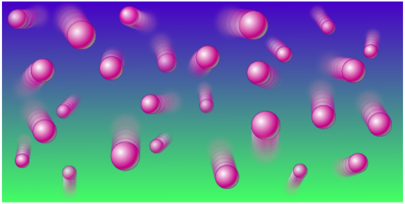
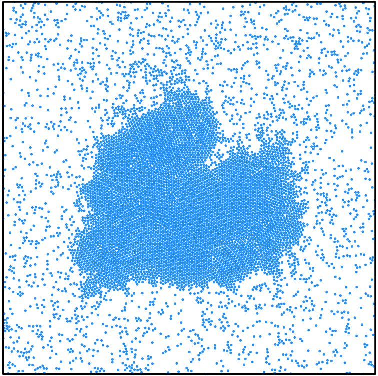
Nonequilibrium soft and active matter

Dpt of Physics and Materials Science

University of Luxembourg



“In, Yet Out of Equilibrium” Physics (2016)



Soft condensed matter

From passive to biological materials

Structure at mesoscale

Sensitivity to thermal energy

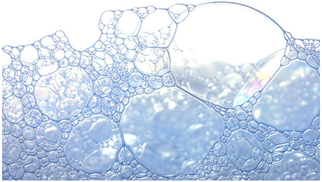
Colloids and Liquid Crystals

Prof Scalia, Winter Sem

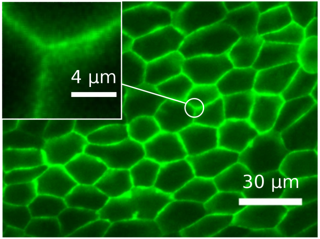
Physics of Living Matter

Prof Sengupta, Summer Sem

Bubble foam



Cell tissue

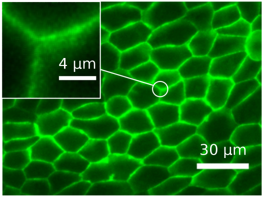


Active matter across scales

Consume energy to produce nonequilibrium forces

Cell assemblies

ÉF *et al*, Biophys J **114**, 939 (2018)



Animal groups

Bialek *et al*, PNAS **109**, 4786 (2012)

Human crowds

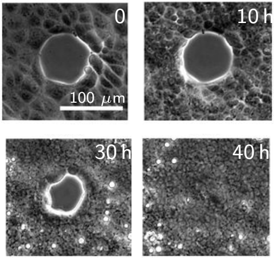
Bain *et al*, Science **363**, 6422 (2019)

Scale

Active matter across domains

From biological and social applications . . . to synthetic systems

Wound healing
Niera *et al*, PNAS **112**, 9546 (2015)

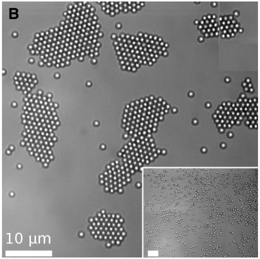


How to improve wound recovery?

Crowd management
Bottinelli *et al*, PRL **117**, 228301 (2016)

How to prevent crowd disaster?

Colloidal self-assembly
Palacci *et al*, Science **339**, 936 (2013)



How to assemble synthetic colloids?

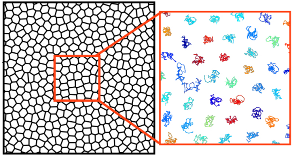
Statistical mechanics of active matter

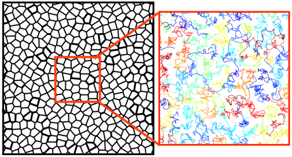
How to control the emerging collective behavior?

- Transition in passive matter: Assembly of water molecules

Solid — Liquid → **Temperature**

- Transition in active matter: Assembly of cells [Bi *et al*, PRX **6**, 021011 (2016)]





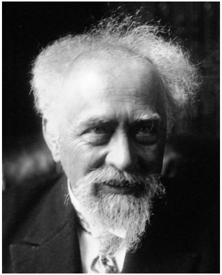
Solid — Liquid → **Energy fuel**

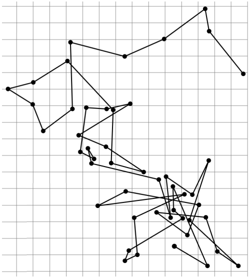
Experiments on fluctuating systems

Passive systems: Equilibrium dynamics

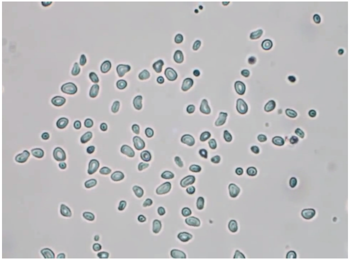
Tracers in a viscous solvent

Jean Perrin (Nobel Prize, 1926)





Pollen grains in water

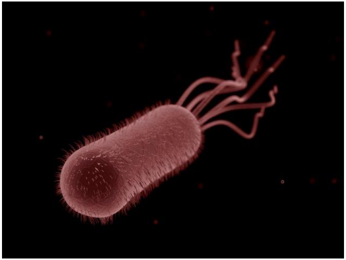


Experiments on fluctuating systems

Active systems: Nonequilibrium dynamics

Extract energy to produce directed motion

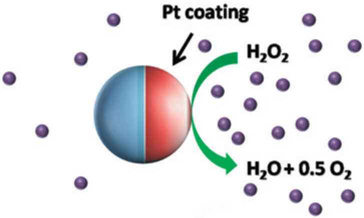
Biological swimmers



Turner, Ryu, Berg,

J Bacteriol **182**, 2793 (2000)

Synthetic active colloids



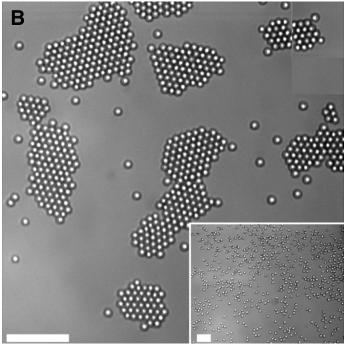
Walther, Müller,

Soft Matter Review **4**, 663 (2008)

Experiments on fluctuating systems

Collective dynamics of active particles

Clustering of colloids

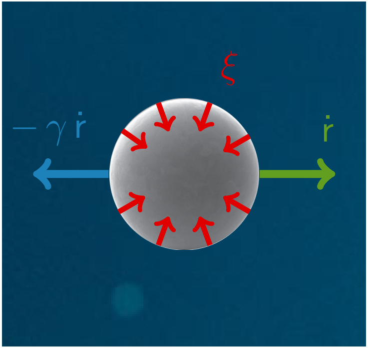


Palacci, Sacanna, Steinberg, Pine, Chaikin, Science **339**, 936 (2013)

Flocking of birds

Bialek, Cavagna, Giardina, Mora, Silvestri, Viale, Walczak, PNAS **109**, 4786 (2012)

Modelling passive fluctuations



Langevin equation

Effective tracer dynamics

$$m\,\ddot{r} \;=\; -\nabla U - \gamma\,\dot{r} + \xi$$

Equilibrium fluctuations

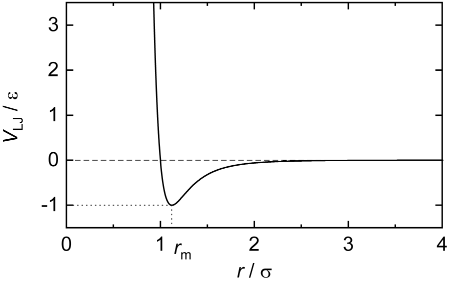
$$\langle\, \xi(t)\,\xi(0)\,\rangle \;=\; 2\,\gamma\,T\,\delta(t)$$

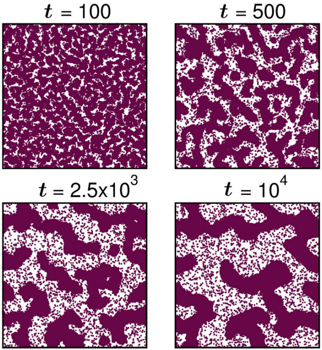
Fluctuating energy $\quad E = U + m\,\dot{r}^2/2$

Boltzmann distribution $\quad P_s \sim e^{-E/T}$

Modelling passive fluctuations

Repulsion and attraction





Equation of state: Connecting thermodynamic observables

pressure P, temperature T, density ρ

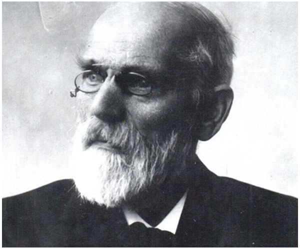
e.g. law of ideal gas $P = \rho T$

Modelling passive fluctuations

Equilibrium phase transitions

Johannes van der Waals

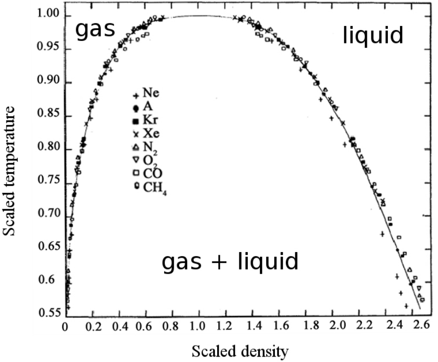
(Nobel Prize, 1910)



Equation of state

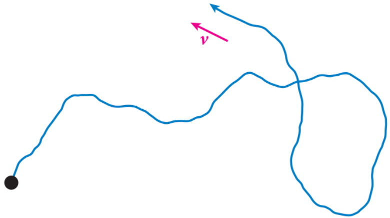
$$(P + a\,\rho^2)\,(1 - b\,\rho) = \rho\,T$$

Law of corresponding state



Guggenheim, J Chem Phys **13**, 253 (1945)

Modelling active fluctuations



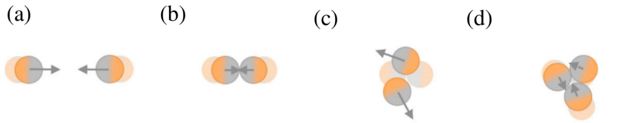
Langevin equation

$$m\ddot{\mathrm{r}} = -\nabla U - \gamma\,\dot{\mathrm{r}} + \xi + f_a$$

Non-equilibrium fluctuations

$$\langle\, f_a(t)\, f_a(0)\,\rangle = \frac{\gamma\, T_a}{\tau}\, e^{-|t|/\tau}$$

Persistence time τ

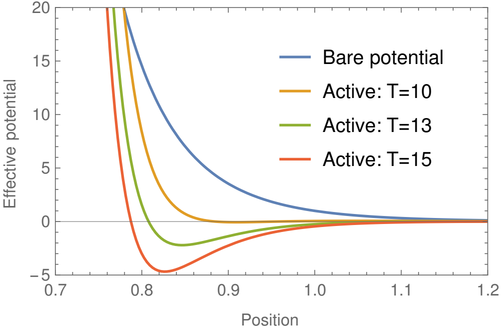


Bechinger at al, Rev Mod Phys **88**, 045006 (2016)

Modelling active fluctuations

Effective potential $\quad U_{\text{eff}} = -T_{\text{A}} \ln P_{\text{S}}$

$$U_{\text{eff}} = U + \frac{\tau}{\gamma}\left[\frac{(\nabla U)^2}{2} - T_{\text{A}}\nabla^2 U\right]$$



Repulsive bare potential

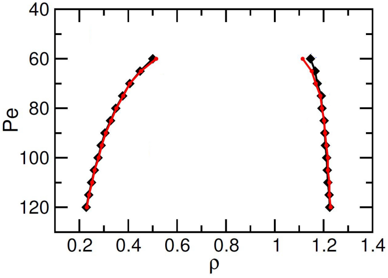
$U \sim 1/r^{12}$

Effective attraction in U_{eff} due to persistence

Modelling active fluctuations

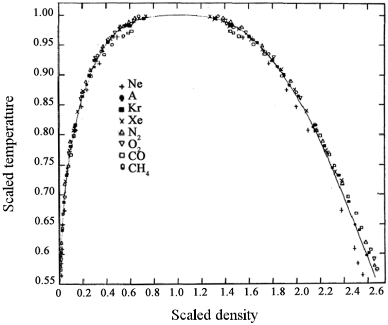
Phase diagram: Persistence (Pe) vs density (ρ)

Active particles



Solon, Stenhammar, Cates, Kafri, Tailleur, PRE **97**, 020602(R) (2018)

Equilibrium analogue

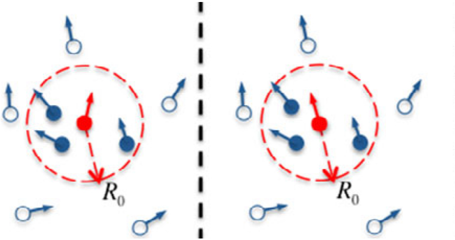


Guggenheim, J Chem Phys **13**, 253 (1945)

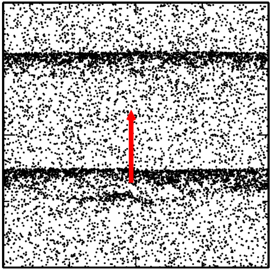
Modelling active fluctuations

Flocking transition towards collective motion

Vicsek model of aligning active particles



Ginelli, Eur Phys J **225**, 2099 (2016)

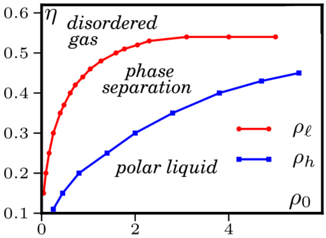


Chaté *et al*, PRE **77**, 046113 (2008)

Modelling active fluctuations

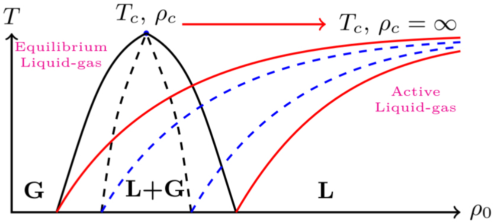
Phase diagram: Persistence $(1/\eta)$ vs density (ρ)

Active particles



Solon *et al*, PRL **114**, 068101 (2015)

Equilibrium analogue

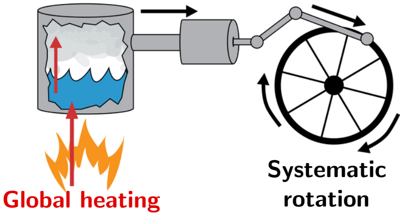


Solon *et al*, PRE **92**, 042119 (2015)

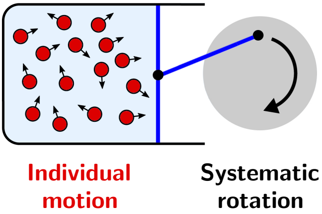
Statistical mechanics of fluctuating systems

How to extract energy from perturbation?

- Passive engine



- Active engine



19^{th} century Physics

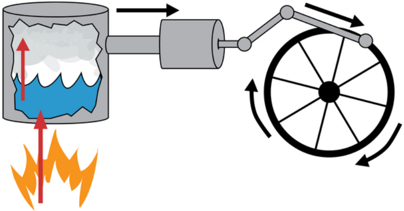
Passive thermodynamics

21^{st} century Physics

Active thermodynamics

Foundations of thermodynamics

Designing and optimizing thermal engines



Sadi Carnot

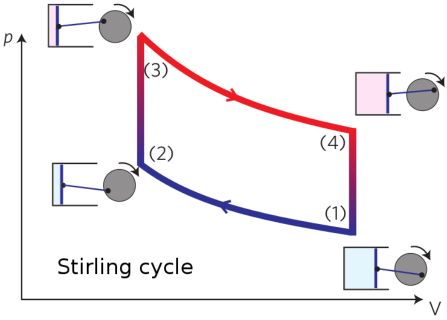
Robert Stirling

"Science owes more to the steam engine
than the steam engine owes to Science"

Lawrence J. Henderson

Foundations of thermodynamics

Designing and optimizing thermal engines



Blickle, Bechinger, Nat Phys **8**, 143 (2011)

Sadi Carnot

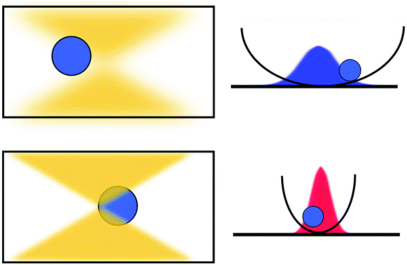
Robert Stirling

Compress at low pressure and expand at high pressure

Foundations of thermodynamics

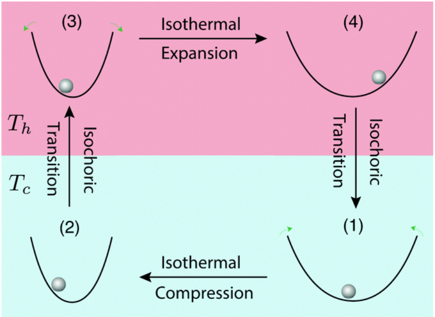
Colloid confined in harmonic trap

Optical tweezers



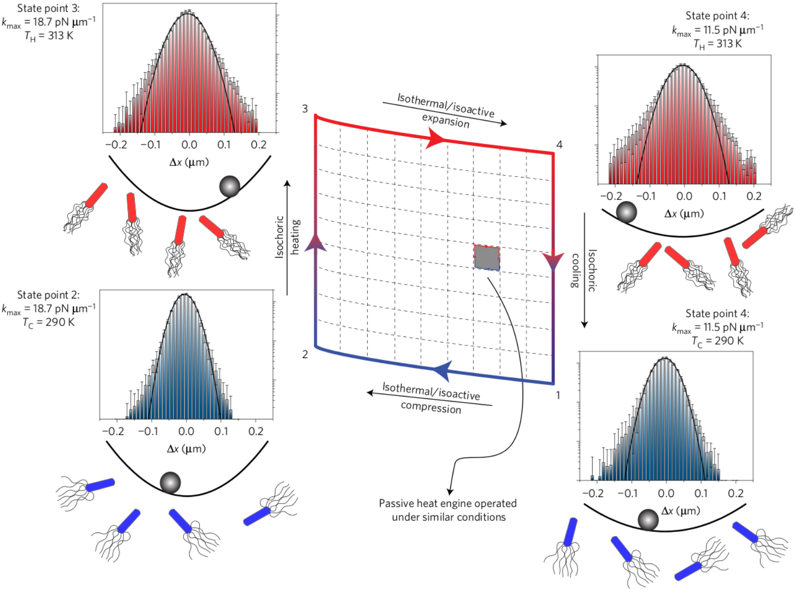
Martínez, Roldán, Dinis, Rica,
Soft Matter **13**, 22 (2017)

Colloidal engine



Blickle, Bechinger, Nat Phys **8**, 143 (2011)

Foundations of thermodynamics



Krishnamurthy, Ghosh, Chatterji, Ganapathy, Sood, Nat Phys **12**, 1134 (2016)

Overview of the course

From equilibrium to nonequilibrium systems

- What are the main features of equilibrium?

  Week 1 to Week 7

  Role of dynamical reversibility

  Thermodynamics at small scales

- What are the consequences of irreversibility?

  Week 8 to Week 14

  Nonequilibrium properties of active matter

  From single particle to collective effects