Emergence in magnets, zebrafish and fruit flies

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Introduction

Goals:

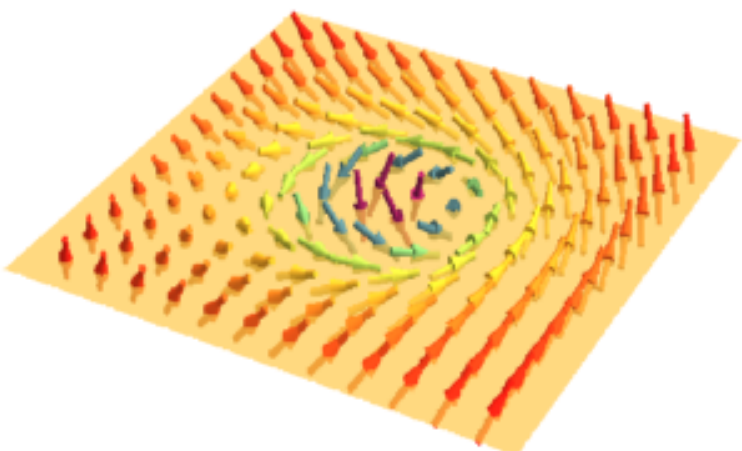
- Introduce myself
- Recap research in previous field of magnetic skyrmions
- Connect and contrast with living systems
- Sketch projects with Madan Rao and Sarthak Chandra

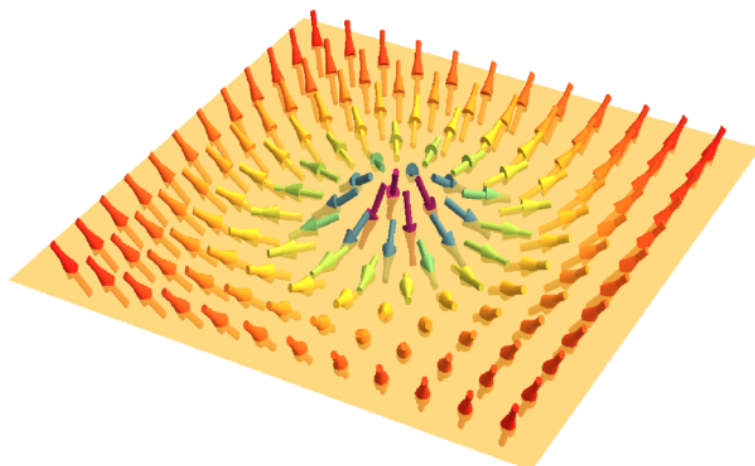
Academic History

Bachelors: Physics	Uni. of Cambridge
Masters: Theoretical Physics (QFT)	Uni. of Cambridge
PhD: Magnetic Skyrmions	Heriot-Watt Uni.
Teaching position: Applied Maths	AIMS-Senegal
First postdoc: more Skyrmions	FORTH/Uni. of Crete
Second postdoc: Biology!	NCBS/ICTS

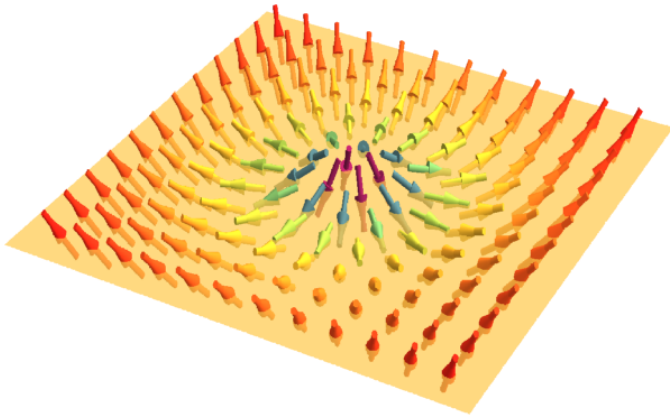
What is a magnetic skyrmion?

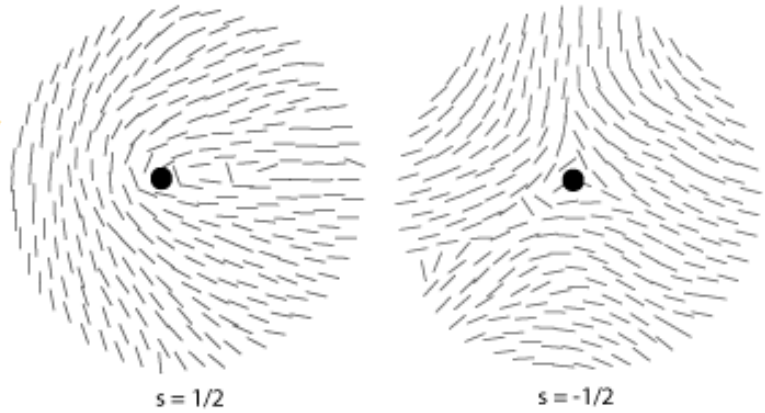
- An emergent, localised, mobile structure, like a water wave or a carpet bump. The medium in this case is magnetic orientations in a thin chiral magnet.
- However fundamentally discrete: you cannot have half a skyrmion*, due to topological constraints - like a knot. This also gives it stability.
- A topological soliton - close to, but not the same as, a topological defect.





Comparison to nematic defects





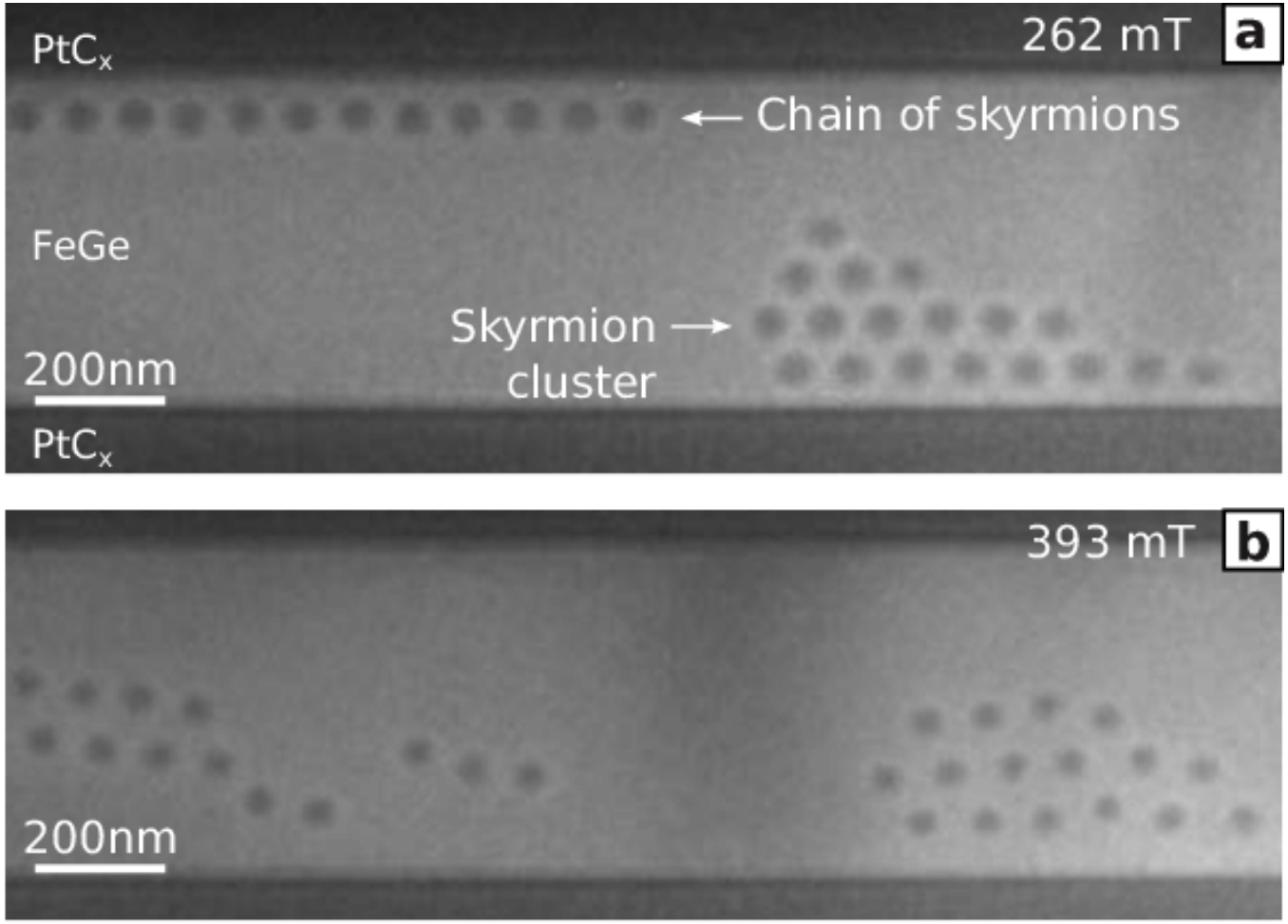
Similarities

- Localised
- Mobile
- Differentiated from uniform state by ‘degree’

Differences

- Skyrmions describe more of the low-energy dynamics
- No ‘active skyrmions’
- Skyrmions continuous everywhere

What are skyrmions good for?

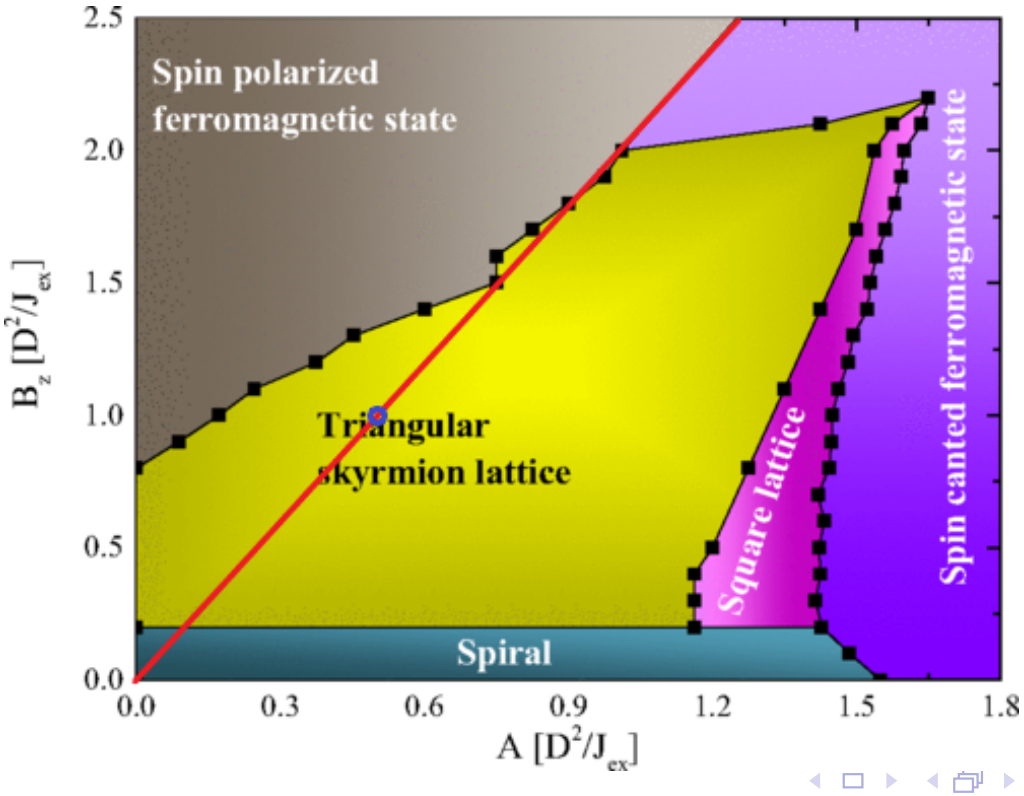


- Theoretical interest: discreteness, particle-vortex duality, multiple-layer emergence
- Mobile data storage
- Neuromorphic/reservoir computing

What do we want to know about skyrmions?

We can start with a model of the underlying magnet and try to derive their properties

- Types of skyrmion
- Conserved quantities
- Inter-skyrmion forces
- Response to probes
- Morphology
- Stability



Methods

Magnetic dynamics on this lengthscale is well-described by the continuum magnetisation field $\boldsymbol{n}(\boldsymbol{x}, t)$, $|\boldsymbol{n}| = 1$, evolving according to the Landau-Lifshitz equation:

$$\dot{\boldsymbol{n}} = \underbrace{\boldsymbol{n} \times \frac{\delta E}{\delta \boldsymbol{n}}}_{\text{precession}} - \underbrace{\alpha \frac{\delta E}{\delta \boldsymbol{n}_{\perp}}}_{\text{damping}} + \ldots \tag{1}$$

NB: both thermal and quantum fluctuations neglected. Governed by energy functional $E(\boldsymbol{n}) = \int \frac{1}{2}(\nabla \boldsymbol{n})^2 + k\boldsymbol{n} \cdot (\nabla \times \boldsymbol{n}) + V(\boldsymbol{n}) d^2x$ We are thus studying a nonlinear PDE. If we want analytical insight beyond numerics, we can simplify by

- focusing on energy E rather than directly on dynamics
- ansatze to reduce PDE to ODE in important d.o.f.
- small perturbations from special cases with exact solutions

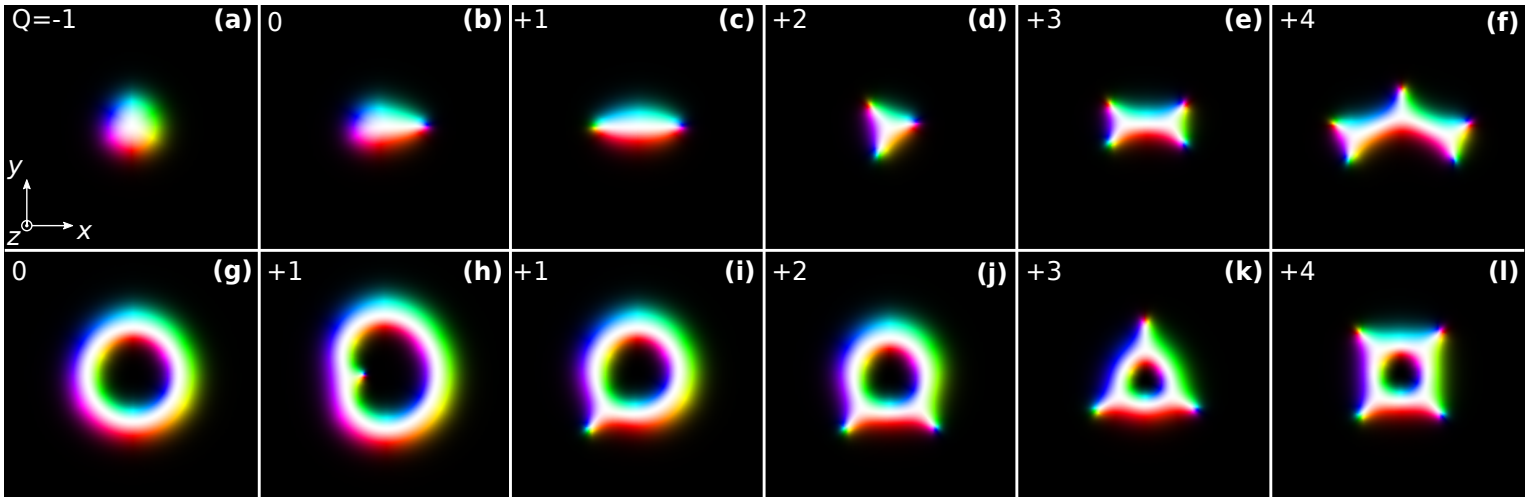
Results: The skyrmion 'zoo'

Standard physically motivated potential:

$$V(\boldsymbol{n} = (n_x, n_y, n_z)) = h(1 - n_z) + u(1 - n_z^2)$$

At special point in the phase diagram $h = -2u = k^2$, there is a huge space of exact energy minima: equilibria of the dynamics.[1]

Away from this special point, we can take these equilibria as starting points and do energy minimization



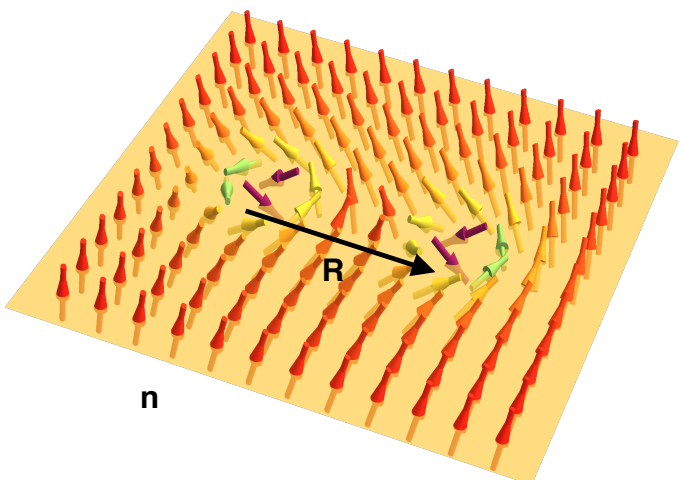
[1] Bogomol'nyi argument, re-interpreting the $\boldsymbol{n} \cdot (\nabla \times \boldsymbol{n})$ term as a cross-term from a covariant derivative.

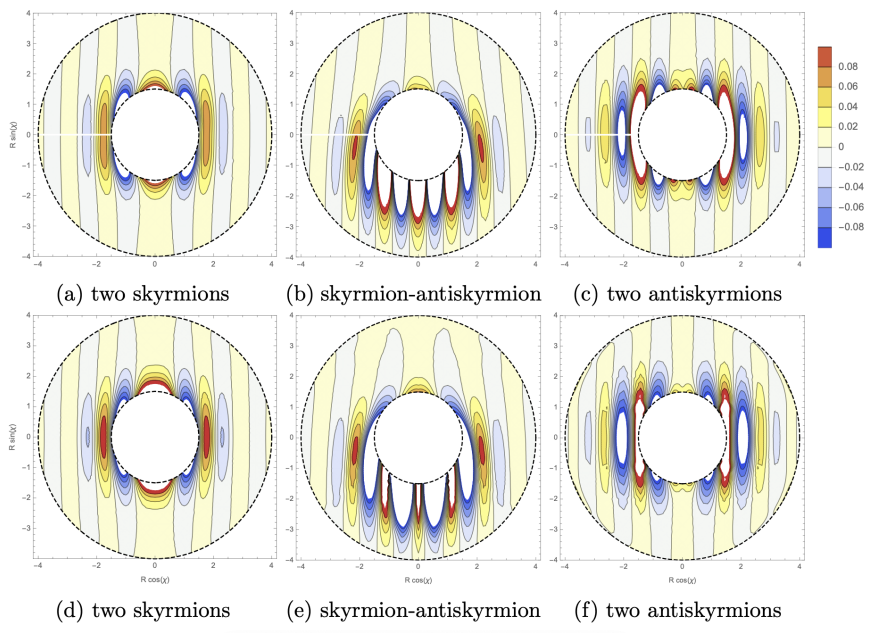
Results: Skyrmion interactions

Will two skyrmions repel or attract? Numerically: fix centres of skyrmions and minimize energy to plot 'inter-skyrmion potential'

In fact, given the profile of an isolated skyrmion (one-shot energy minimization), we can reproduce this potential to high accuracy[2]

Particular example: $V(\boldsymbol{n}) = h(1 - \hat{\boldsymbol{h}} \cdot \boldsymbol{n})$



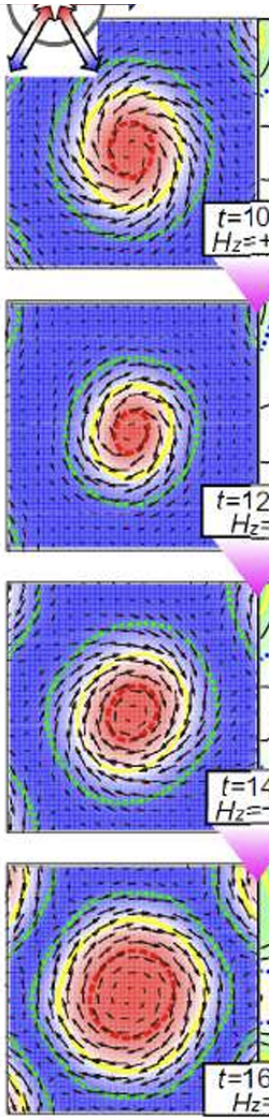


(a) two skyrmions (b) skyrmion-antiskyrmion (c) two antiskyrmions

(d) two skyrmions (e) skyrmion-antiskyrmion (f) two antiskyrmions

[2] As distance increases, each skyrmion is a small perturbation on the other and thus on its energy. This applies to localised structures in general.

Results: Skyrmion breathers and collapse



Dynamically, skyrmions don't only translate: they have a 'size mode' which is coupled to a 'helicity mode'.

If fluctuations in size become large enough the skyrmion can collapse.

We can find this behaviour from another strange limit: $k \to \infty$, $V(\boldsymbol{n}) \to \infty$

In this limit, Landau-Lifshitz dynamical equation becomes a fluid-flow (Euler) equation: $\dot{\boldsymbol{n}} = -2k(\boldsymbol{n} \cdot \nabla)\boldsymbol{n} + \boldsymbol{n} \times \frac{\partial V}{\partial \boldsymbol{n}}$ with many explicit solutions from method of characteristics.

Image credit: Mochizuki, "Spin-Wave Modes and Their Intense Excitation Effects in Skyrmion Crystals", Phys. Rev. Lett. 2012

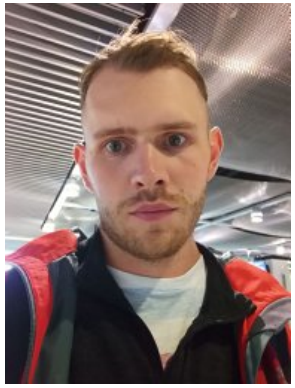
Half-time acknowledgments

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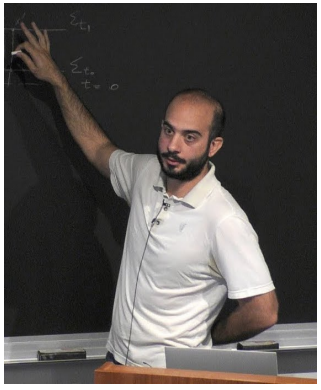

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Why biology?

Research theme: multi-layered emergence of surprising collective behaviour from microscale to macroscale

Skills: model building, dynamical systems, differential geometry, asymptotics and simulation

Both aspects of this are more exciting in living systems!

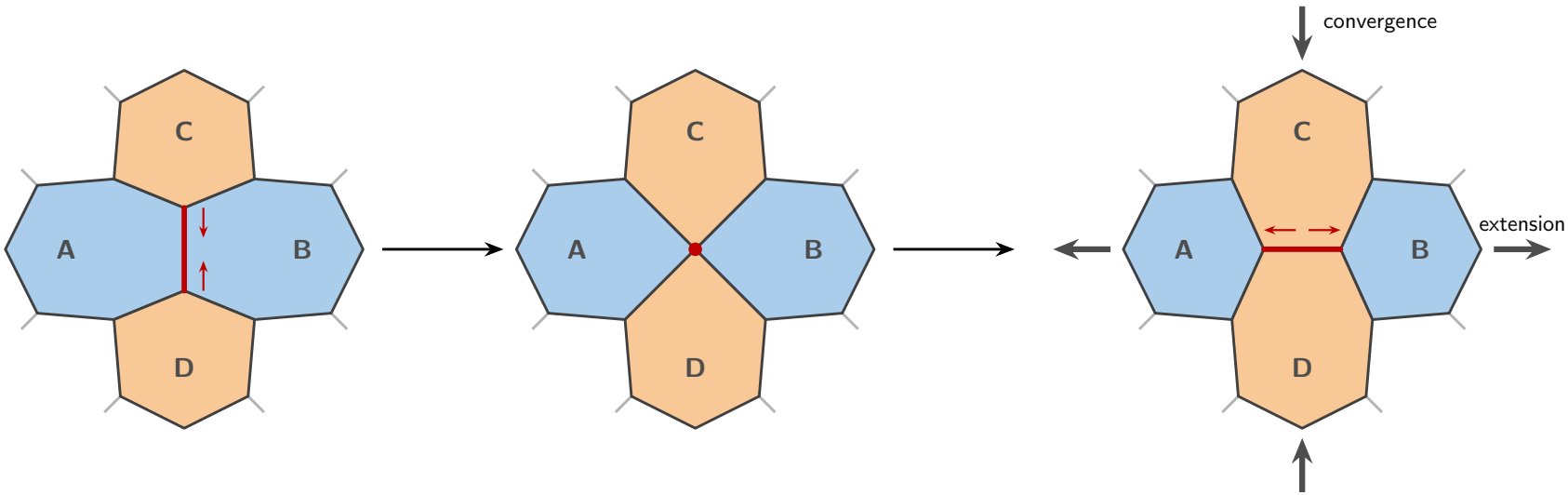
- Collective behaviour is aimed at a goal on macroscale and learned on microscale.
- Systems are so complex that space of potentially useful models is large.

Control theory of ratcheting in Drosophila morphogenesis (Madan Rao)

Question: Why does morphogenesis involve tissues 'ratcheting'?

Example: Germband extension in Drosophila

- Mediated by T1 transitions
- Epithelial junction length ratchets down in response to pulses of myosin (LeCuit)



Goal: Model this process and determine what problems ratcheting is solving, what picks the parameters. Look at other ratcheting processes.

Single junction dynamics

Modelled with ODE coupling length, junctional myosin, etc.

In existing models, different feedbacks between mechanics and chemical signals are proposed:

- length change $\mapsto$ change in rates of myosin (un)binding
- length down $\mapsto$ cadherin concentration up $\mapsto$ myosin down
- length change $\mapsto$ change in monomer vs cluster cadherin $\mapsto$ change in tension, relaxation time

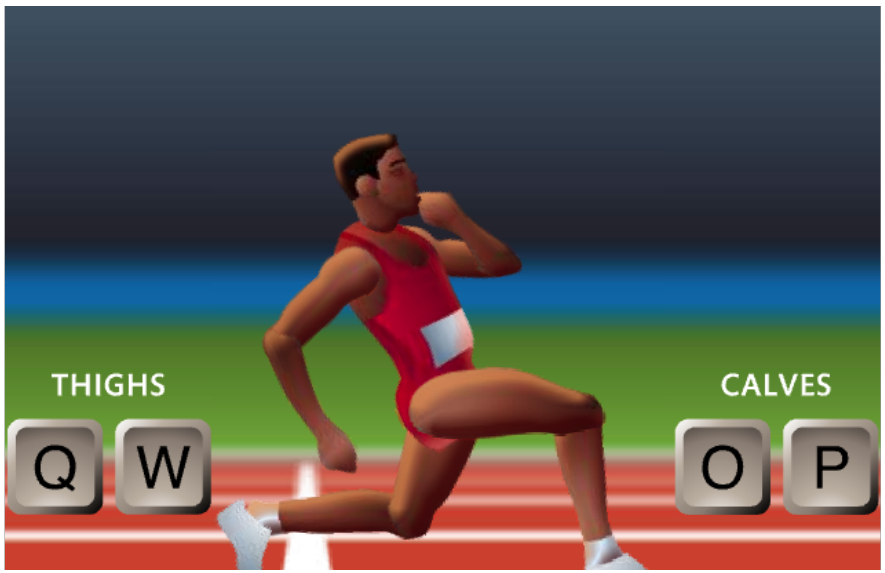
We must first find which of these models reproduce ratcheting in response to myosin pulses.

Beyond that we want to understand why and how the pulse parameters are chosen and controlled. On the tissue level, we must infer active forces and learn their interplay with medial and junctional myosin etc.

Learning motor control in developing spiking networks (Sarthak Chandra)

Question: How do animals learn to move early in development?
Example: Zebrafish learn basic tail motion before hatching

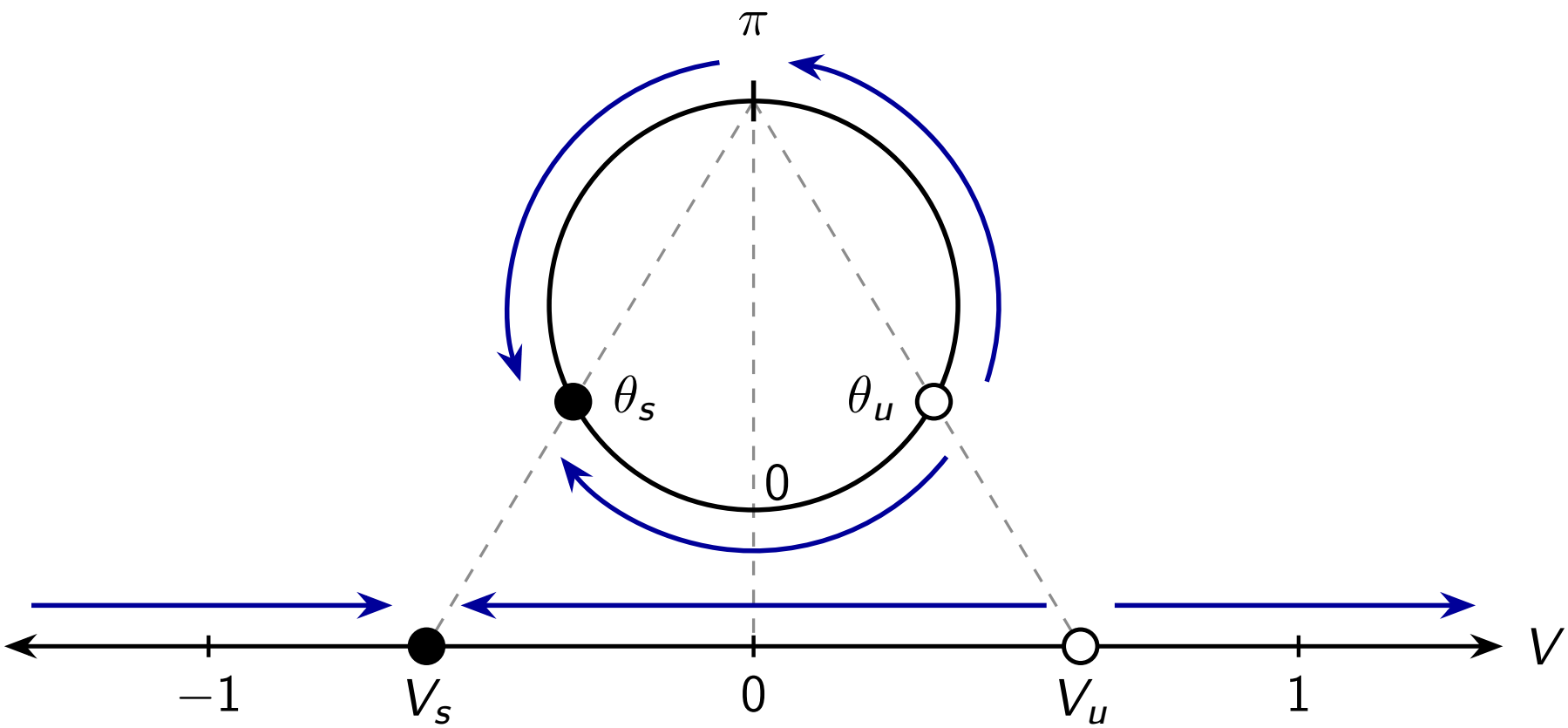
- synchronisation, but also...
- phase differences
- low-D space of activations (e.g. antagonistic muscles)



Goal: Come up with a learning spiking neuron model which changes size/topology over time, that generates this behaviour. Take lessons for robotics/schedule learning.

Theta neuron networks

$$\dot{\theta}_i = (1 - \cos\theta) + (I_i + \eta_i)(1 + \cos\theta), \quad I_i = \sum_j A_{ij} P(\theta_j) \qquad (2)$$



Search for synchronisation/phases/dimension in different topologies

Thanks for listening!