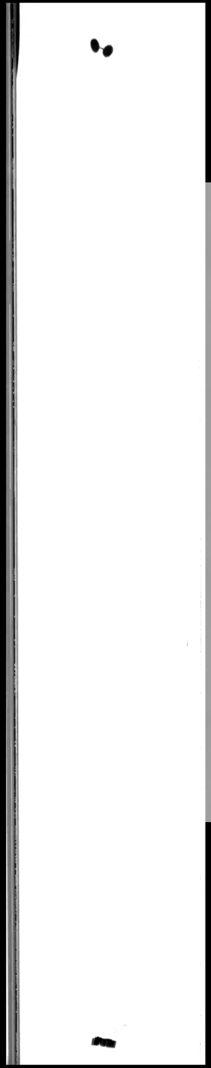
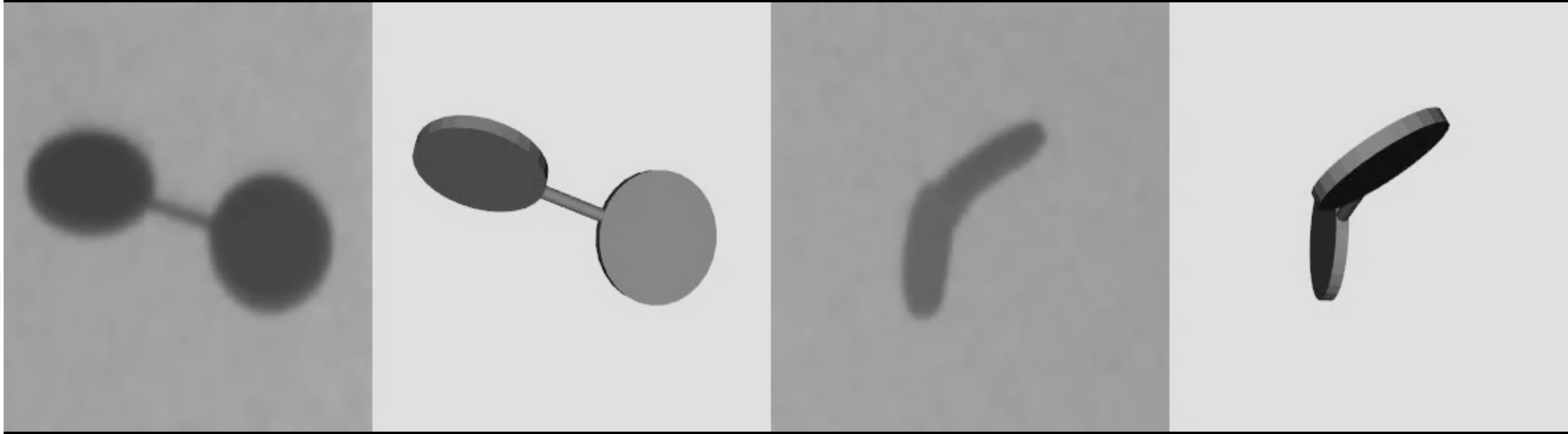
Eindhoven, January 2026

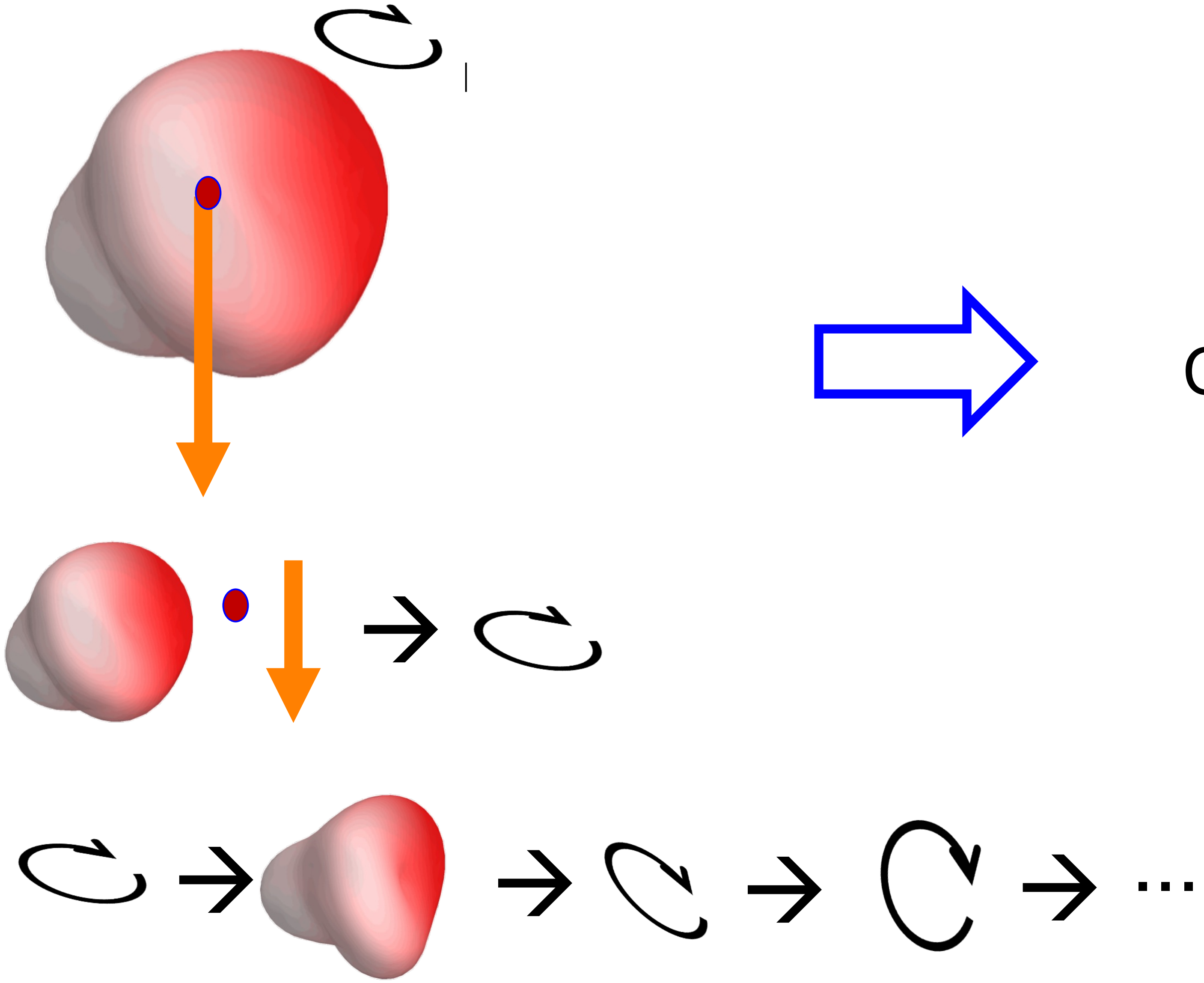


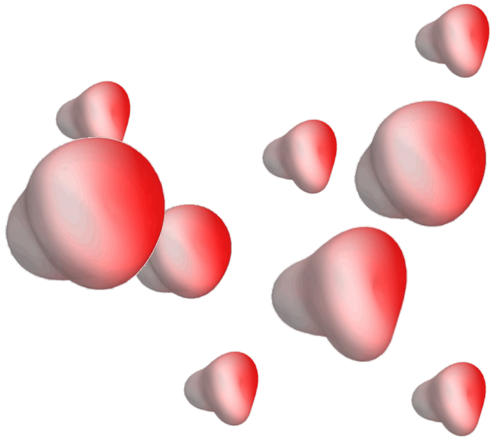


Tom Witten, University of Chicago

Forced objects in viscous fluid → "meta-suspensions"

Viscous sedimentation





Controlled

collective orientation,

positioning,homogeneity

constitutive properties

hydrodynamic
optical

...

Engineering sedimentation-based meta-suspensions

Laws of rotational motion for sedimenting objects

Self-organizing motion:
what organized states?
how to produce them

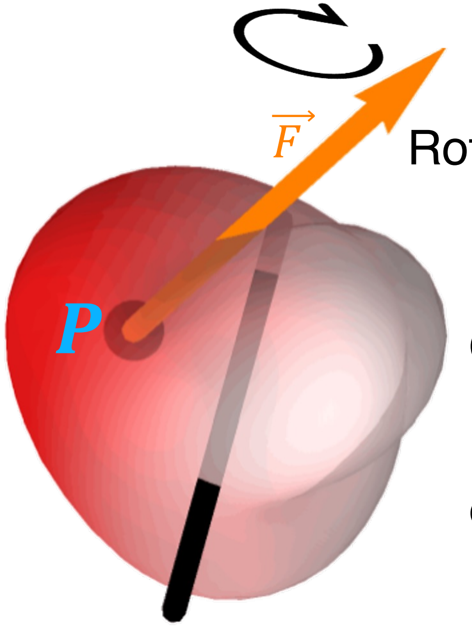
Predicting motion of real objects

Experiments: predicted vs real motion

US-Israel Binational Science foundation
Emory University
Tel-Aviv University
University of Chicago

How force direction affects rotation: **B** tensor

Viscous sedimentation



Rotation $\vec{\omega}$ depends on

External force $\vec{F}$

Object shape

Forcing point $\vec{P}$
eg center of mass

Rotational velocity
$\vec{\omega} \propto \vec{F}$,via “twist” tensor **B**:
$\vec{\omega}$ = **B** $\vec{F}$

In *body-fixed frame,*
B is *constant* in time, but
$\vec{F}$ *rotates:*
$\dot{F}\,(t) = \vec{\omega} \times \vec{F}$ = (**B** $\vec{F}$) $\times \vec{F}$

Parts of **B** tensor

Symmetric part $\mathbf{B}_S$

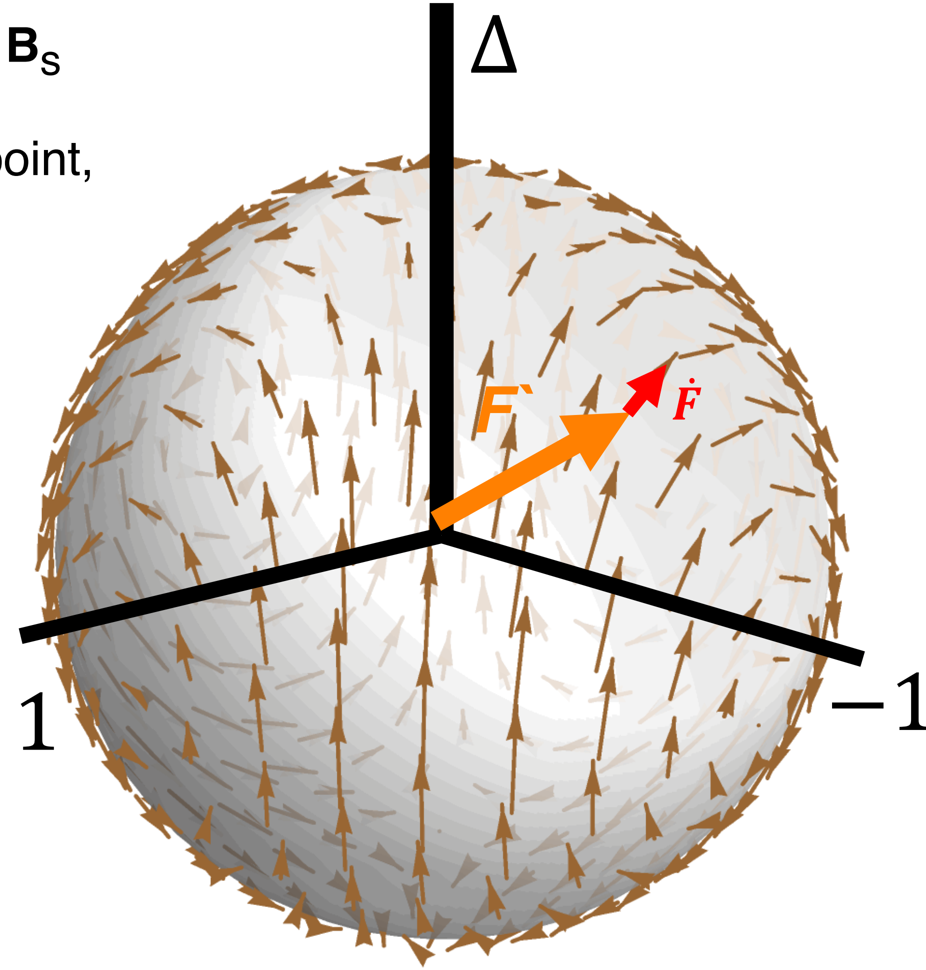
For a given shape and forcing point,
Chose axes so that

$$\mathbf{B}_S = \begin{bmatrix} b1 & 0 & 0 \\ 0 & b2 & 0 \\ 0 & 0 & b3 \end{bmatrix}$$

Simpler form is sufficient

$$\mathbf{B}_S = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \Delta & 0 \\ 0 & 0 & -1 \end{bmatrix}$$

Only Δ affects geometry.
We suppose Δ .=0.2



All motions are qualitatively the same

Origin of antisymmetric part of **B**: $\mathbf{B}_a$

$$\mathbf{B}_a = \begin{bmatrix} 0 & -ba3 & ba2 \\ ba3 & 0 & -ba1 \\ -ba2 & ba1 & 0 \end{bmatrix}$$

where

$$\overrightarrow{B_a} = (ba1, ba2, ba3)$$

$\overrightarrow{B_a}$ Depends *only* on forcing point ● $\vec{P}$:

$$\overrightarrow{B_a} = (matrix)\,(\vec{P} - \vec{P}_0)$$

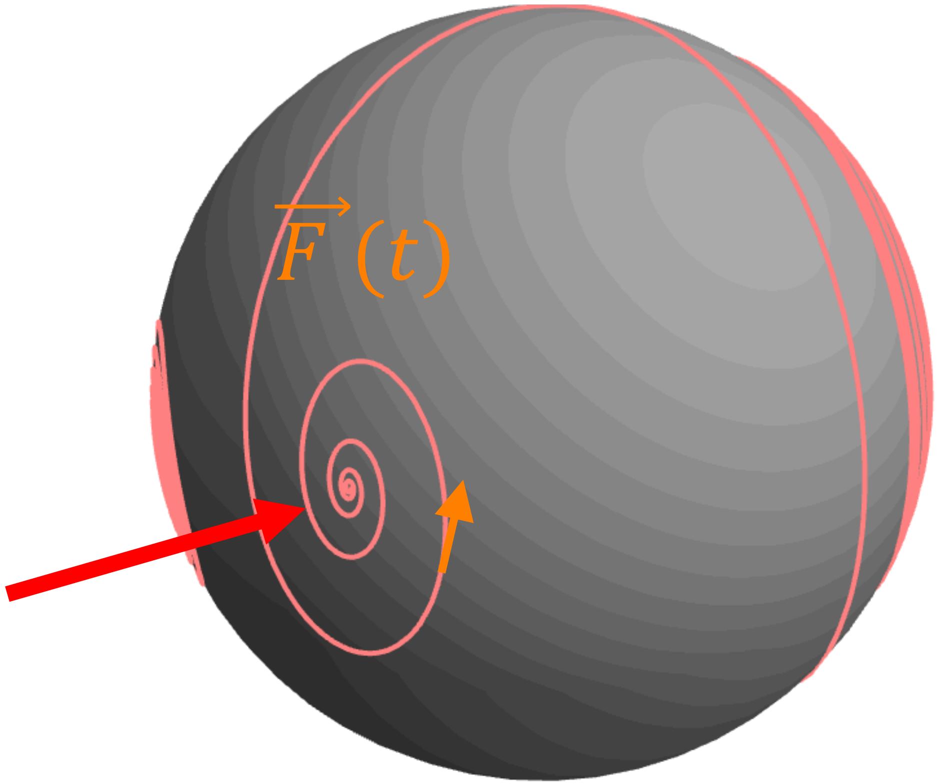
So... One may select *any* $\vec{B}_a$ by moving ●

(eigen axes of $\mathbf{B}_s$ also change)

$\mathbf{B}_a$"organizes" the motion

Many F(0)'s → single final F

... Makes a few final orientations



Stable fixed point

What makes a fixed point stable, unstable?

Fixed points

Fixed point: $\dot{F} = 0$

B F || F ...F is *eigenvector*

Reversing *time* reverses stability

$$\mathbf{B} \rightarrow -\mathbf{B}$$

$$\dot{F} \;(= (\mathbf{B}\,\overrightarrow{F}) \times \overrightarrow{F}) \rightarrow -\dot{F}$$

$$\nabla \cdot \dot{F} \rightarrow -\nabla \cdot \dot{F}$$

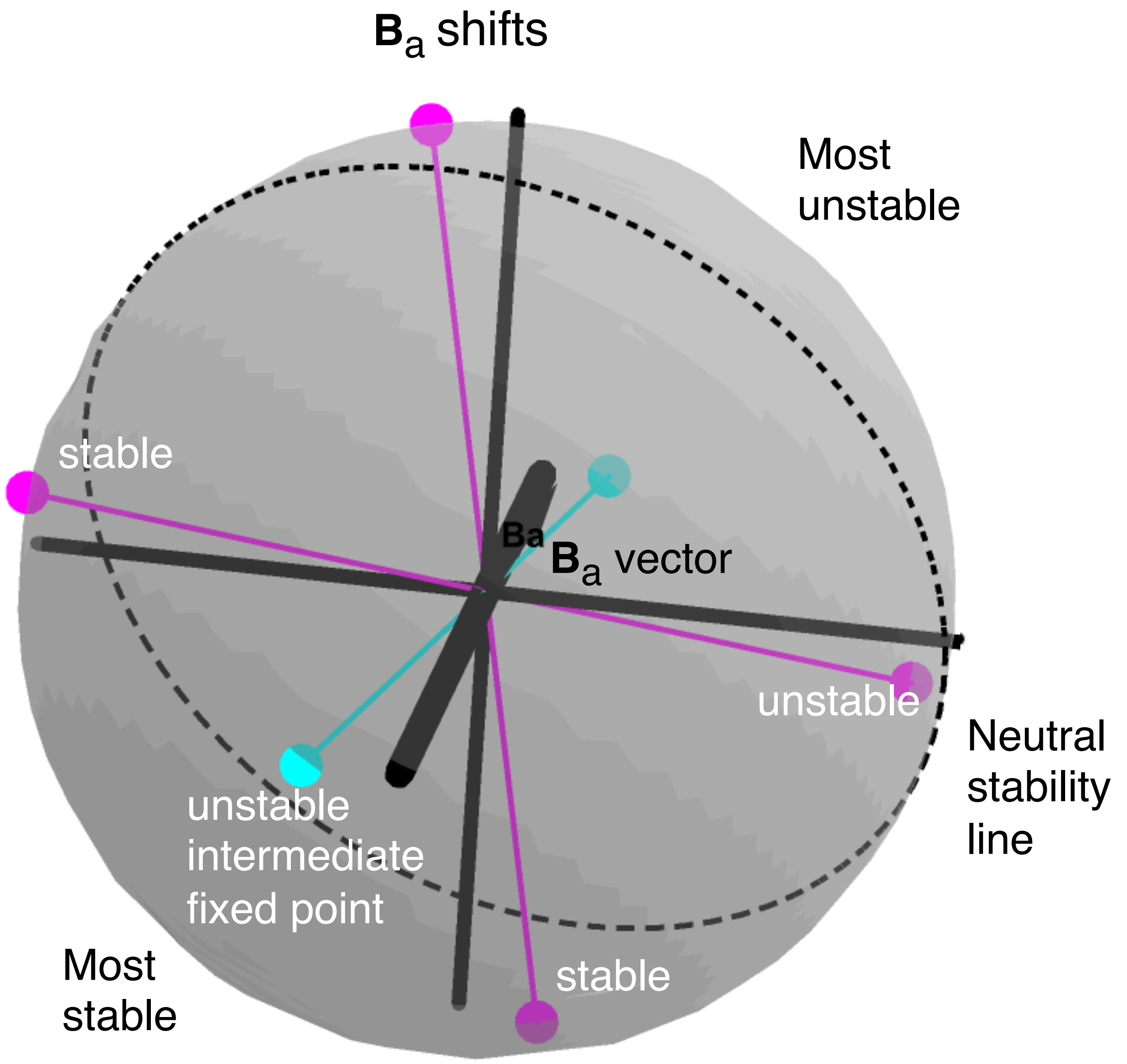
stability means $\nabla \cdot \dot{F} < 0$

Opposite eigenvectors have opposite stability

Divergence $\nabla \cdot \dot{F}$ depends only on B_a

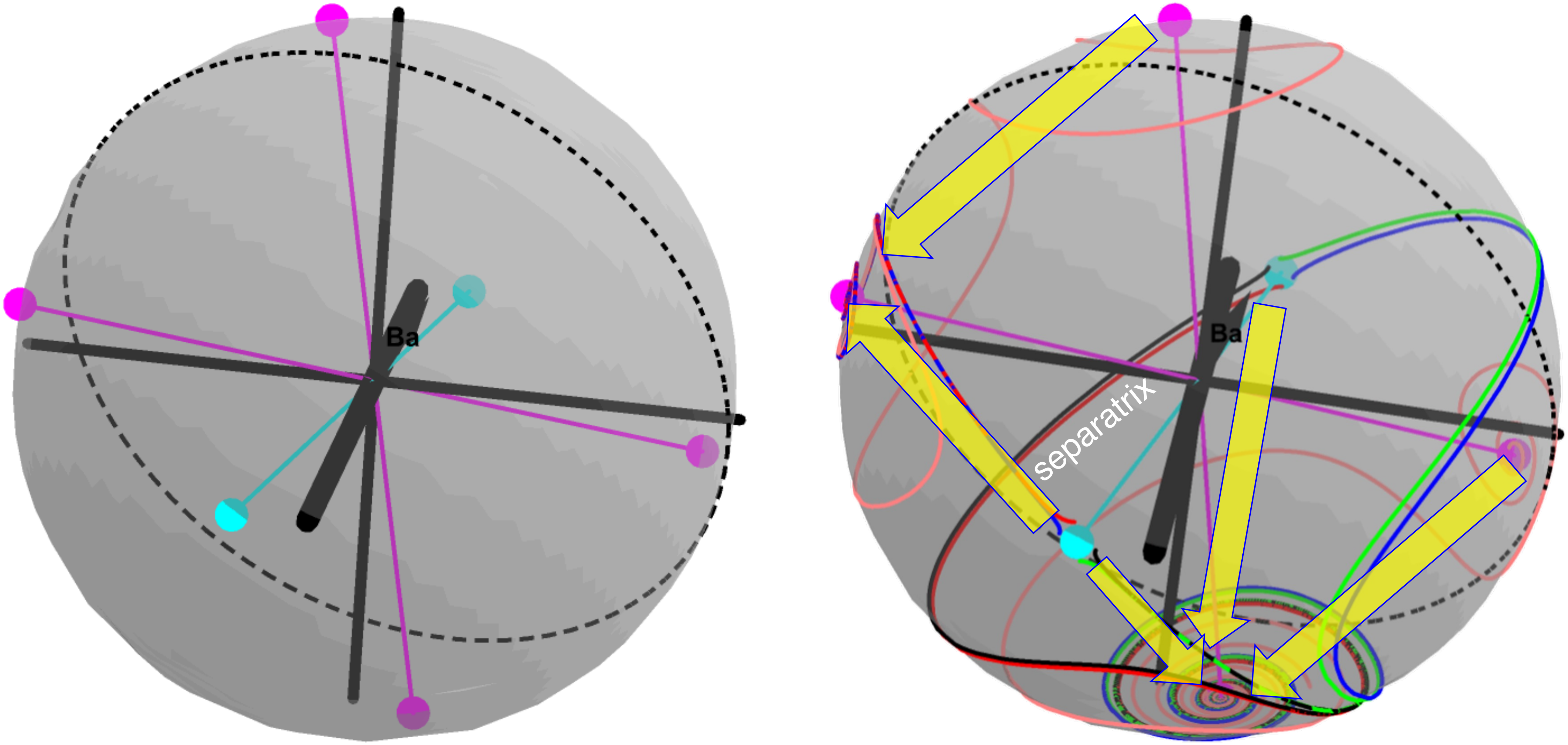
$$\nabla \cdot \dot{F} = 2\,\mathbf{B}_a \cdot \dot{F}$$

All trajectories F(t) begin or end at a fixed point



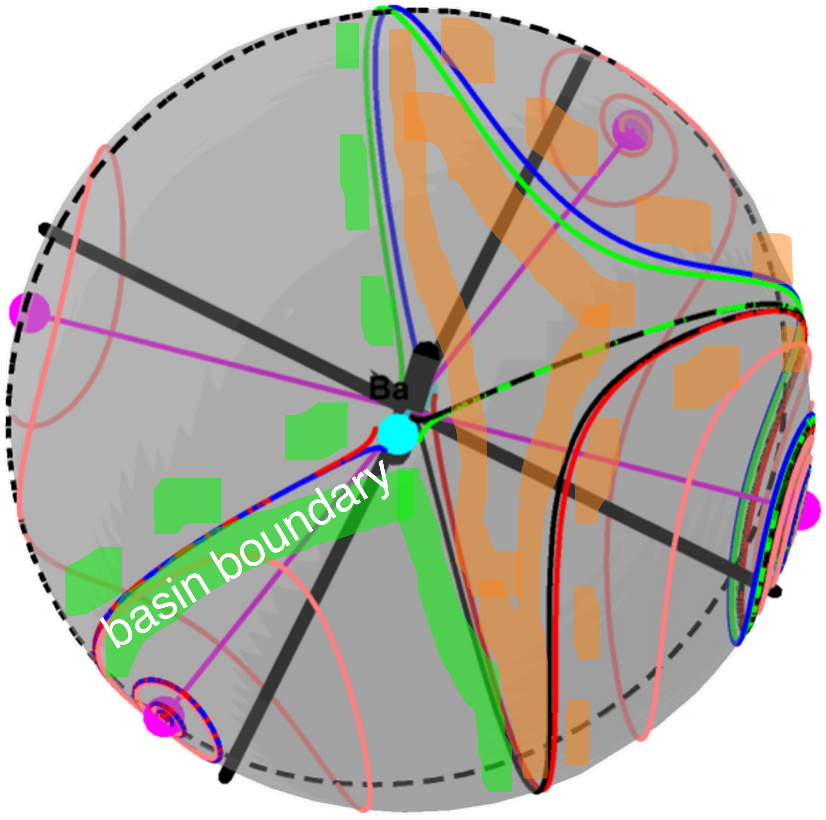
How does the flow connect the fixed points?

Generic case: Trajectories link unstable points to stable ones



Two qualitative, final-state topologies

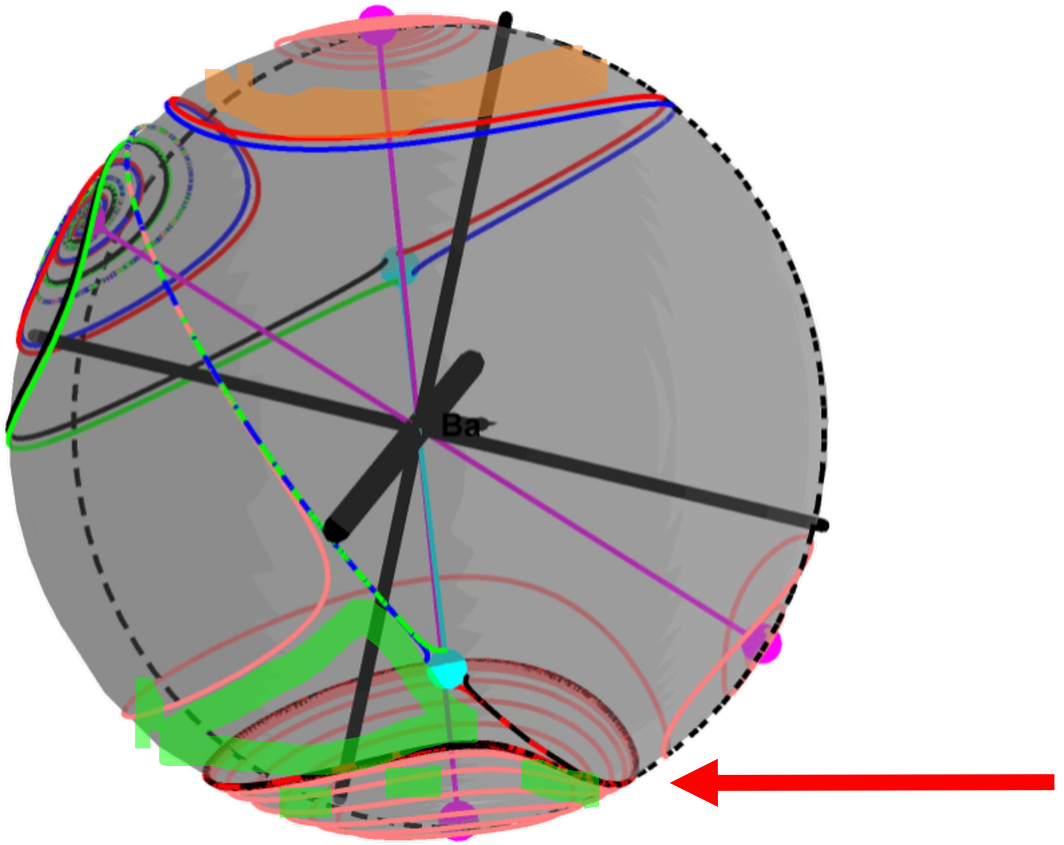
Standard topology: Two stable fixed points.



Trajectories from intermediate fixed points indicate basin boundaries

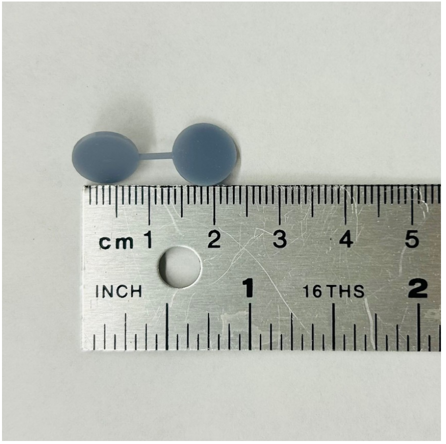
Novel topology: Two stable fixed points and a single stable orbit

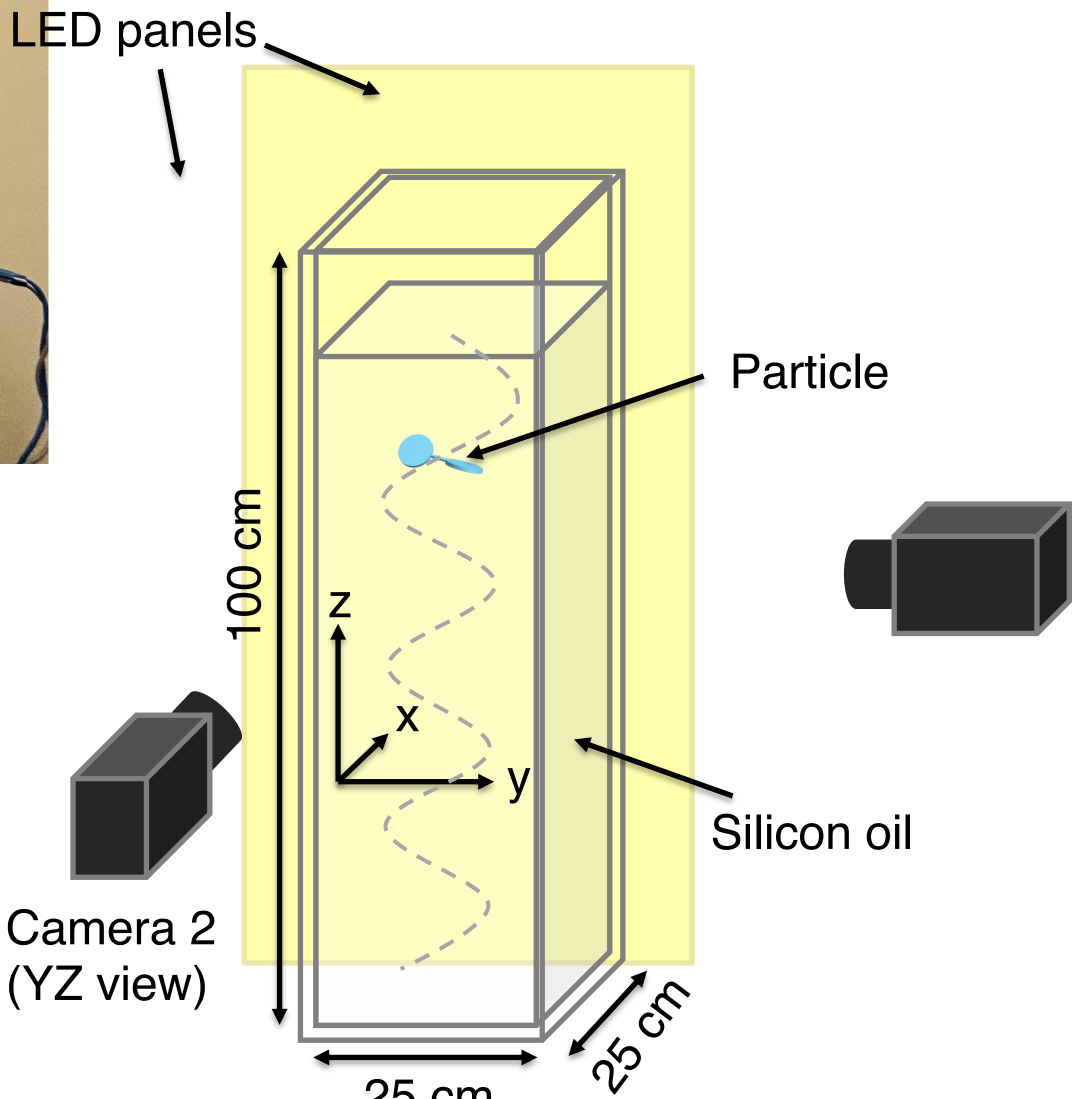
Ba = 0.15, 0.6, -0.07



Fixed orbit is bounded by a neutral boundary trajectory

Our experiment monitors real rotational sedimentation

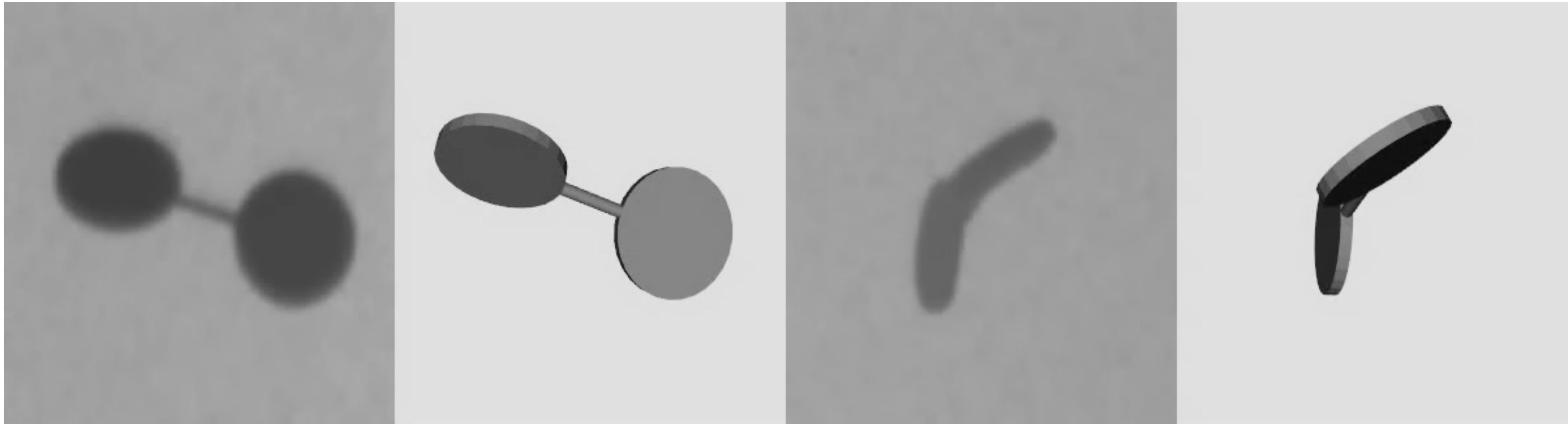




Reconstructing 3D motion

2 frames/sec, fall time (1 meter) is 2 minutes.

Silicon oil, 500 centistokes (cm^2/sec)



We reliably reconstruct 3d trajectories from video

Next step: match real motion with prediction.

Calculating **B** matrix from 3D-printed objects

STL file for 3D-printed object → Set of vertex points over boundary → Point sources of drag at each vertex represent object → Matrix inversion finds set of drag forces to create rigid body motion with given

Linear velocity V

Angular velicity ω

→ Total of drag forces is F

Gives portionality between F and V and F and ω

B

< 10000-vertices represent objects well

Few minutes on modern laptop

Conclusion

Well accepted theories of Stokes flow →

Shaped objects can make rich rotational self-organization in sedimentation

These can impart collective rotational state to a suspension

Meta-suspension

Future

How far can these predictions be realized in practice