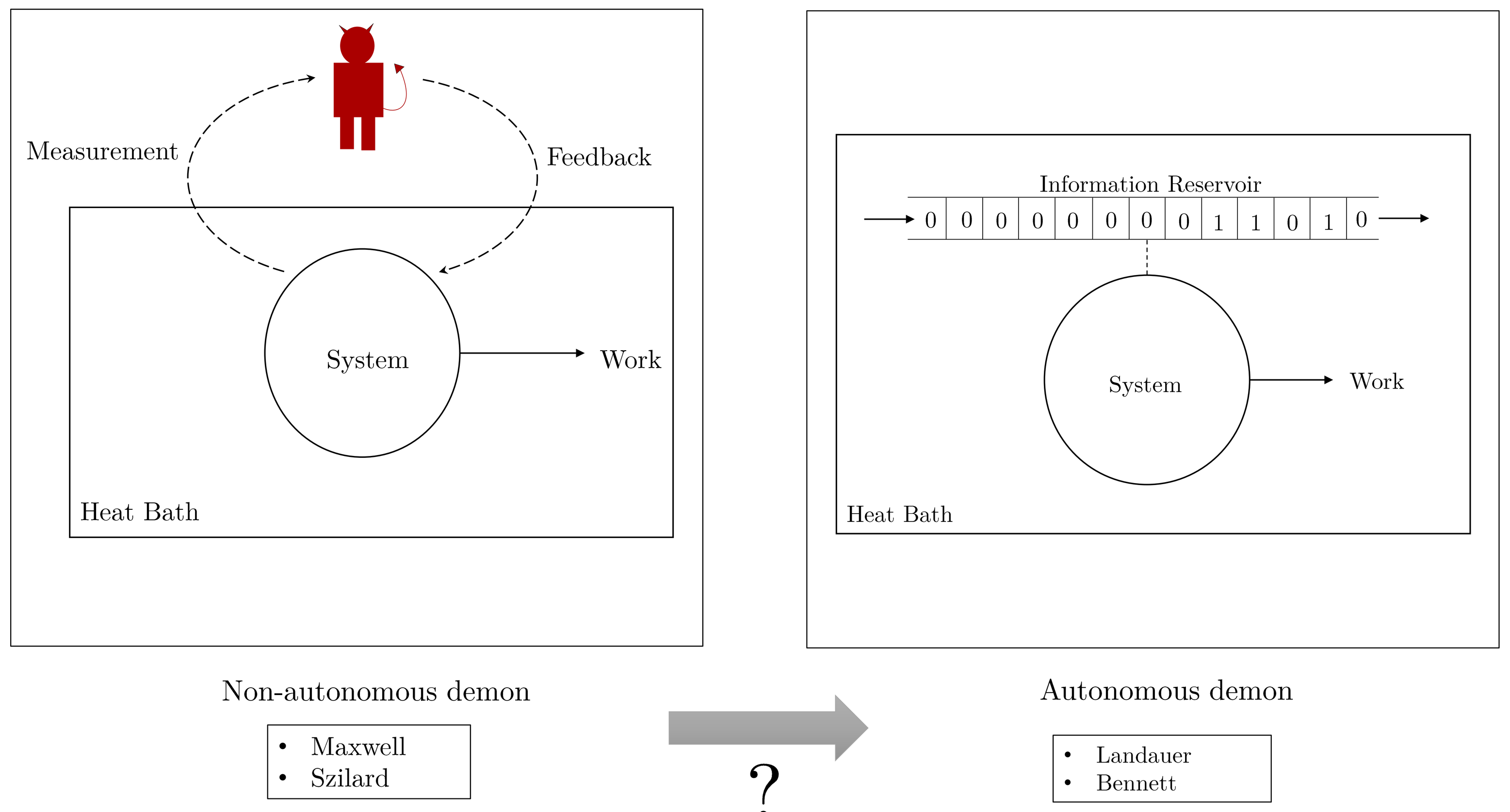
Designing an autonomous Maxwell's Demon in a double quantum dot system

Debankur Bhattacharyya & Christopher Jarzynski

Institute for Physical Science and Technology, University of Maryland, College Park, USA

Email: dbhattac@terpmail.umd.edu

Introduction



- Non-autonomous Maxwell's Demon: A Maxwell's Demon setup where an external agent makes measurement on the system and provides feedback based on that.

  Example: Szilard Engine, Original Maxwell's Demon thought experiment

- Autonomous Maxwell's Demon: In this setup of Maxwell's Demon, there is no external feedback agent. Instead of an external feedback agent there is an Information Reservoir(IR) that interacts with the system based on certain rules. These systems can extract heat from a single heat reservoir and completely convert it to work at the cost of writing down information in the IR. The idea of the autonomous is based on works of R. Landauer and C. Bennett.

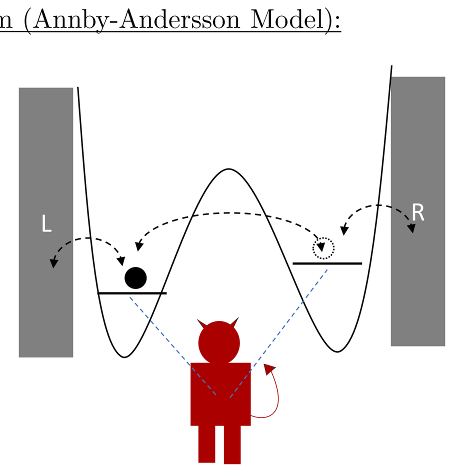
  Example: Mandal-Jarzynski Model

How do we design an autonomous model of Maxwell's Demon from a non-autonomous Maxwell's Demon?

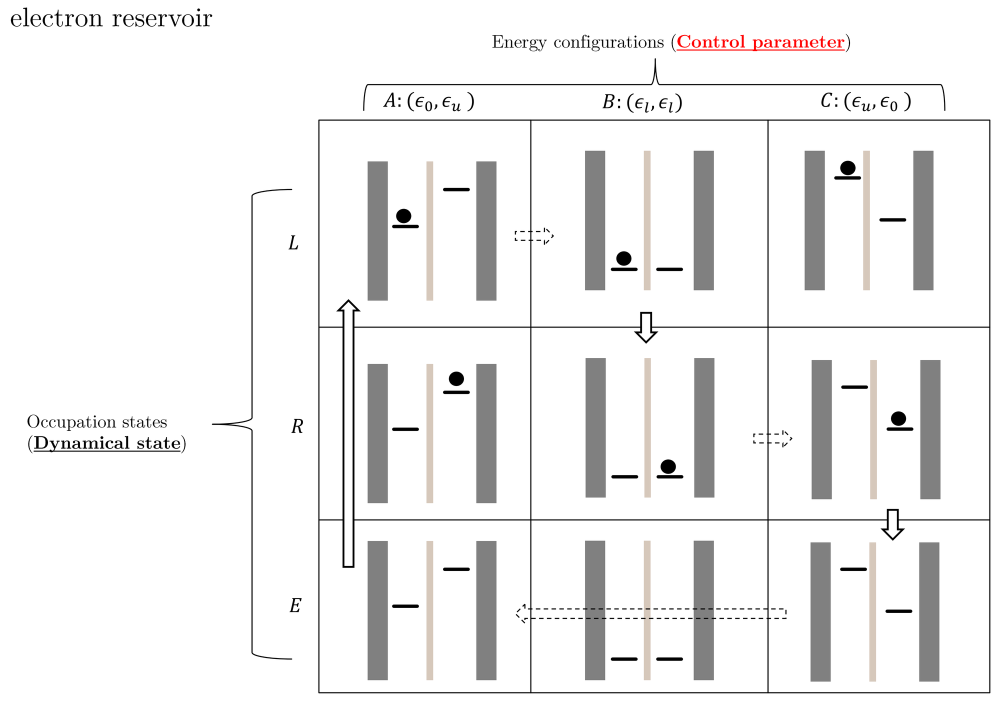
Background & Setup

Non-autonomous version of Maxwell's Demon using a Double Quantum Dot System (Annby-Andersson Model):

- Quantum Dots (QD): Nanostructure that can confine electron
- Double QD: Two QDs coupled through a barrier
- Tunable discrete energy levels on both dots
- Only one electron can be inside the DQD at any instant
- Two electron reservoirs are attached on the both sides of the DQD system with chemical potentials $\mu_L < \mu_R$
- External agent continuously measures the charge state of DQD system and provides feedback to take electrons from the left electron reservoir to the right electron reservoir



Annby-Andersson Model

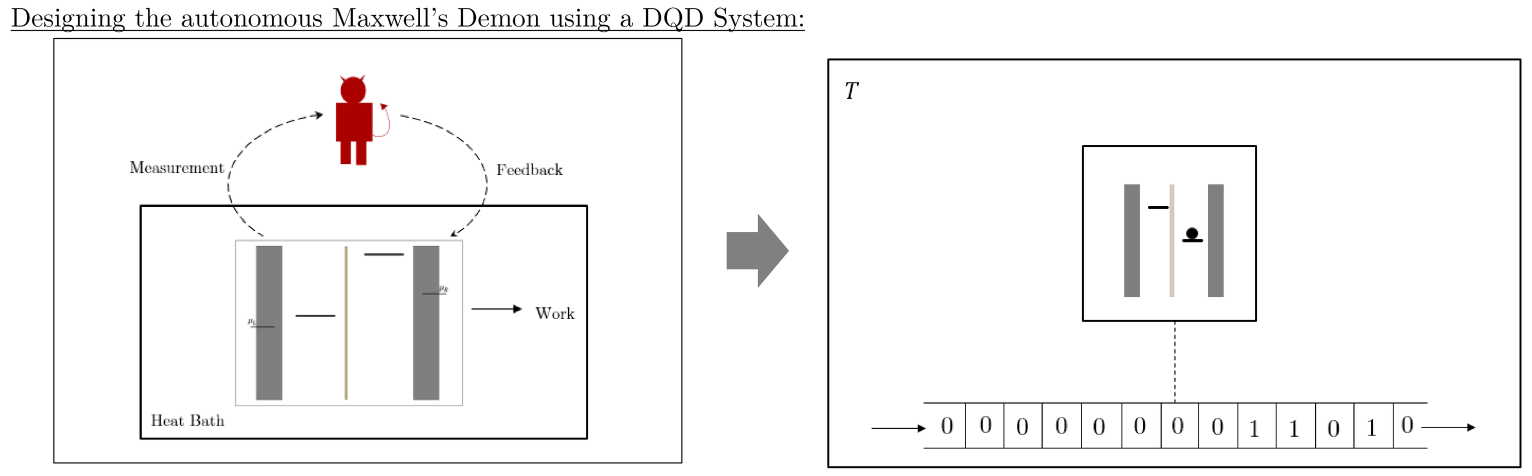


Solid arrow: thermal electron jump or tunneling steps

Dotted arrow: Instant feedback steps

Model

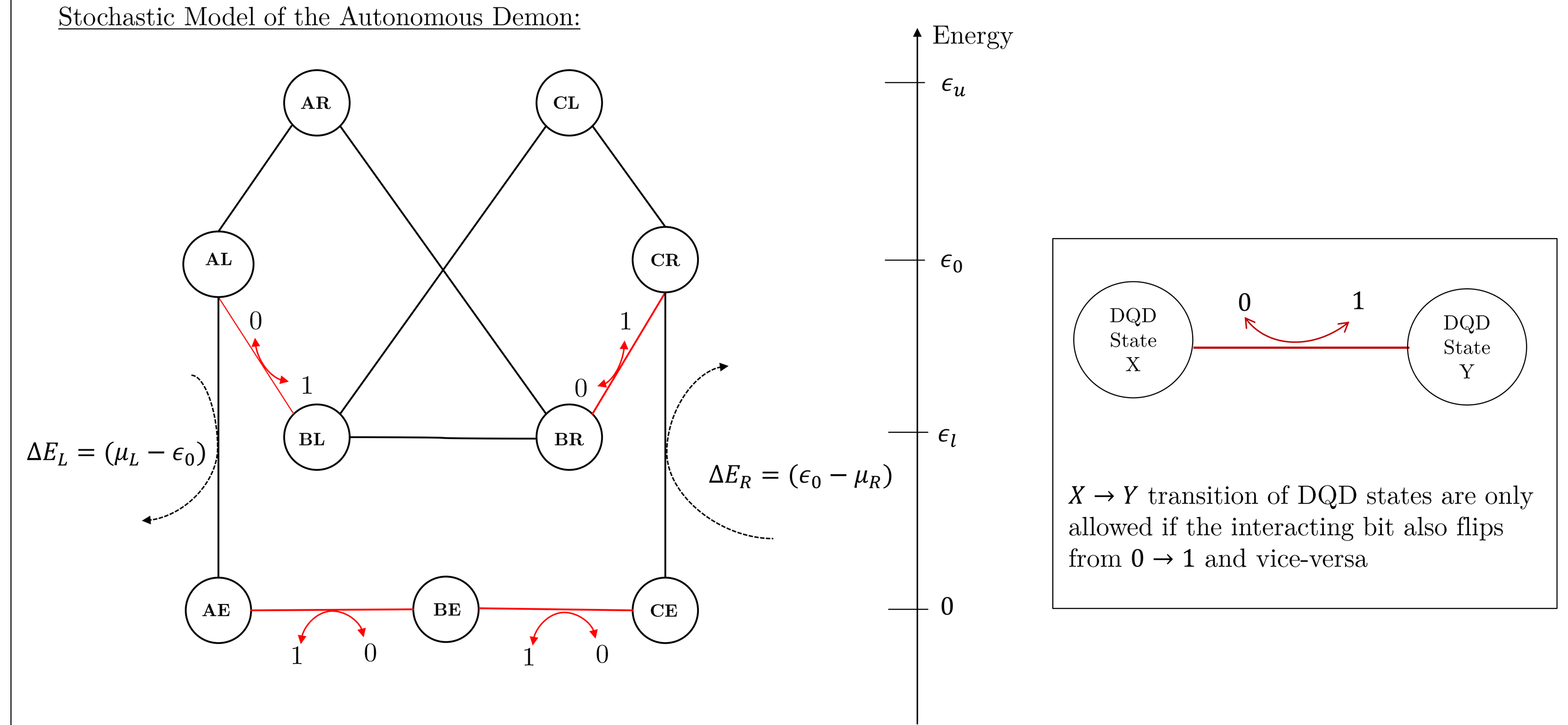
Designing the autonomous Maxwell's Demon using a DQD System:



Non-autonomous demon (Annby-Andersson *et al*)

Autonomous demon

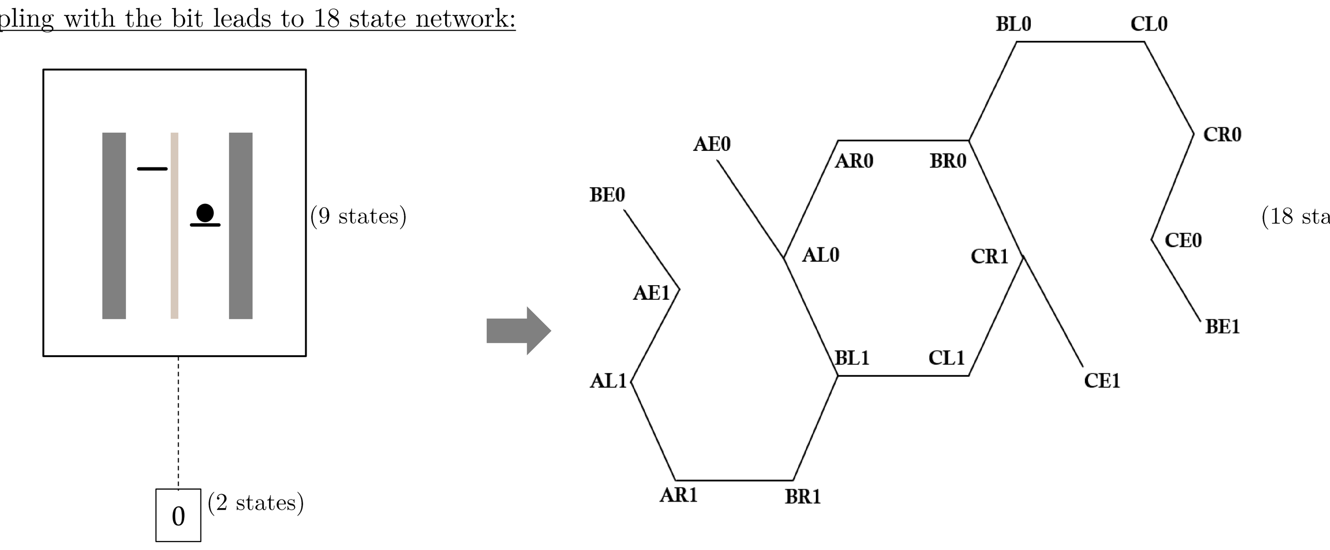
Stochastic Model of the Autonomous Demon:



Key ideas:

- Set up the interaction rules between the DQD system and bits to mimic the behavior of the nonautonomous demon.
- Connect the bits to the transitions that corresponds to the feedback steps in the nonautonomous model.
- Clockwise(CW) flow of the probability currents imply flow of electrons from the left to the right reservoir.
- Flipping of bits from 0 to 1 favors CW of flow of probability current.
- Each bit interacts with the DQD system for a fixed interval τ
- Excess of 0's to 1's in the incoming memory tape (IR) favors the clockwise flow of probability current.

Coupling with the bit leads to 18 state network:



Methods

Time evolution of the probability distribution in full network:

$$\frac{d}{dt}\boldsymbol{p_f}(t) = \boldsymbol{R}\,\boldsymbol{p_f}(t)$$

18 X 18 rate matrix

Time periodic dynamics of probability distribution:

$$\boldsymbol{p}^D(\tau) = \boldsymbol{P}_D e^{\boldsymbol{R}\tau}\boldsymbol{M}\ \boldsymbol{p}^D(0)$$

9X18 projection operator; 18X9 coupling matrix; 9X1 state vector; 18X18 time evolution operator; 9X1 state vector

$\boldsymbol{I}$ 9X9 identity matrix

$\boldsymbol{R}$ 18X18 rate matrix

(p_0, p_1) Probability distribution of the incoming bit stream

$$\boldsymbol{M} = \begin{pmatrix} p_0\boldsymbol{I} \\ p_1\boldsymbol{I} \end{pmatrix}$$

$$\boldsymbol{P}_D = (\ \boldsymbol{I}\ \ \boldsymbol{I}\ )$$

Transition rates satisfy local detailed balance:

$$\frac{R_{ij}}{R_{ji}} = e^{-\beta(E_i - E_j)}$$

The system will reach a unique periodic steady state:

$$\lim_{n\to\infty}\boldsymbol{T}(\tau)^n\,\boldsymbol{p}^D(0) = \boldsymbol{q_{pss}}(\tau)$$

9X1 periodic steady state vector

$$\boldsymbol{T}(\tau) = (\boldsymbol{P}_D e^{\boldsymbol{R}\tau}\boldsymbol{M})$$

9X9 transition matrix

The periodic steady state can be obtained by solving:

$$\boldsymbol{T}(\tau)\boldsymbol{q_{pss}}(\tau) = \boldsymbol{q_{pss}}(\tau)$$

Results

Analytical results for the special case of very large interaction intervals ($\tau \to \infty$):

- Average chemical work done per interaction interval at periodic steady state:

$$W = (\mu_R - \mu_L)\phi$$

Average number of electrons transferred from left to right reservoir in one interaction interval

$$\phi_\infty = N\,[p_0 e^{-\beta\mu_R} - p_1 e^{-\beta\mu_L}]$$

$$N = \frac{r\,e^{2\beta\epsilon_0}}{r[3e^{2\beta\epsilon_0}(e^{-\beta\mu_L} + e^{-\beta\mu_R}) + 4] + 4r^2 + 4}$$

$$r = e^{-\beta\epsilon}$$

$$\epsilon = (\epsilon_u - \epsilon_0) = (\epsilon_0 - \epsilon_l)$$

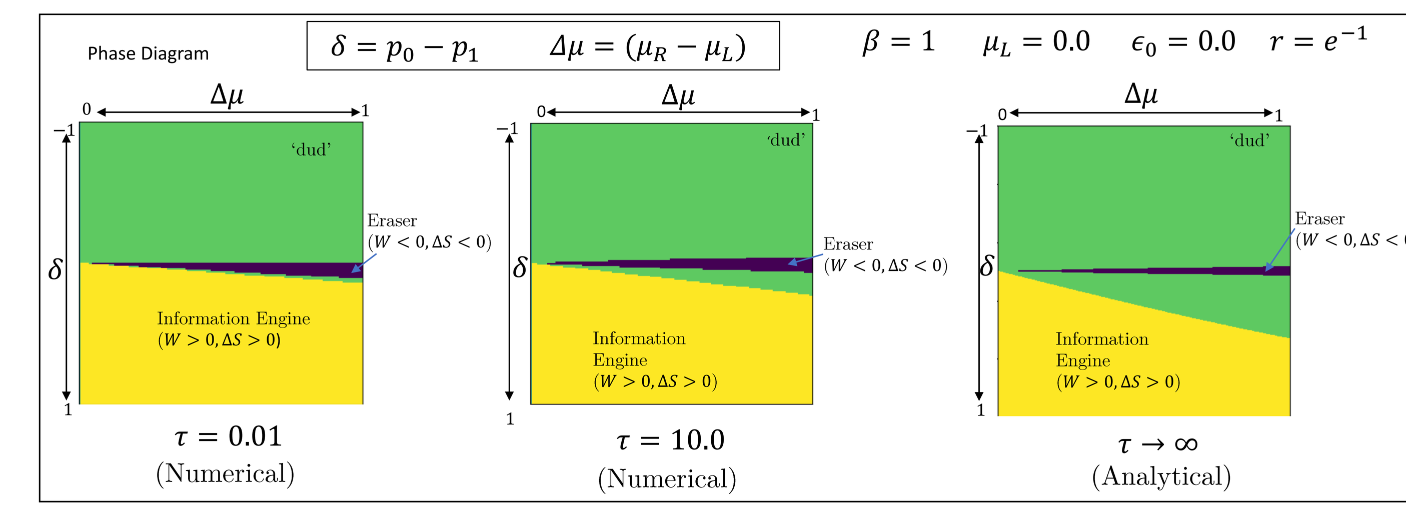
- Average entropy change of bit per interaction interval at periodic steady state:

$$\Delta S = S' - S$$

(p_0', p_1') ← Probability distribution of the outgoing bit

$$S' = -\sum_{i=0,1} p_i' \ln p_i' \qquad S = -\sum_{i=0,1} p_i \ln p_i$$

Phase diagram of operational modes:



- Higher δ favors CW circulation (flow of electron from left to right reservoir)
- Higher $\Delta\mu$ favors CCW circulation (flow of electrons from right to left reservoirs)

Conclusion

- With an illustrative example, we show how a model of autonomous Maxwell's Demon can be constructed starting from a non-autonomous Maxwell's Demon
- This model can work as an Information Engine for a particular set of parameters and alternatively it can work as a Landauer Eraser for a different set of parameters
- Analytical results were obtained for long interaction intervals
- Phase diagram of the operational modes are calculated.

References

- Mandal-Jarzynski Model: D. Mandal & C. Jarzynski, PNAS **109**, 11641 (2012)
- Annby-Andersson Model: B. Annby-Andersson *et al.* , Phys. Rev. B, **101**:165404, (2020)
- Autonomous Maxwell's Demon in DQD system: D. Bhattacharyya & C. Jarzynski (in preparation)

Acknowledgements

- C. Jarzynski Research Group (University of Maryland)
- FQXi collaborators:
  - P. Samuelsson Research Group (Lund University)
  - V. Maisi Research Group (Lund University)
  - K. Ensslin Research Group (ETH Zürich)

Financial Support: FQXi FOUNDATIONAL QUESTIONS INSTITUTE