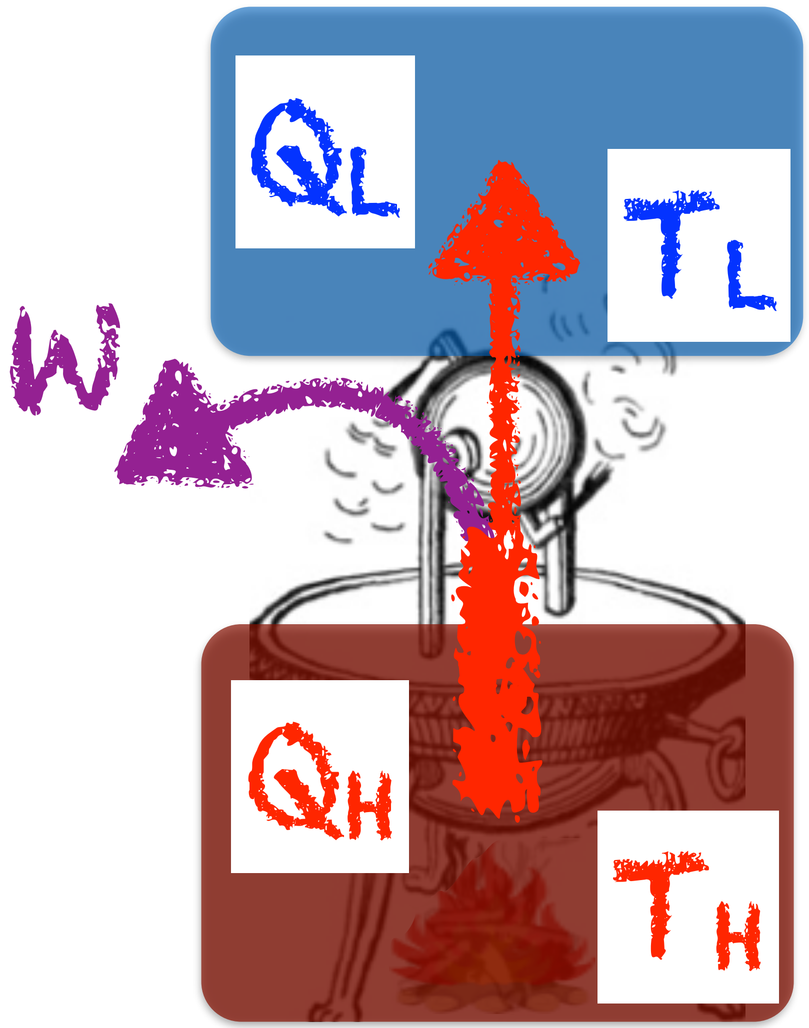
Heat engine



$$\langle W \rangle = -\langle Q_H \rangle - \langle Q_L \rangle$$

$$\beta_H \langle Q_H \rangle + \beta_L \langle Q_L \rangle \geq 0$$

Heat engine vs. Info engine



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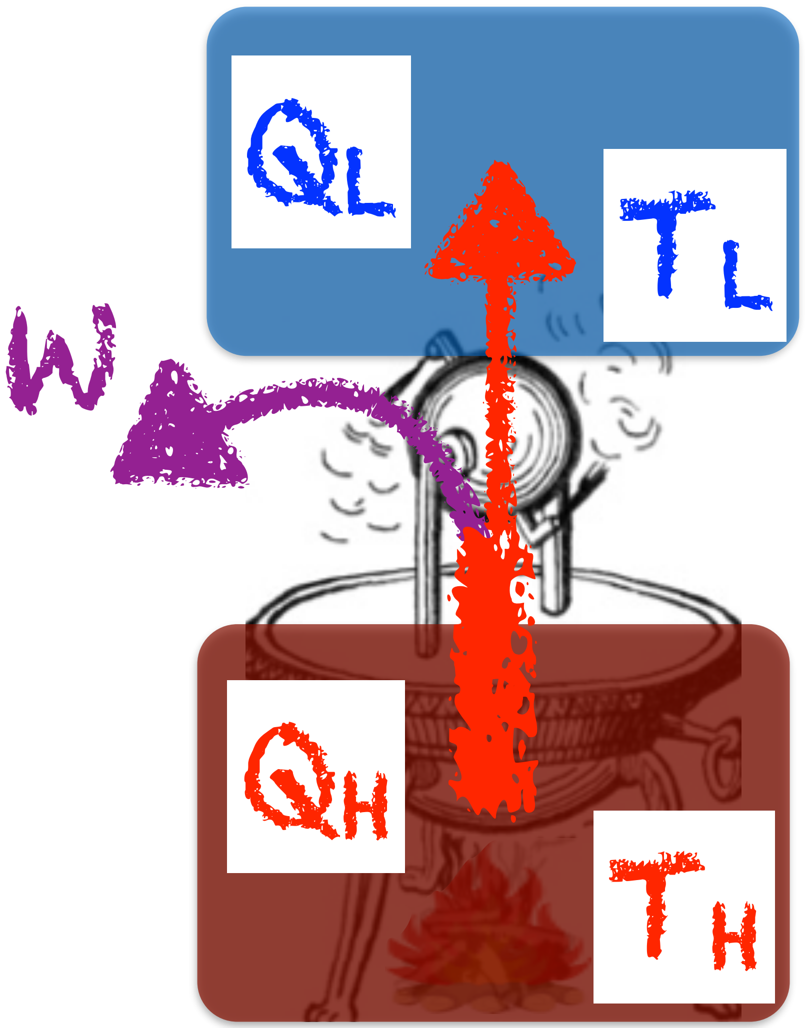

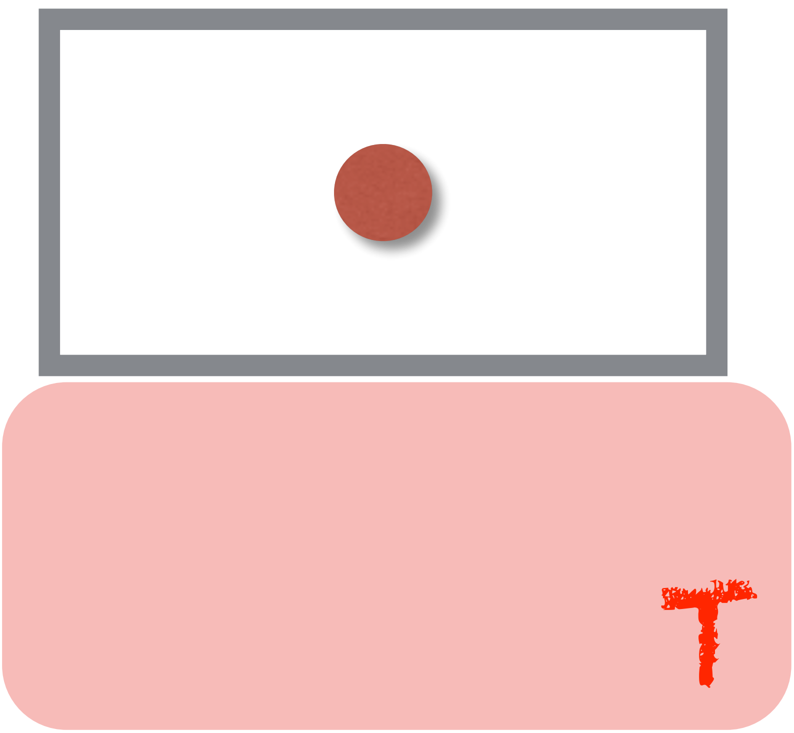

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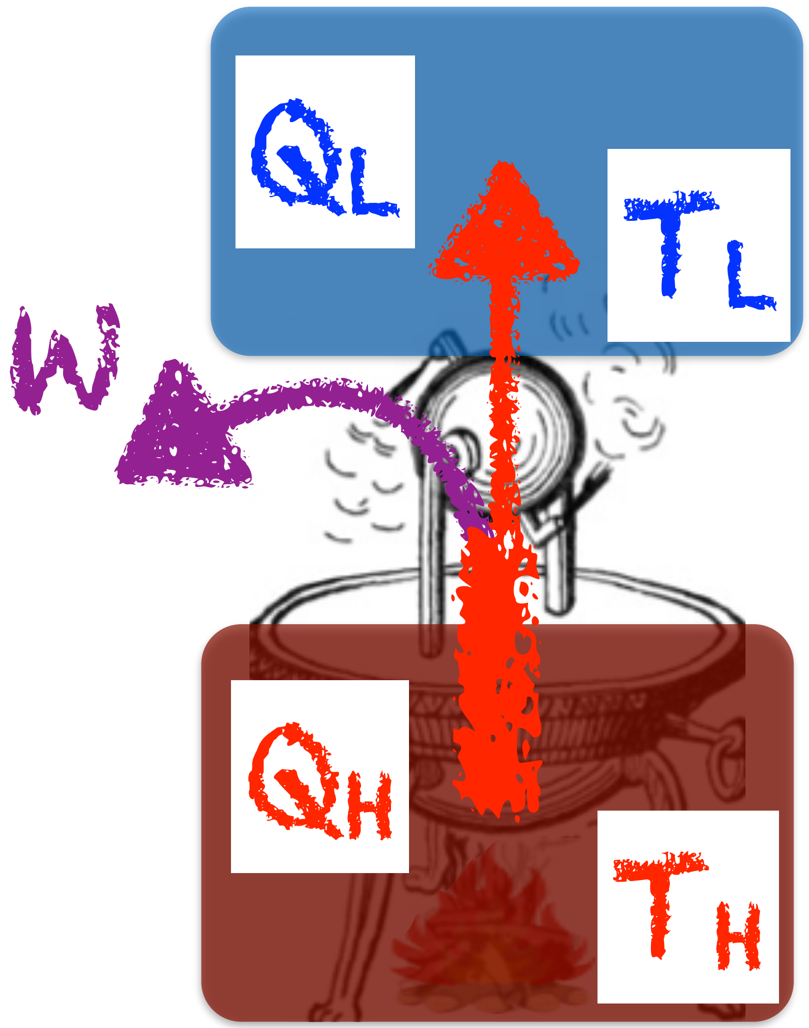

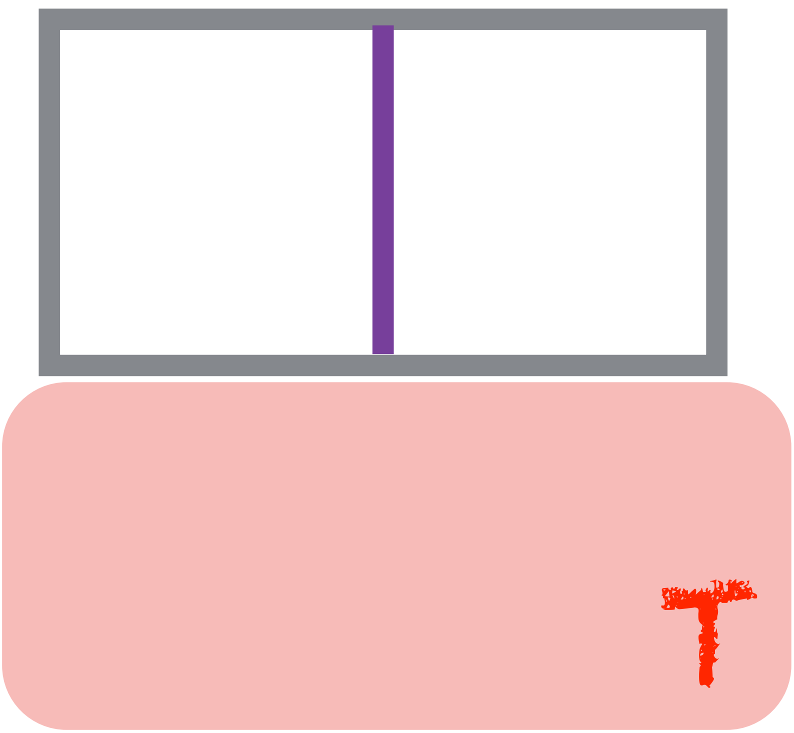

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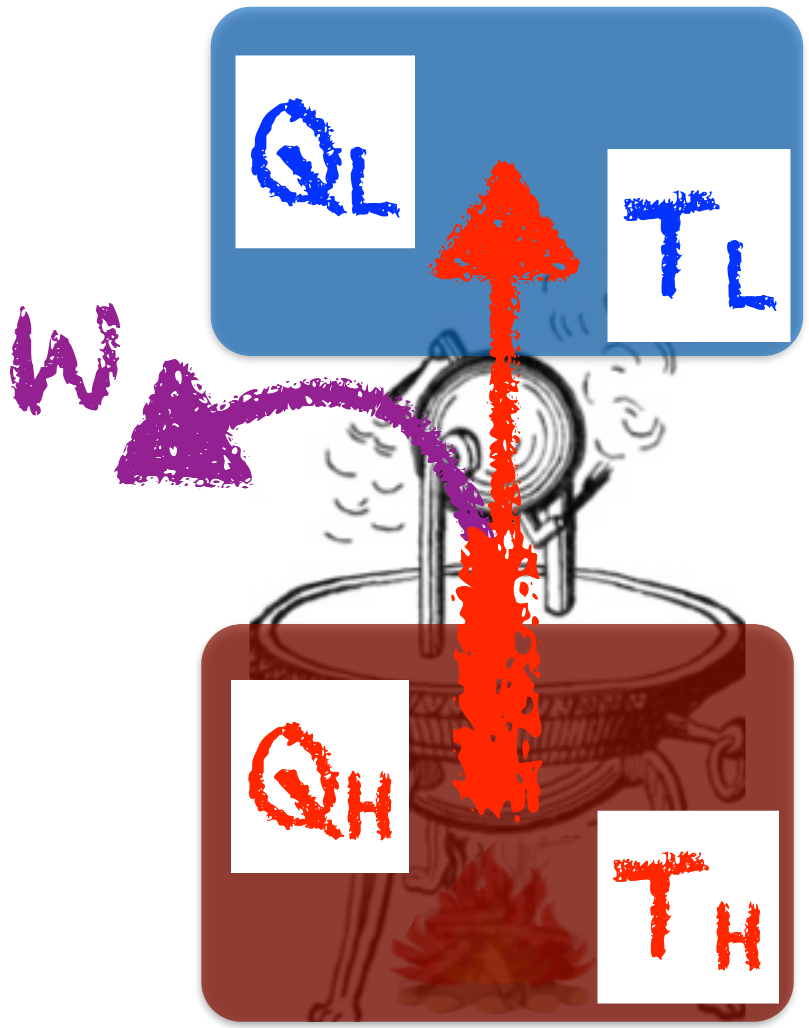

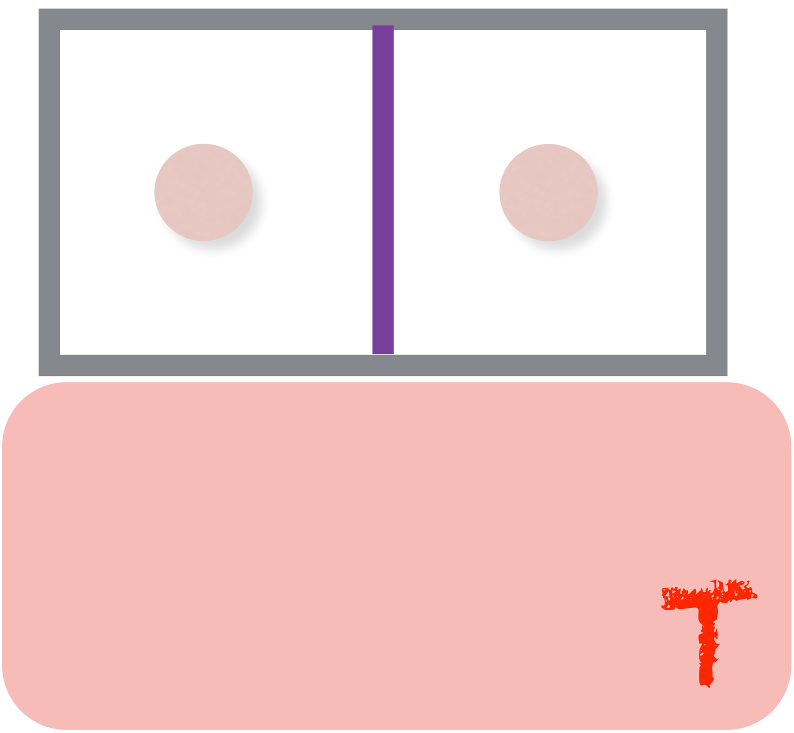

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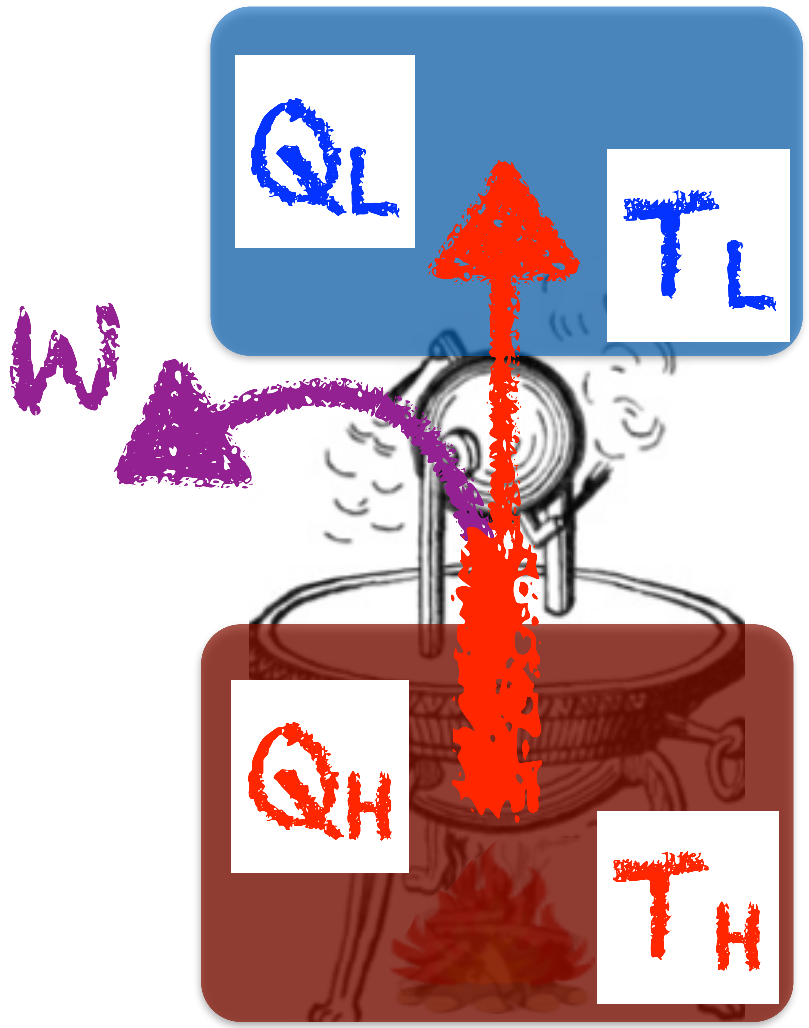

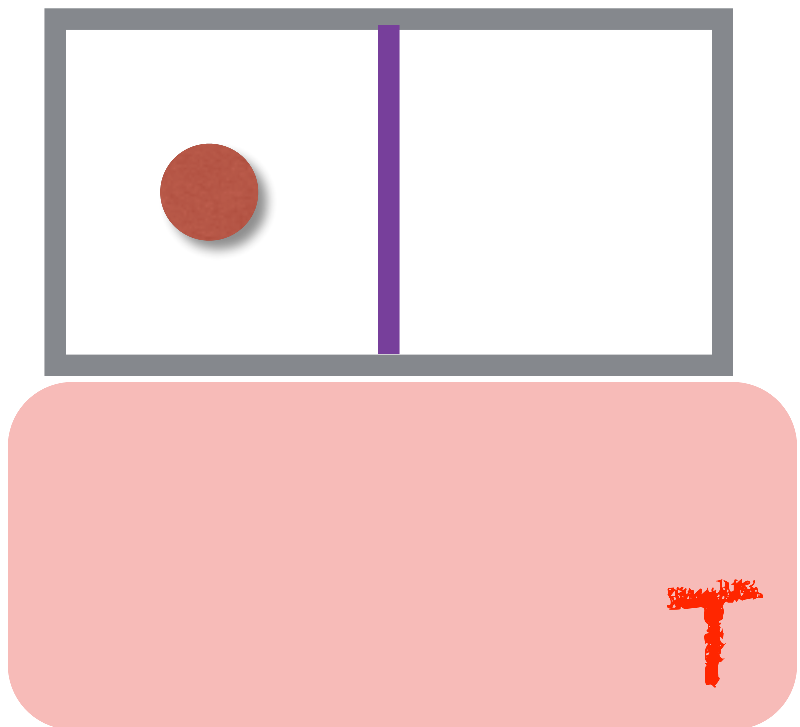

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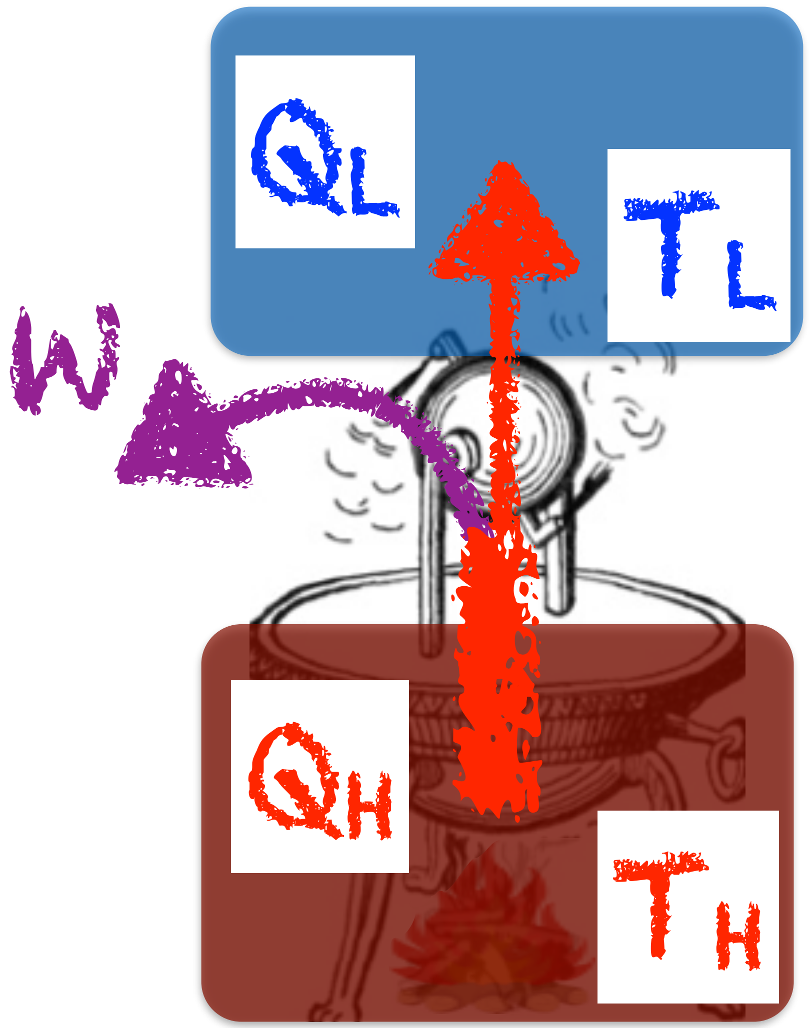

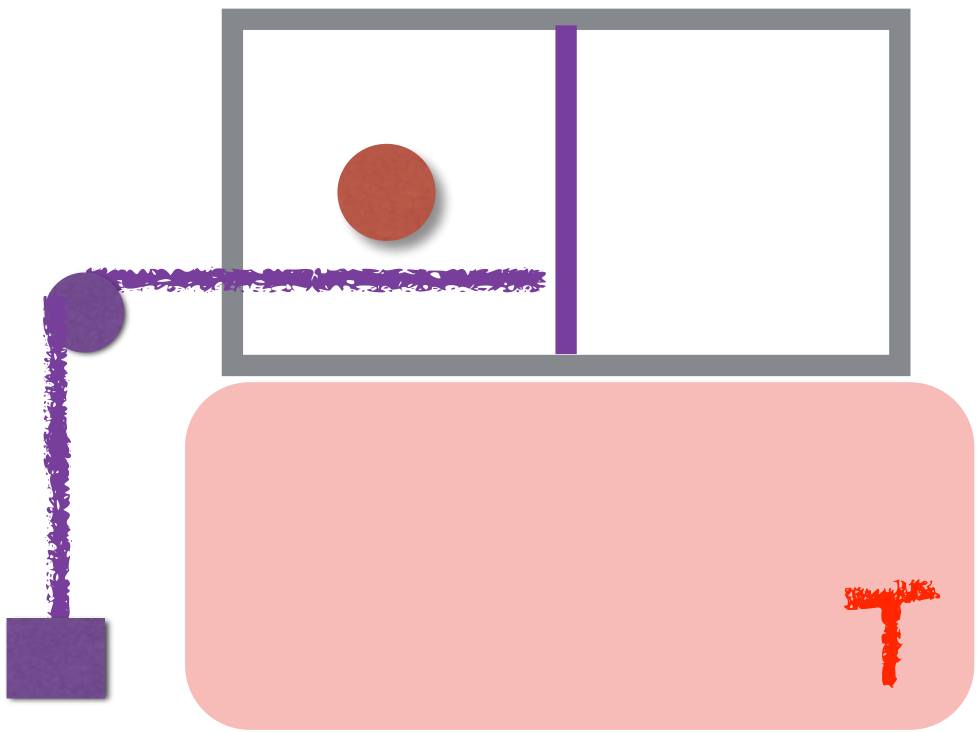

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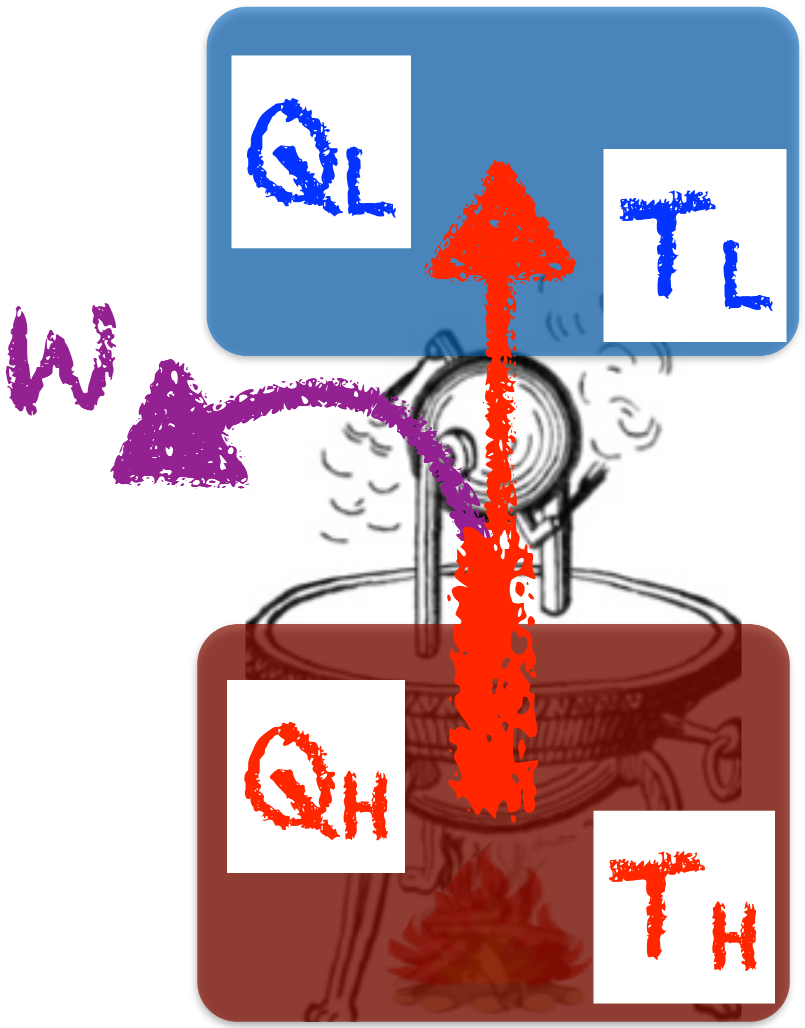

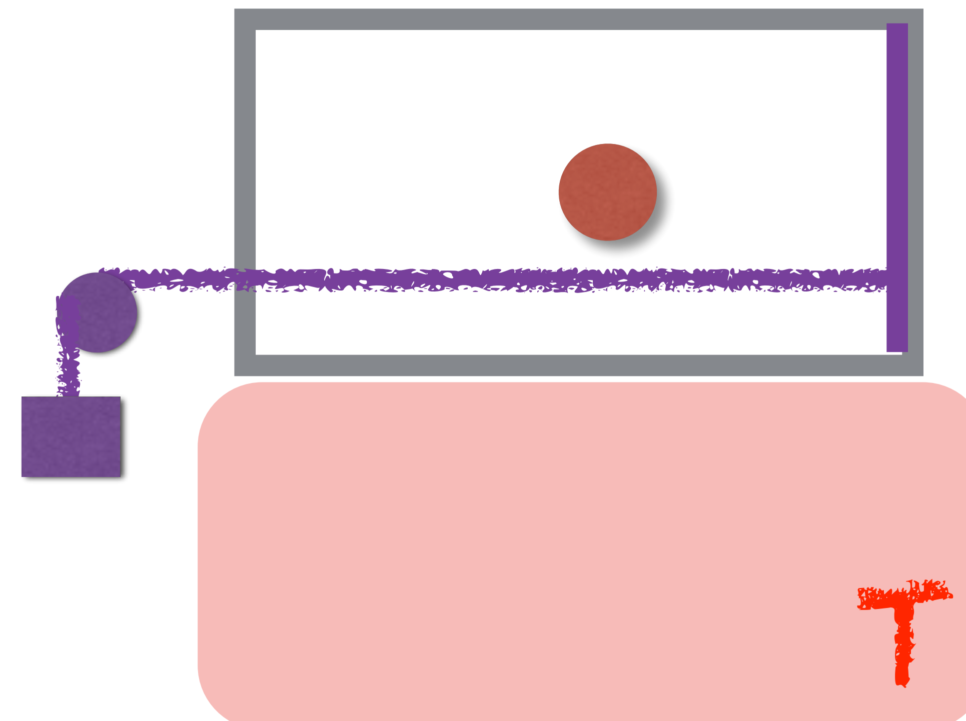

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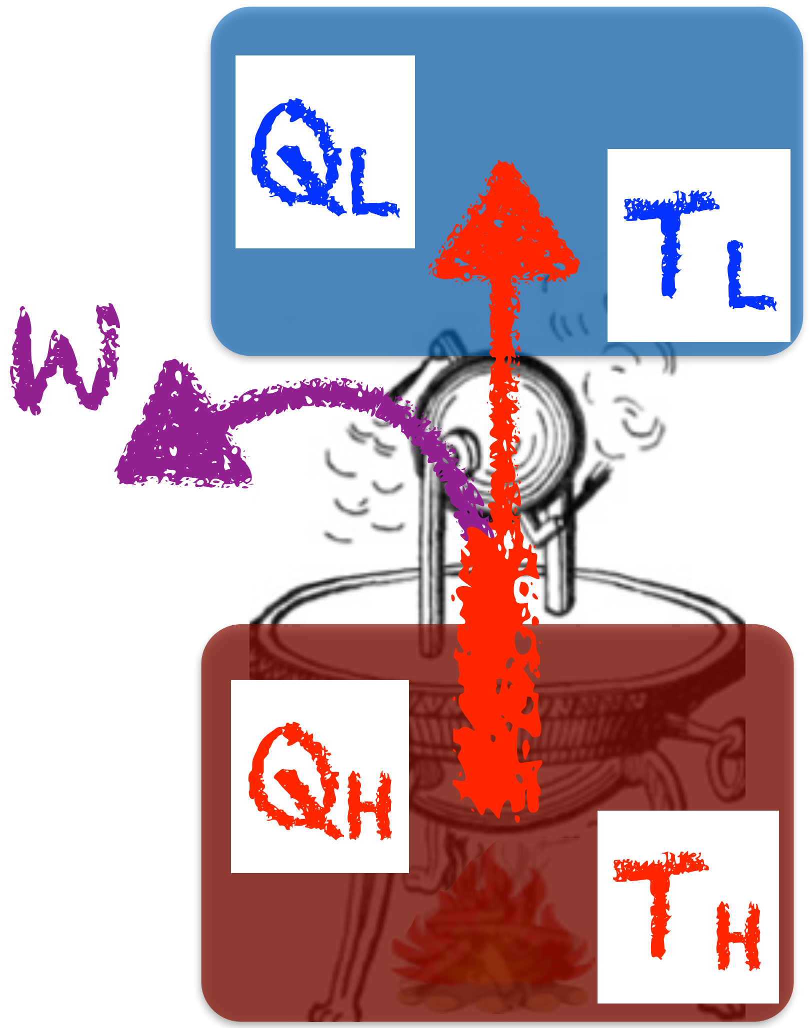

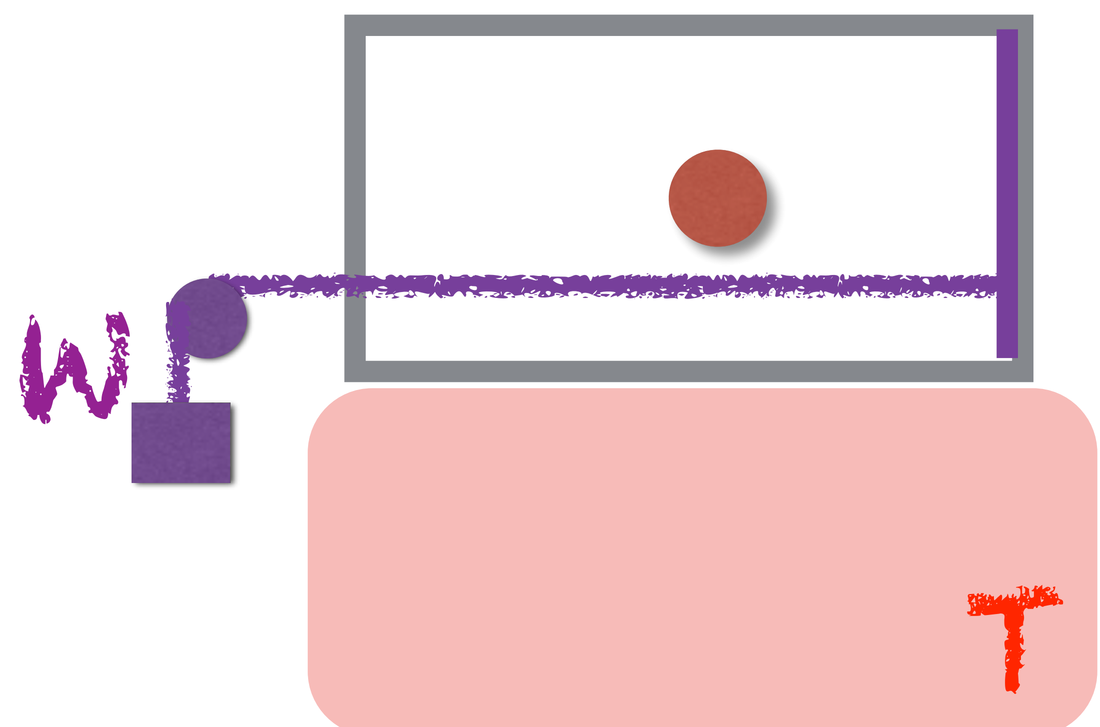

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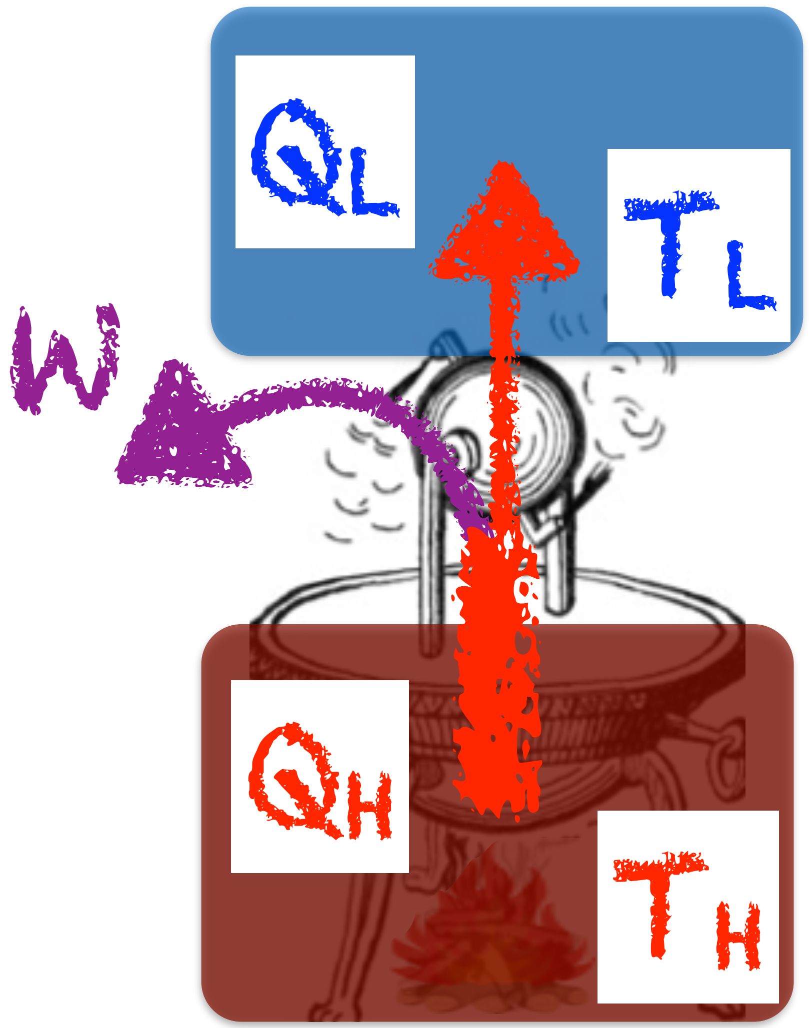

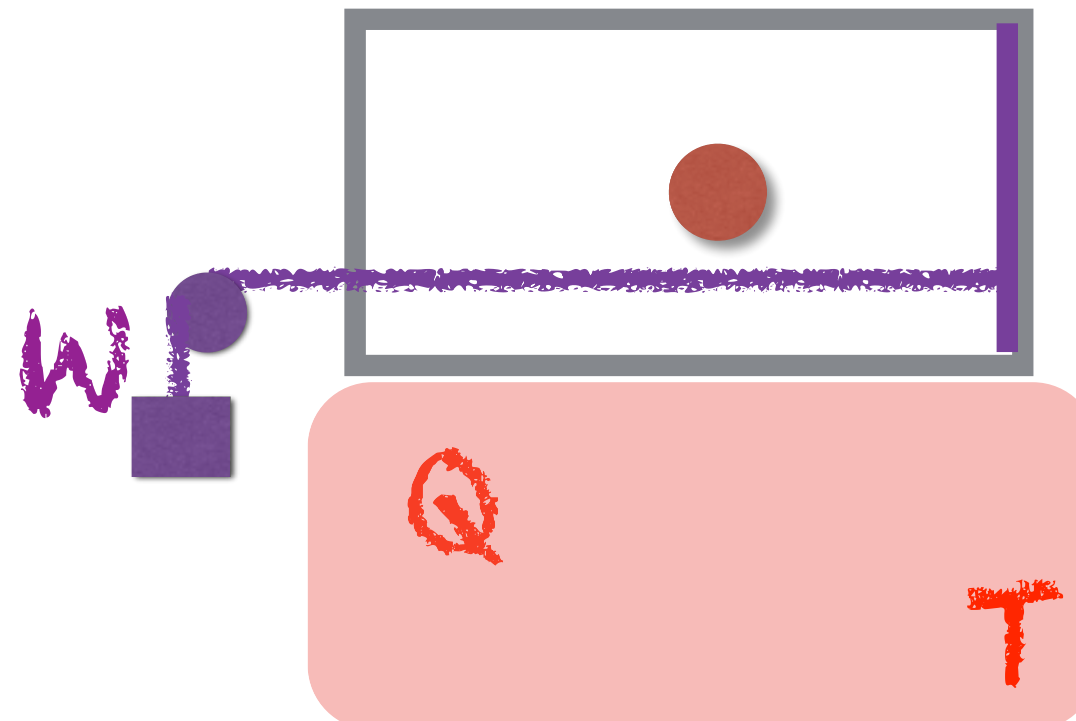

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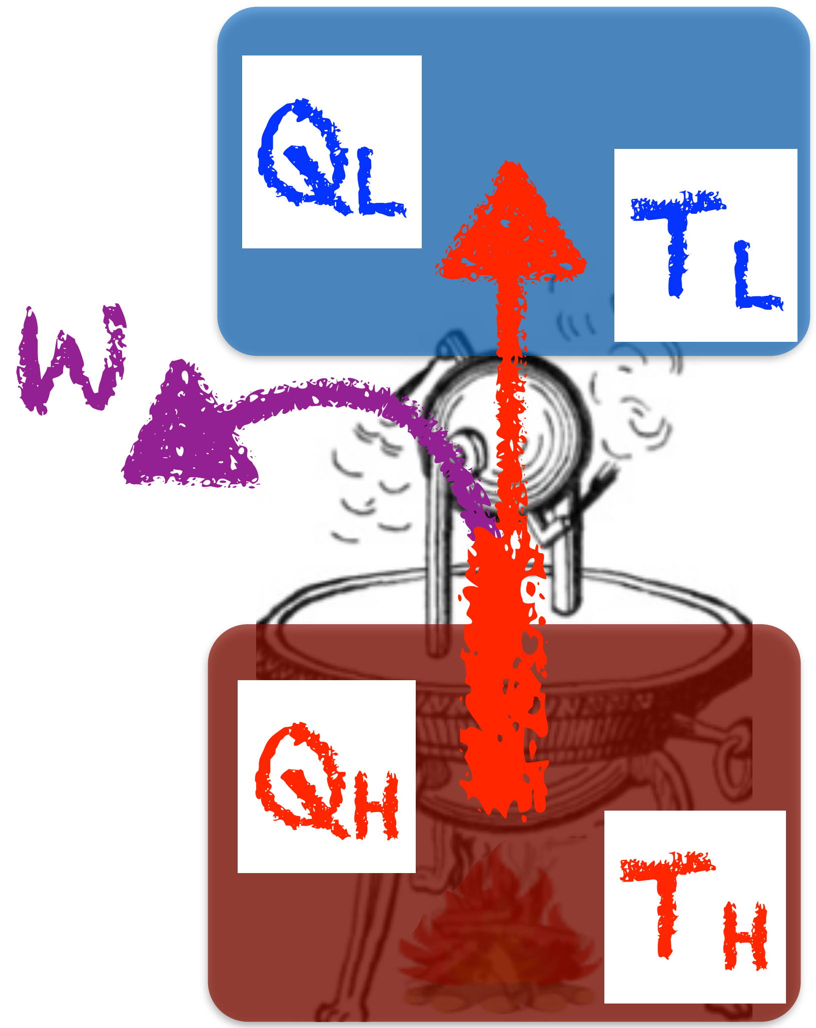

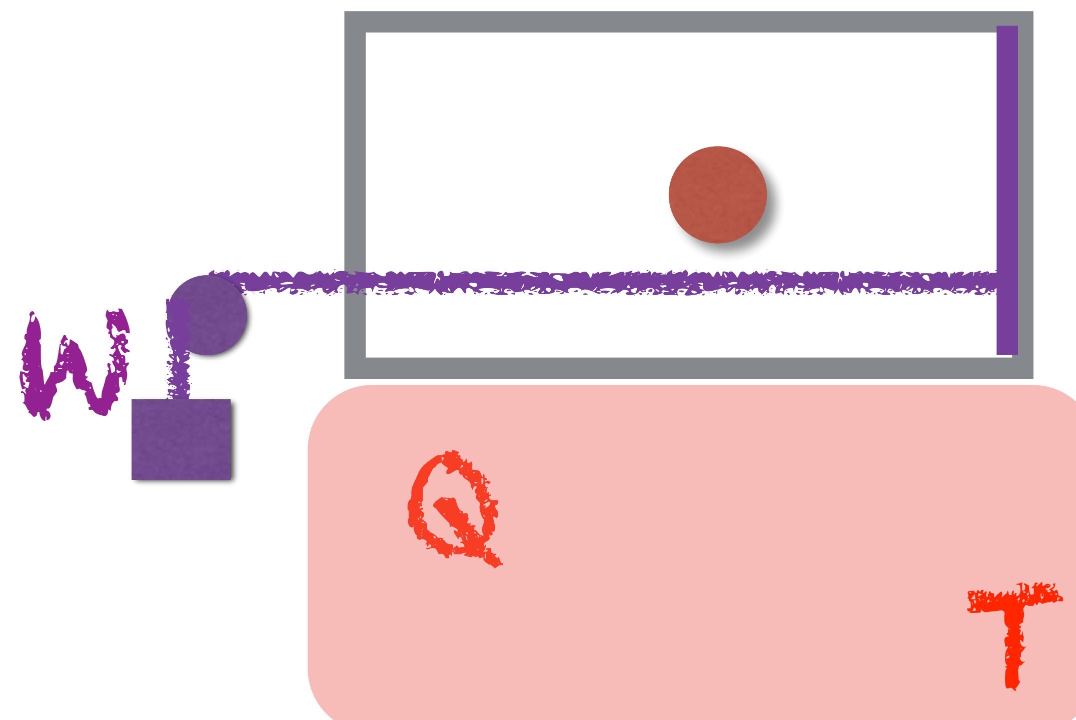

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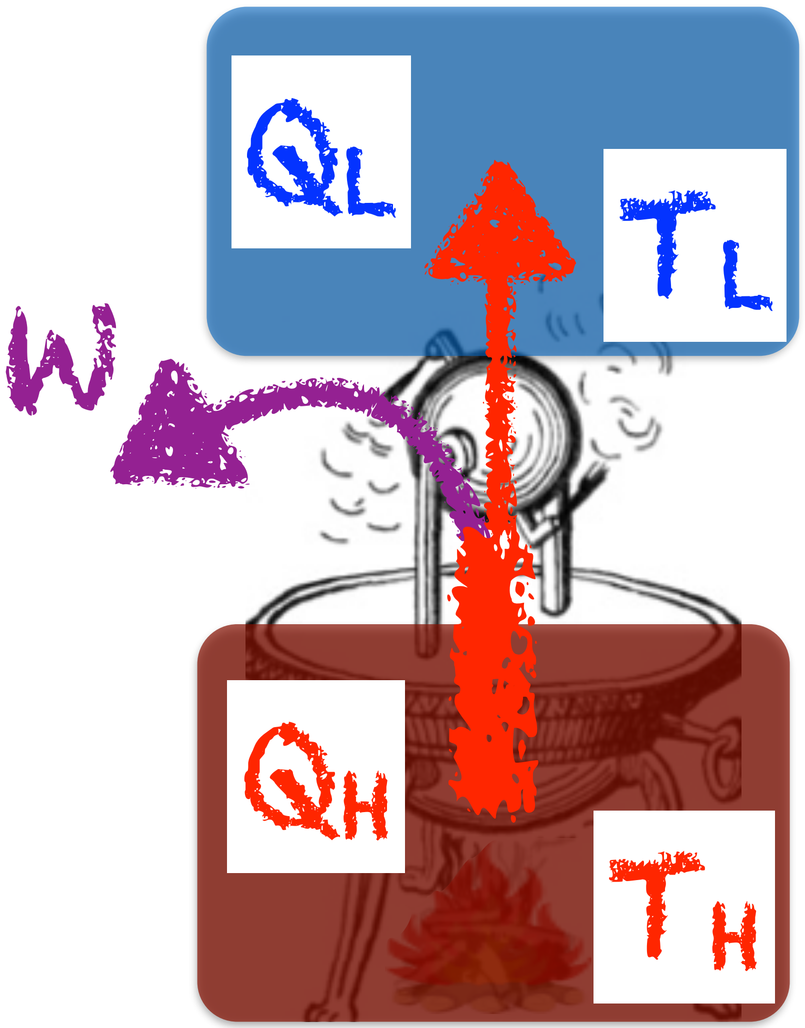
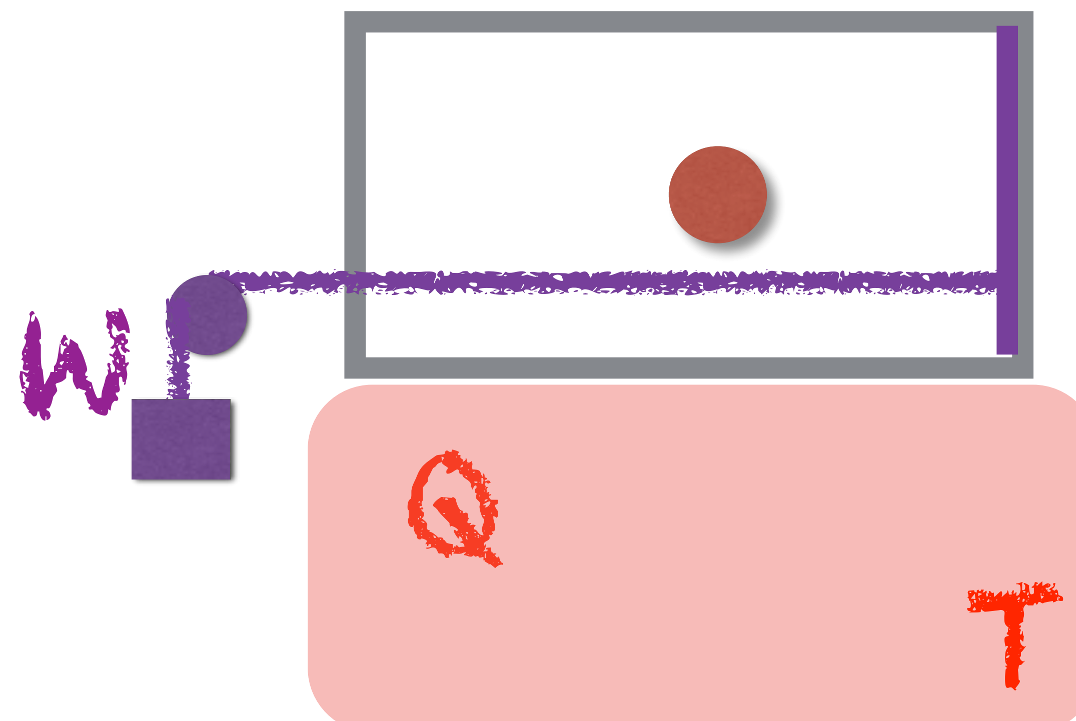
Heat engine vs. Info engine





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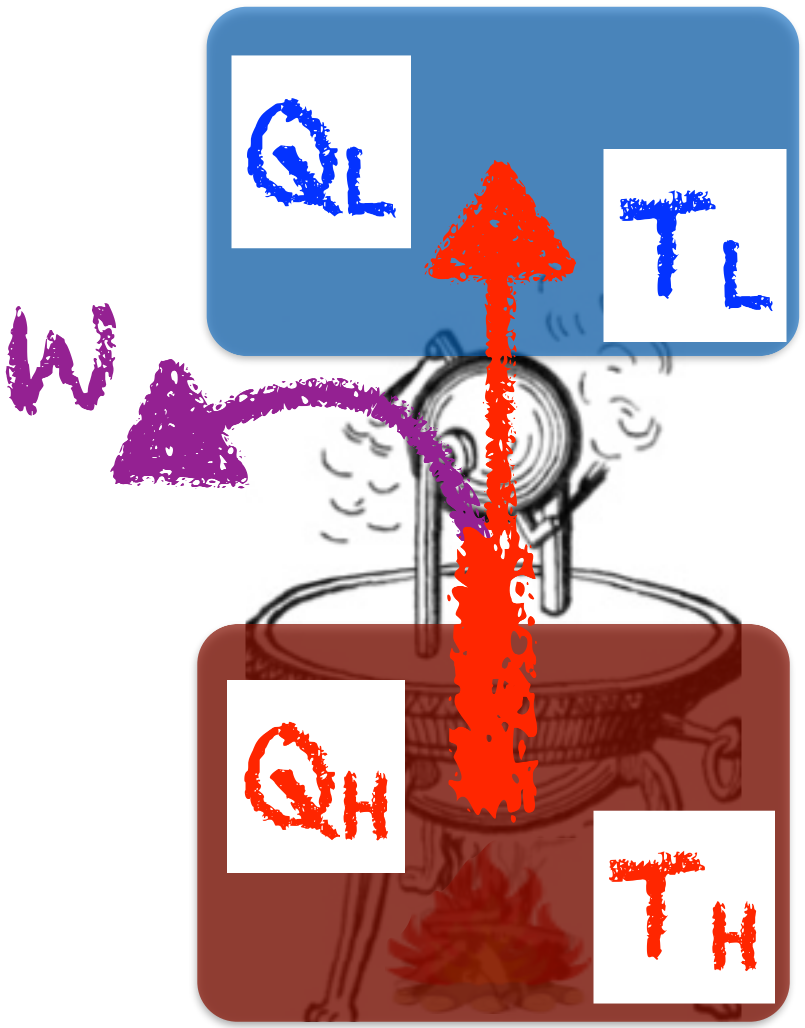

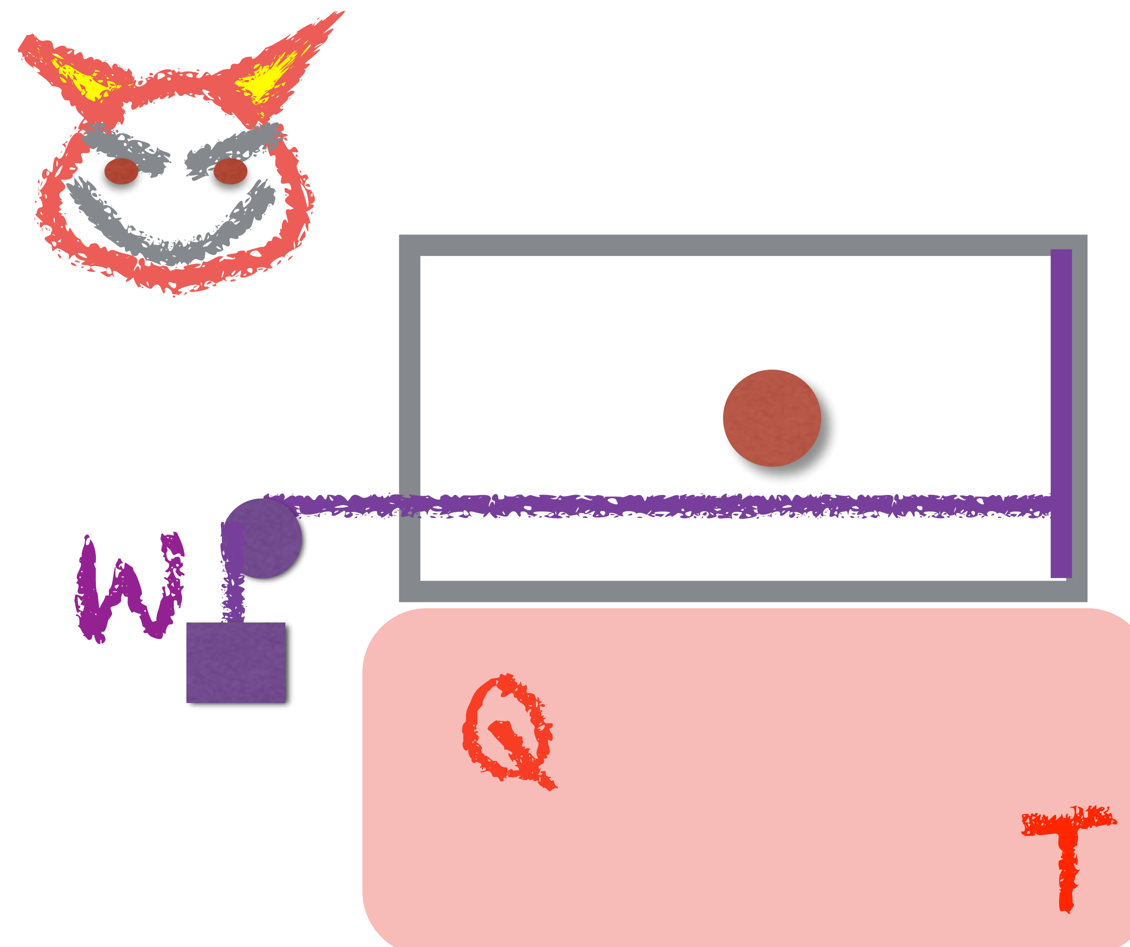

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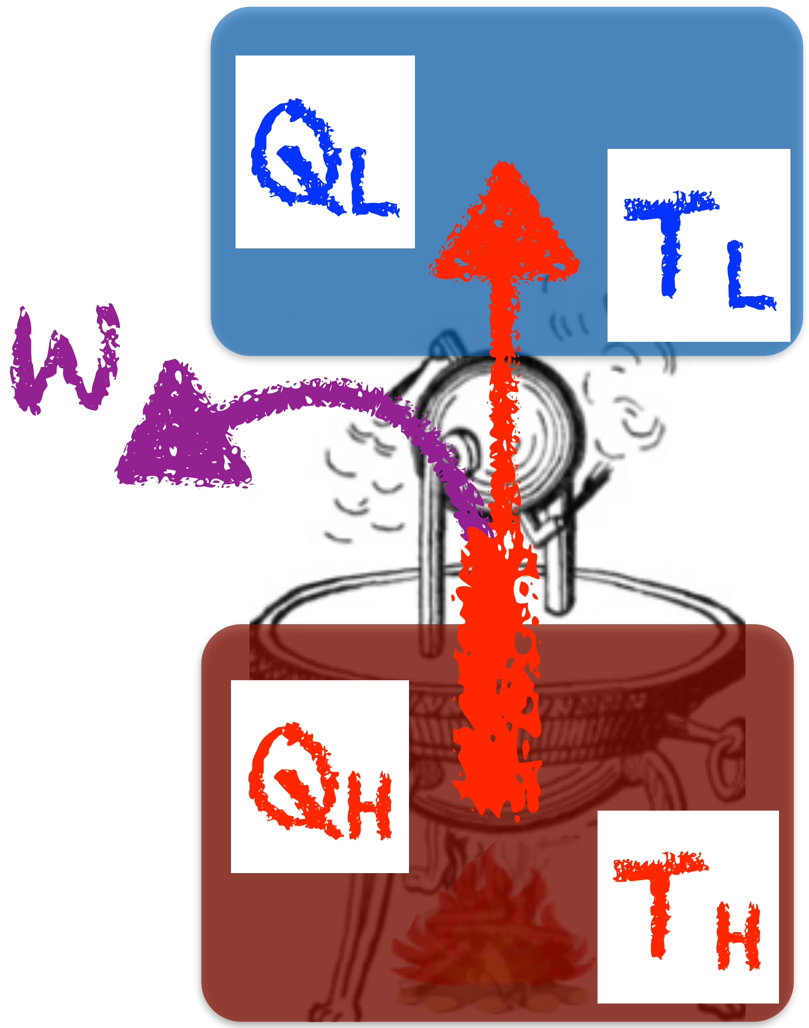

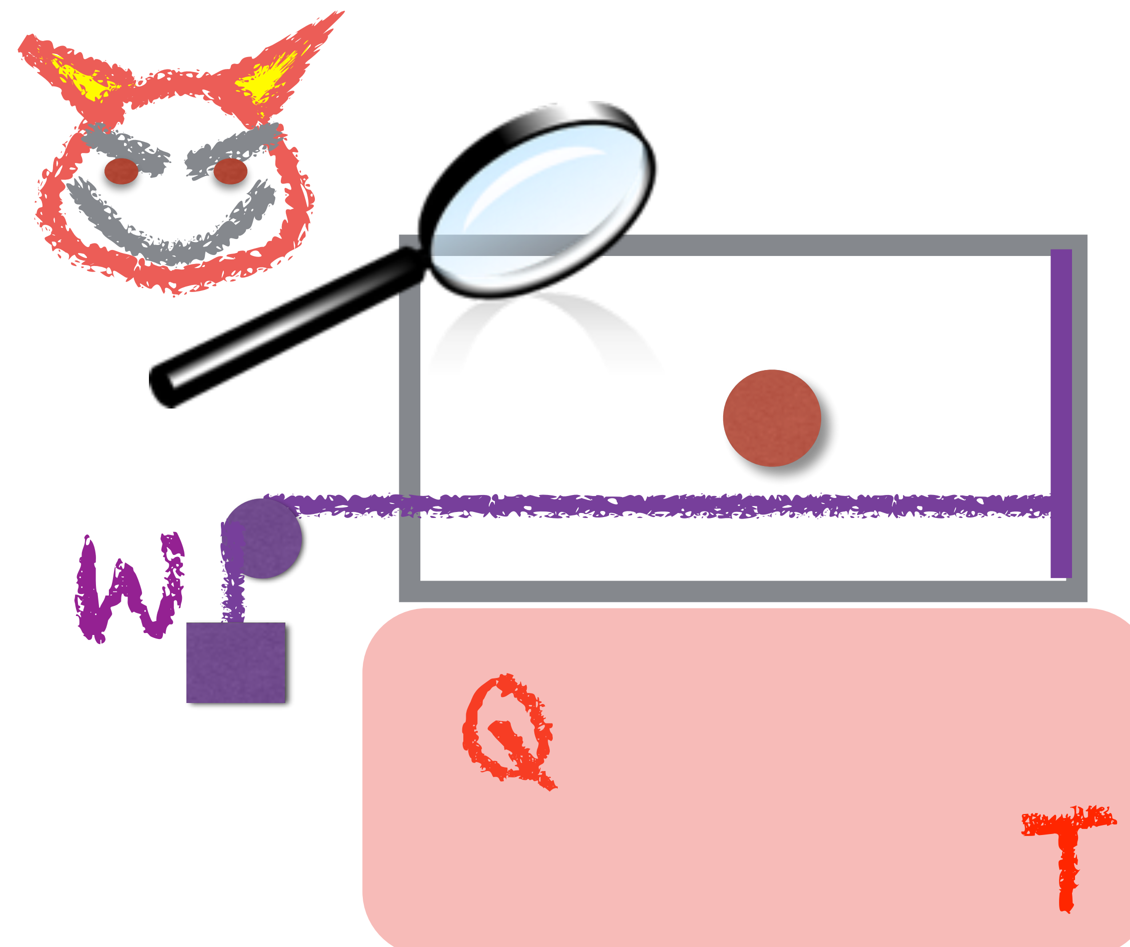

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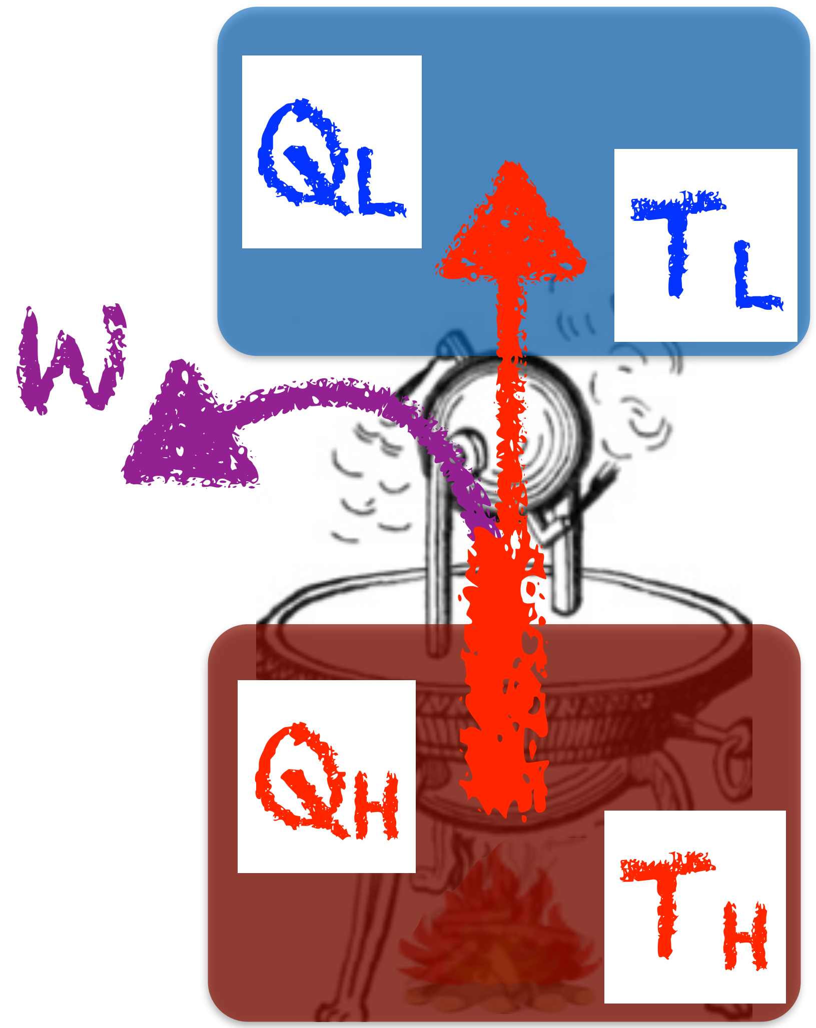

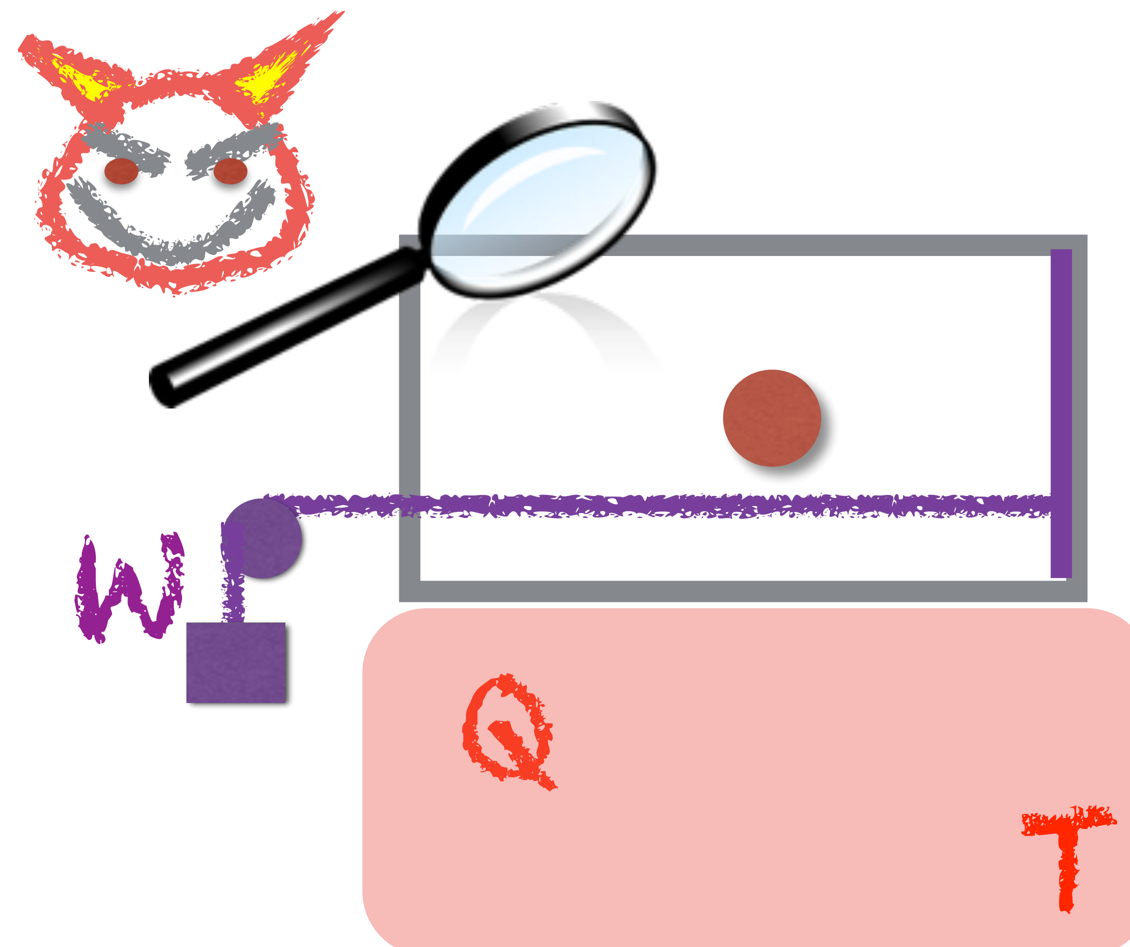

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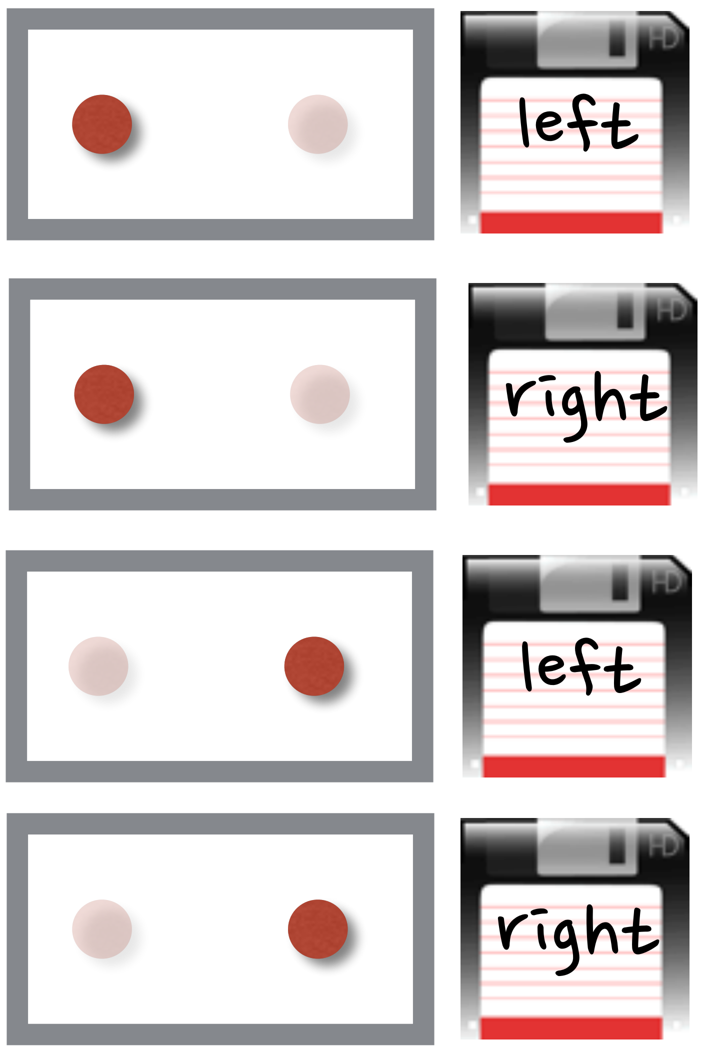
composite system!!

Composite system & Shannon entropy

$$H = -\sum_c P^c \ln P^c$$



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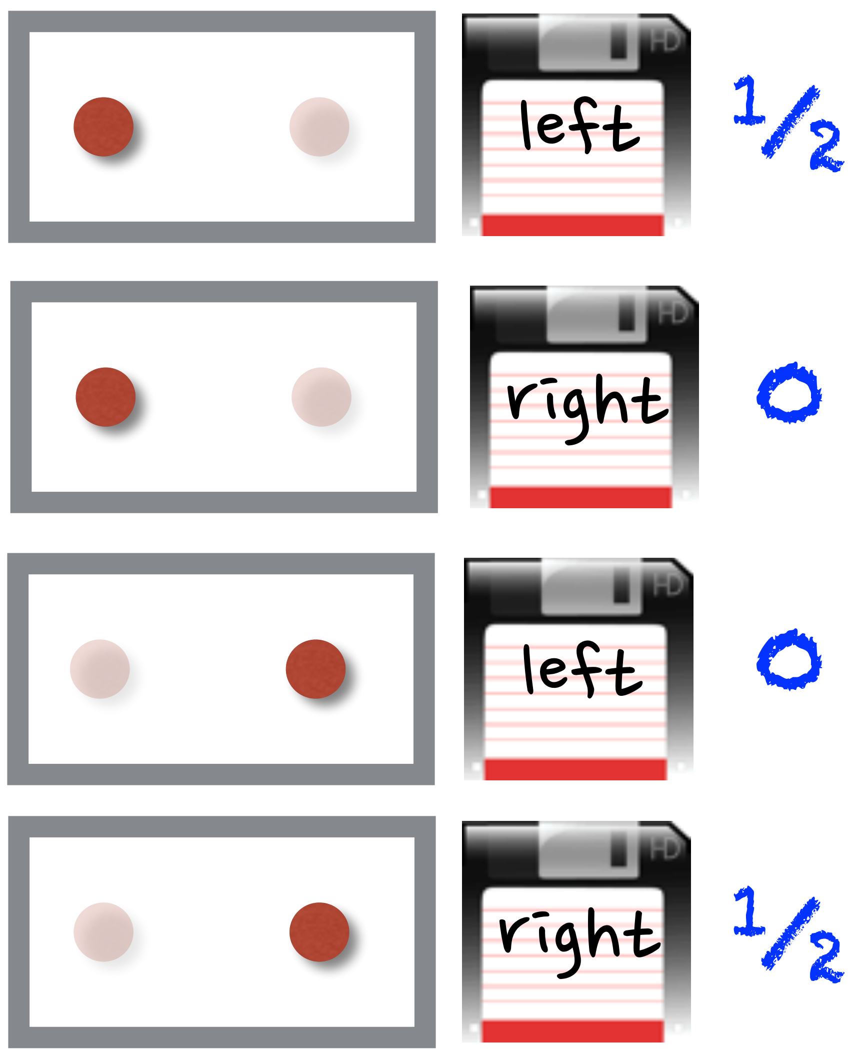

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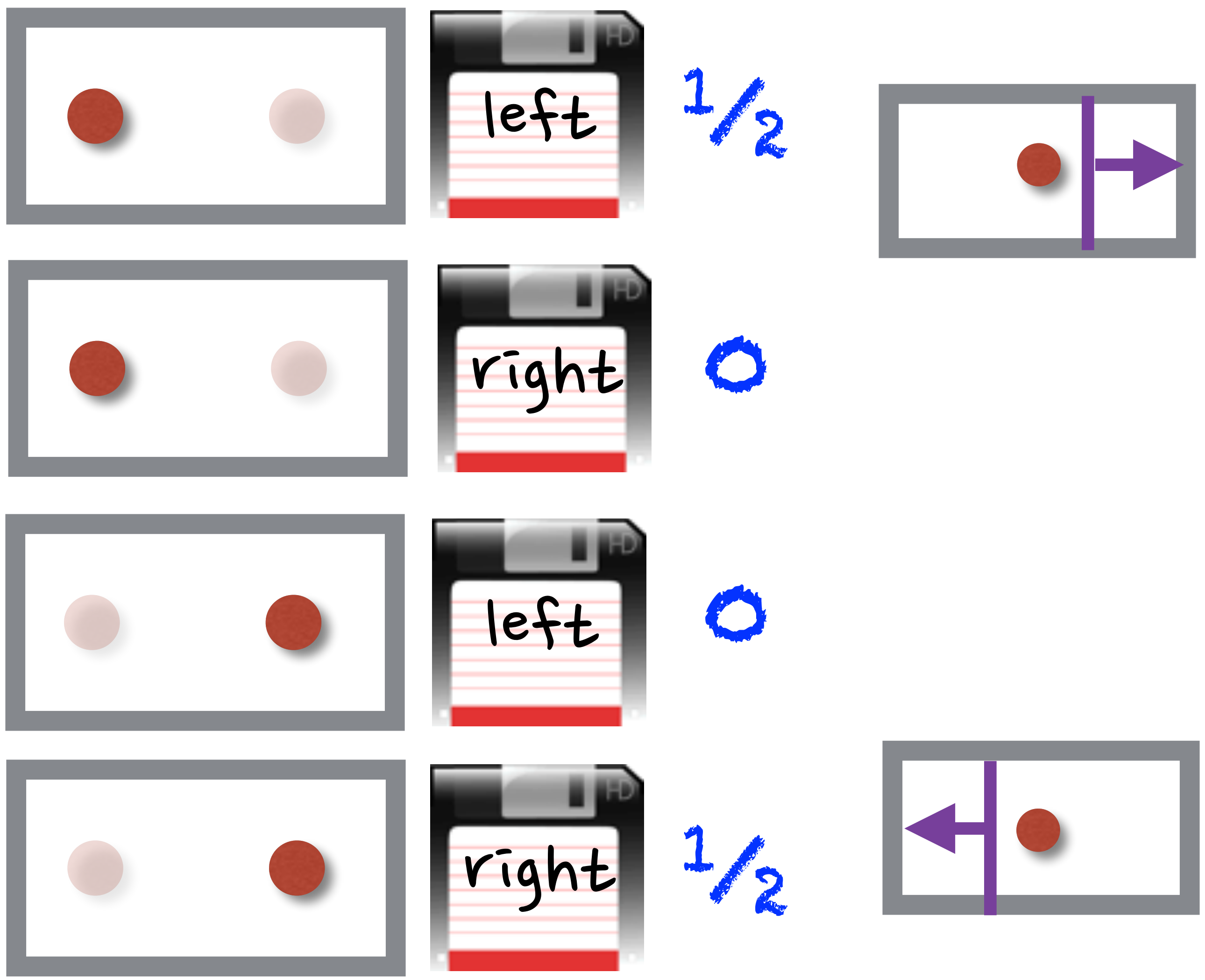

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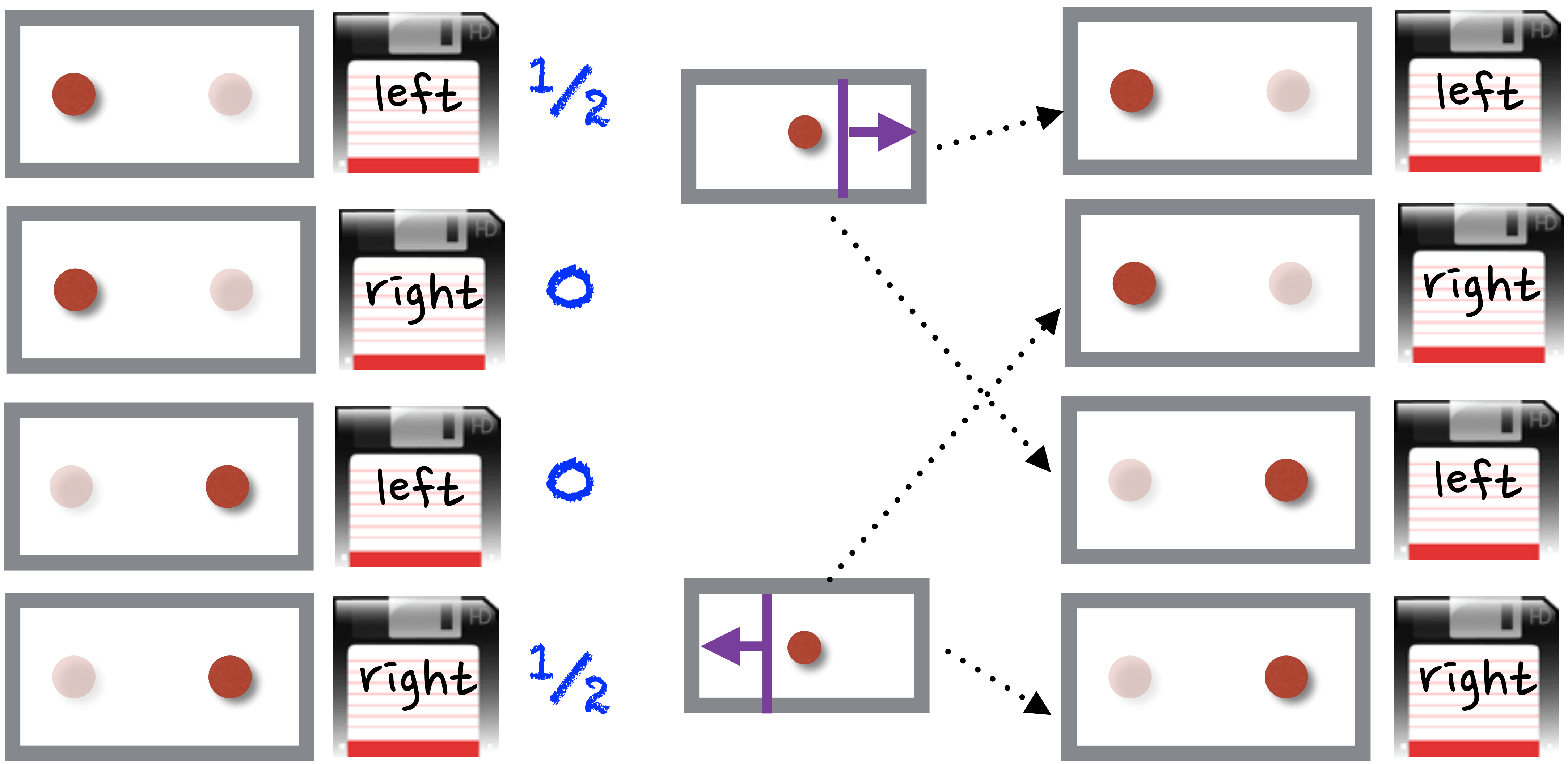

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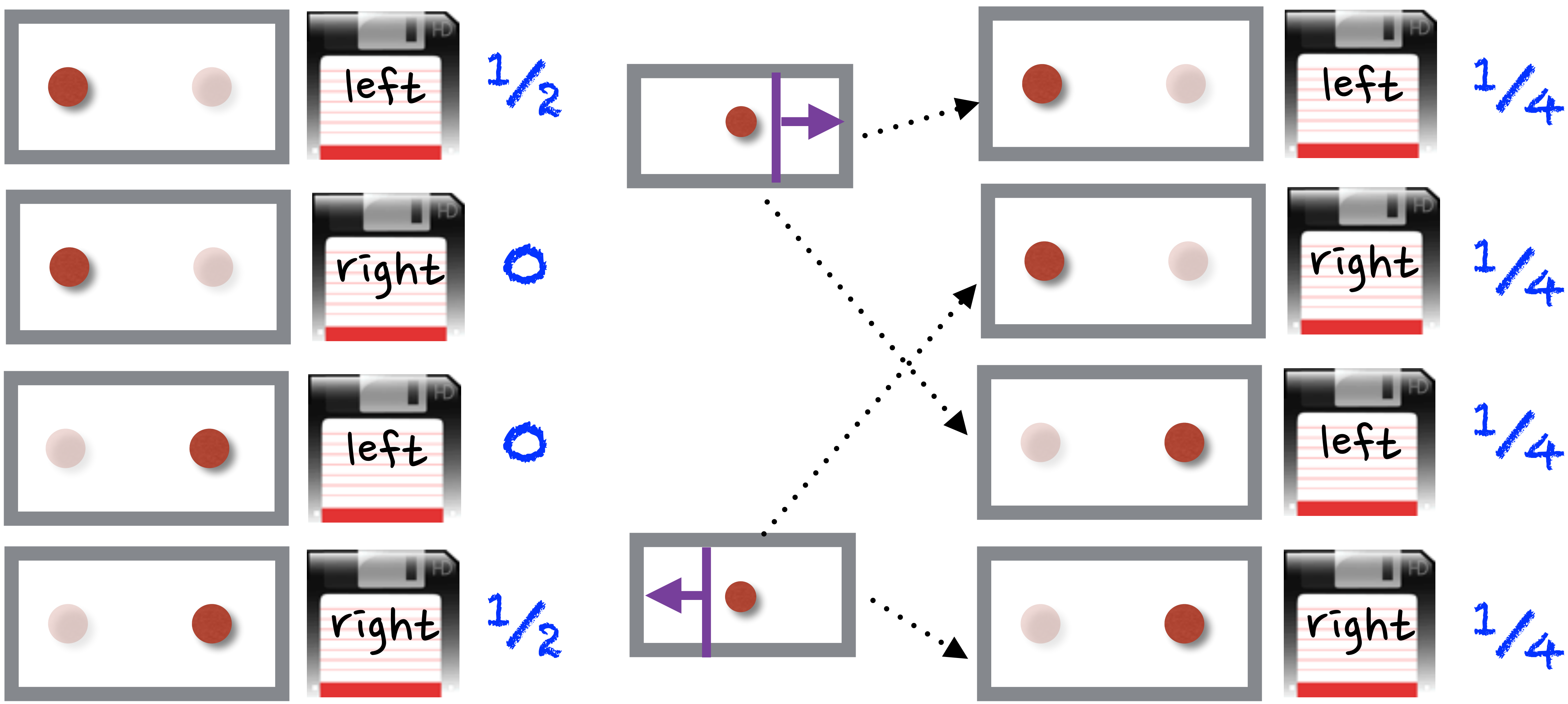

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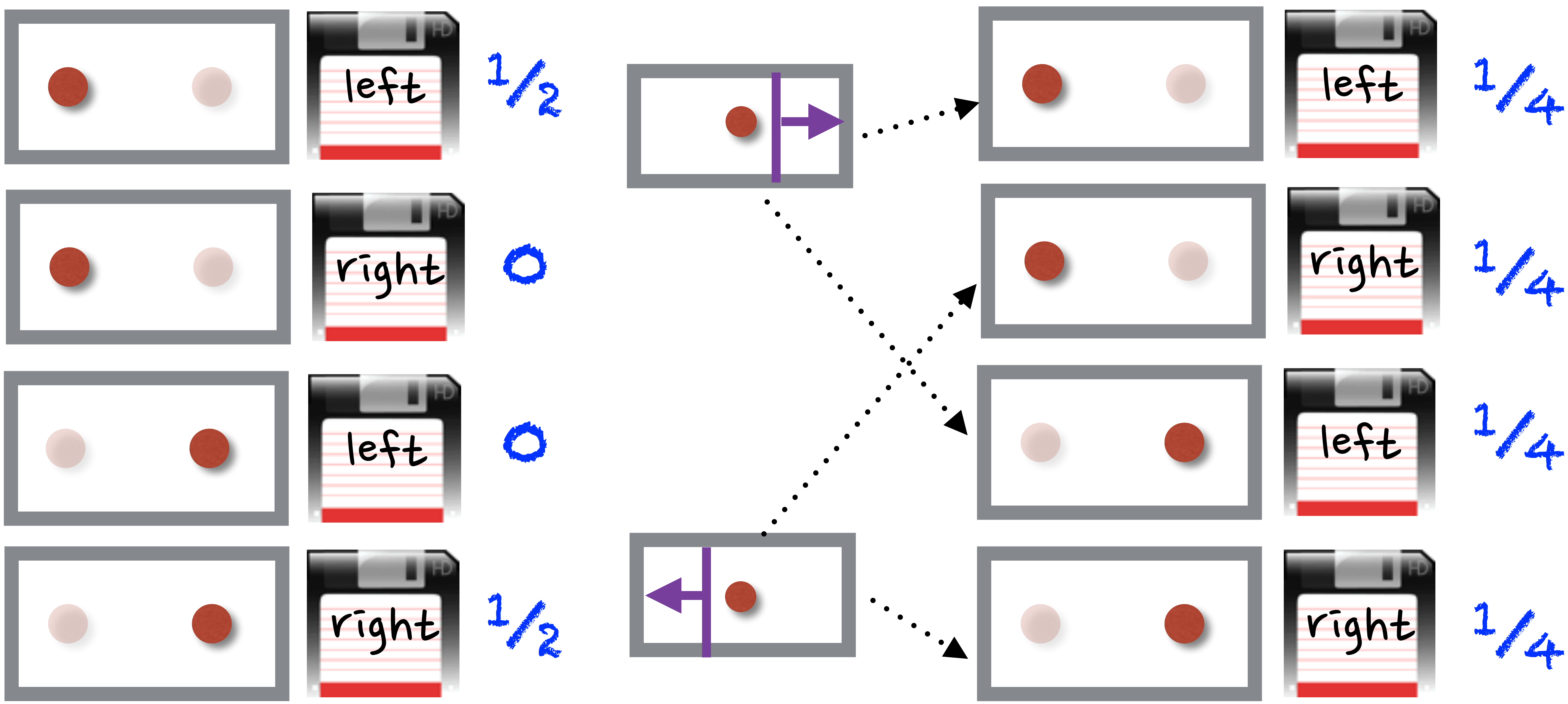

$$H_0^{(sm)} = \ln 2$$

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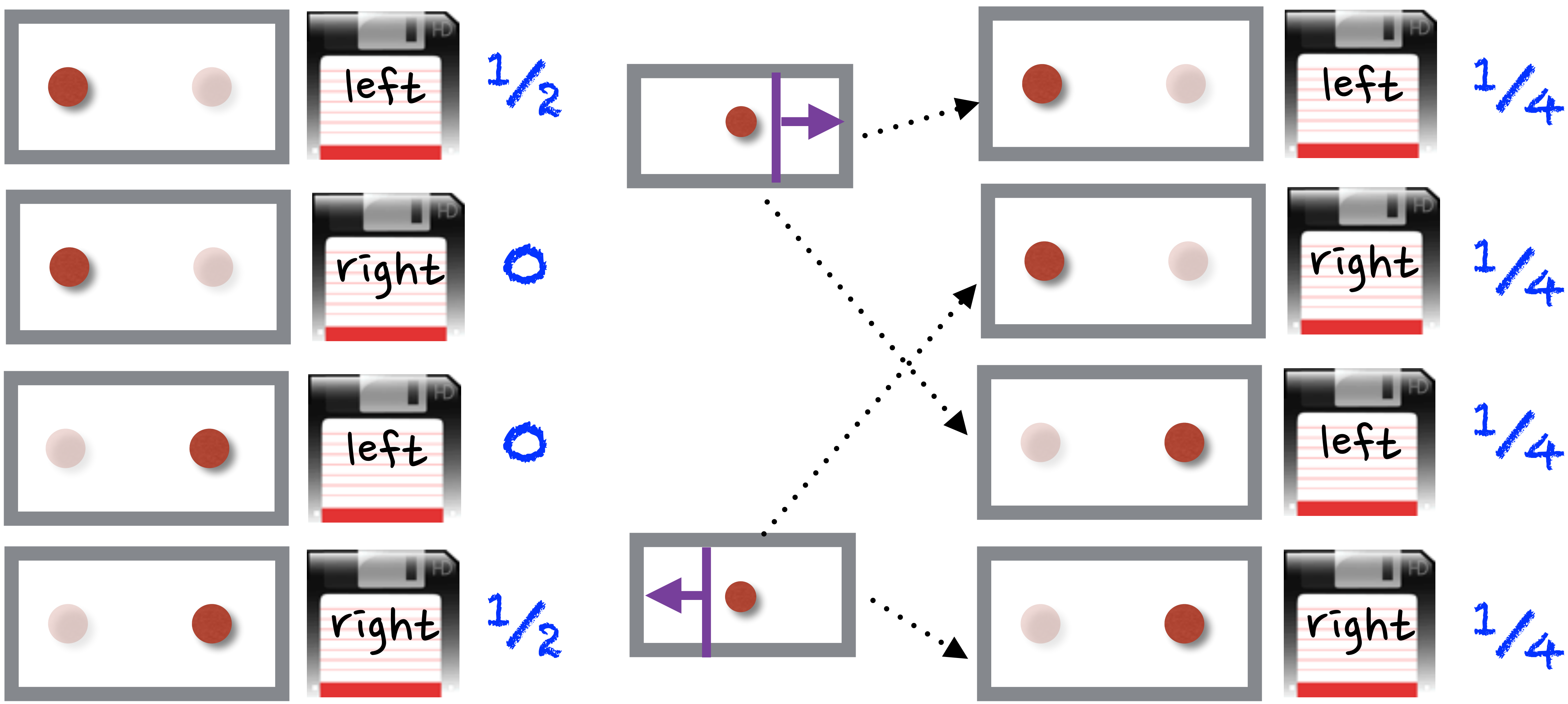

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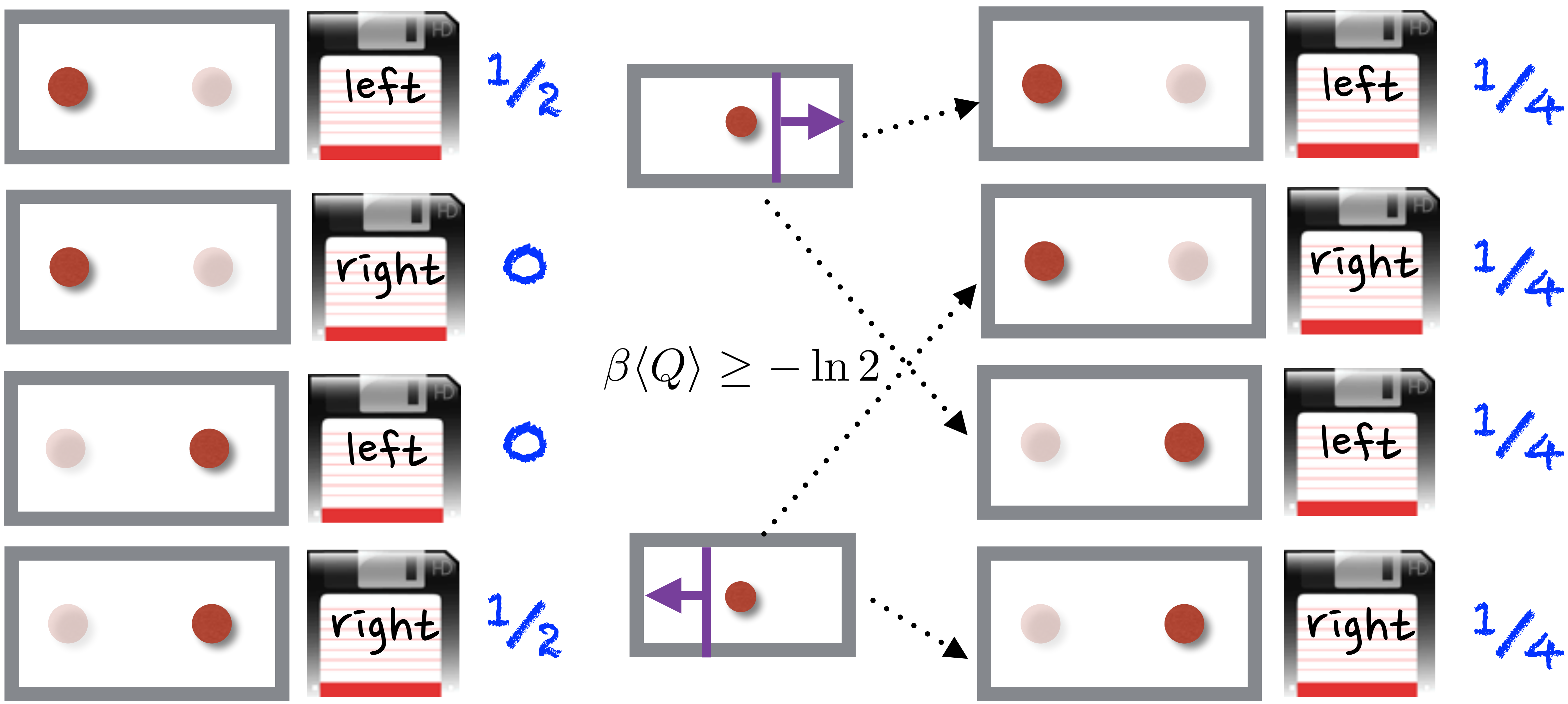

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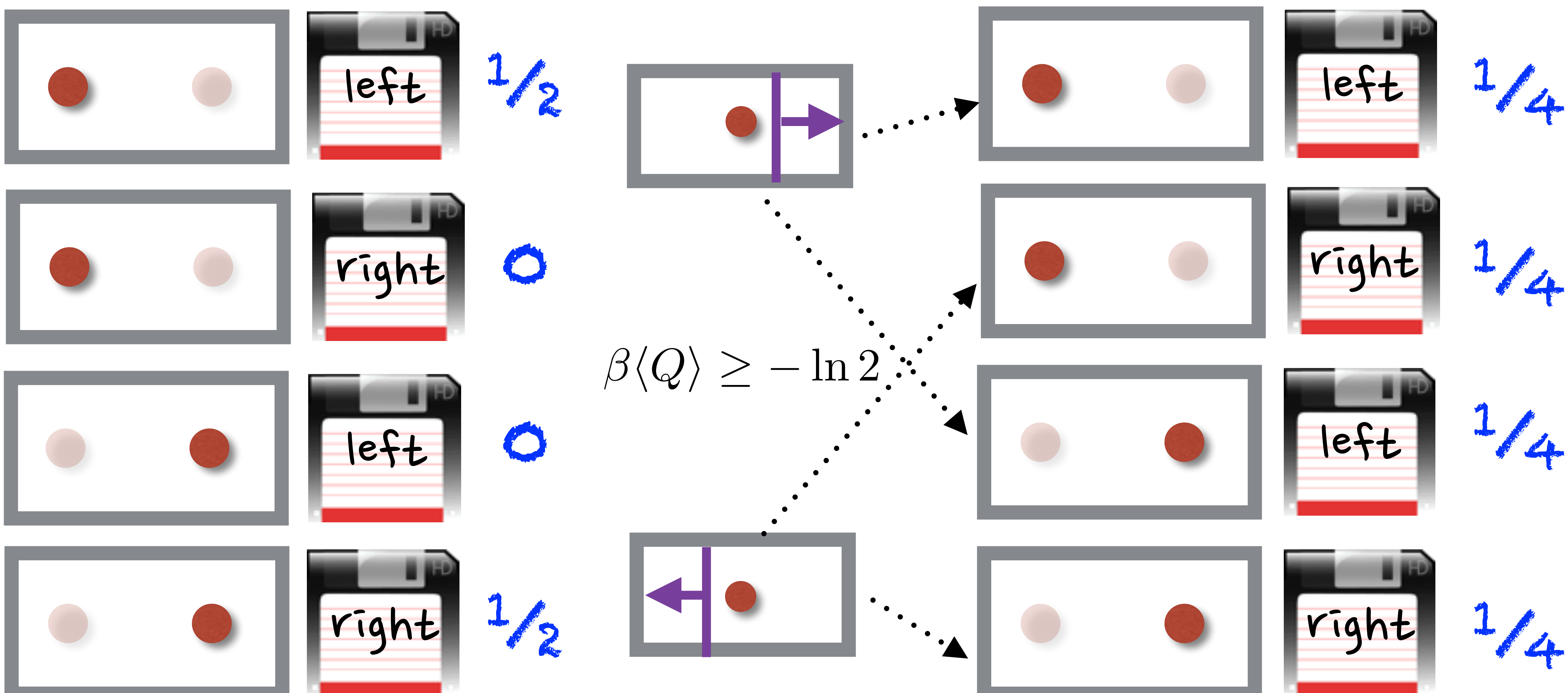

$H_0^{(sm)} = \ln 2$

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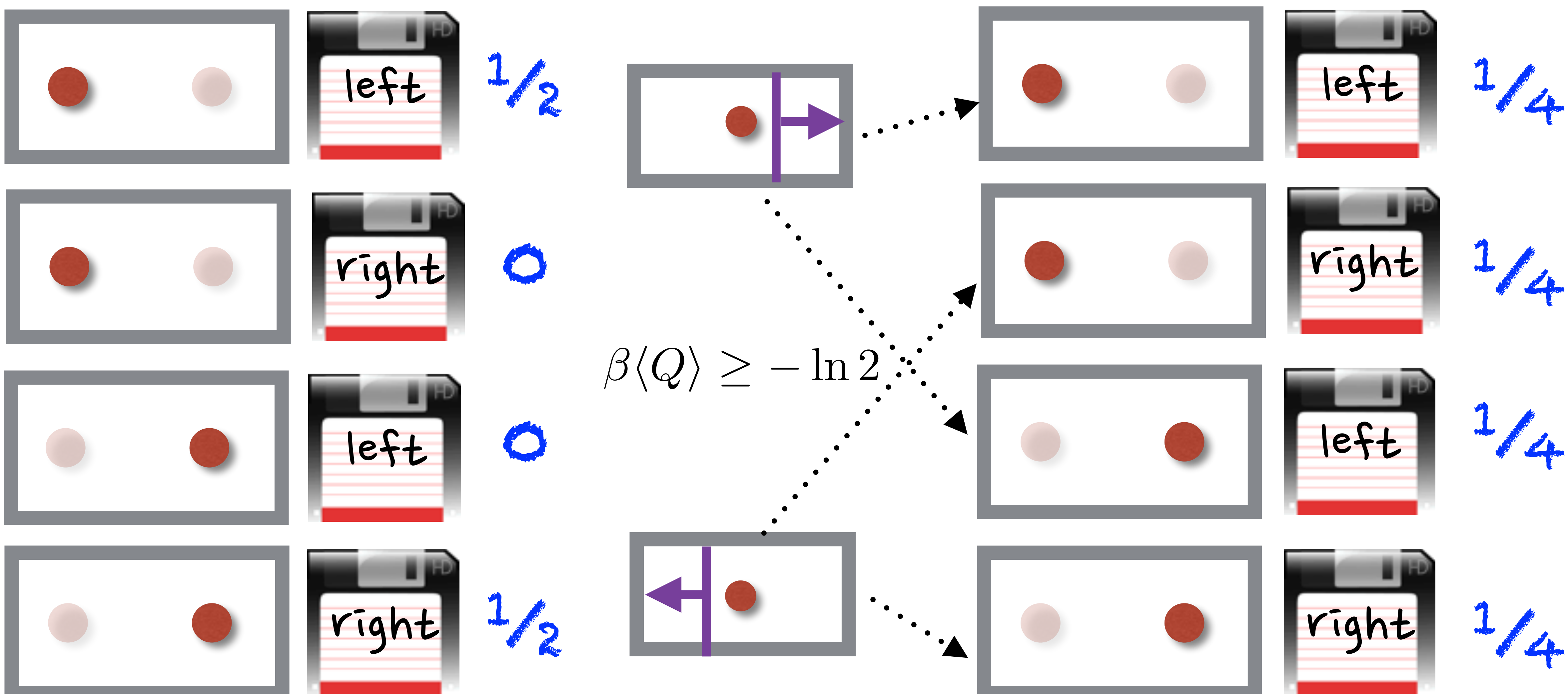

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Sagawa & Ueda

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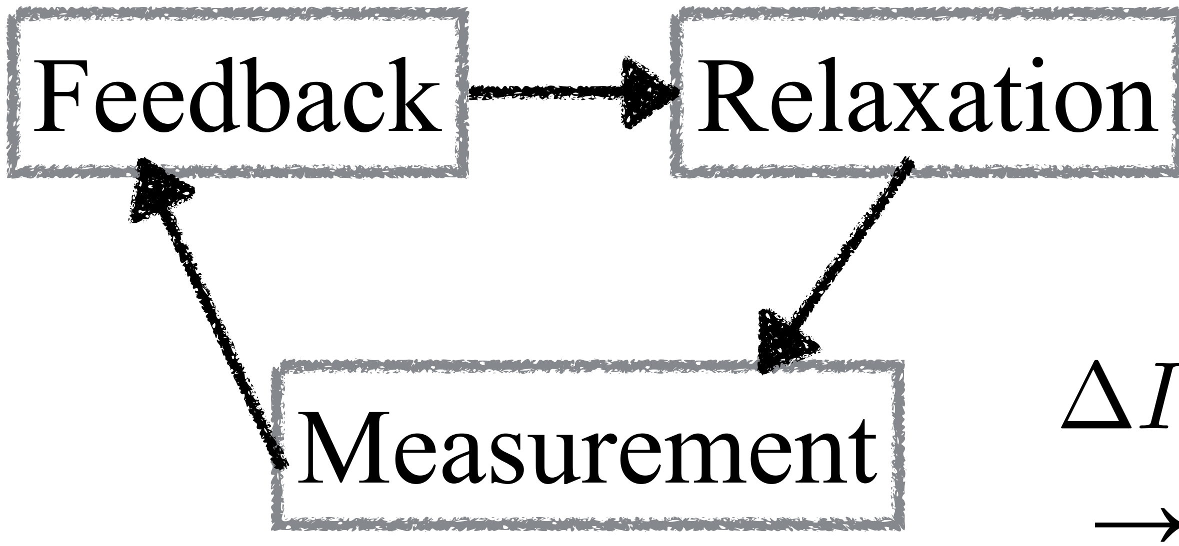
Cyclic engine

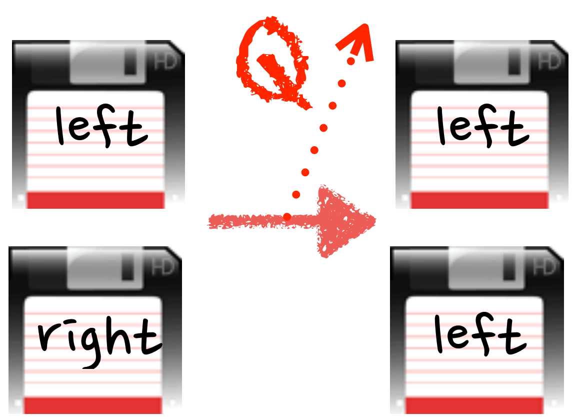


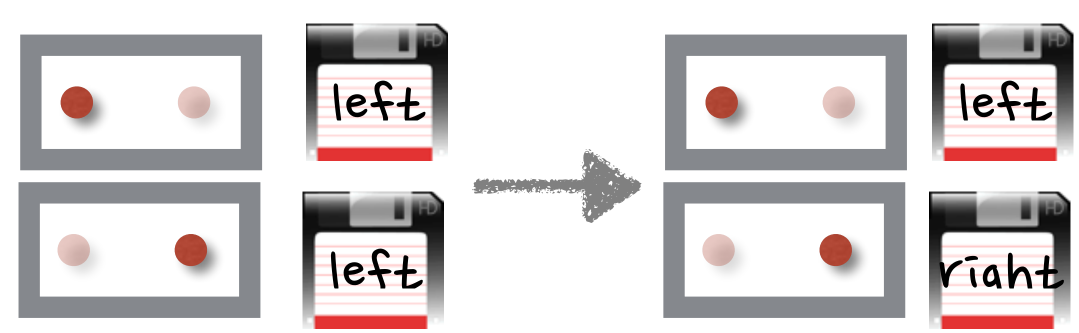
$$\Delta I_R \leq 0 \qquad \Delta H_R^{(sm)} \geq 0$$

$$\Delta I_M \geq 0 \quad \Delta H_M^{(sm)} < 0$$

$\rightarrow$ irreversible process

- Landauer: before measuring, memory resetting (heat dissipation)
  $\rightarrow$ reversible measurement





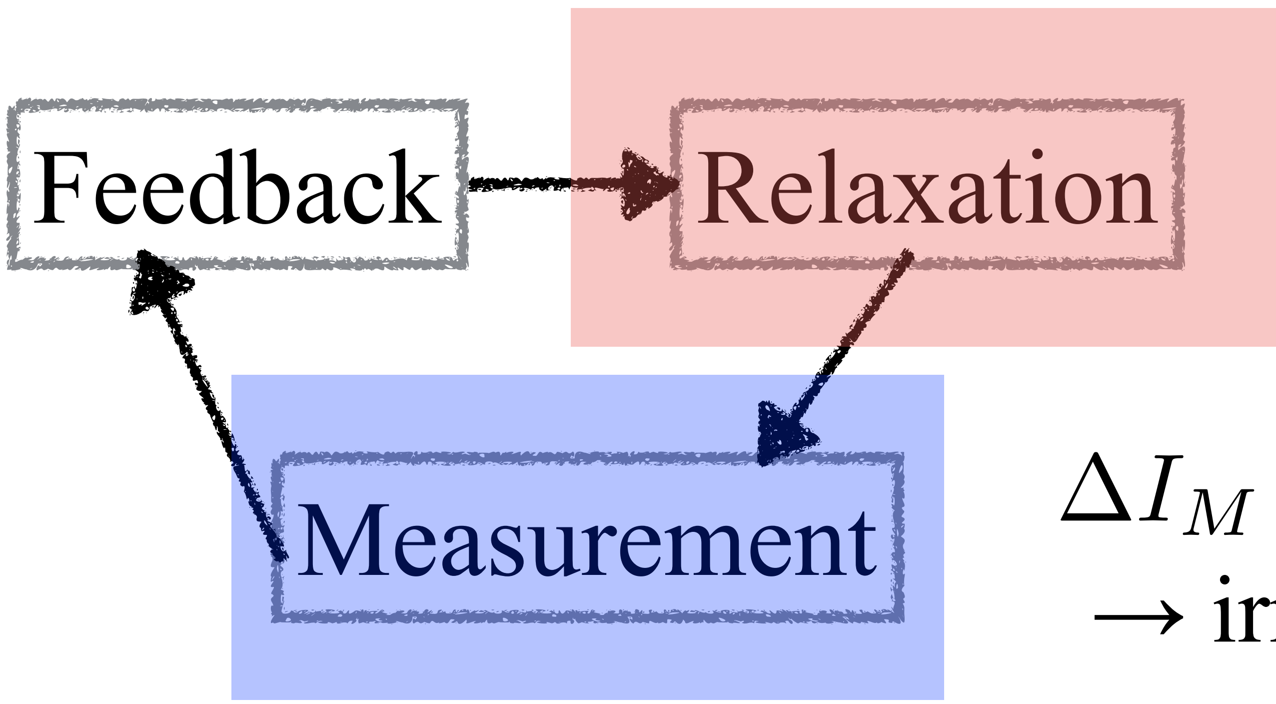
energy cost ?

- Stochastic measurement : info. engine $\rightarrow$ heat engine

  in terms of composite system

  information assisted

Cyclic engine



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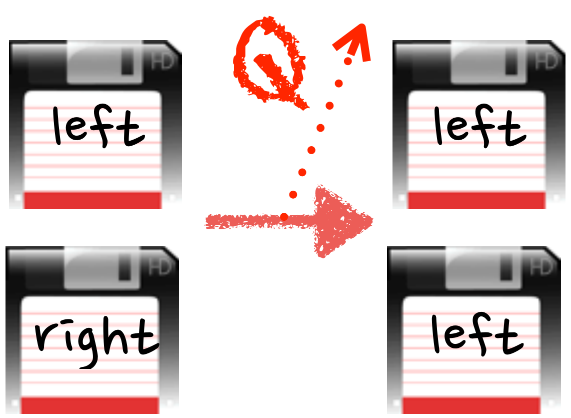

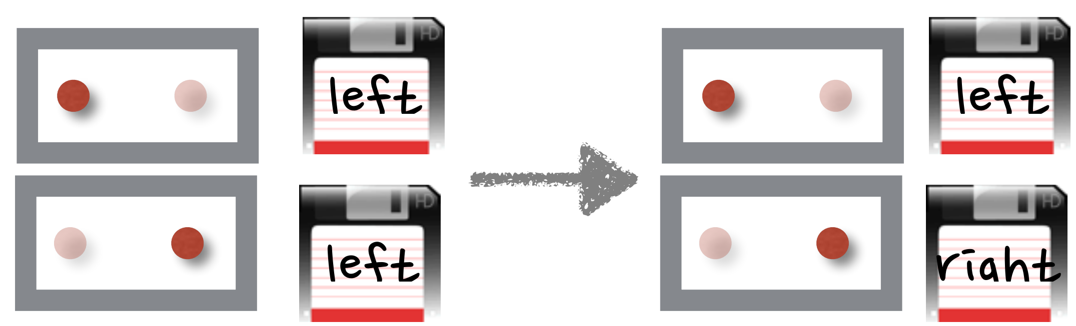

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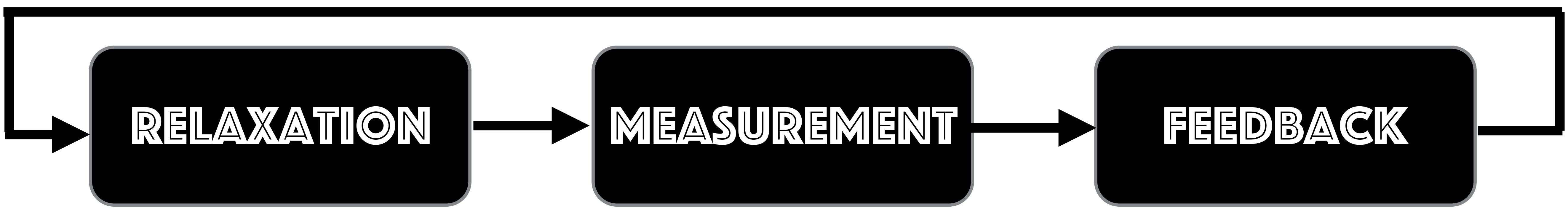
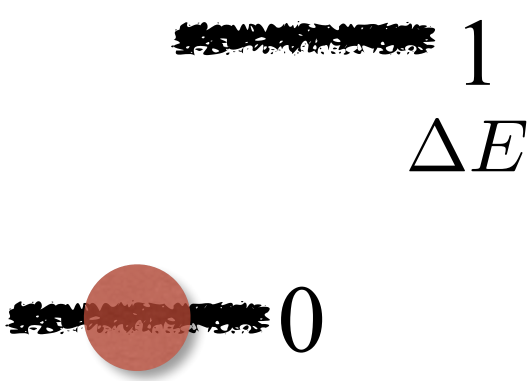
Two-state model



$$|P\rangle = \left(P^{00}, P^{01}, P^{10}, P^{11}\right)^T$$



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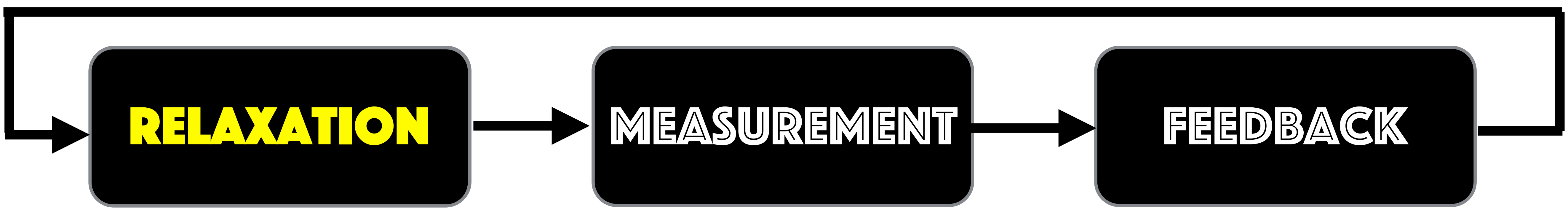

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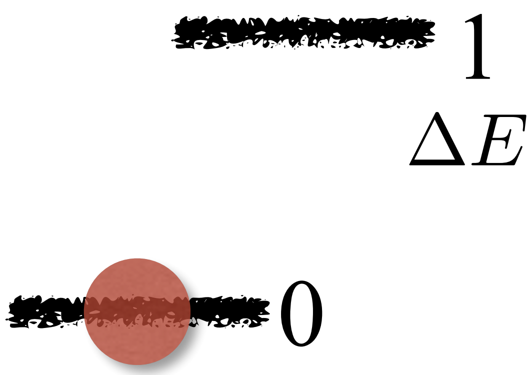

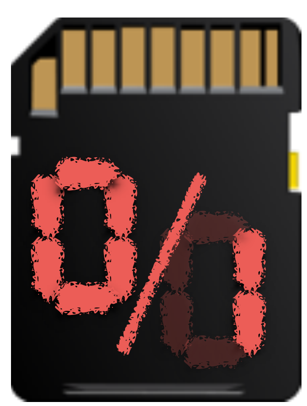

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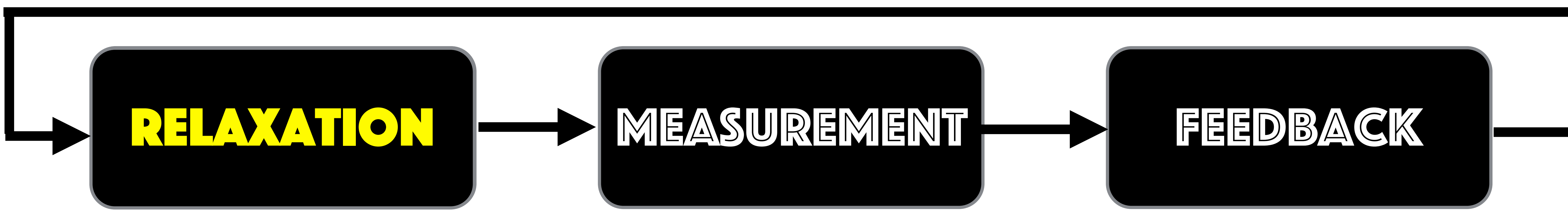

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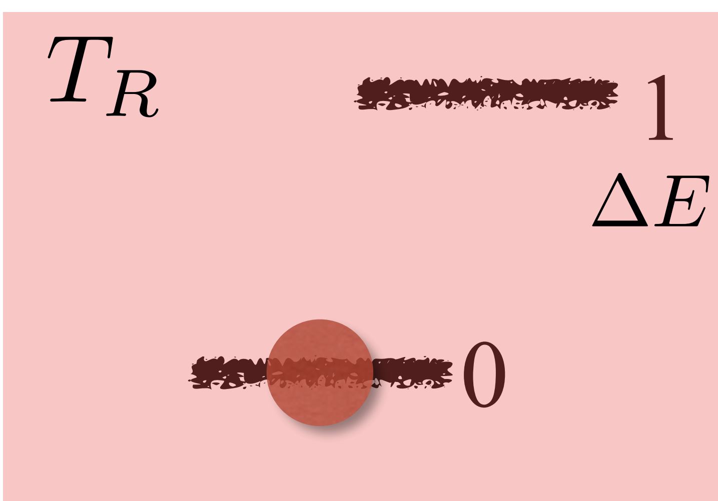

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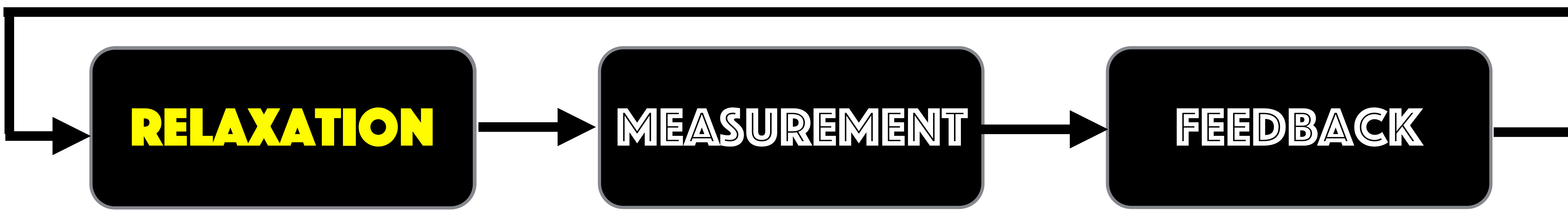

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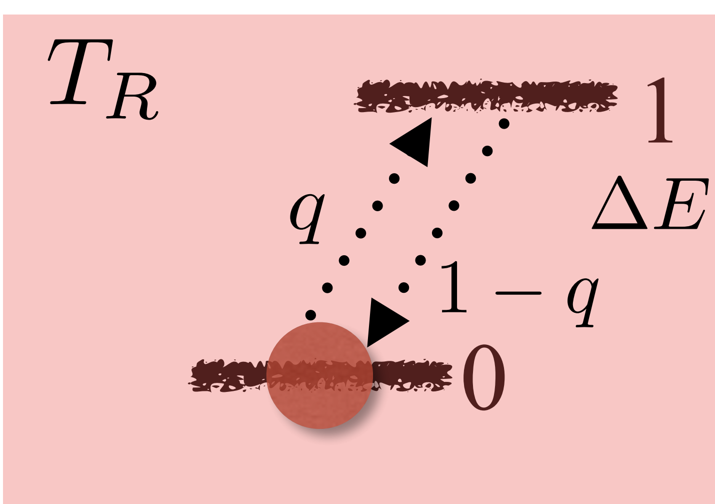

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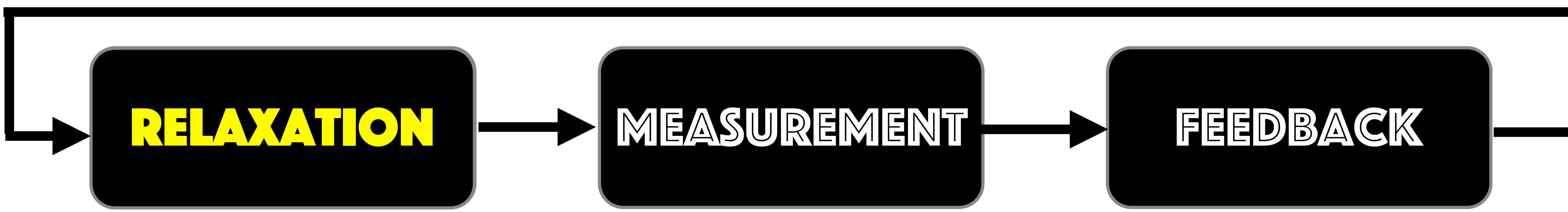

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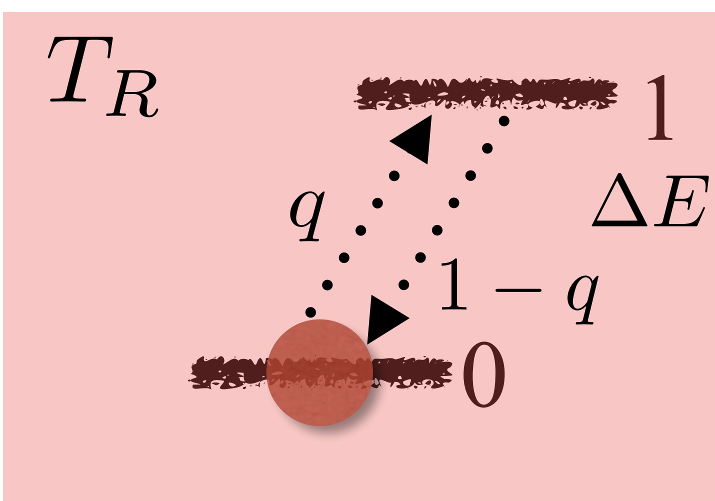
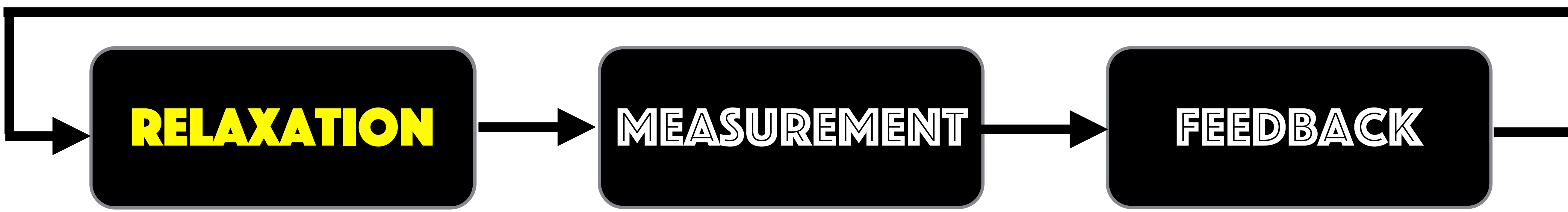


$$q/(1-q) = e^{-\Delta E/T_R}$$

Two-state model



$|P_0\rangle \qquad \mathcal{T}_R(t_R)|P_0\rangle = |P_1\rangle$

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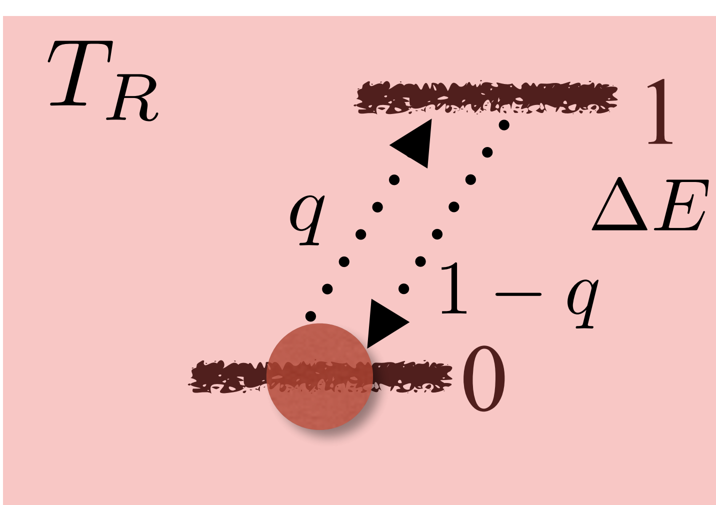


$$q/(1-q) = e^{-\Delta E/T_R}$$

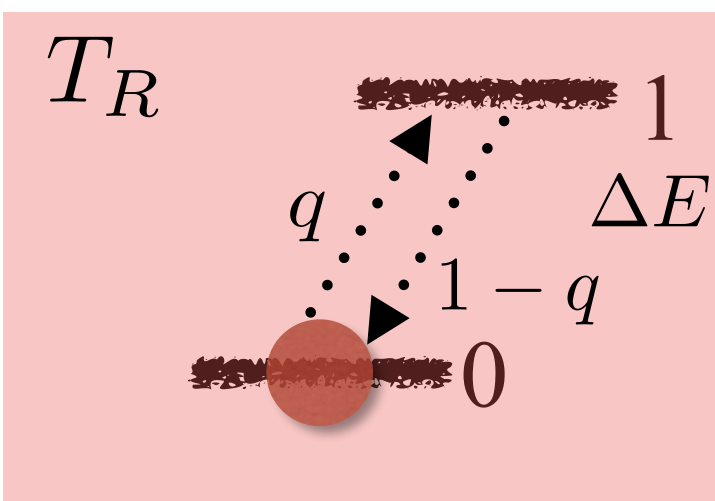
$$\mathcal{R} \equiv e^{-t_R} \quad \bar{\mathcal{R}} \equiv 1 - \mathcal{R} \quad \bar{q} \equiv 1 - q$$

$$\mathcal{T}_R(t_R) = \begin{pmatrix} \mathcal{R} + \bar{\mathcal{R}}\bar{q} & 0 & \bar{\mathcal{R}}\bar{q} & 0 \\ 0 & \mathcal{R} + \bar{\mathcal{R}}\bar{q} & 0 & \bar{\mathcal{R}}\bar{q} \\ \bar{\mathcal{R}}q & 0 & \mathcal{R} + \bar{\mathcal{R}}q & 0 \\ 0 & \bar{\mathcal{R}}q & 0 & \mathcal{R} + \bar{\mathcal{R}}q \end{pmatrix}$$

Two-state model

$|P_0\rangle$ $\quad \mathcal{T}_R(t_R)|P_0\rangle = |P_1\rangle$

$$|P\rangle = \left(P^{00}, P^{01}, P^{10}, P^{11}\right)^T$$

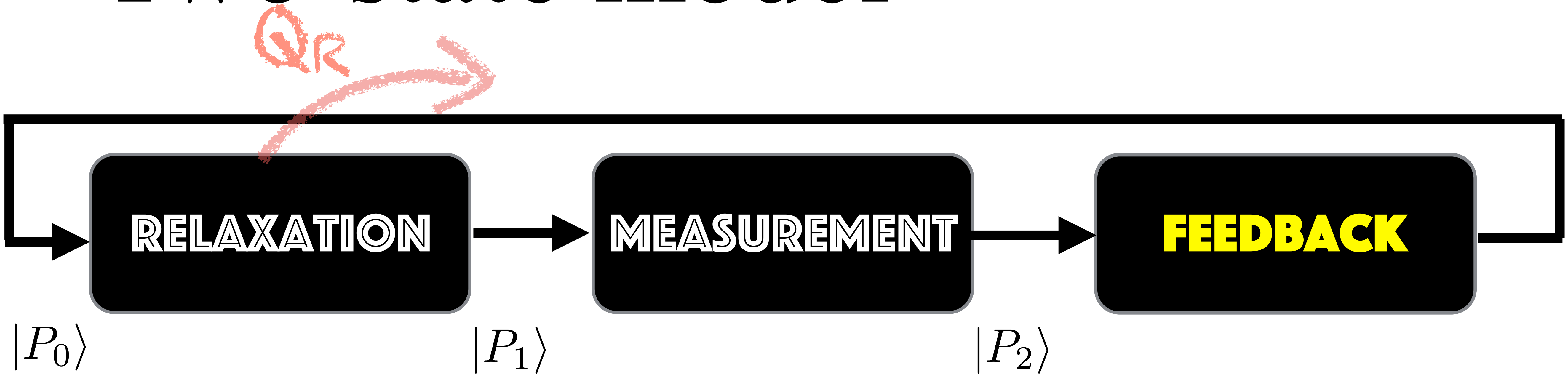


$$q/(1-q) = e^{-\Delta E/T_R}$$

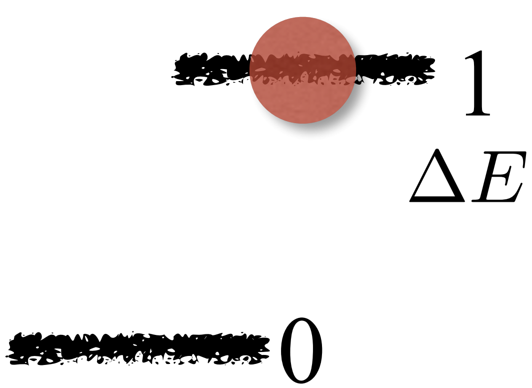
$\mathcal{R} \equiv e^{-t_R}$ $\quad \bar{\mathcal{R}} \equiv 1 - \mathcal{R}$ $\quad \bar{q} \equiv 1 - q$

$$\mathcal{T}_R(t_R) = \begin{pmatrix} \mathcal{R} + \bar{\mathcal{R}}\bar{q} & 0 & \bar{\mathcal{R}}\bar{q} & 0 \\ 0 & \mathcal{R} + \bar{\mathcal{R}}\bar{q} & 0 & \bar{\mathcal{R}}\bar{q} \\ \bar{\mathcal{R}}q & 0 & \mathcal{R} + \bar{\mathcal{R}}q & 0 \\ 0 & \bar{\mathcal{R}}q & 0 & \mathcal{R} + \bar{\mathcal{R}}q \end{pmatrix}$$

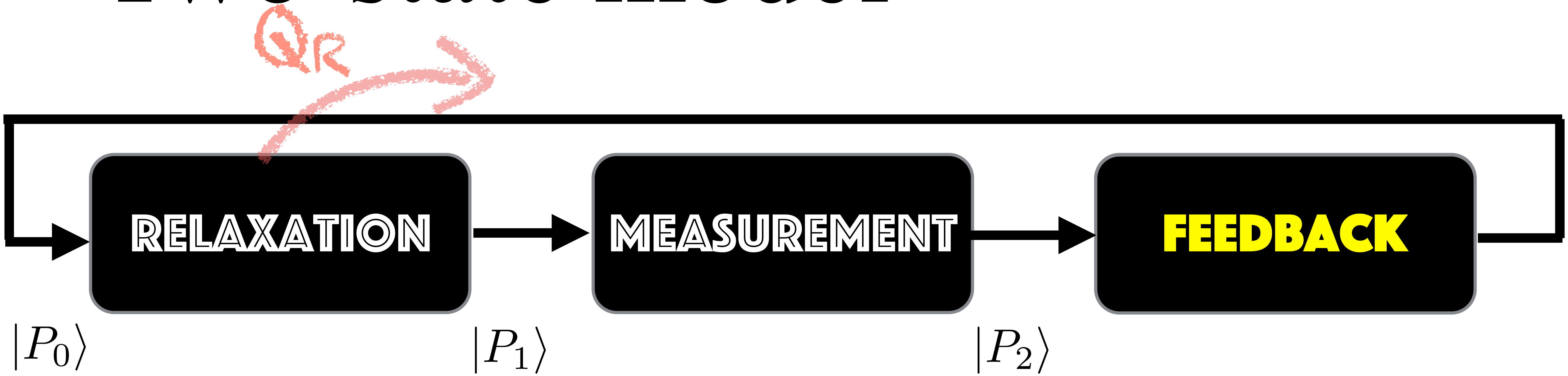
Two-state model



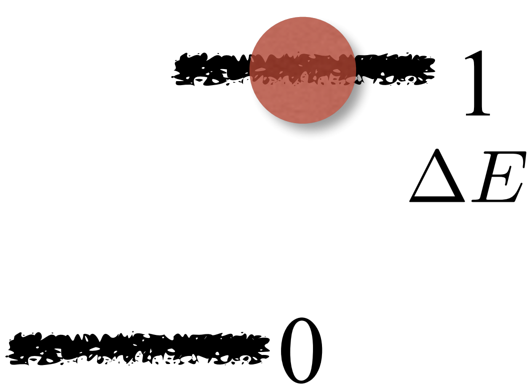
$$|P\rangle = \left(P^{00}, P^{01}, P^{10}, P^{11}\right)^T$$



Two-state model



$$|P\rangle = \left(P^{00}, P^{01}, P^{10}, P^{11}\right)^T$$

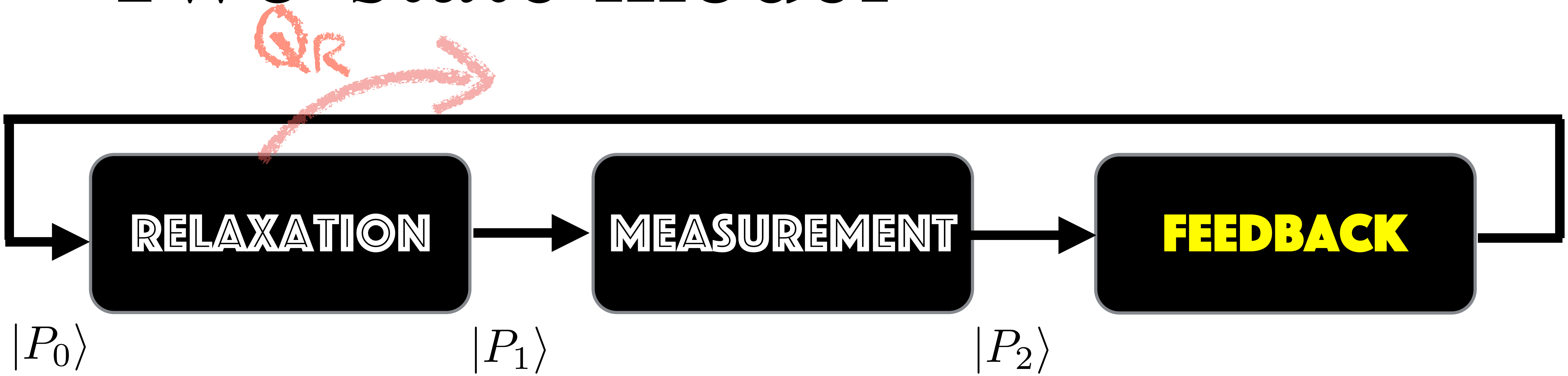


incorrect

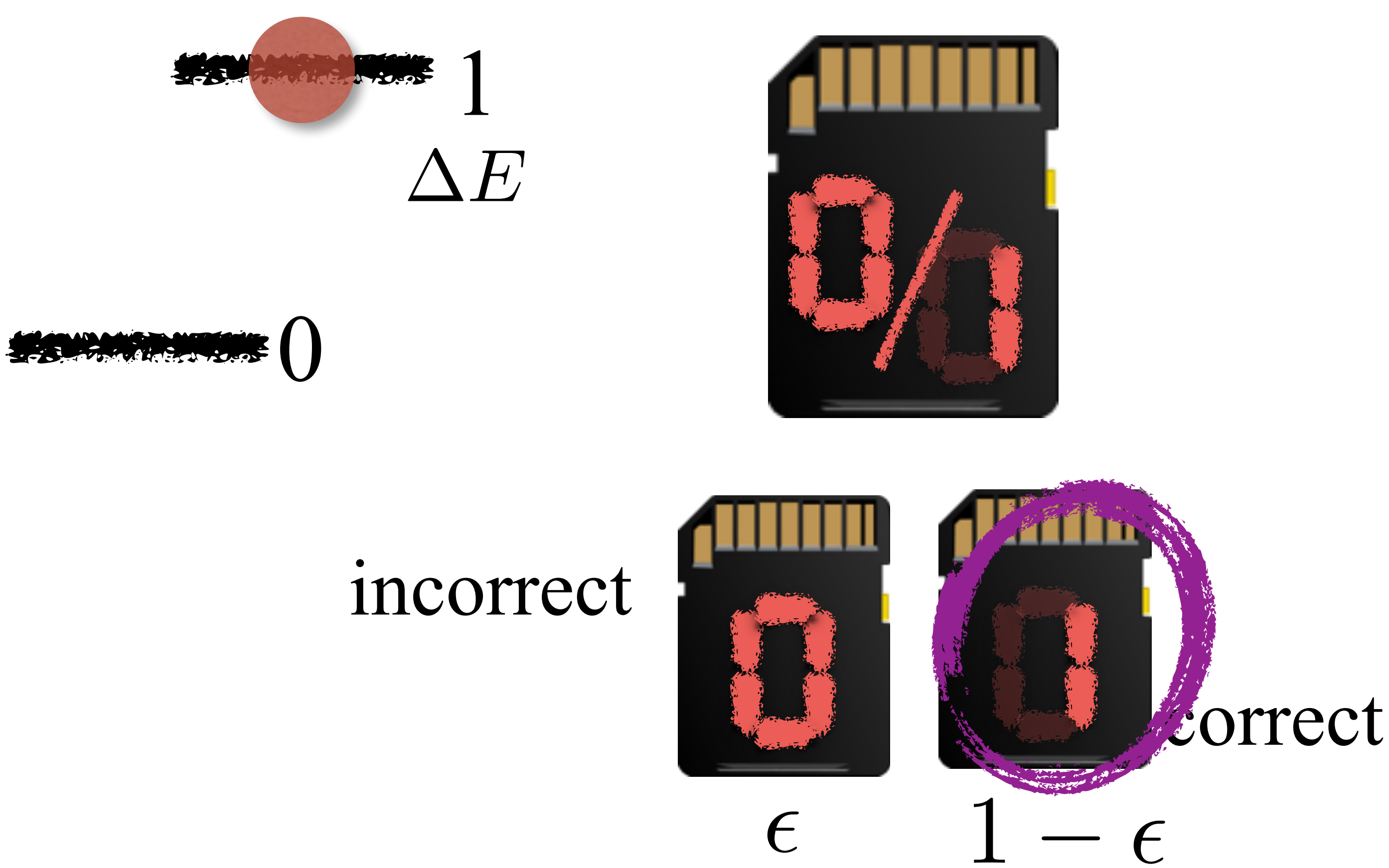
correct

ϵ $1 - \epsilon$

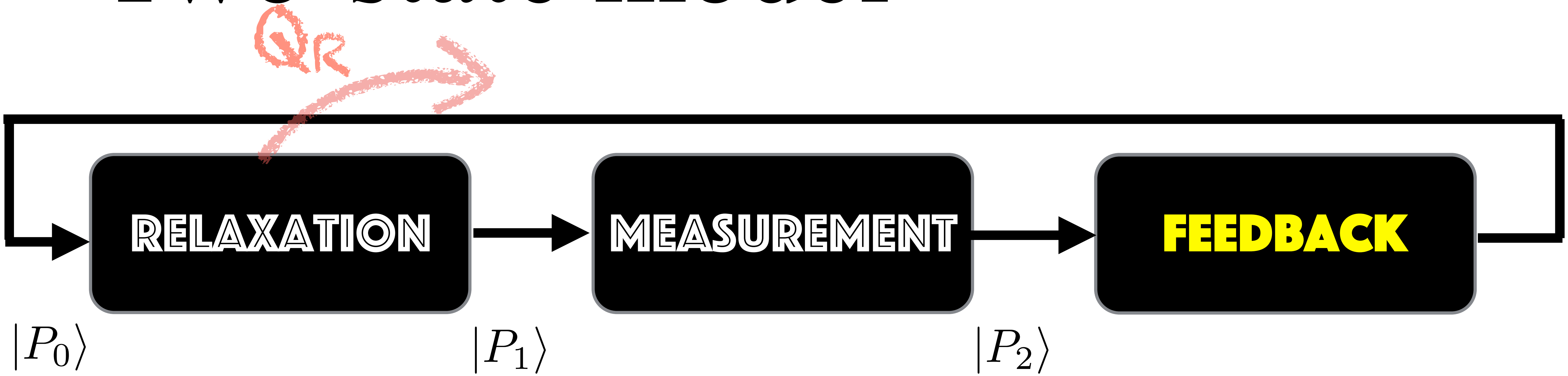
Two-state model



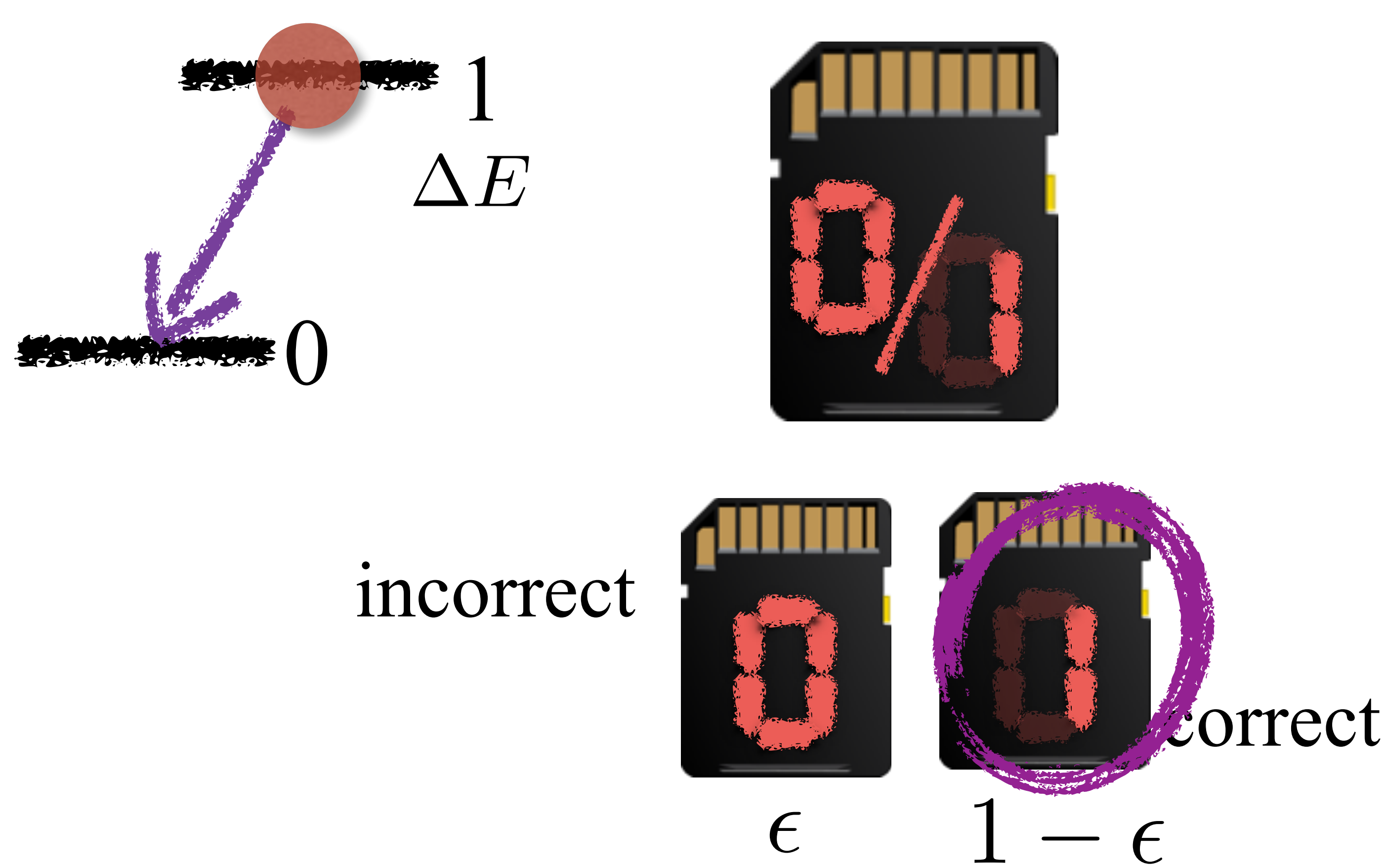
$$|P\rangle = \left(P^{00}, P^{01}, P^{10}, P^{11}\right)^T$$



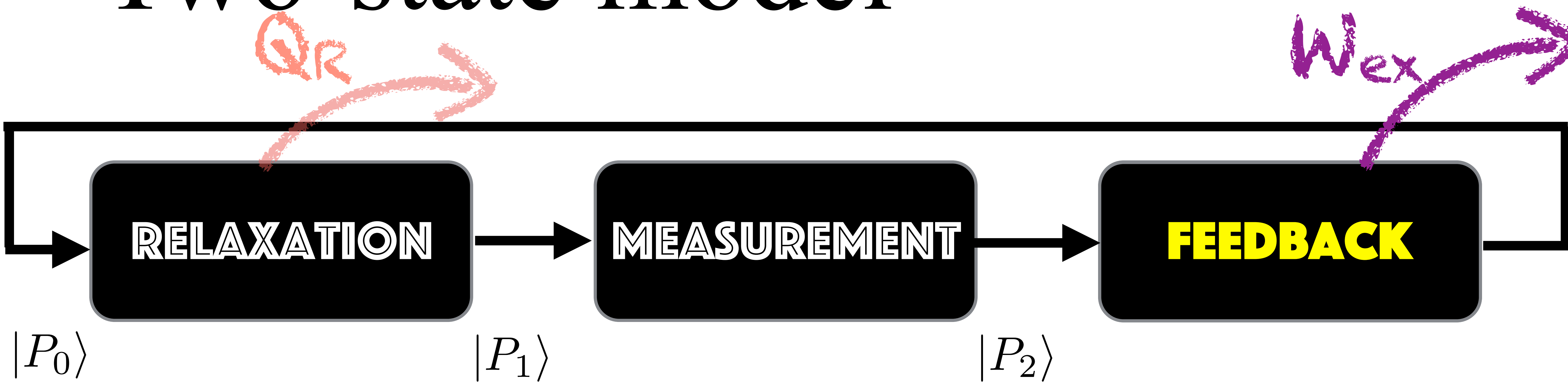
Two-state model



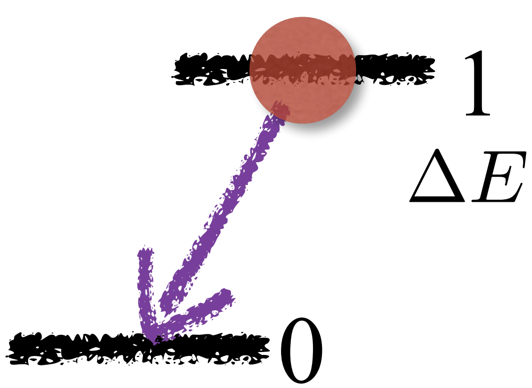
$$|P\rangle = \left(P^{00}, P^{01}, P^{10}, P^{11}\right)^T$$

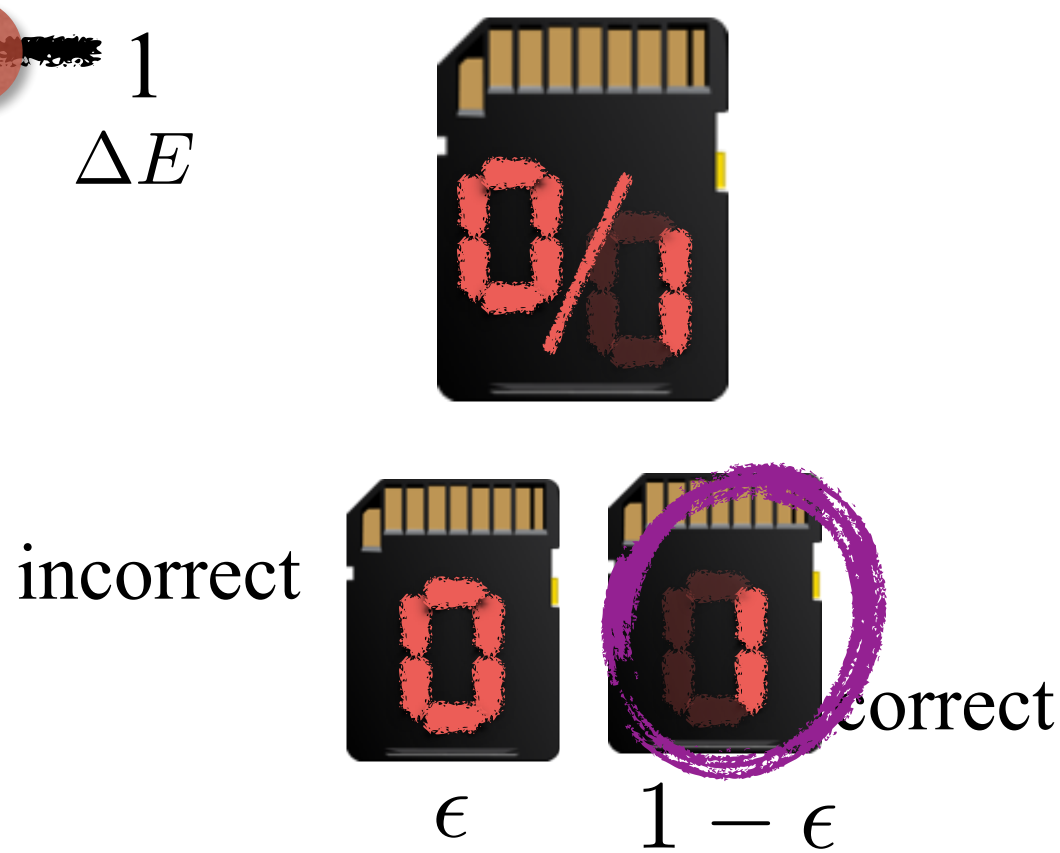


Two-state model

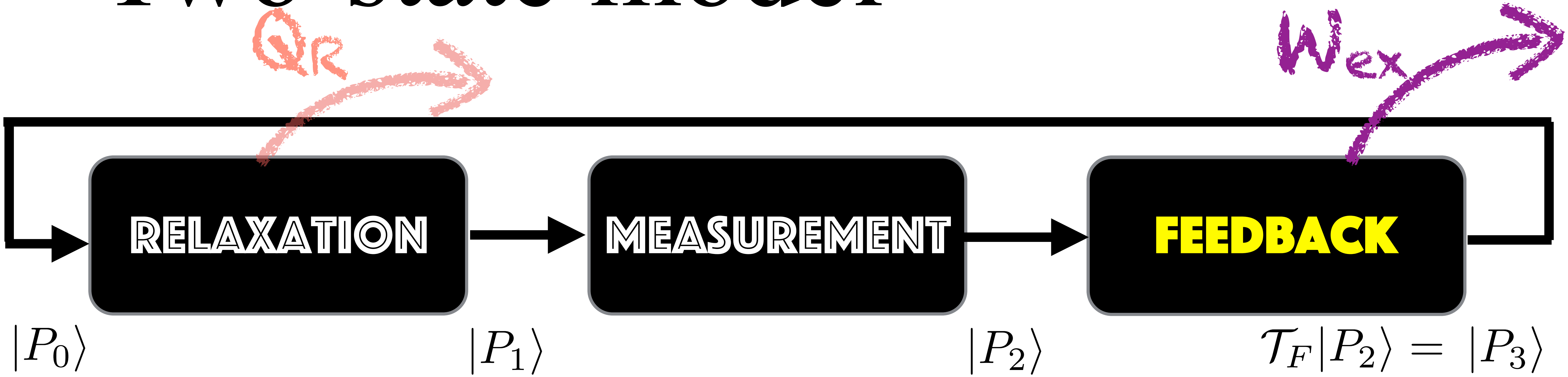


$$|P\rangle = \left(P^{00}, P^{01}, P^{10}, P^{11}\right)^T$$

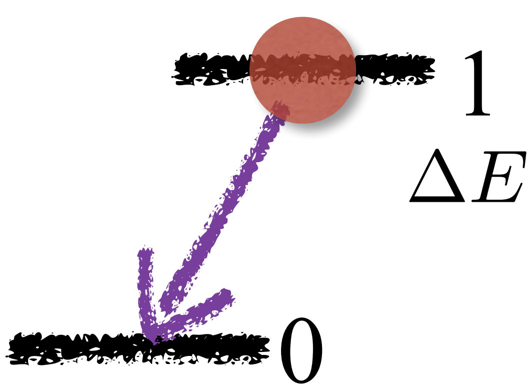




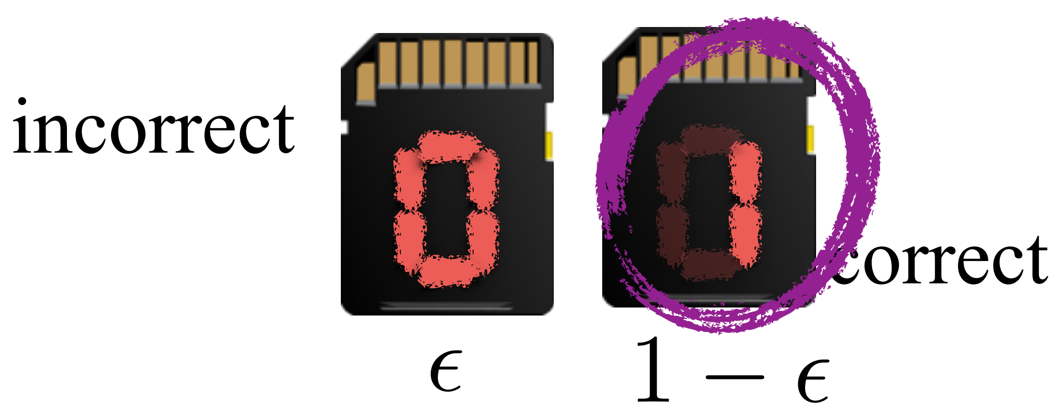
Two-state model



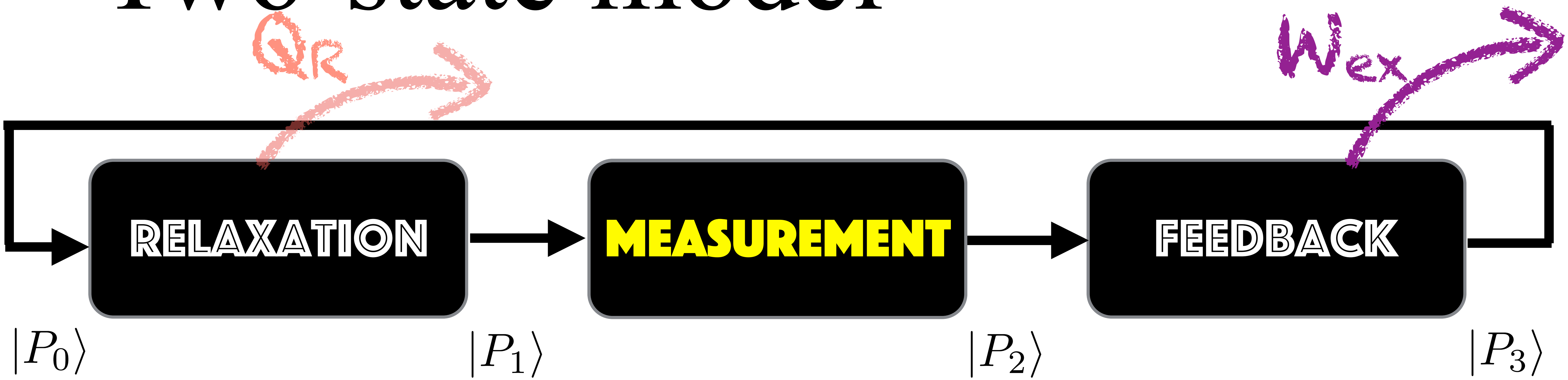
$$|P\rangle = \left(P^{00}, P^{01}, P^{10}, P^{11}\right)^T$$



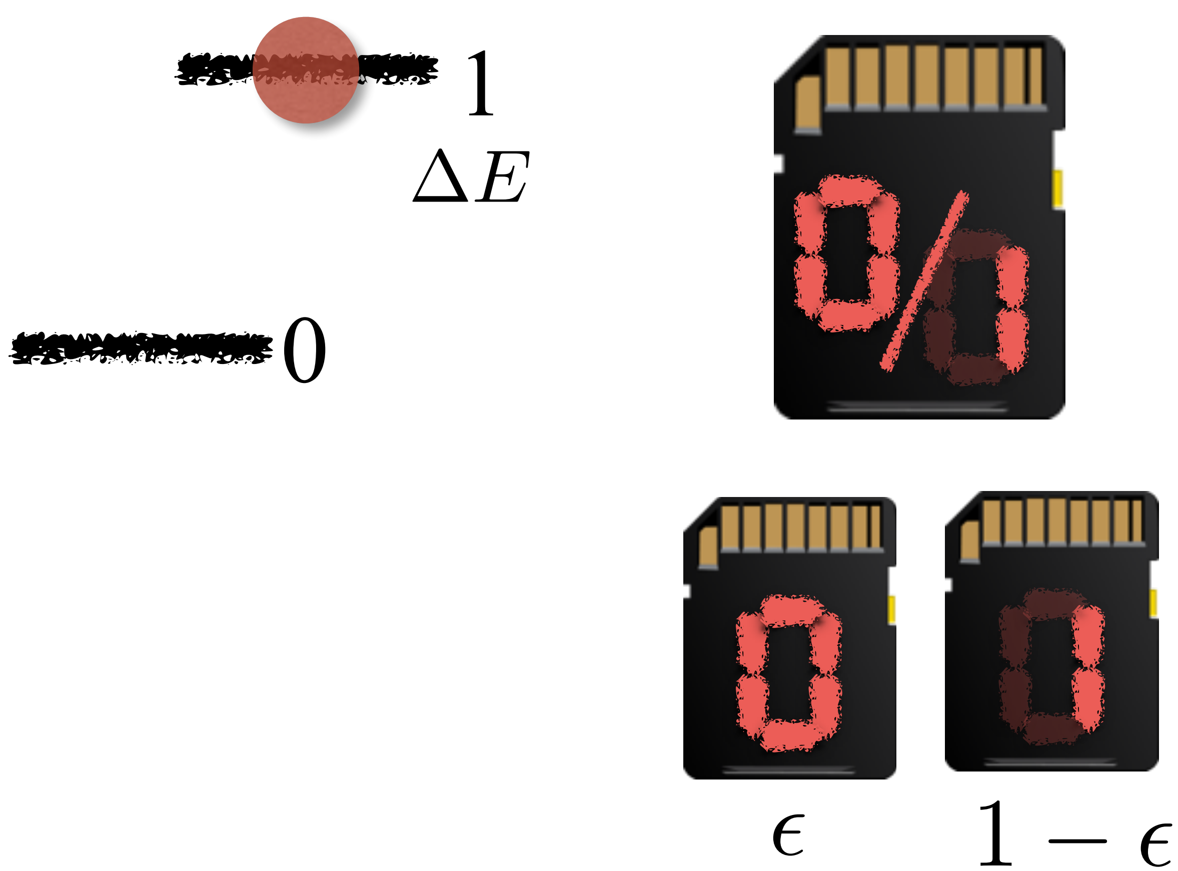
$$\mathcal{T}_F = \begin{pmatrix} \mathbf{1} & 0 & 0 & 0 \\ 0 & 0 & 0 & \mathbf{1} \\ 0 & 0 & \mathbf{1} & 0 \\ 0 & \mathbf{1} & 0 & 0 \end{pmatrix}$$



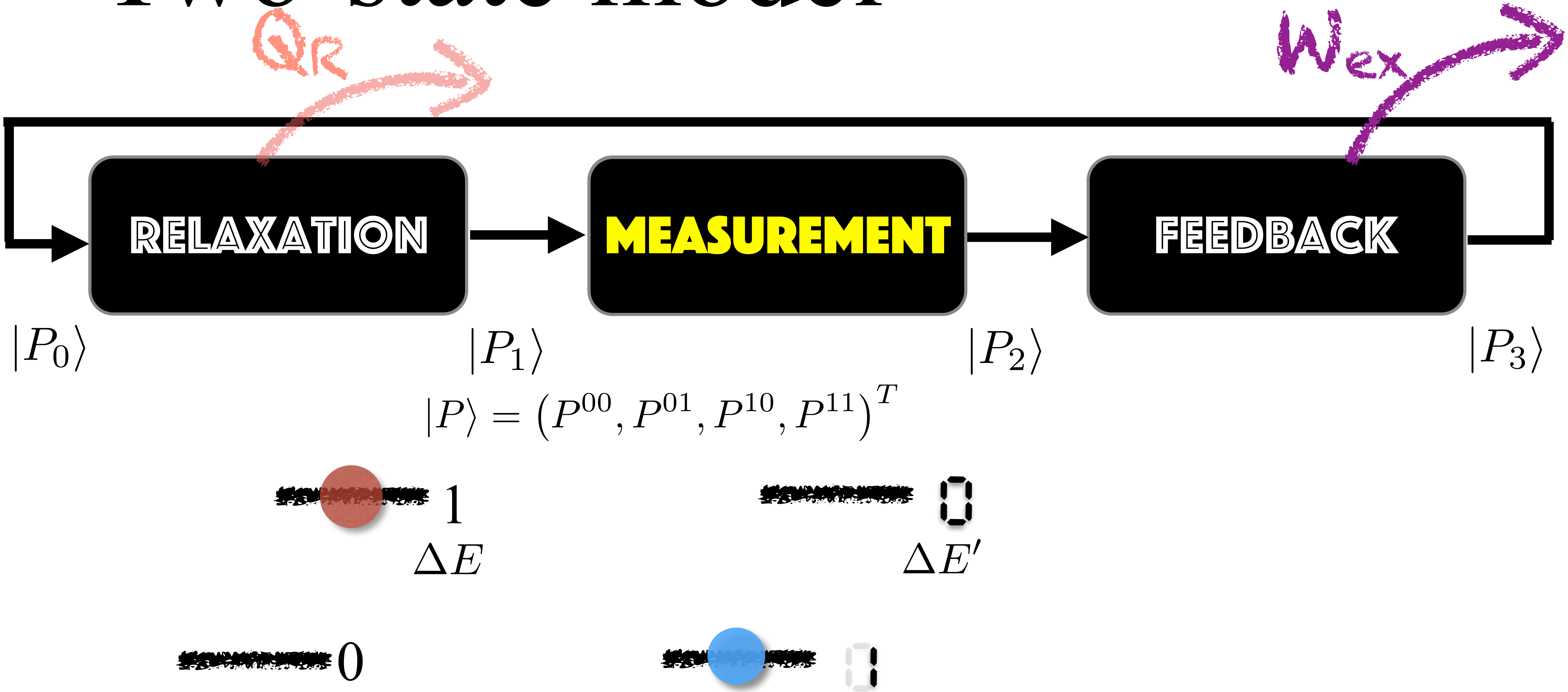
Two-state model



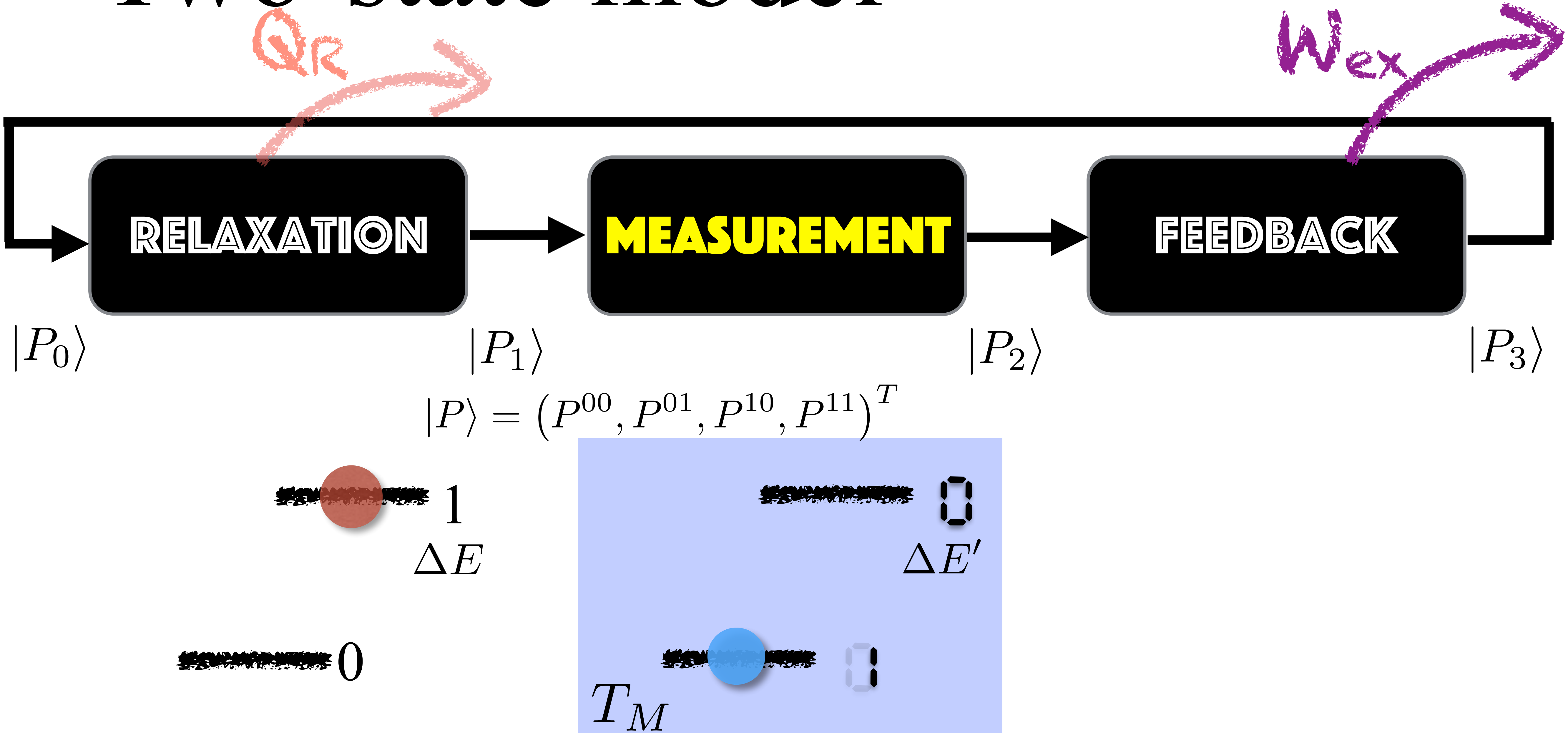
$$|P\rangle = \left(P^{00}, P^{01}, P^{10}, P^{11}\right)^T$$



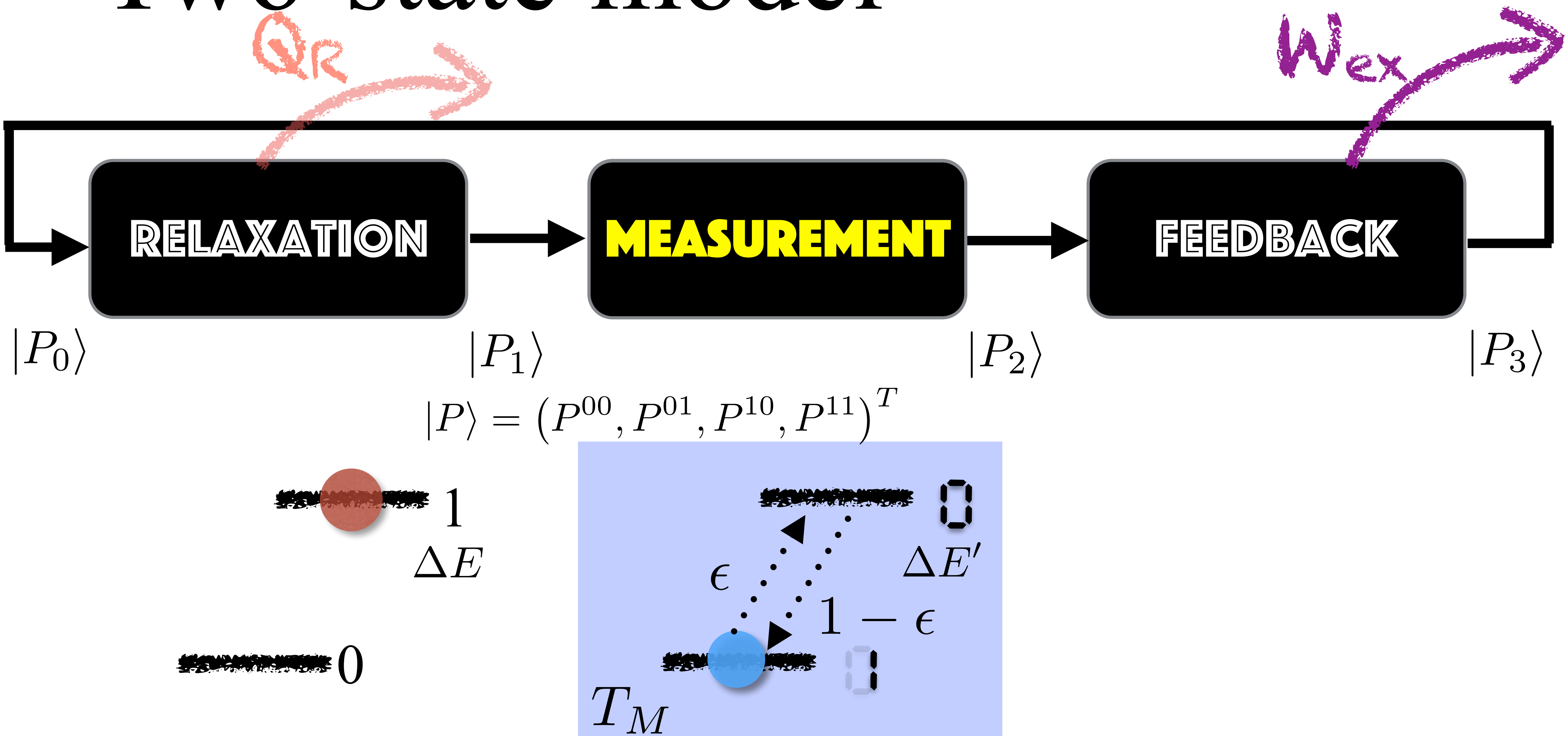
Two-state model



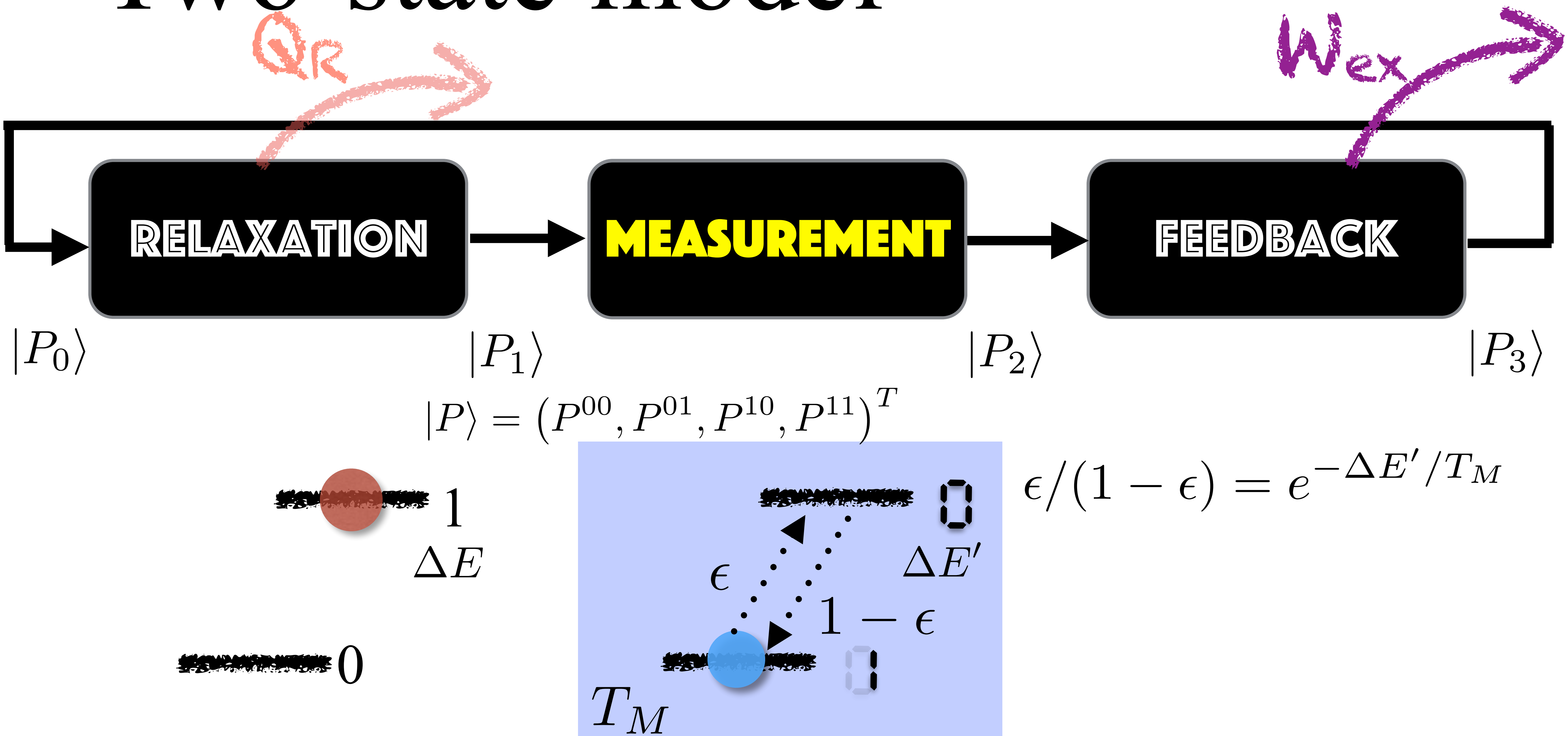
Two-state model



Two-state model



Two-state model



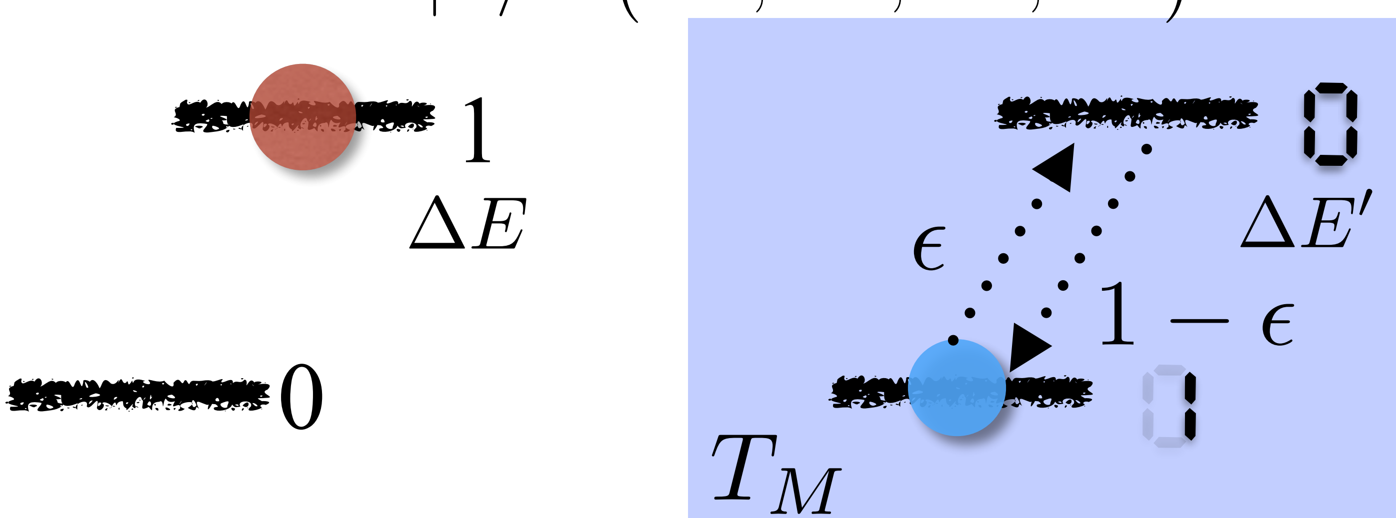
$$|P\rangle = \left(P^{00}, P^{01}, P^{10}, P^{11}\right)^T$$

$$\epsilon/(1-\epsilon) = e^{-\Delta E'/T_M}$$

Two-state model

$|P_0\rangle$ $\quad |P_1\rangle \quad \mathcal{T}_M(t_M)|P_1\rangle = |P_2\rangle \quad |P_3\rangle$

$$|P\rangle = \left(P^{00}, P^{01}, P^{10}, P^{11}\right)^T$$



$$\epsilon/(1-\epsilon) = e^{-\Delta E'/T_M}$$

$$\bar{\epsilon} \equiv 1-\epsilon$$

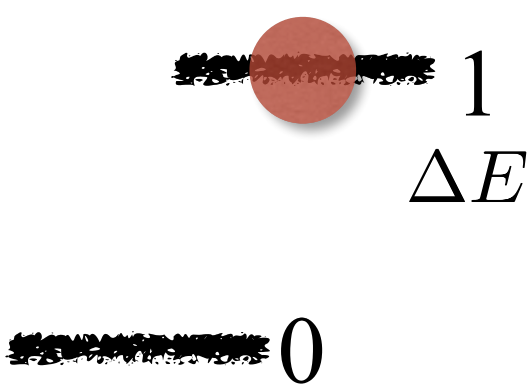
$$\mathcal{M} \equiv e^{-t_M} \quad \bar{\mathcal{M}} \equiv 1 - \mathcal{M}$$

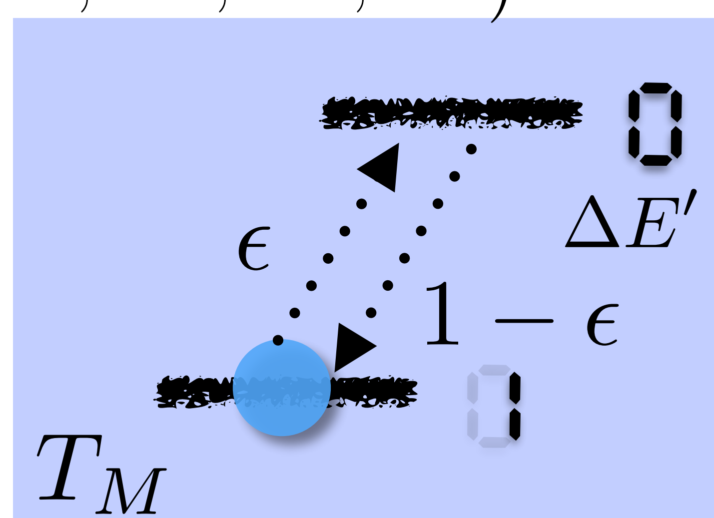
$$\mathcal{T}_M(t_M) = \begin{pmatrix} \mathcal{M}+\bar{\mathcal{M}}\bar{\epsilon} & \bar{\mathcal{M}}\bar{\epsilon} & 0 & 0 \\ \bar{\mathcal{M}}\epsilon & \mathcal{M}+\bar{\mathcal{M}}\epsilon & 0 & 0 \\ 0 & 0 & \mathcal{M}+\bar{\mathcal{M}}\epsilon & \bar{\mathcal{M}}\epsilon \\ 0 & 0 & \bar{\mathcal{M}}\bar{\epsilon} & \mathcal{M}+\bar{\mathcal{M}}\bar{\epsilon} \end{pmatrix}$$

Two-state model

$|P_0\rangle$ $|P_1\rangle$ $\mathcal{T}_M(t_M)|P_1\rangle = |P_2\rangle$ $|P_3\rangle$

$$|P\rangle = \left(P^{00}, P^{01}, P^{10}, P^{11}\right)^T$$



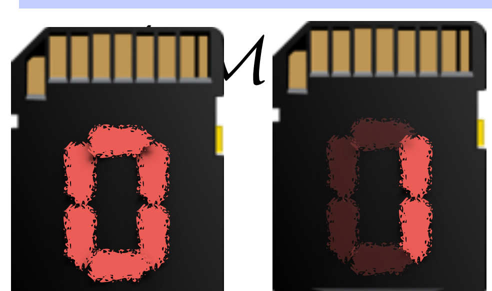


$$\epsilon/(1-\epsilon) = e^{-\Delta E'/T_M}$$

$$\bar{\epsilon} \equiv 1 - \epsilon$$

$$\mathcal{M} \equiv e^{-t_M} \quad \bar{\mathcal{M}} \equiv 1 - \mathcal{M}$$

$t_M \to \infty$



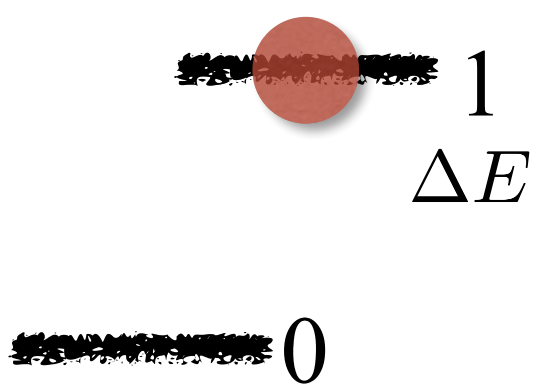
$$\mathcal{T}_M(t_M) \quad \begin{array}{ccc} \bar{\mathcal{M}}\bar{\epsilon} & 0 & 0 \\ \mathcal{M} + \bar{\mathcal{M}}\epsilon & 0 & 0 \\ 0 & \mathcal{M} + \bar{\mathcal{M}}\epsilon & \bar{\mathcal{M}}\epsilon \\ 0 & \bar{\mathcal{M}}\bar{\epsilon} & \mathcal{M} + \bar{\mathcal{M}}\bar{\epsilon} \end{array} \Bigg)$$

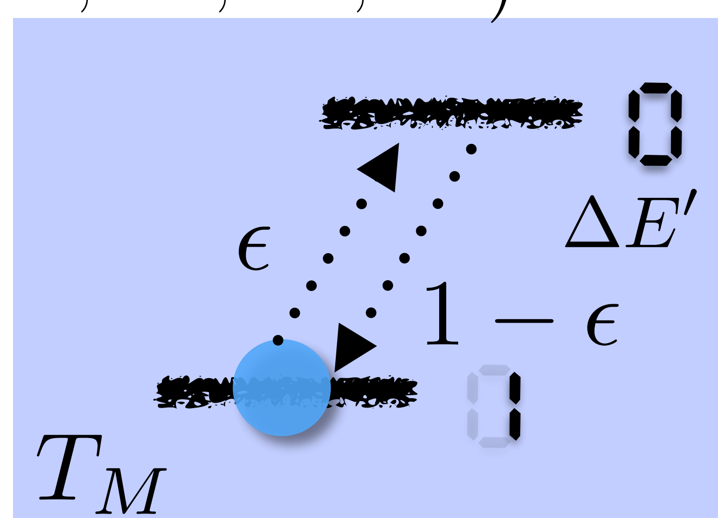
ϵ $\quad 1 - \epsilon$

Two-state model

$|P_0\rangle$ $\quad |P_1\rangle$ $\quad \mathcal{T}_M(t_M)|P_1\rangle = |P_2\rangle$ $\quad |P_3\rangle$

$$|P\rangle = \left(P^{00}, P^{01}, P^{10}, P^{11}\right)^T$$

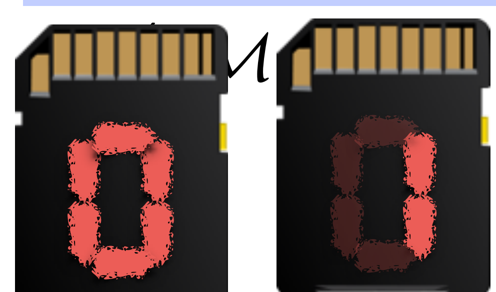




$$\epsilon/(1-\epsilon) = e^{-\Delta E'/T_M}$$

$$\bar{\epsilon} \equiv 1-\epsilon$$

$$\mathcal{M} \equiv e^{-t_M} \quad \bar{\mathcal{M}} \equiv 1-\mathcal{M}$$



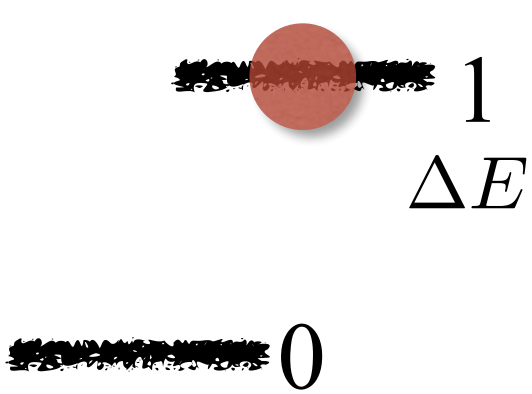
$$\mathcal{T}_M(t_M) \quad \begin{matrix} \bar{\mathcal{M}}\bar{\epsilon} & 0 & 0 \\ \mathcal{M}+\bar{\mathcal{M}}\epsilon & 0 & 0 \\ 0 & \mathcal{M}+\bar{\mathcal{M}}\epsilon & \bar{\mathcal{M}}\epsilon \\ 0 & \bar{\mathcal{M}}\bar{\epsilon} & \mathcal{M}+\bar{\mathcal{M}}\bar{\epsilon} \end{matrix} \Bigg)$$

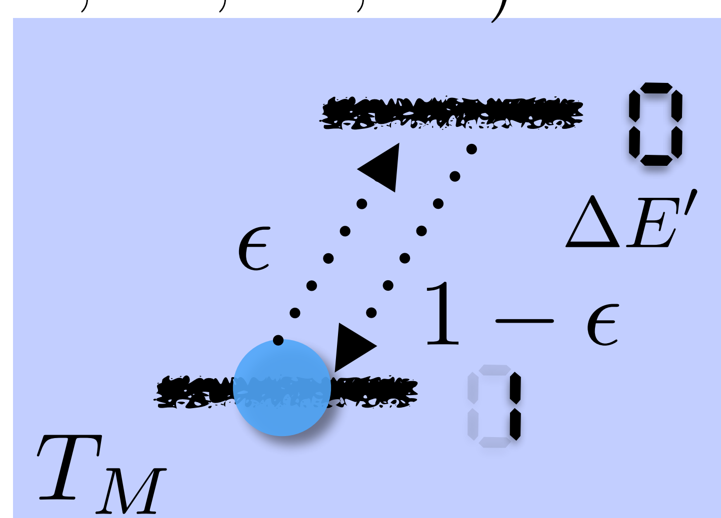
$$t_M \to \infty$$

Two-state model

$|P_0\rangle$ $|P_1\rangle$ $\mathcal{T}_M(t_M)|P_1\rangle = |P_2\rangle$ $|P_3\rangle$

$$|P\rangle = \left(P^{00}, P^{01}, P^{10}, P^{11}\right)^T$$

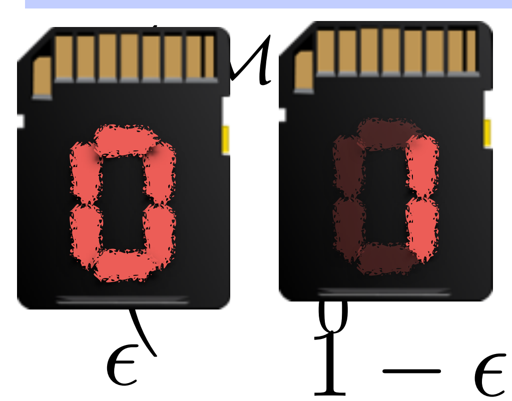




$$\epsilon/(1-\epsilon) = e^{-\Delta E'/T_M}$$

$$\bar{\epsilon} \equiv 1 - \epsilon$$

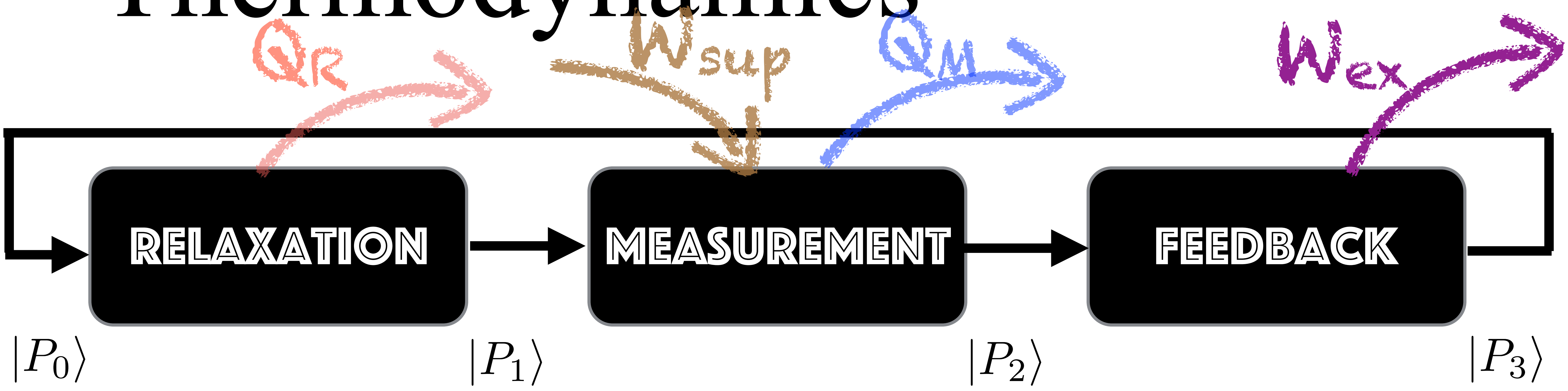
$$\mathcal{M} \equiv e^{-t_M} \quad \bar{\mathcal{M}} \equiv 1 - \mathcal{M}$$



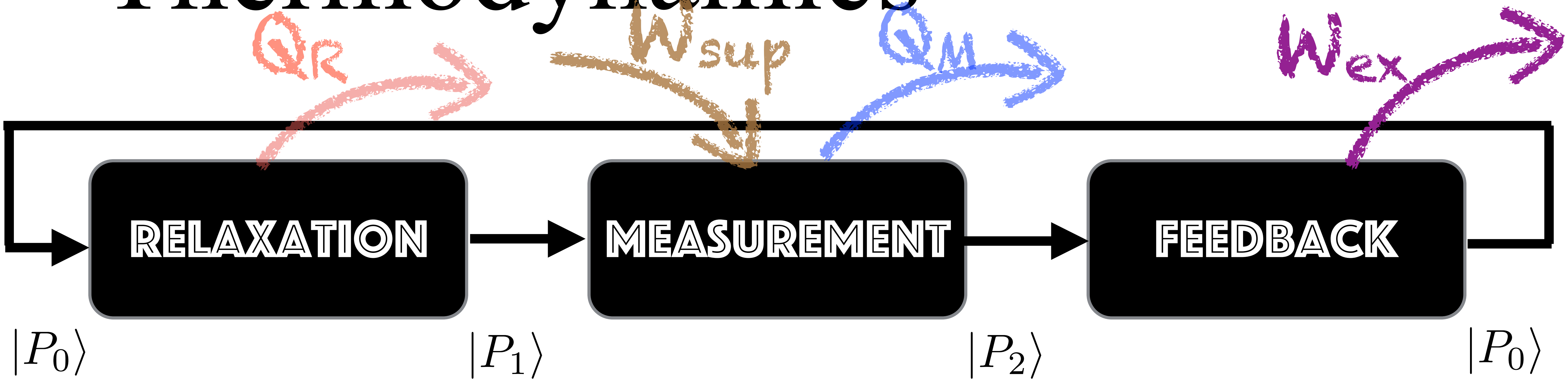
$$\mathcal{T}_M(t_M) \quad \begin{matrix} \bar{\mathcal{M}}\bar{\epsilon} & 0 & 0 \\ \mathcal{M}+\bar{\mathcal{M}}\epsilon & 0 & 0 \\ 0 & \mathcal{M}+\bar{\mathcal{M}}\epsilon & \bar{\mathcal{M}}\epsilon \\ 0 & \bar{\mathcal{M}}\bar{\epsilon} & \mathcal{M}+\bar{\mathcal{M}}\bar{\epsilon} \end{matrix} \Bigg)$$

$$t_M \to \infty$$

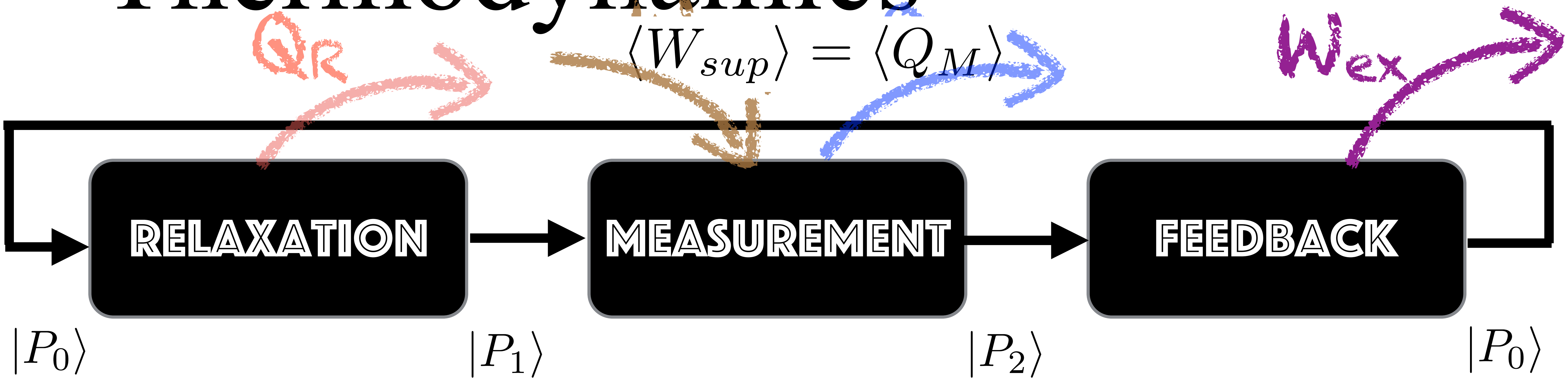
Thermodynamics



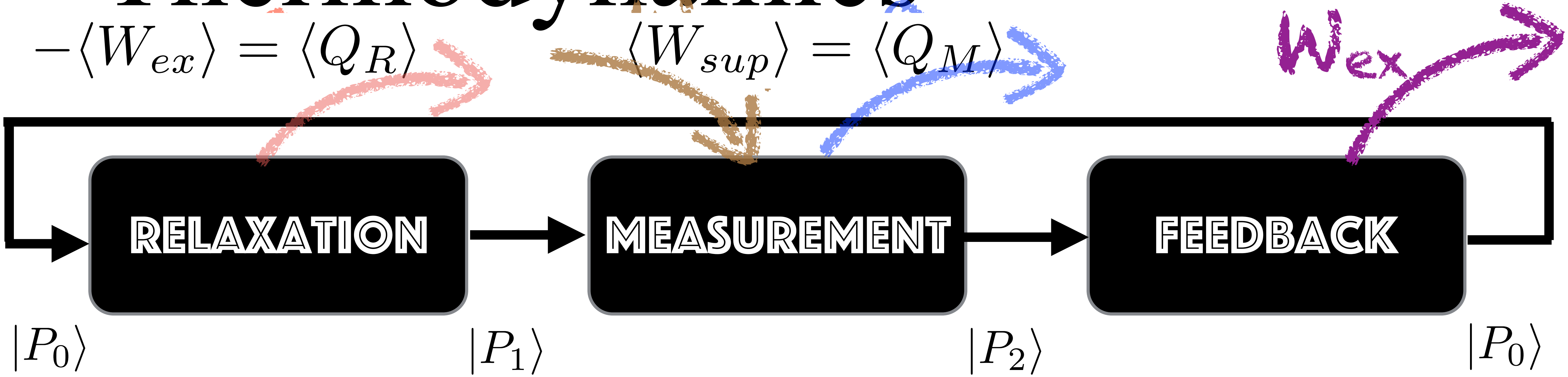
Thermodynamics



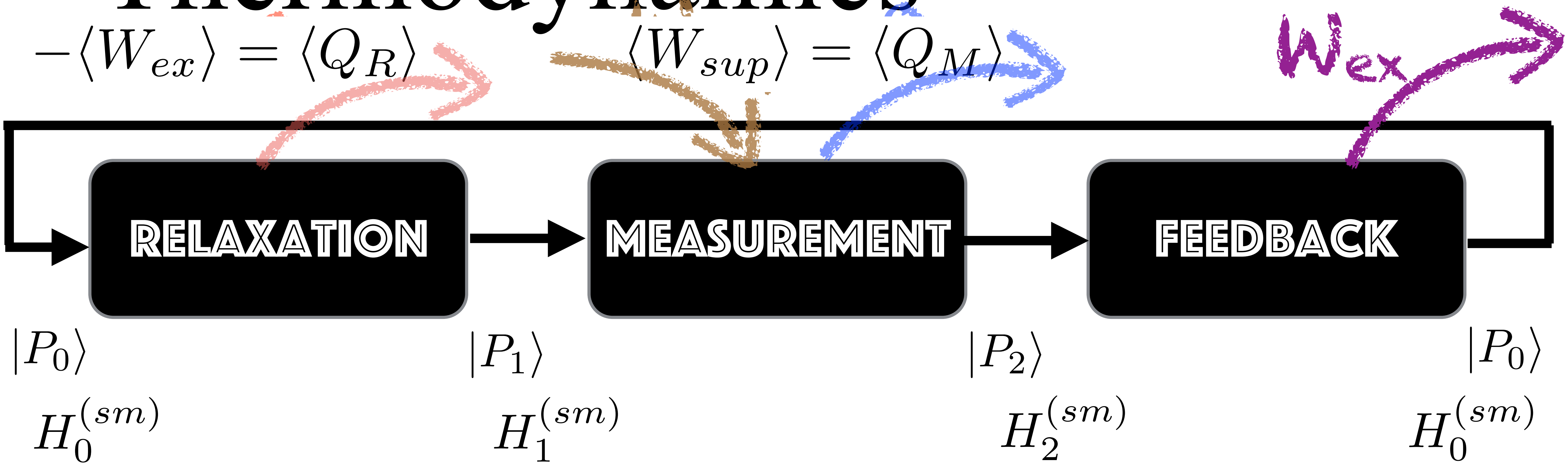
Thermodynamics



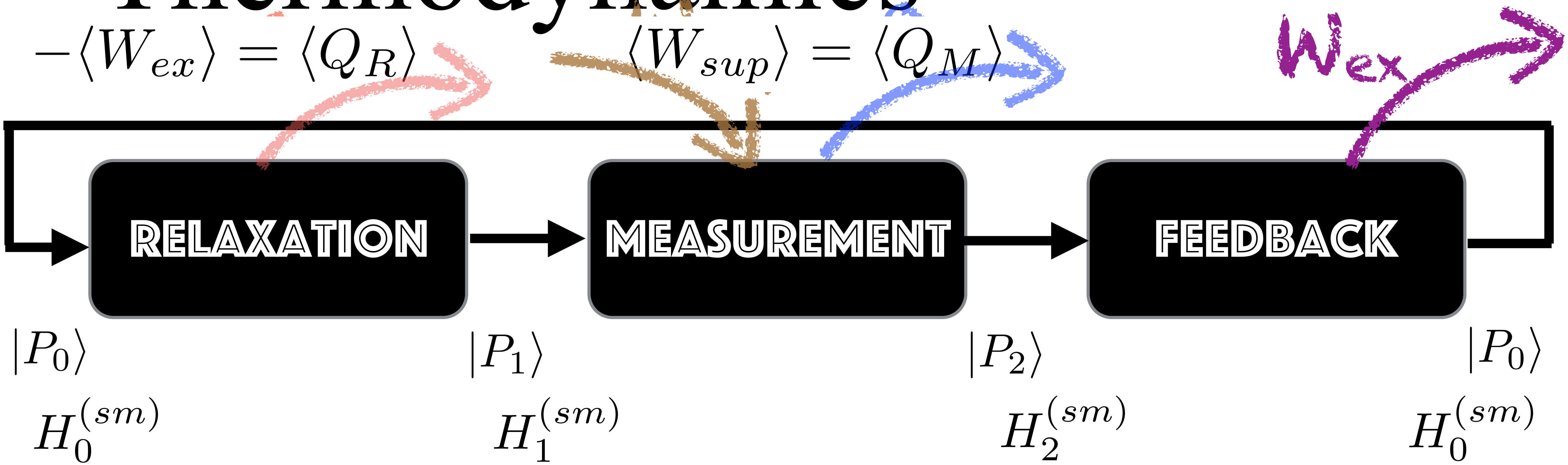
Thermodynamics



Thermodynamics

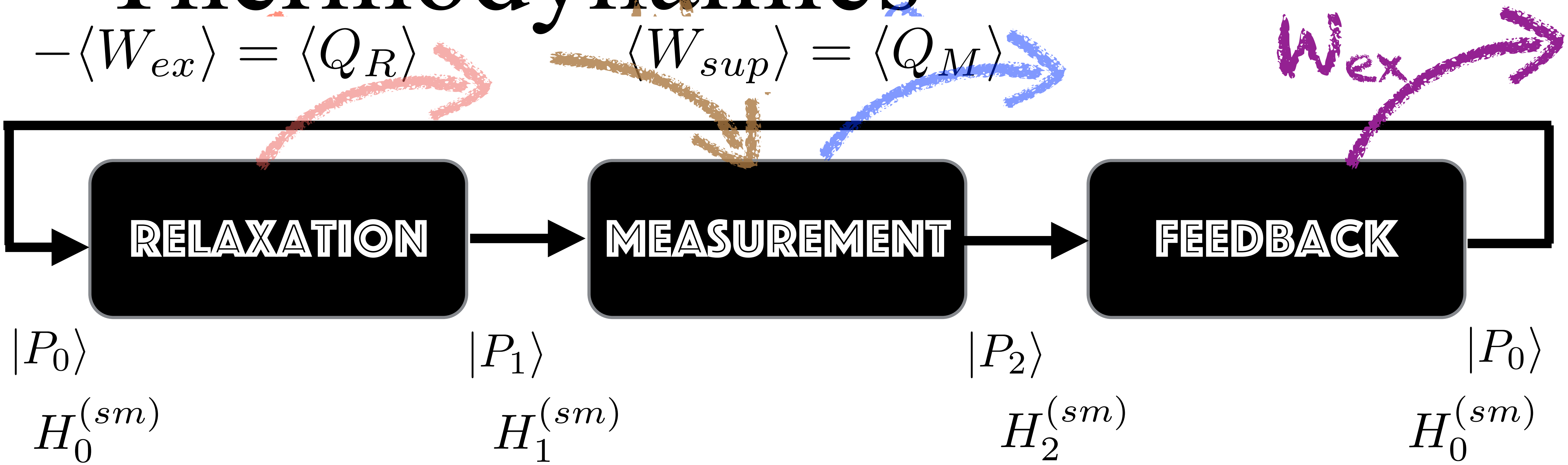


Thermodynamics



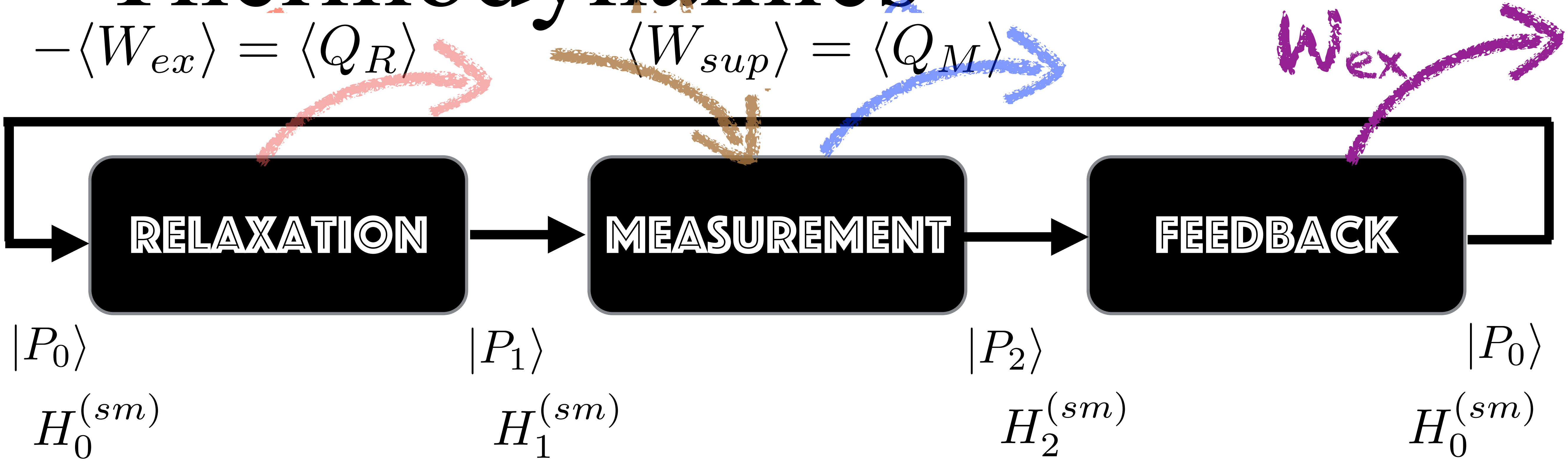
$$\Delta H_R^{(sm)} + \beta_R \langle Q_R \rangle \geq 0$$

Thermodynamics



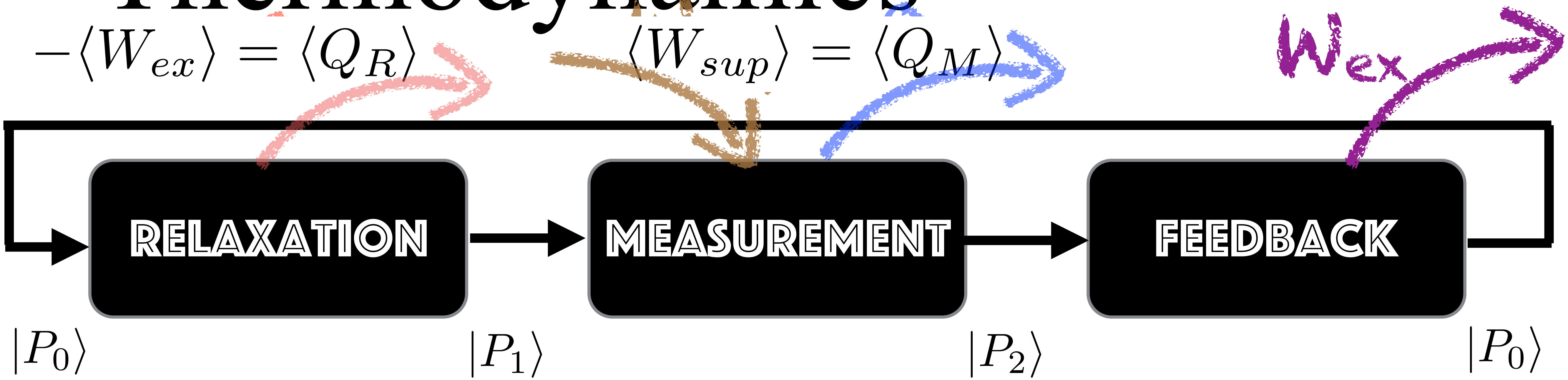
$$\Delta H_R^{(sm)} + \beta_R \langle Q_R \rangle \geq 0 \qquad \Delta H_M^{(sm)} + \beta_M \langle Q_M \rangle \geq 0$$

Thermodynamics



$\Delta H_R^{(sm)} + \beta_R \langle Q_R \rangle \geq 0 \quad \Delta H_M^{(sm)} + \beta_M \langle Q_M \rangle \geq 0 \quad \Delta H_F^{(sm)} = 0$

Thermodynamics

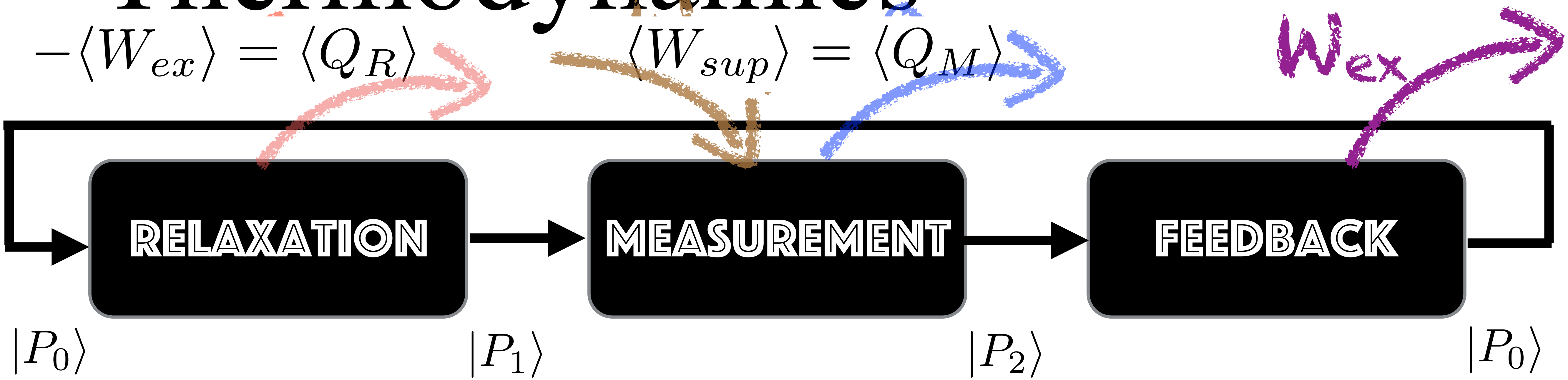


$H_0^{(sm)}$ $H_1^{(sm)}$ $H_2^{(sm)}$ $H_0^{(sm)}$

$= -\Delta H_M^{(sm)}$

$\Delta H_R^{(sm)} + \beta_R\langle Q_R\rangle \geq 0$ $\quad \Delta H_M^{(sm)} + \beta_M\langle Q_M\rangle \geq 0$ $\quad \Delta H_F^{(sm)} = 0$

Thermodynamics



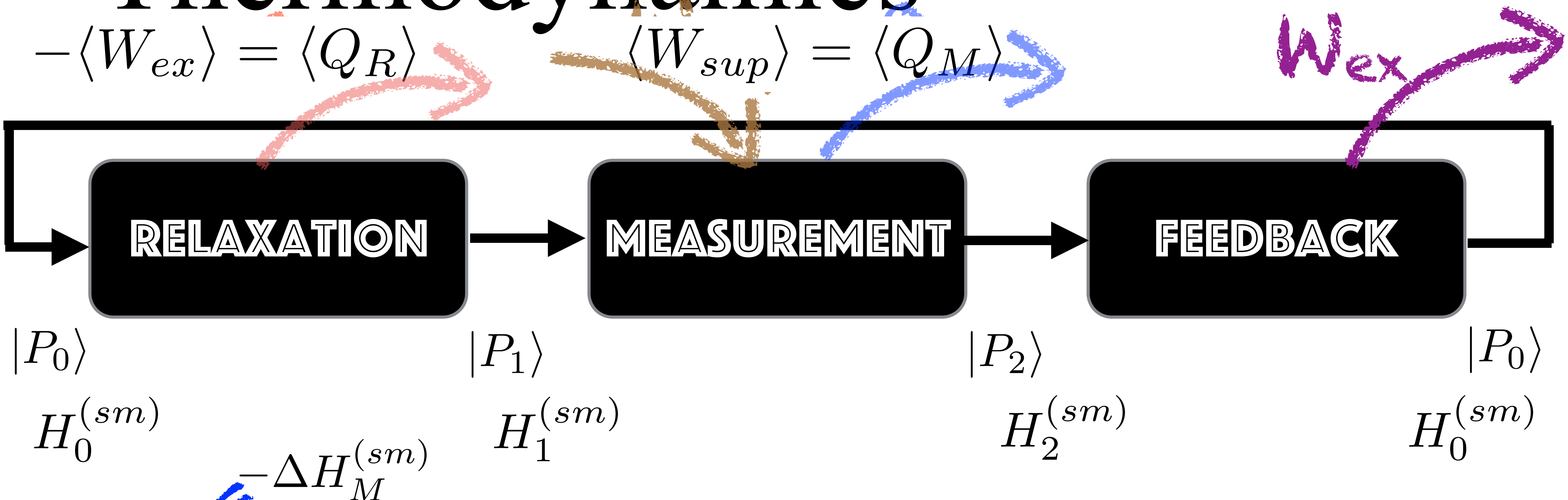
$H_0^{(sm)}$ $H_1^{(sm)}$ $H_2^{(sm)}$ $H_0^{(sm)}$

$-\Delta H_M^{(sm)}$

$$\Delta H_R^{(sm)} + \beta_R\langle Q_R\rangle \geq 0 \qquad \Delta H_M^{(sm)} + \beta_M\langle Q_M\rangle \geq 0 \qquad \Delta H_F^{(sm)} = 0$$

$$(1) \quad \beta_R\langle Q_R\rangle + \beta_M\langle Q_M\rangle \geq 0$$

Thermodynamics



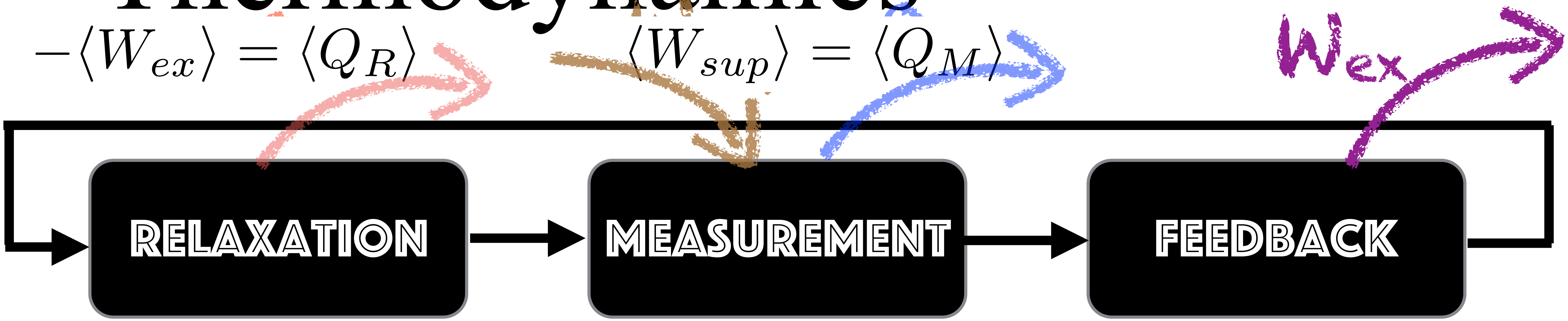
$\Delta H_R^{(sm)} + \beta_R \langle Q_R\rangle \geq 0 \quad \Delta H_M^{(sm)} + \beta_M \langle Q_M\rangle \geq 0 \quad \Delta H_F^{(sm)} = 0$

$$(1) \quad \beta_R \langle Q_R\rangle + \beta_M \langle Q_M\rangle \geq 0$$

$$(2) \quad -\beta_R \langle Q_R\rangle \leq -\Delta H_M^{(sm)} \leq \beta_M \langle Q_M\rangle$$

Thermodynamics

$-\langle W_{ex}\rangle = \langle Q_R\rangle$ $\langle W_{sup}\rangle = \langle Q_M\rangle$



$|P_0\rangle$ $|P_1\rangle$ $|P_2\rangle$ $|P_0\rangle$

$H_0^{(sm)}$ $H_1^{(sm)}$ $H_2^{(sm)}$ $H_0^{(sm)}$

$= -\Delta H_M^{(sm)}$

$\Delta H_R^{(sm)} + \beta_R\langle Q_R\rangle \geq 0$ $\quad \Delta H_M^{(sm)} + \beta_M\langle Q_M\rangle \geq 0$ $\quad \Delta H_F^{(sm)} = 0$

$$(1) \quad \beta_R\langle Q_R\rangle + \beta_M\langle Q_M\rangle \geq 0$$

$$(2) \quad -\beta_R\langle Q_R\rangle \leq -\Delta H_M^{(sm)} \leq \beta_M\langle Q_M\rangle$$

$$\beta_R\langle W_{ex}\rangle \leq \Delta I_M \leq \beta_M\langle W_{sup}\rangle$$

Thermodynamics

$-\langle W_{ex}\rangle$

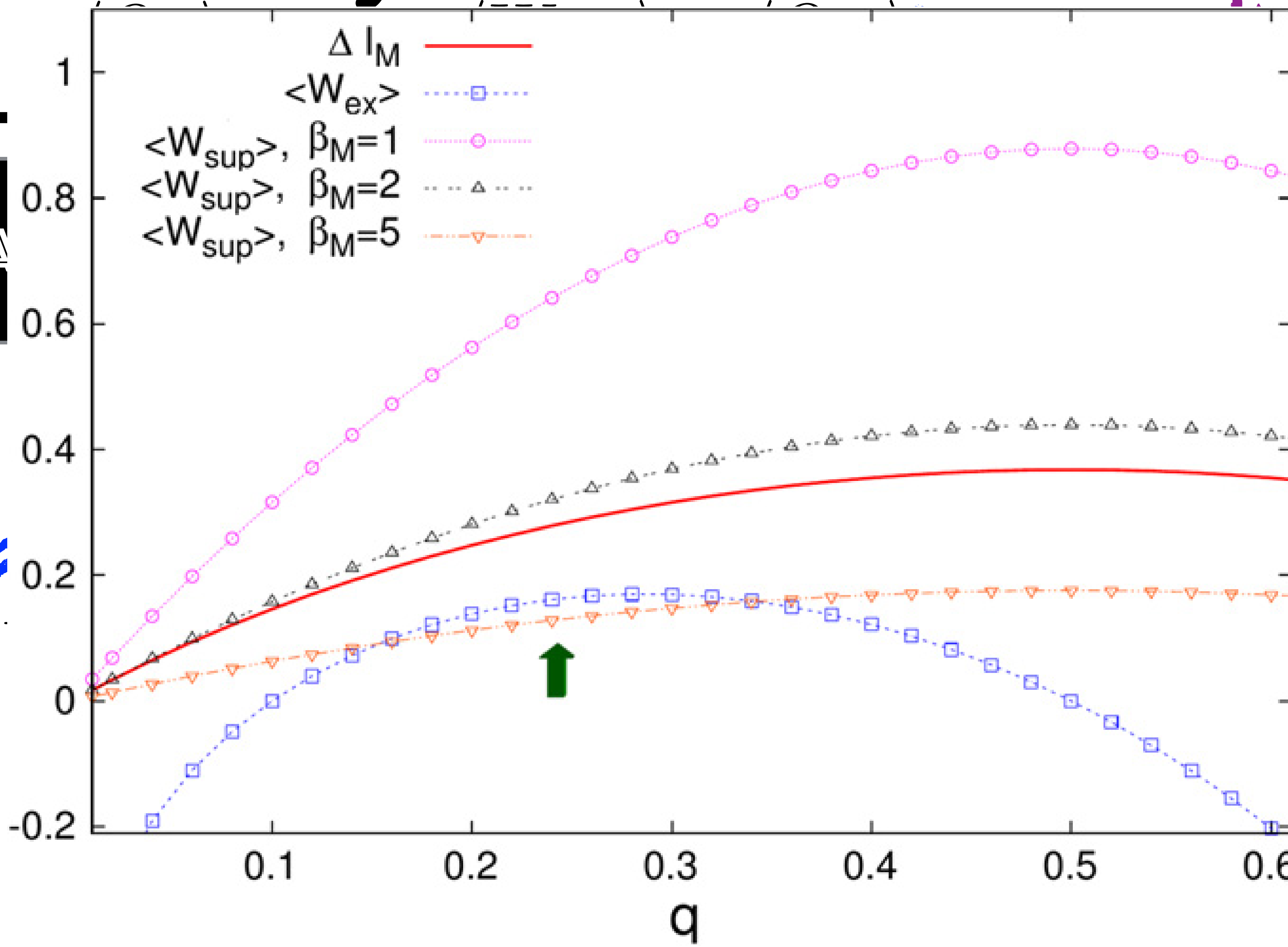
$|P_0\rangle$ $|P_0\rangle$

$H_0^{(sm)}$ $H_0^{(sm)}$

$\Delta H_R^{(sm)}$ $= 0$

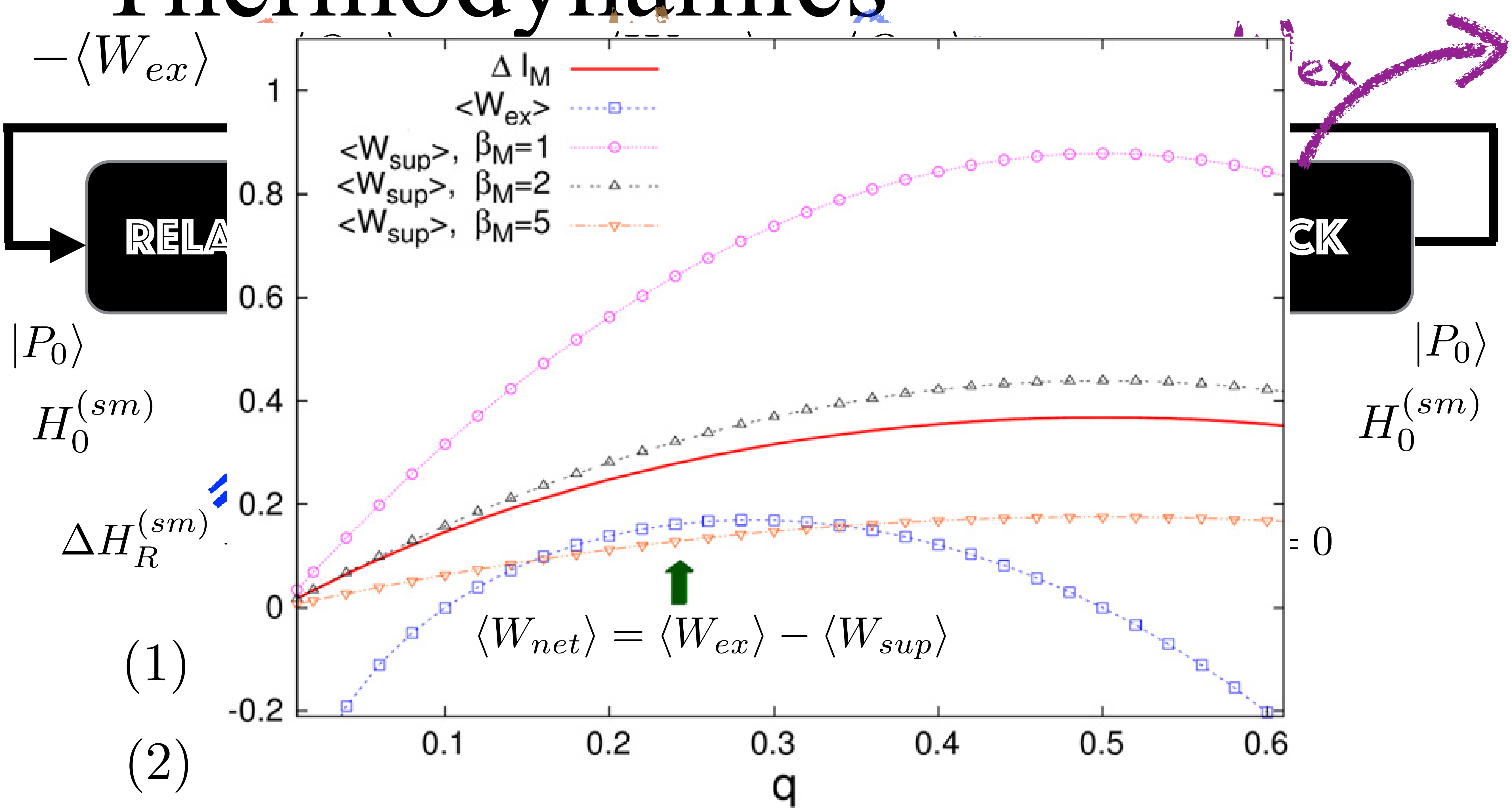
(1)

(2)



$$\beta_R\langle W_{ex}\rangle \leq \Delta I_M \leq \beta_M\langle W_{sup}\rangle$$

Thermodynamics



$$\beta_R\langle W_{ex}\rangle \leq \Delta I_M \leq \beta_M\langle W_{sup}\rangle$$

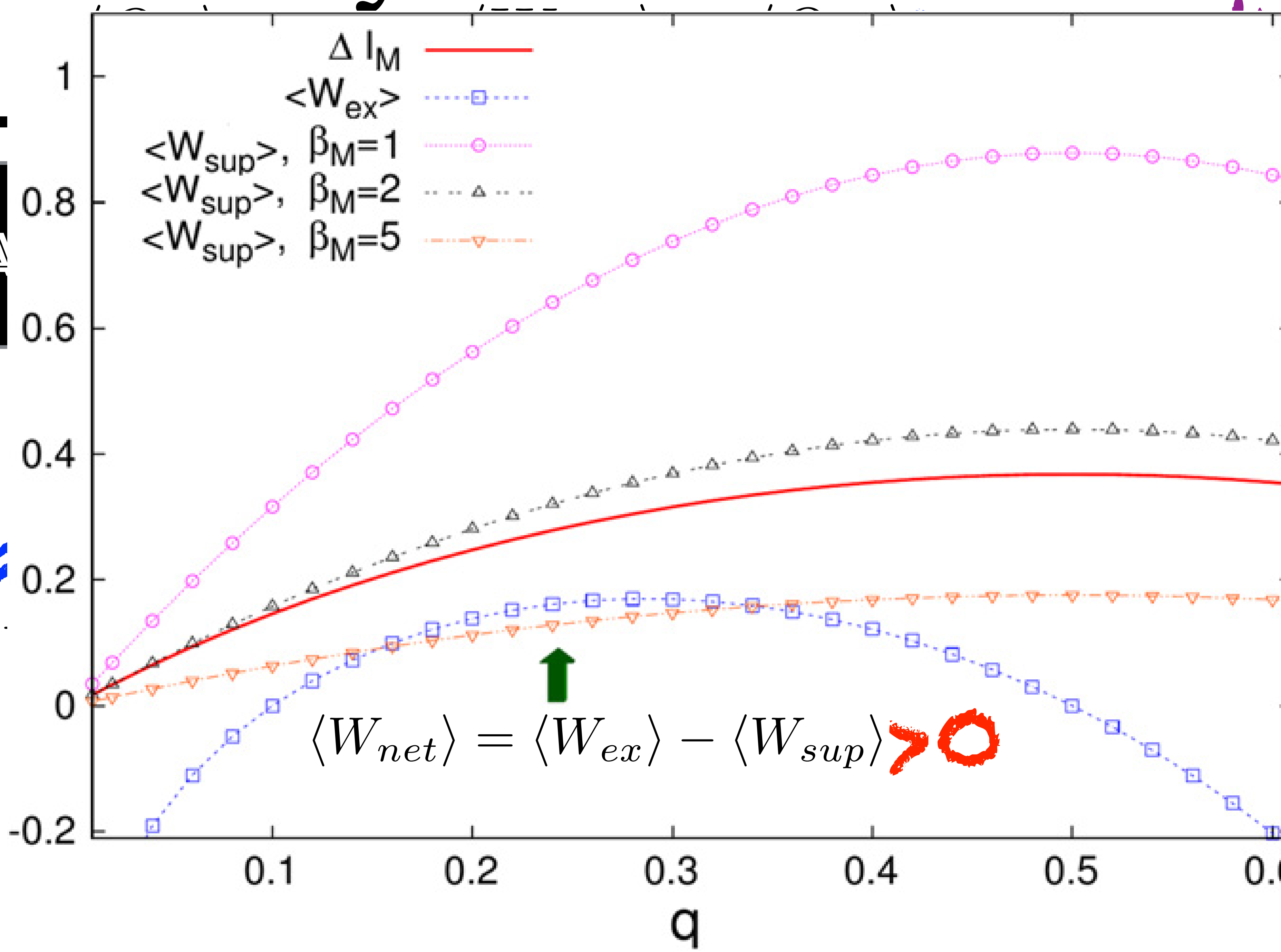
Thermodynamics

$-\langle W_{ex} \rangle$

$|P_0\rangle$ $|P_0\rangle$

$H_0^{(sm)}$ $H_0^{(sm)}$

$\Delta H_R^{(sm)}$ $= 0$



(1)

(2)

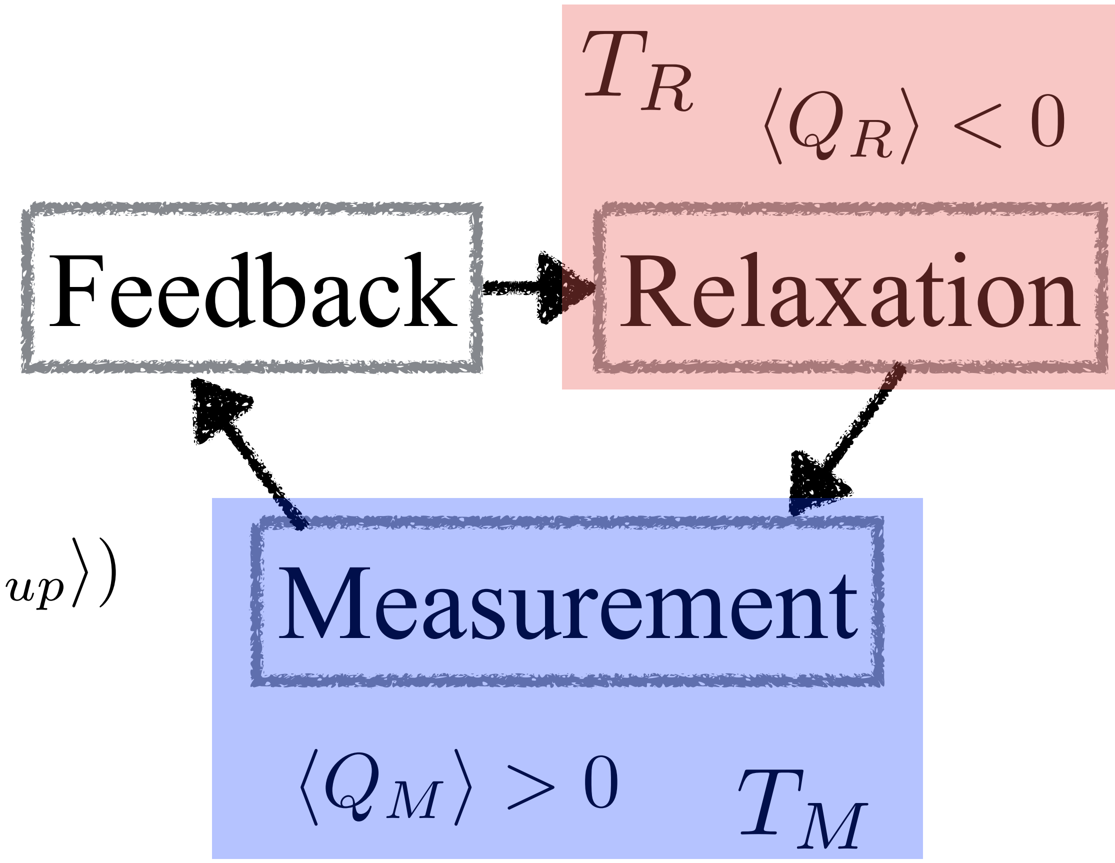
$$\beta_R \langle W_{ex} \rangle \leq \Delta I_M \leq \beta_M \langle W_{sup} \rangle$$

Efficiency

- information assisted heat engine
- efficiency

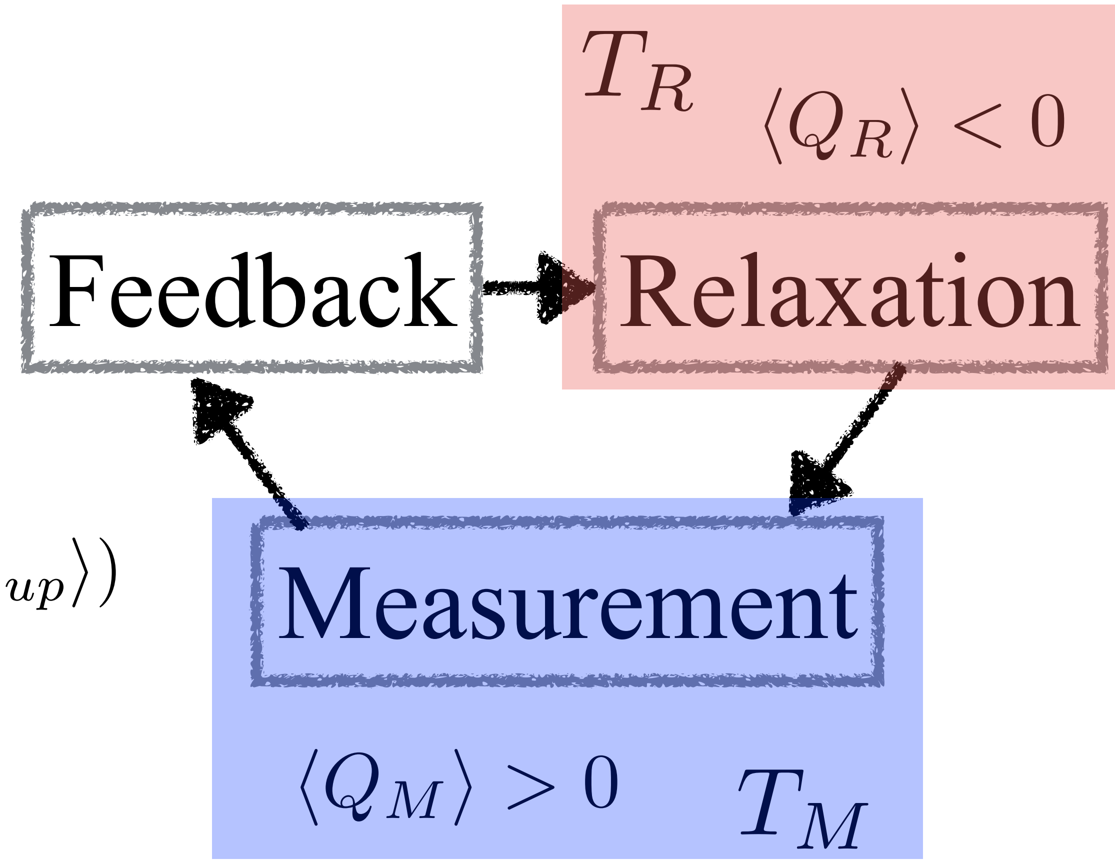
$$\langle W_{net}\rangle = -\langle Q_R\rangle - \langle Q_M\rangle \ \ (= \langle W_{ex}\rangle - \langle W_{sup}\rangle)$$

$$\eta = \frac{\langle W_{net}\rangle}{-\langle Q_R\rangle} \leq 1 - \frac{T_M}{T_R}$$



$$\beta_R\langle Q_R\rangle + \beta_M\langle Q_M\rangle \geq 0$$

Efficiency



- information assisted heat engine
- efficiency

$$\langle W_{net} \rangle = -\langle Q_R \rangle - \langle Q_M \rangle \ \ (= \langle W_{ex} \rangle - \langle W_{sup} \rangle)$$

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Efficiency

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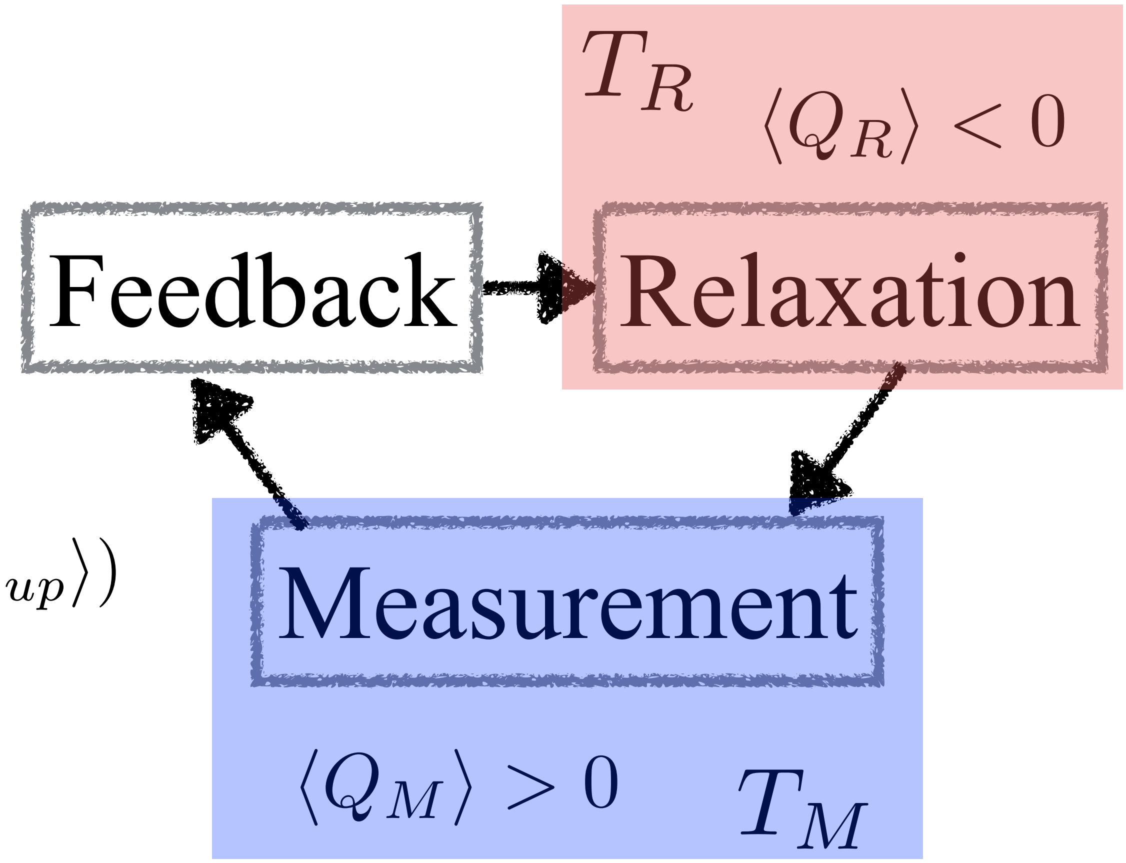

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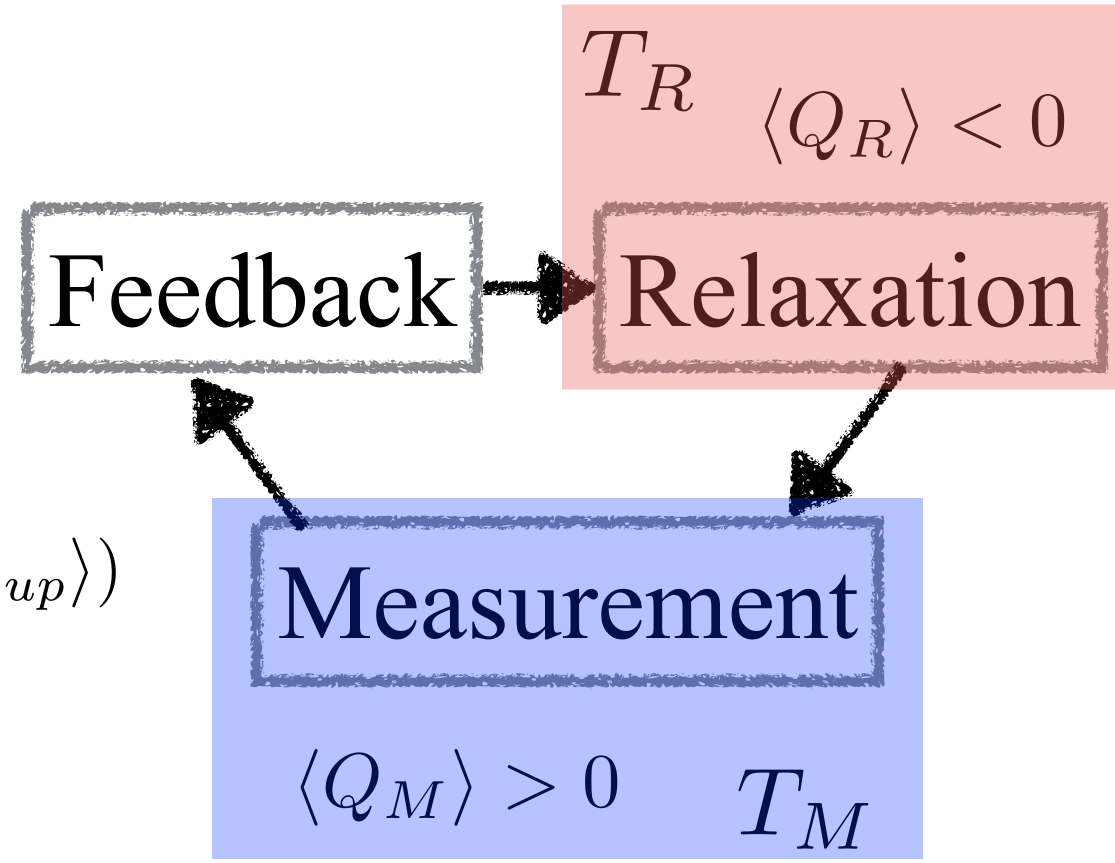

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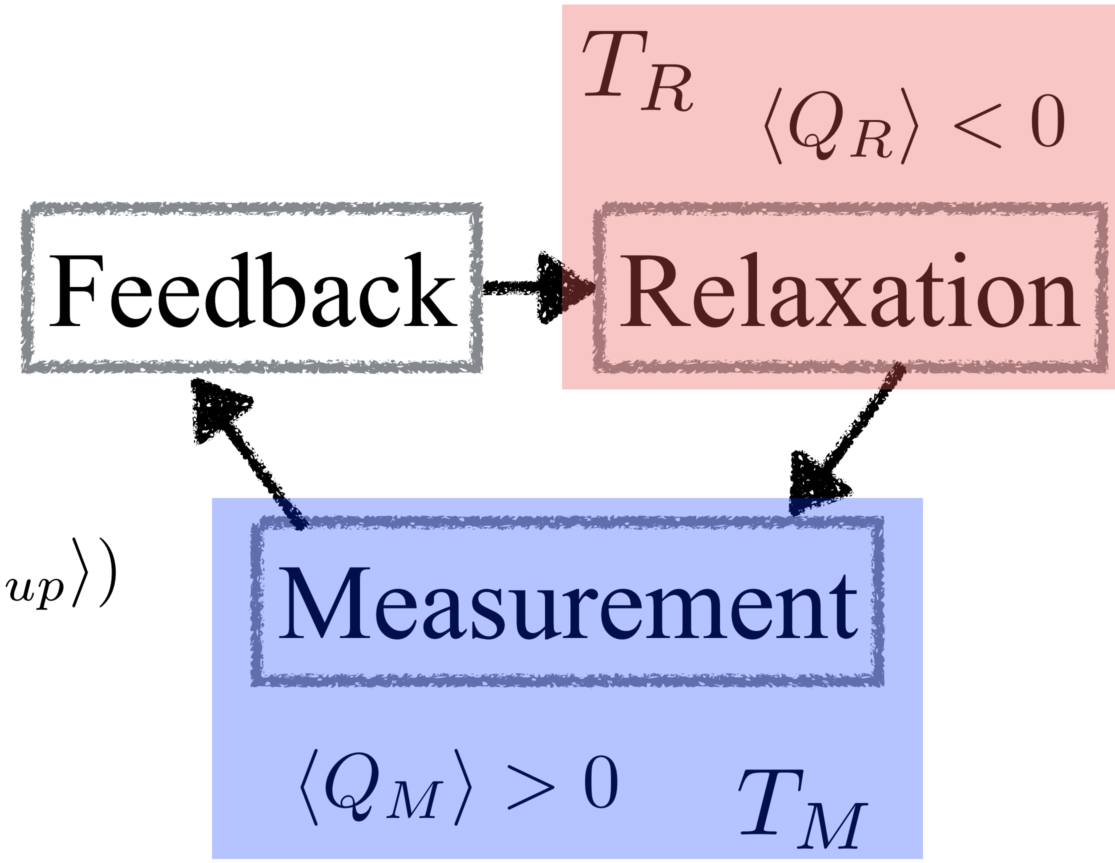
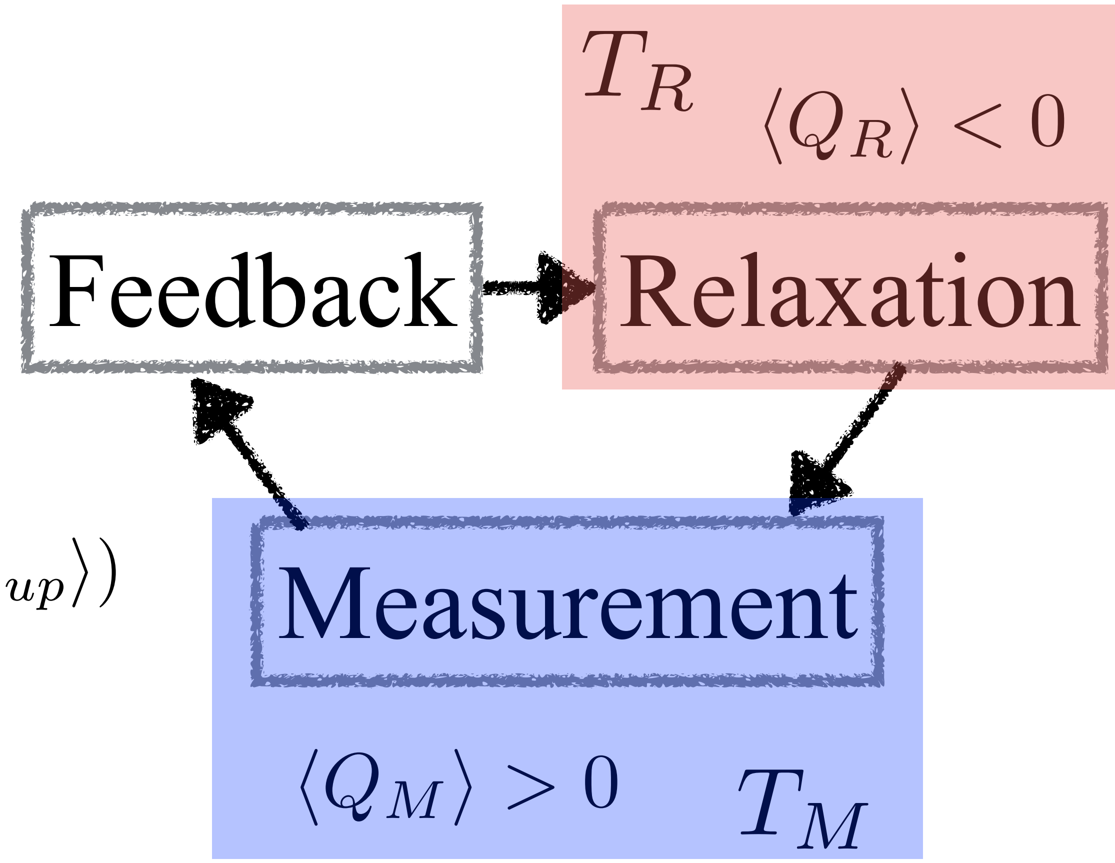


Efficiency



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$$(\mathcal{E} - \epsilon) \rightarrow \frac{\bar{\mathcal{R}}\left(\bar{\epsilon} q + \epsilon \bar{q}\right) + \alpha\left(\bar{\mathcal{R}} q + \mathcal{R}\bar{\mathcal{M}}\epsilon\right)}{1 - \alpha \mathcal{R}\mathcal{M}}$$

Efficiency

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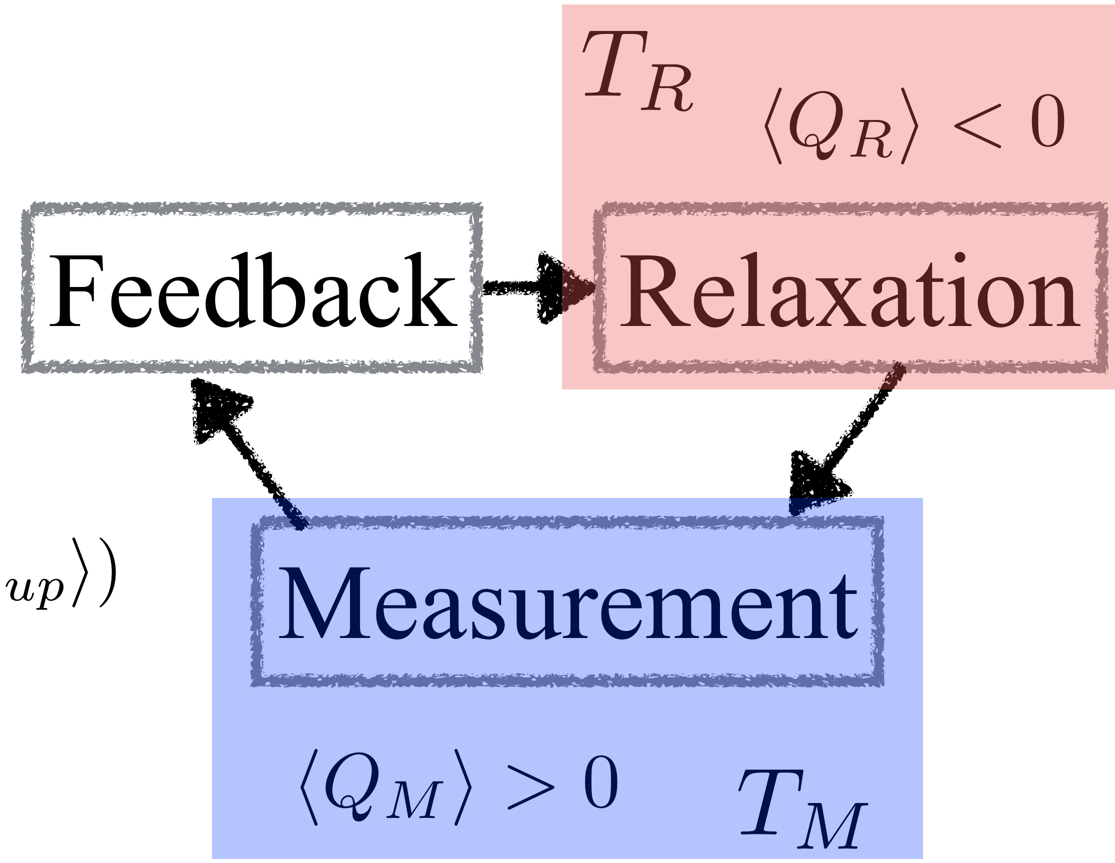

Efficiency

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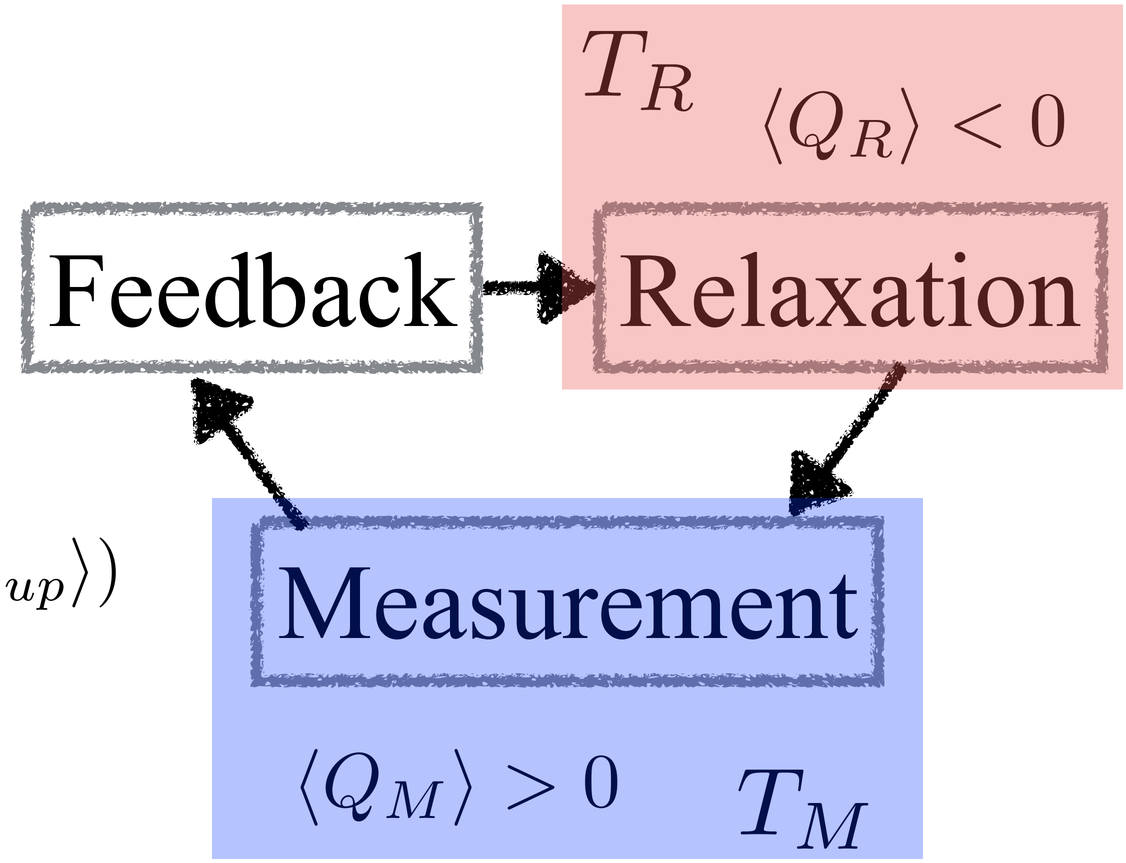

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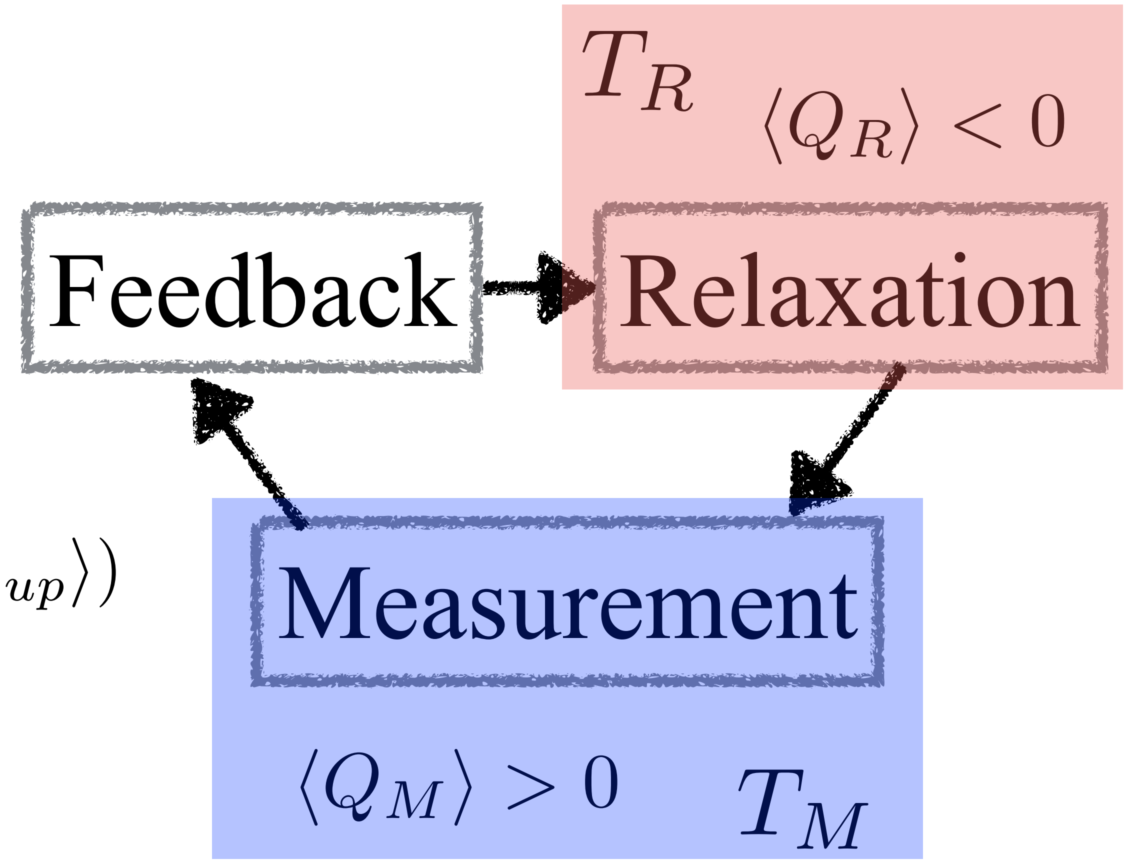
$$\lambda(t_R, t_M) \ge 2$$

Efficiency



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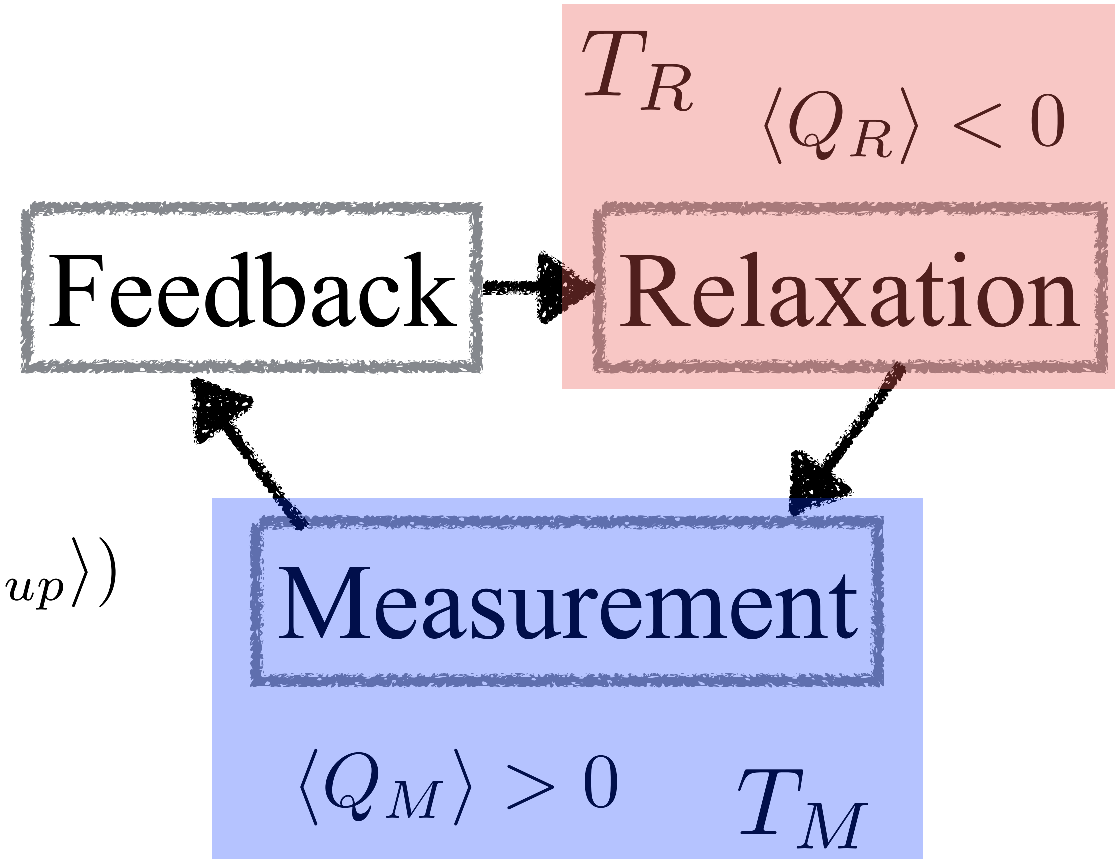
- maximum efficiency

Efficiency



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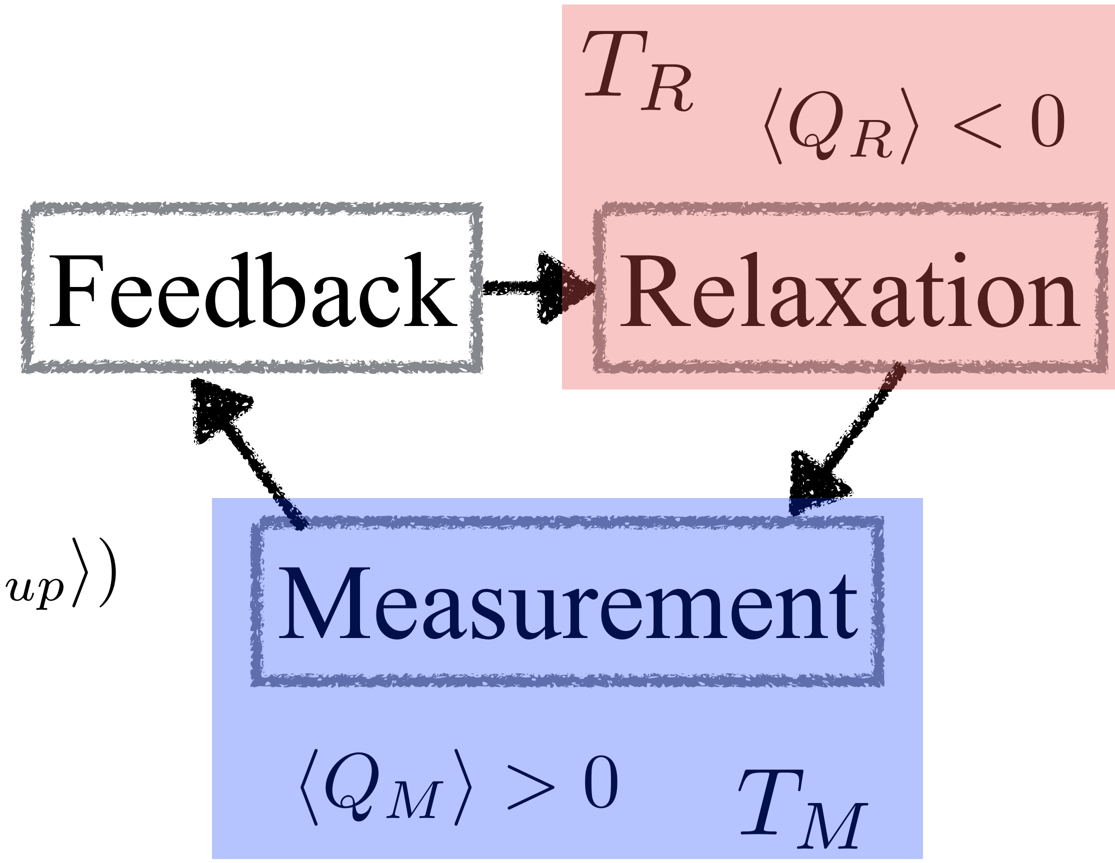
Efficiency



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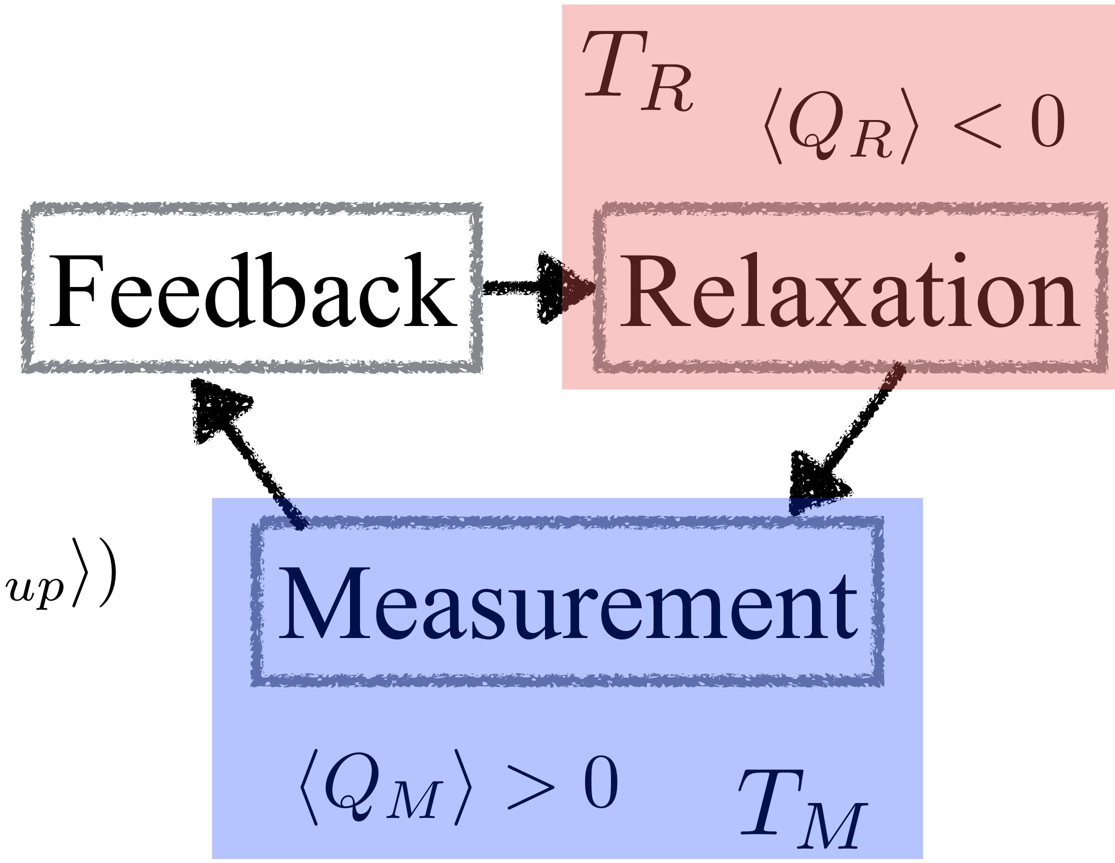
Efficiency



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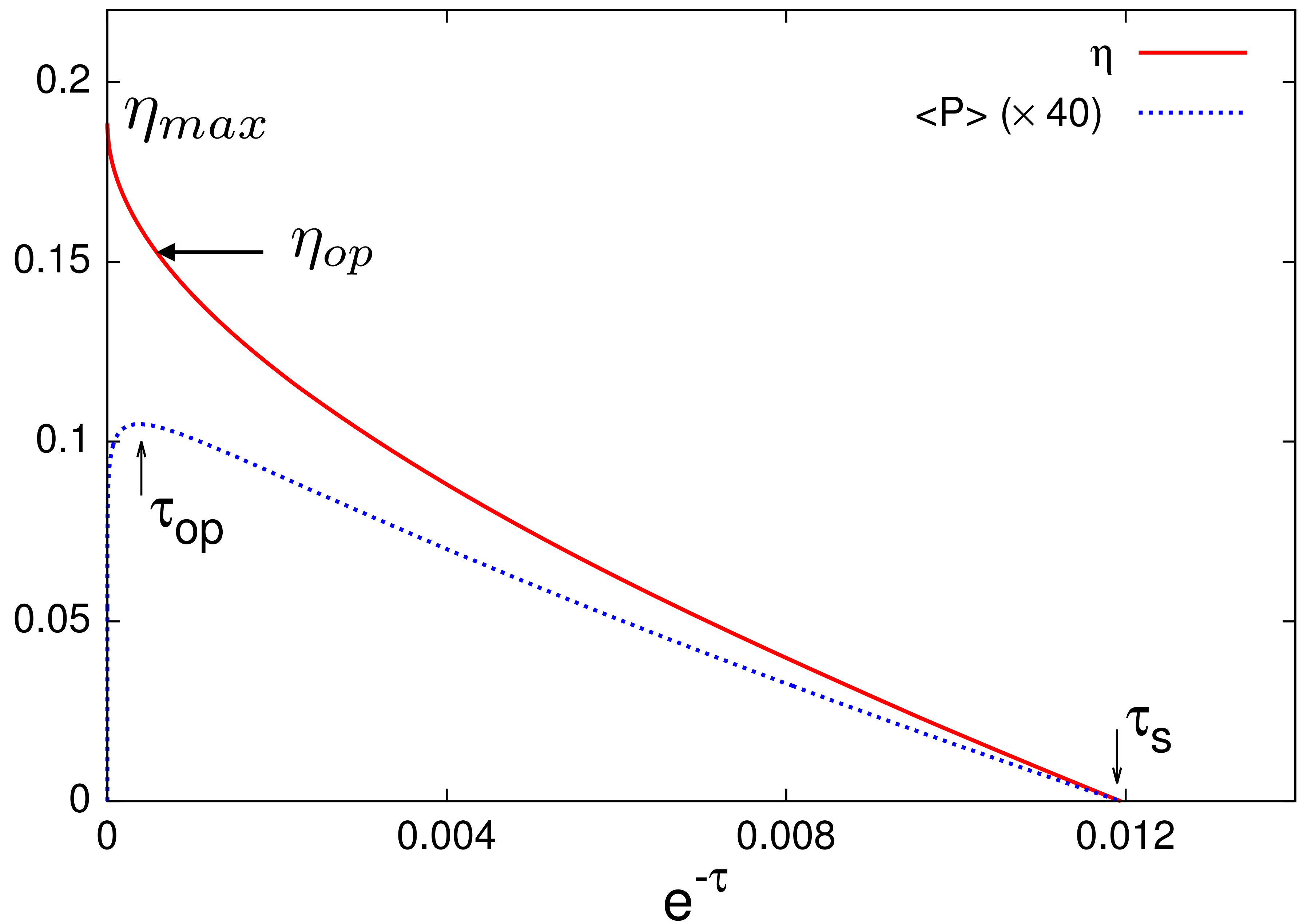
not quasi-static process

Efficiency at max power



$$\beta_M/\beta_R = 5$$

$$q = 0.2$$

$$\epsilon = 0.1$$

$$t_R = t_M = \tau/2$$

$$\eta_{op} \approx \eta_{max} - \frac{\eta_{max}}{|\ln \eta_{max}|}$$

Summary

- We have investigated an information assisted heat engine in terms of composite system.
- It is found that the mutual information developed by measurement gives the upper and lower bound for work extraction and supply, respectively.
- Efficiency is found to be distinguished from the efficiency of usual heat engine.