Injection, dissipation, efficiency of motor activity in a living cell

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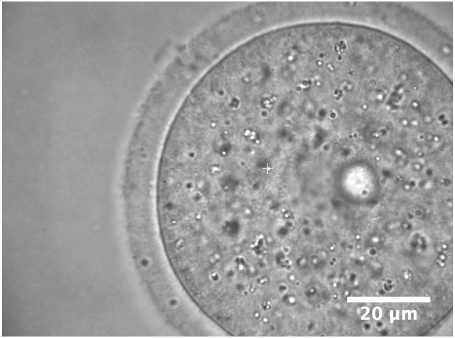
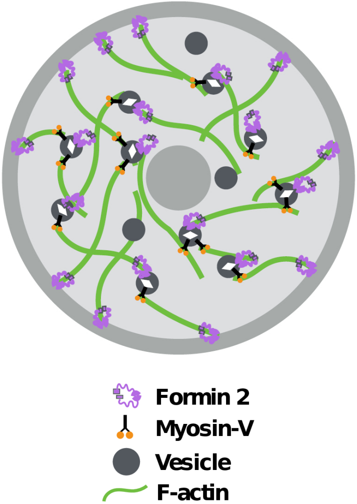
Statphys26 – Biological physics

Introduction

Living mouse oocytes





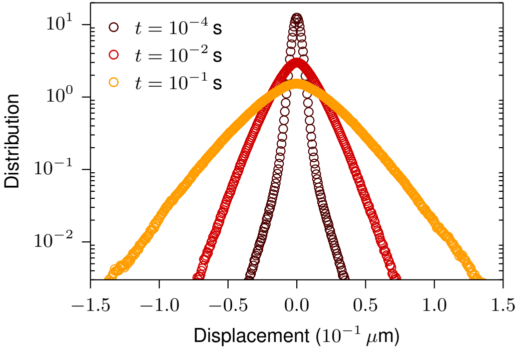
W. W. Ahmed, M. Bussonnier, T. Betz (Curie Institute)

M. Almonacid, M.-H. Verlhac (Collège de France)

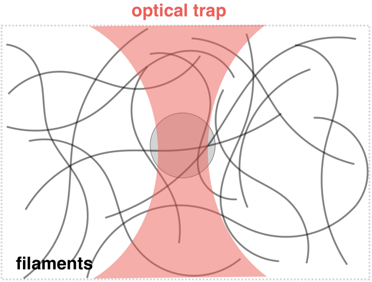
N. S. Gov (Weizmann Institute of Science)

Introduction

Statistics of tracer displacement



Measuring the mechanics



$$\langle \delta r(t) \rangle = \int_0^t \underbrace{R(t-s)}_{\text{Response}} F(s) \mathrm{d}s$$

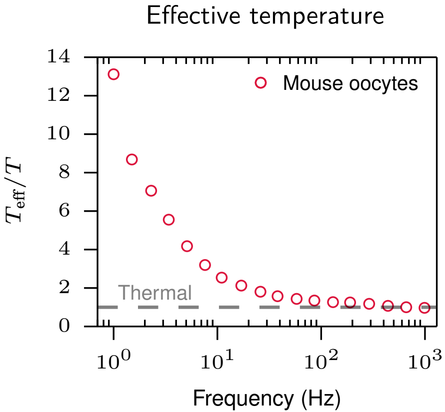
Introduction

Trademark of equilibrium

$$R(t) = -\frac{1}{T}\frac{\mathrm{d}}{\mathrm{d}t}\underbrace{\langle x(t)x(0)\rangle}_{C(t)} \quad \rightarrow \quad T = \frac{\omega C(\omega)}{2R''(\omega)}$$

Fluctuation-dissipation theorem

Introduction



Violation of FDT

$$\color{red}{T_{\mathrm{eff}}(\omega)} = \frac{\omega C(\omega)}{2R''(\omega)}$$

D. Mizuno *et al.*, Science **315**, 370 (2007)

C. Wilhelm, Phys. Rev. Lett. **101**, 028101 (2008)

F. Gallet *et al.*, Soft Matter **5**, 2947 (2009)

H. Turlier *et al.*, Nat. Phys. **12**, 512 (2016)

Bridging departure from equilibrium to the microscopics

Outline

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1. Tracer dynamics: phenomenological model

2. Energy transfers: stochastic energetics

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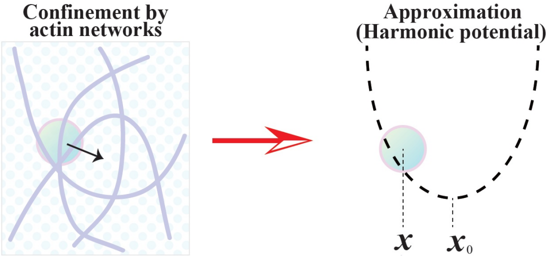
2. Energy transfers: stochastic energetics

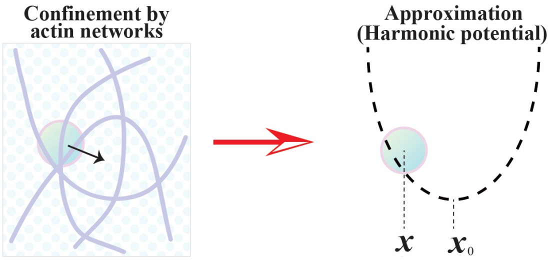
Tracer dynamics in living cells



$$0 = -k(x - x_0) - \gamma \frac{\mathrm{d}x}{\mathrm{d}t} + \xi$$

ξ Gaussian white noise

Tracer dynamics in living cells

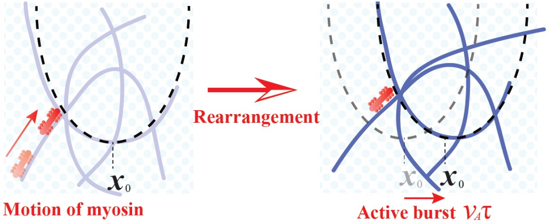


$$0 = -k(x - x_0) - \gamma * \frac{\mathrm{d}x}{\mathrm{d}t} + \xi$$

ξ Gaussian colored noise

Tracer dynamics in living cells

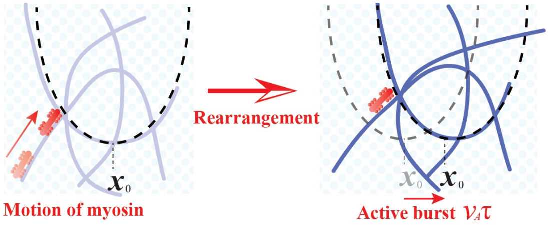
Active motion of local minimum



$$\gamma * \frac{\mathrm{d}x}{\mathrm{d}t} = -k(x - x_0) + \xi, \quad \gamma * \frac{\mathrm{d}x_0}{\mathrm{d}t} = F_{\mathrm{M}}$$

F_{M} colored noise: persistence time τ

Active motion of local minimum



$$\gamma * \frac{\mathrm{d}x}{\mathrm{d}t} = -kx + \underbrace{F_A}_{kx_0} + \xi, \quad \gamma * \frac{\mathrm{d}x_0}{\mathrm{d}t} = F_M$$

F_M colored noise: persistence time τ

Outline

1. Tracer dynamics: phenomenological model
2. Energy transfers: stochastic energetics

Energy transfers in living cells

Active force power

$$J_{\text{tracer}} = \left\langle F_{\text{A}} \frac{\mathrm{d}x}{\mathrm{d}t} \right\rangle$$

Stochastic energetics

$$J_{\text{tracer}} = \left\langle \left(\gamma * \frac{\mathrm{d}x}{\mathrm{d}t} - \xi \right) \frac{\mathrm{d}x}{\mathrm{d}t} \right\rangle + \left\langle kx \frac{\mathrm{d}x}{\mathrm{d}t} \right\rangle$$

Energy transfers in living cells

Active force power

$$J_{\text{tracer}} = \left\langle F_{\text{A}} \frac{\mathrm{d}x}{\mathrm{d}t} \right\rangle$$

Stochastic energetics

$$J_{\text{tracer}} = \underbrace{\left\langle \left(\gamma * \frac{\mathrm{d}x}{\mathrm{d}t} - \xi \right) \frac{\mathrm{d}x}{\mathrm{d}t} \right\rangle}_{\text{Dissipated power}} + \cancel{\left\langle kx \frac{\mathrm{d}x}{\mathrm{d}t} \right\rangle}$$

Energy transfers in living cells

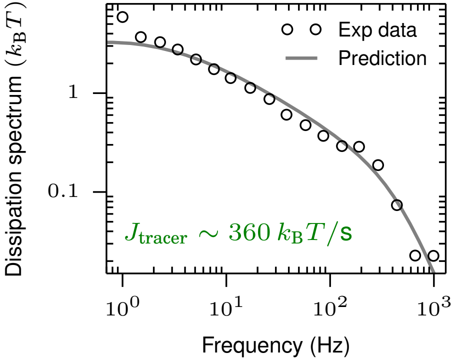
Spectral decomposition

$$J_{\text{tracer}} = \int I(\omega) \frac{\mathrm{d}\omega}{2\pi}$$

Spectrum of dissipated power

$$I(\omega) = \frac{2\left[T_{\text{eff}}(\omega) - T\right]}{1 - \left[R''(\omega)/R'(\omega)\right]^2}$$

Energy transfers in living cells



Persistence time $\tau \sim 0.3\,\mathrm{ms}$

Myosin-V power stroke $\sim 0.5\,\mathrm{ms}$

G. Cappello *et al.*, PNAS **104**, 15328 (2007)

Energy transfers in living cells

Tracer dynamics

$$\gamma * \frac{\mathrm{d}x}{\mathrm{d}t} = -kx + F_{\mathrm{A}} + \xi, \quad \gamma * \frac{\mathrm{d}x_0}{\mathrm{d}t} = F_{\mathrm{M}}$$

Power injected by motors into cage

$$J_{\mathrm{cage}} = \left\langle F_{\mathrm{M}} \frac{\mathrm{d}x_0}{\mathrm{d}t} \right\rangle \sim 2 \cdot 10^5 \, k_{\mathrm{B}} T / s$$

Power injected by one myosin-V $\sim 10^4 \, k_{\mathrm{B}} T/\mathrm{s}$

K. Fujita *et al.*, Nat. Com. **3**, 956 (2012)

Energy transfers in living cells

Efficiency of power transduction

$$\frac{\text{cage} \to \text{tracer}}{\text{motors} \to \text{cage}} = \frac{J_{\text{tracer}}}{J_{\text{cage}}} \sim 10^{-3}$$

Main energy injection goes to network remodeling

Conclusion

Energetics in living cells

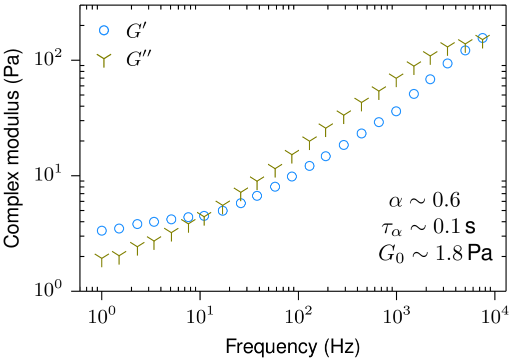
What have we learned?

- Kinetics of fluctuations
- Separating injection and dissipation
- Efficiency of energy transfers

References | arXiv:1510.08299, arXiv:1511.00921

Complex modulus

$$G^*(\omega) = \frac{1}{6\pi a R(\omega)}$$



$$G^* = \underbrace{G'}_{\text{Elastic mod.}} + \underbrace{\mathrm{i}G''}_{\text{Viscous mod.}}$$

$$G^*(\omega) = G_0\left[1 + (\mathrm{i}\omega\tau_\alpha)^\alpha\right]$$

Visco-elastic material

Force spectrum

Spectrum of stochastic forces

$$S_{\text{cell}}(\omega) = \mathcal{F}\left\langle (\xi + F_{\text{A}})(t)\,(\xi + F_{\text{A}})(0)\right\rangle$$

$$= \underbrace{S_{\text{th}}(\omega)}_{\text{mechanics (FDT)}} + S_{\text{A}}(\omega)$$