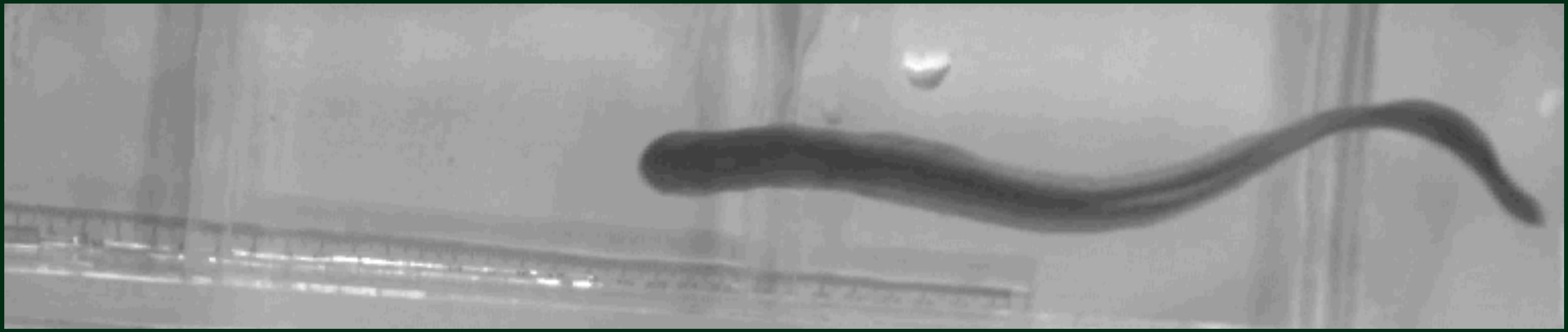
Multiscale Modeling of Coordinated Behavior in Lamprey Swimming



Christina Hamlet[1], Eric Tytell[2], Kathleen Hoffman[3], Lisa Fauci[4]

[1]Bucknell University, [2]Tufts University, [3]UMBC, [4]Tulane University,

Outline

- Why lampreys?
- Questions and goals
- Integrative computational model
- Focus on neural activation
- Sensory feedback
- Results
- New directions
- What’s next?

Image: www.redorbit.com

Lampreys have a PR problem

Horrifying Fish Monsters Are Falling From the Sky in Alaska

Blood Lake (2014)

http://cabinetoffreshwatercuriosities.com/

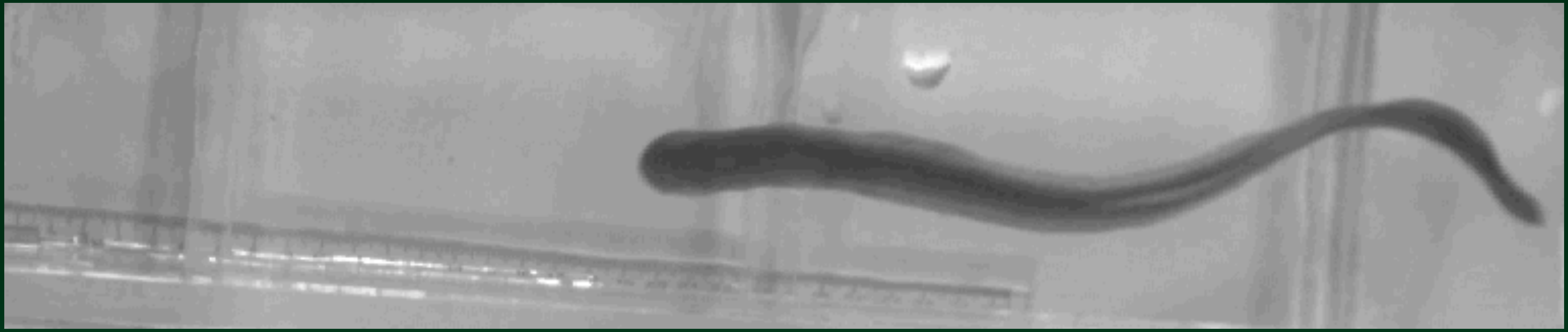
New Jersey 'sea monster' is likely a lamprey (+video)

Photos of an eel-like creature captured in New Jersey have gone viral, prompting speculations of a 'sea monster.' The animal appears to be a sea lamprey, a type of parasite common in northern Atlantic waters, experts say.

Lampreys are model organisms for swimming studies

- Anguilliform (eel-like) swimming

- Passes waves of activation down the body to contract muscles and produce traveling curvature wave

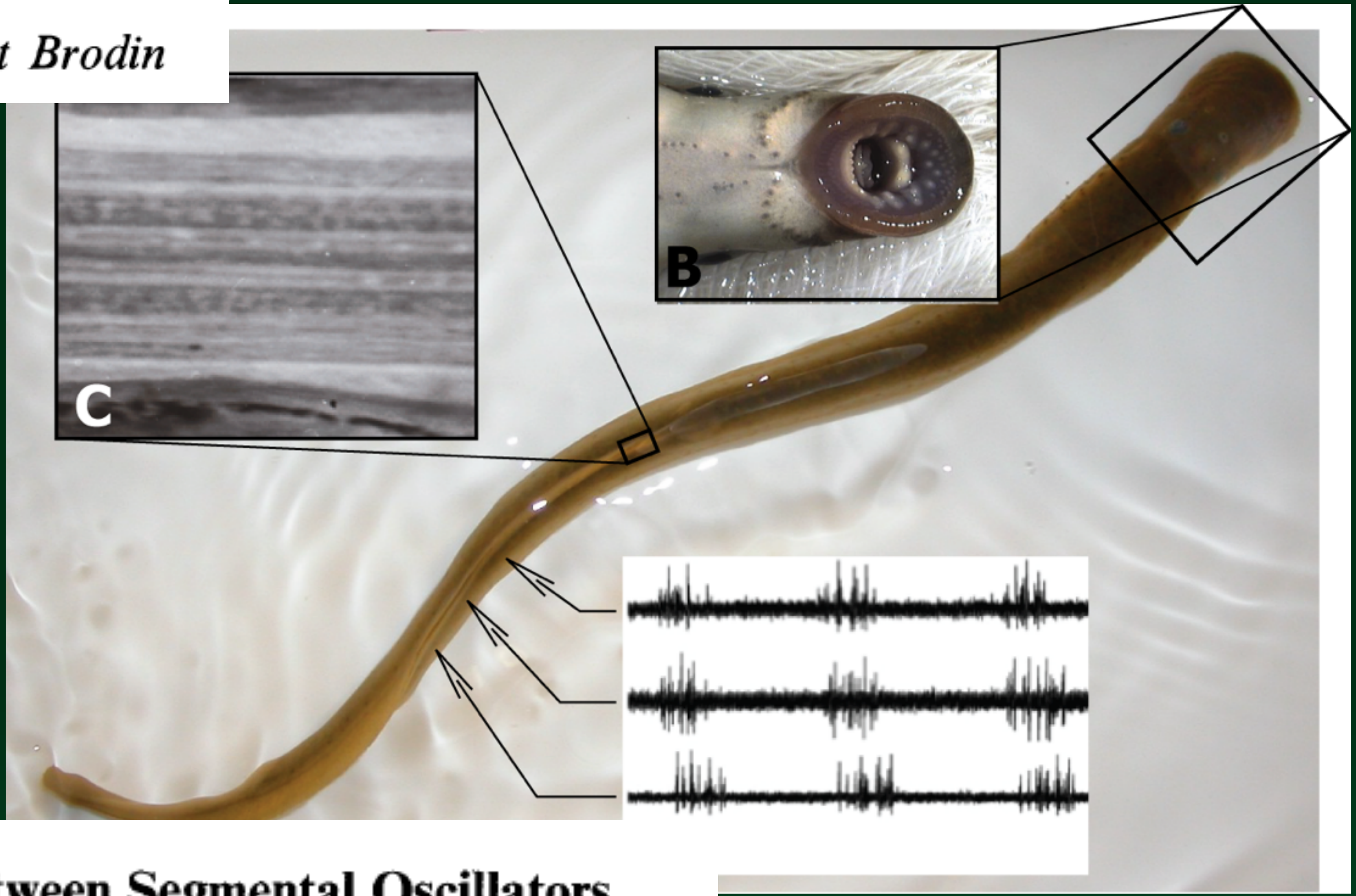


Courtesy: E. Tytell (Tufts) and M. Leftwich (GWU)

Lampreys are model organisms for neurophysiology

NEURONAL NETWORK GENERATING LOCOMOTOR BEHAVIOR IN LAMPREY:

Sten Grillner, Peter Wallén and Lennart Brodin



The Nature of the Coupling Between Segmental Oscillators of the Lamprey Spinal Generator for Locomotion: A Mathematical Model

Avis H. Cohen[1], Philip J. Holmes[2] and Richard H. Rand[2]

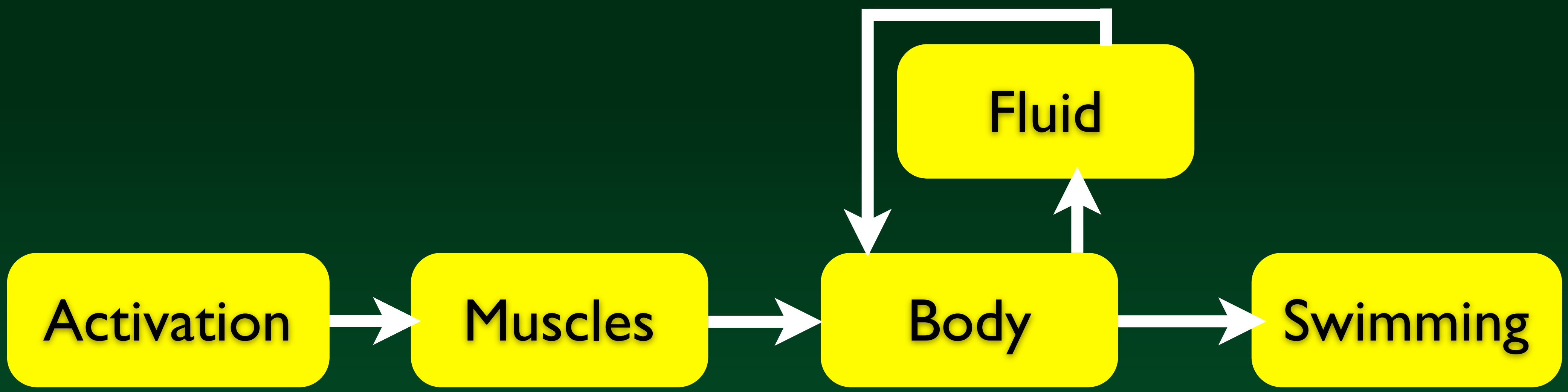
Questions

- How does a lamprey swim?
- What components are involved in producing swimming behavior?
- What is the role of sensory feedback in maintaining steady swimming and in maneuvering?

Approach

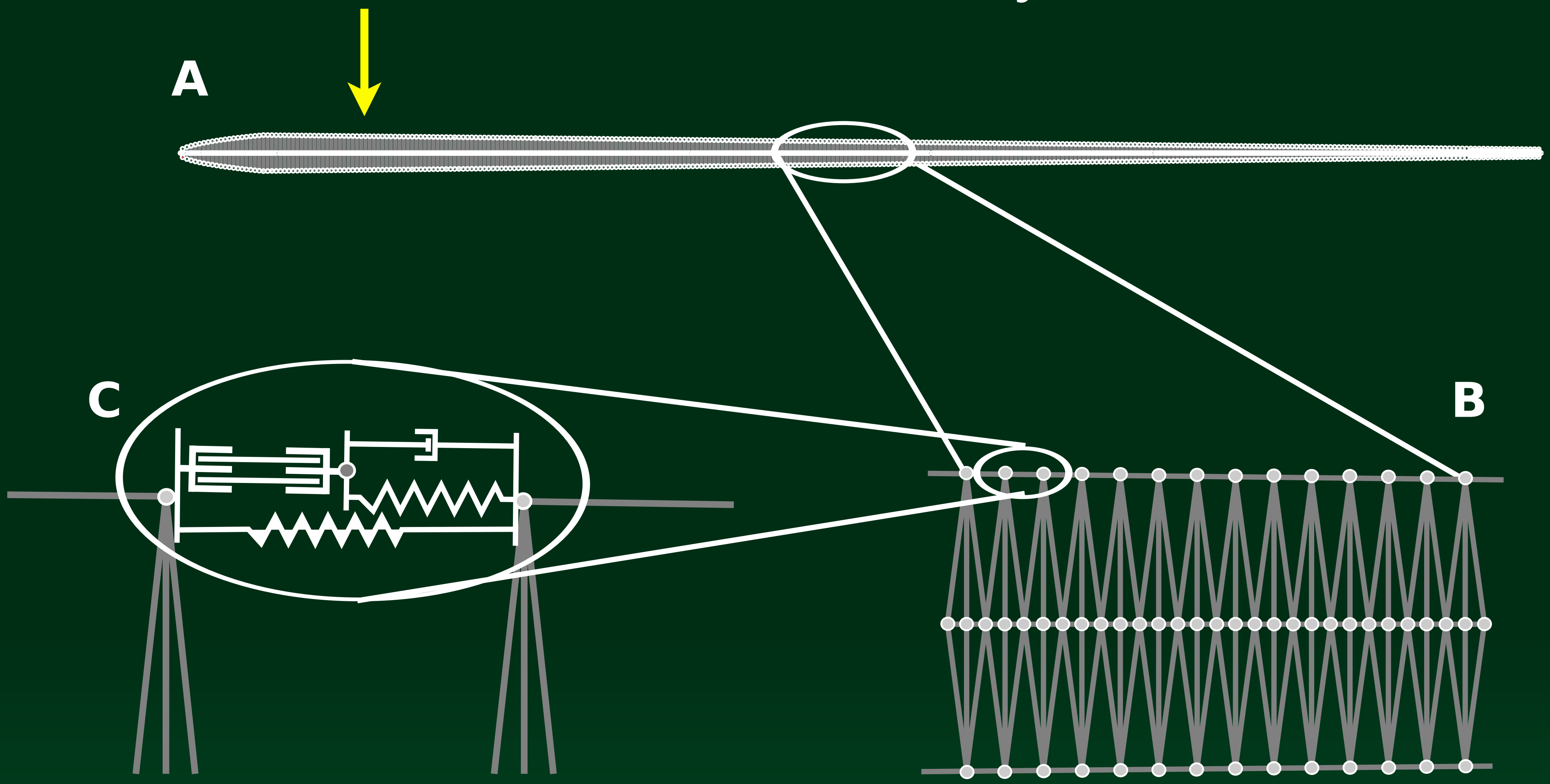
- Construct individual models
- Coordinate the models
- Construct multi-scale integrative computational model
- Compare computational results to experiment

Individual models



Computational body

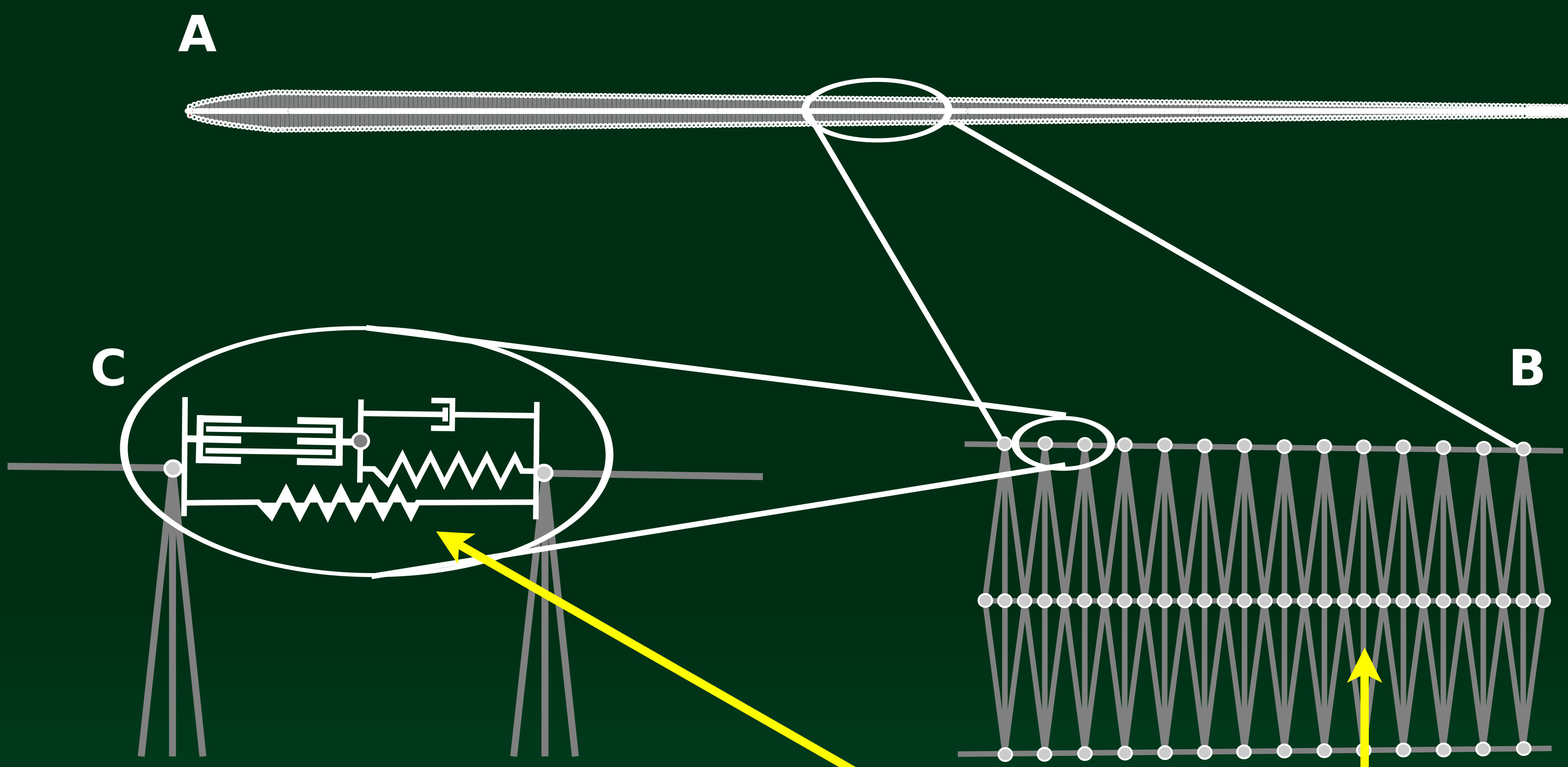
Points describe body



Hamlet, Fauci, Tytell, J.Theo. Bio 2015

Tytell, Hsu, William, Cohen, Fauci, PNAS 2011

Springs resist deformation

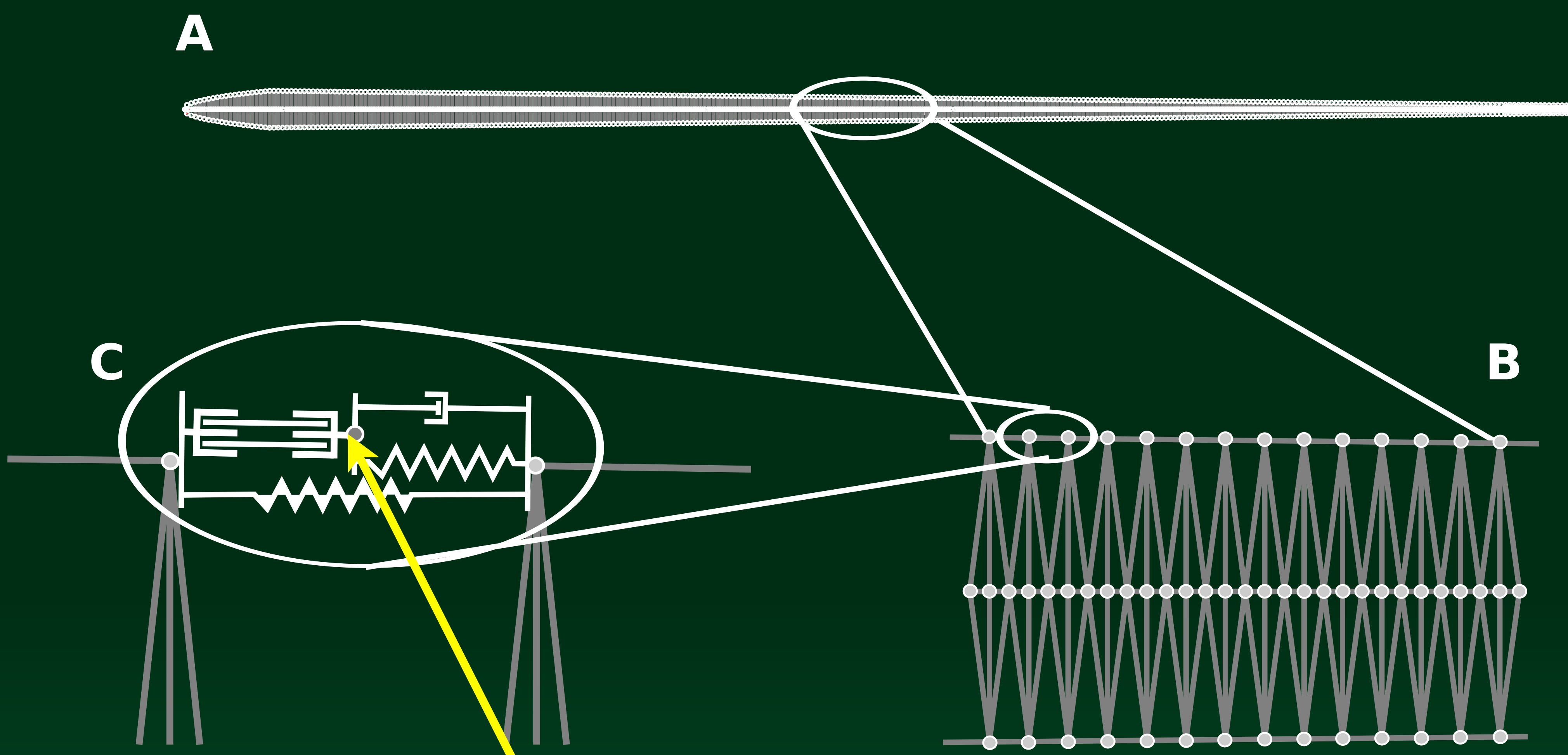


Springs describe passive tissues

Hamlet, Fauci, Tytell, J.Theo. Bio 2015

Tytell, Hsu, William, Cohen, Fauci, PNAS 2011

Muscles modeled as a forced spring-mass-damper

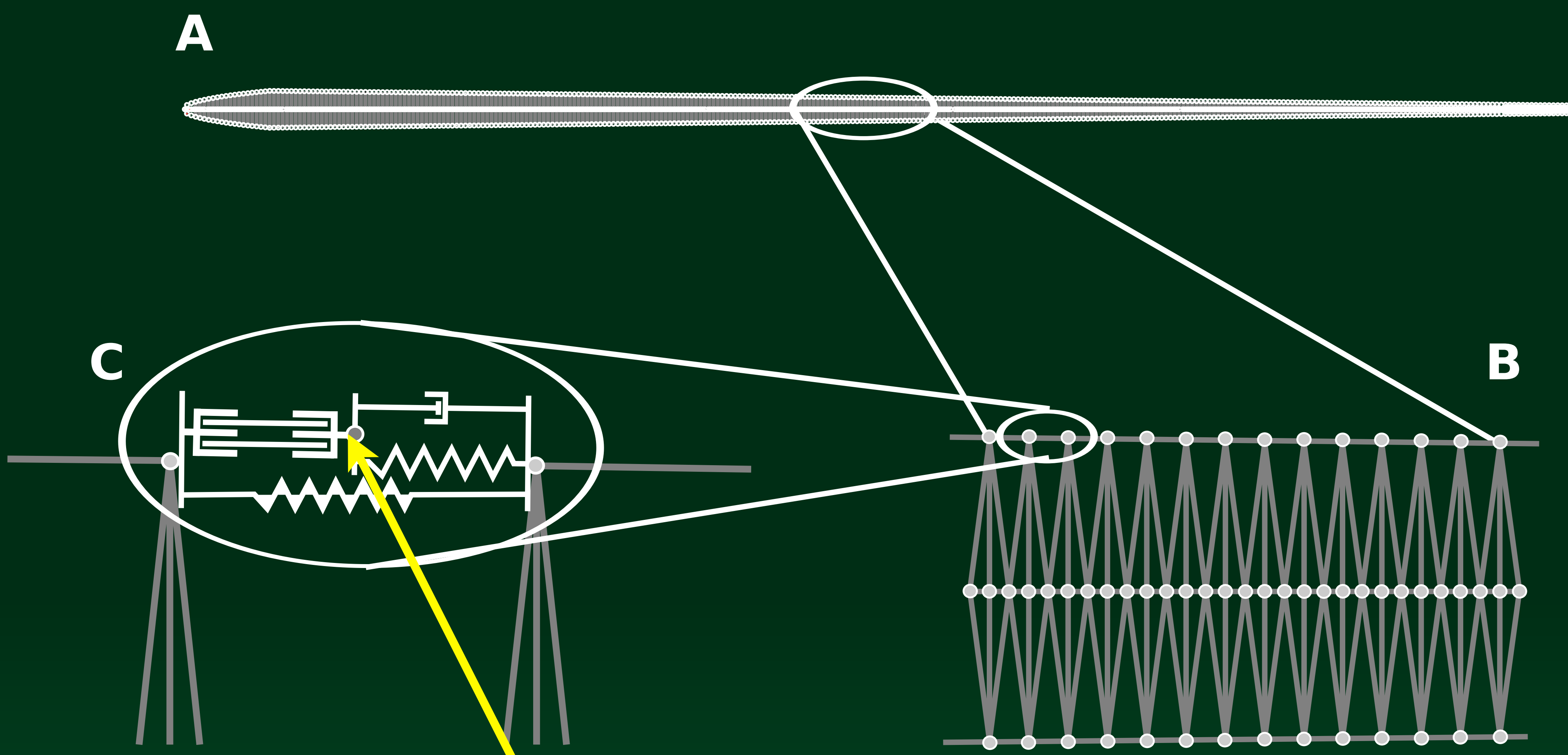


Muscle model inserted on lateral sides

Hamlet, Fauci, Tytell, J.Theo. Bio 2015

Tytell, Hsu, William, Cohen, Fauci, PNAS 2011

Muscles modeled as a forced spring-mass-damper



Neural signal activates muscles as it travels

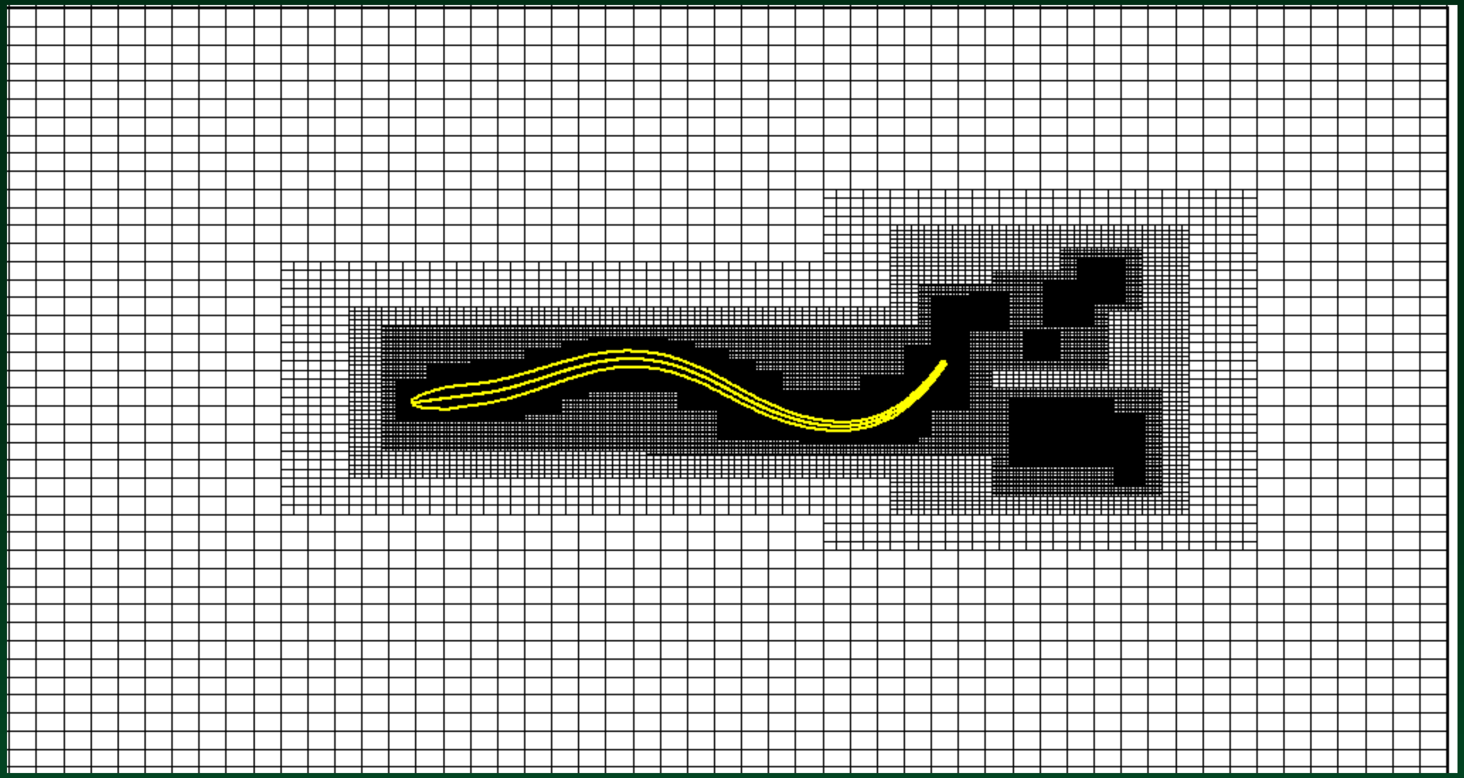
Hamlet, Fauci, Tytell, J.Theo. Bio 2015

Tytell, Hsu, William, Cohen, Fauci, PNAS 2011

Fluid structure interactions

- Fluid structure-interactions modeled using immerse boundary method

- Computationally intensive model, interface with IBAMR (Boyce Griffith, UNC)



Immersed boundary simulations of a swimmer in an incompressible viscous fluid

Lamprey (black) immersed in a fluid (white region)

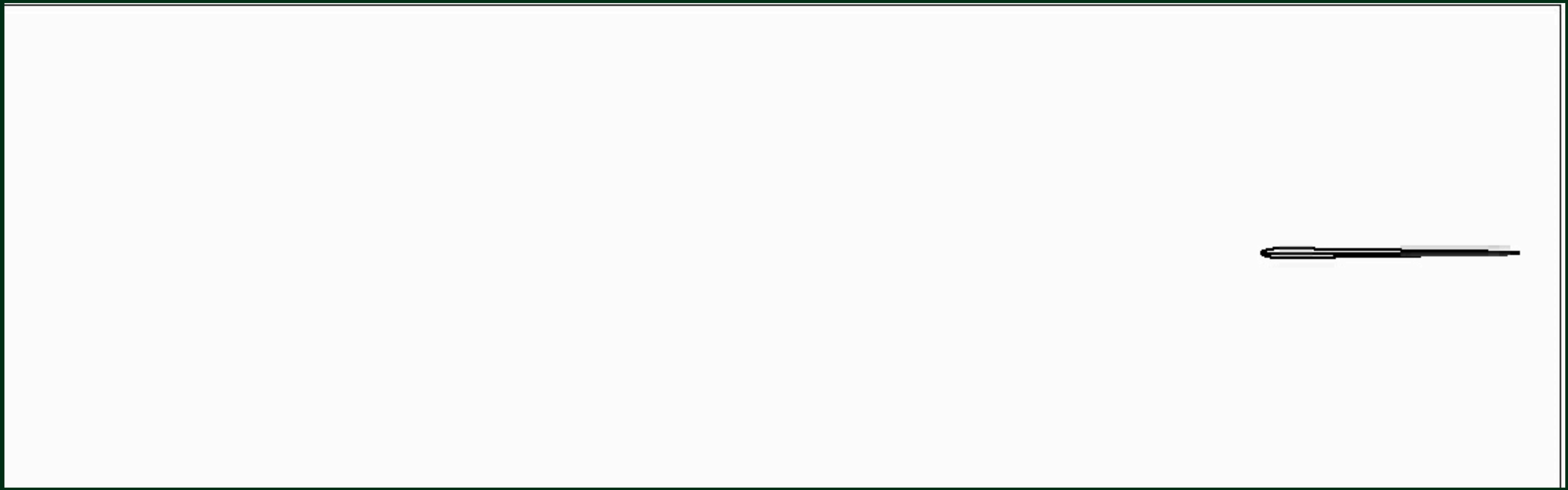
Given initial conditions

Evolved in time in immersed boundary simulation

Muscle segments generate forces

Hamlet, Fauci, Tytell, J.Theo. Bio 2015

Simulations show emergent swimming behavior



Vorticity plots, lamprey model immersed in fluid

Red = counterclockwise vorticity

Blue = clockwise vorticity

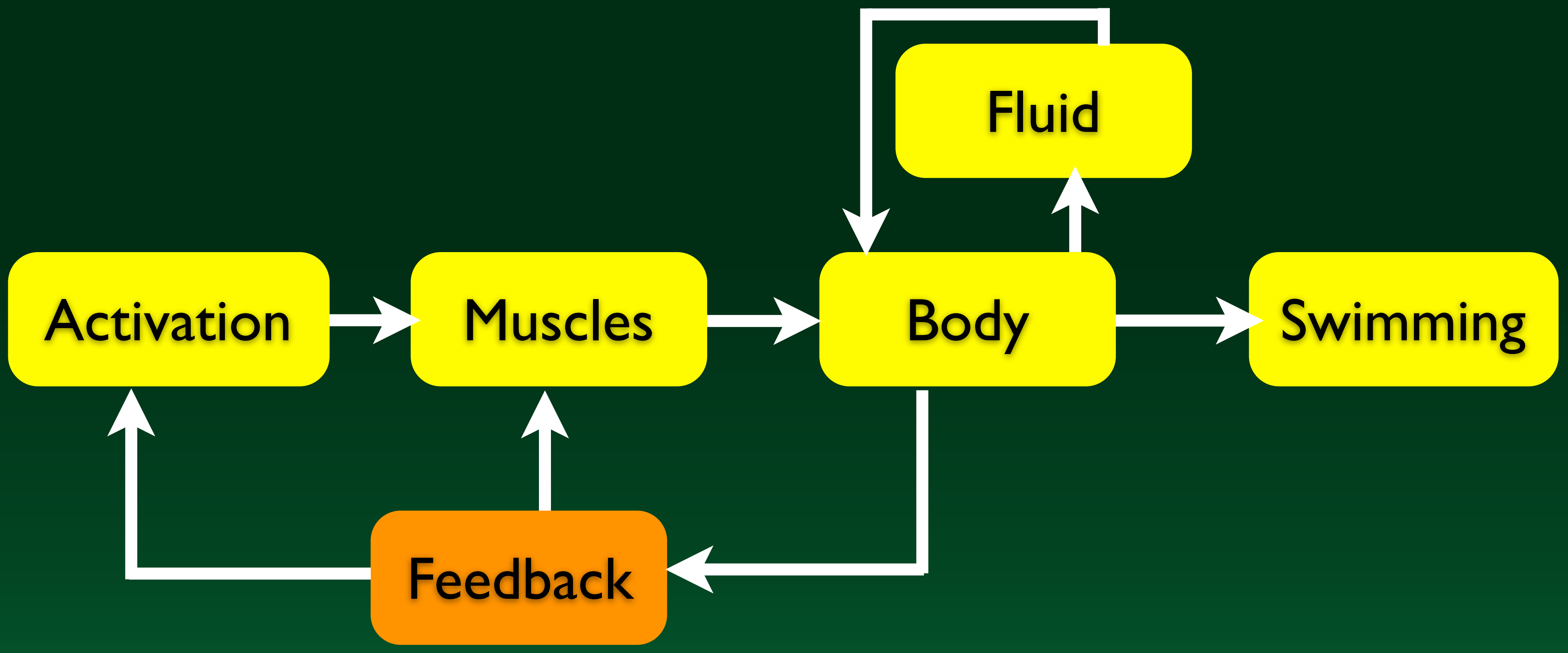
Hamlet, Fauci, Tytell, J.Theo. Bio 2015

Questions

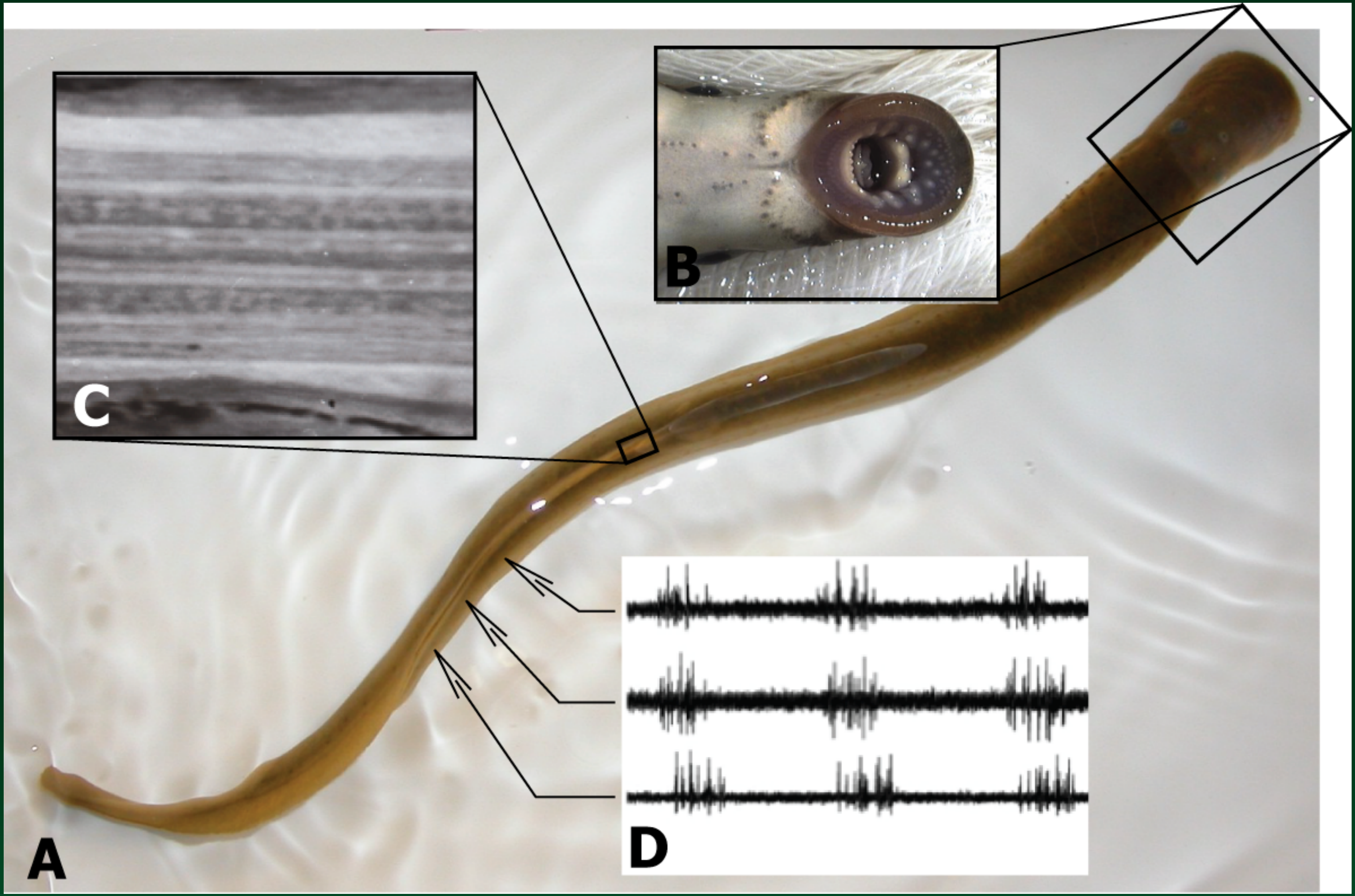
- How does a lamprey swim?
- What components are involved in producing swimming behavior?
- What is the role of sensory feedback in maintaining steady swimming and in maneuvering?

Sensory feedback closes the loop

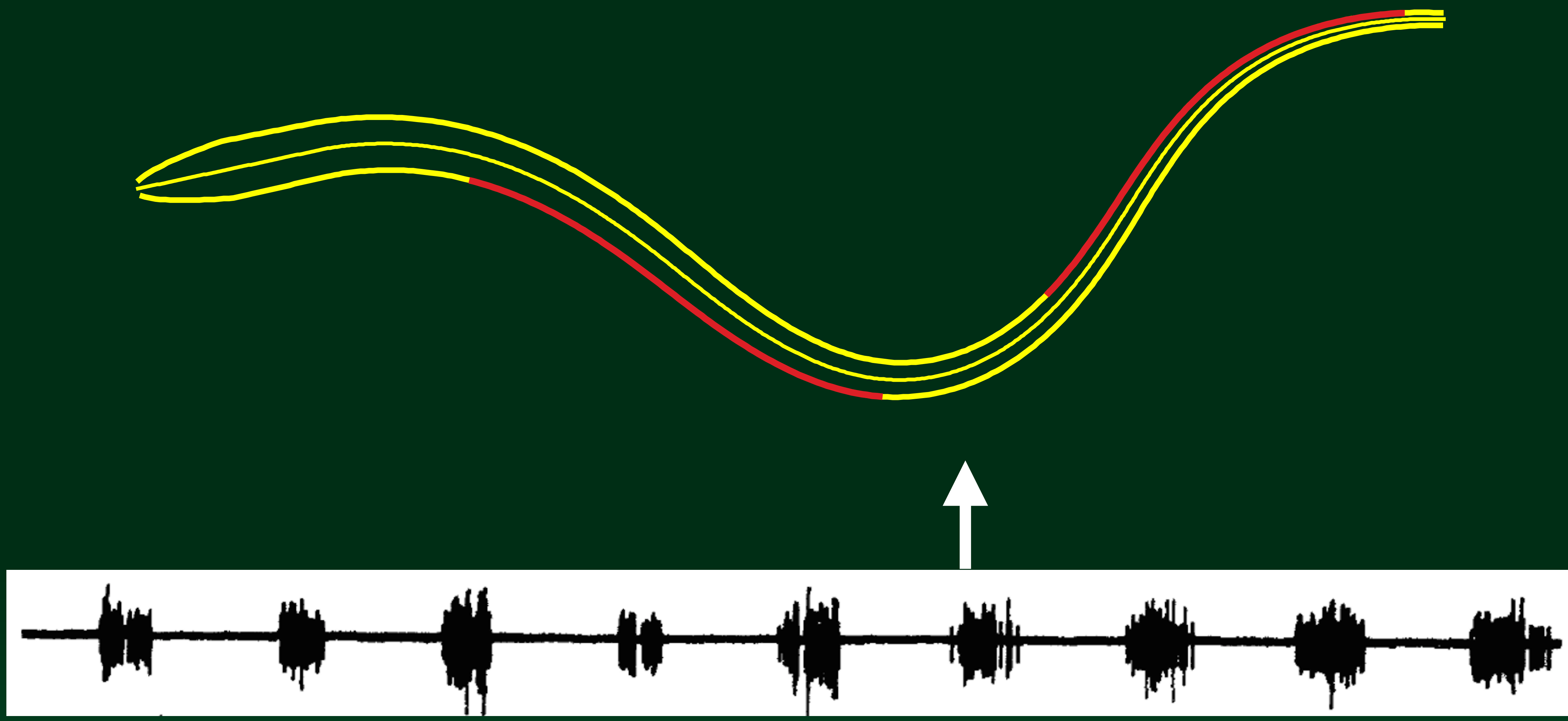
- Add feedback to the central pattern generator (CPG)



CPGs - neural networks produce rhythmic signal patterns along the body without sensory input



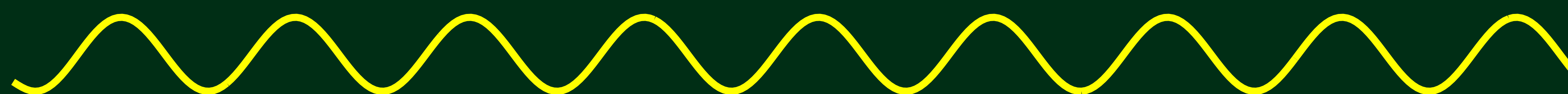
Modeling a CPG using oscillators



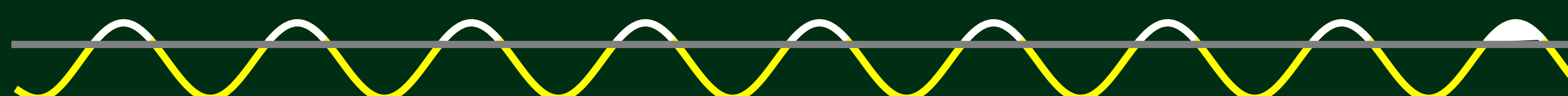
Cohen, Holmes, Rand, J. Math Biol. 1982

Periodic nature of CPG motivates modeling by an oscillator

Sample signal

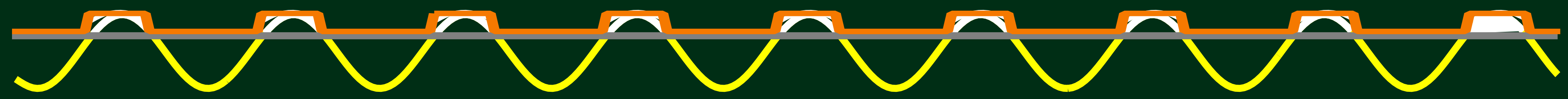


Oscillator generates a signal at a given frequency



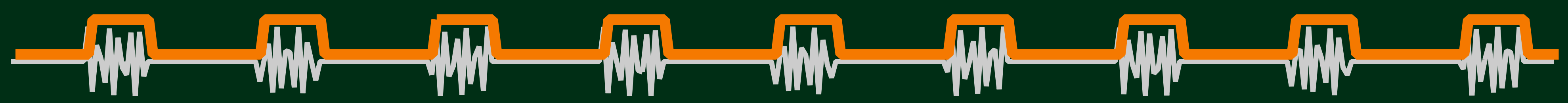
Choose threshold based on steady swimming duration and frequency from experiments

Oscillators generate a signal

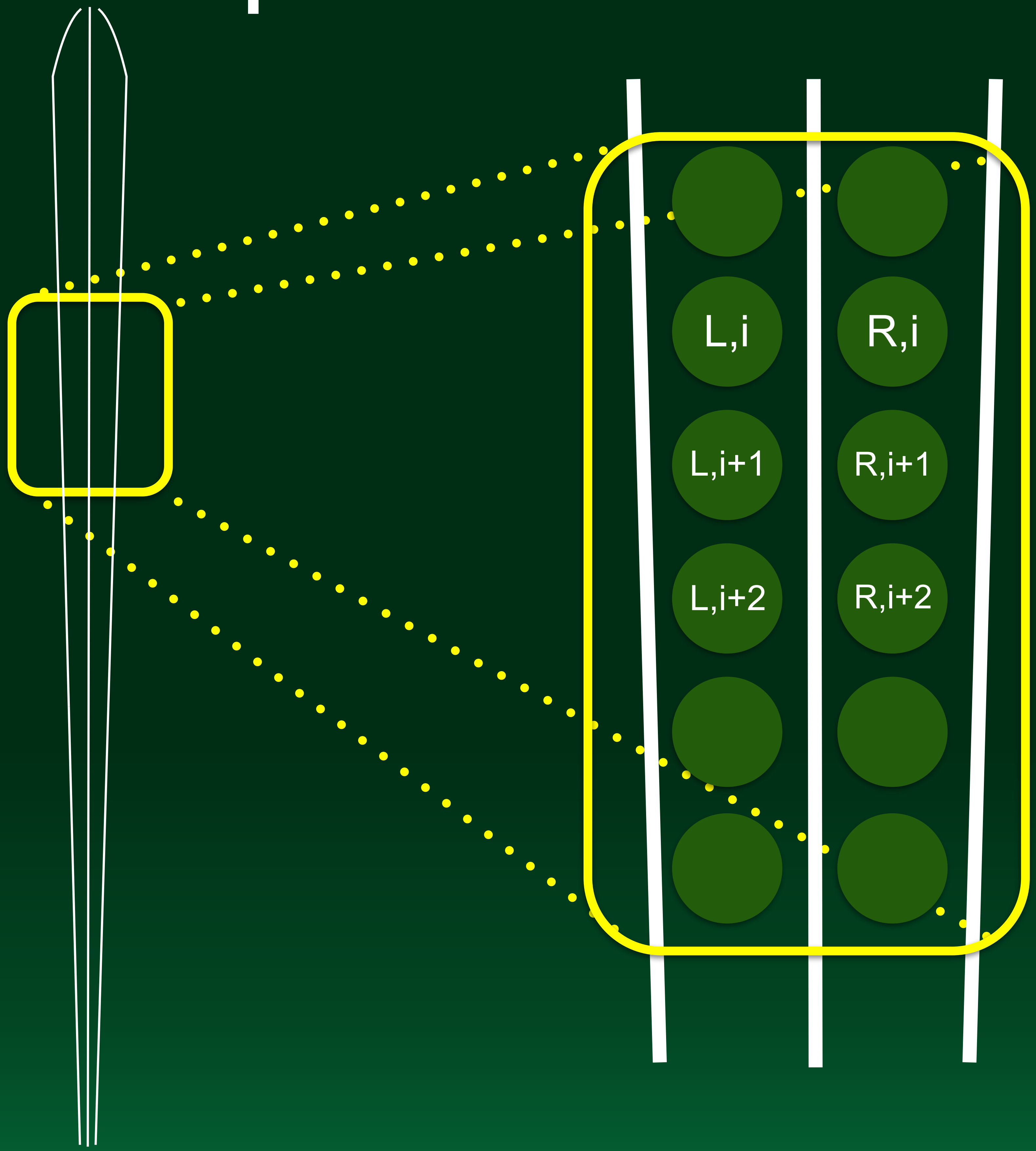


Determine activation signal

Produces a signal that models steady state swimming as an emergent property

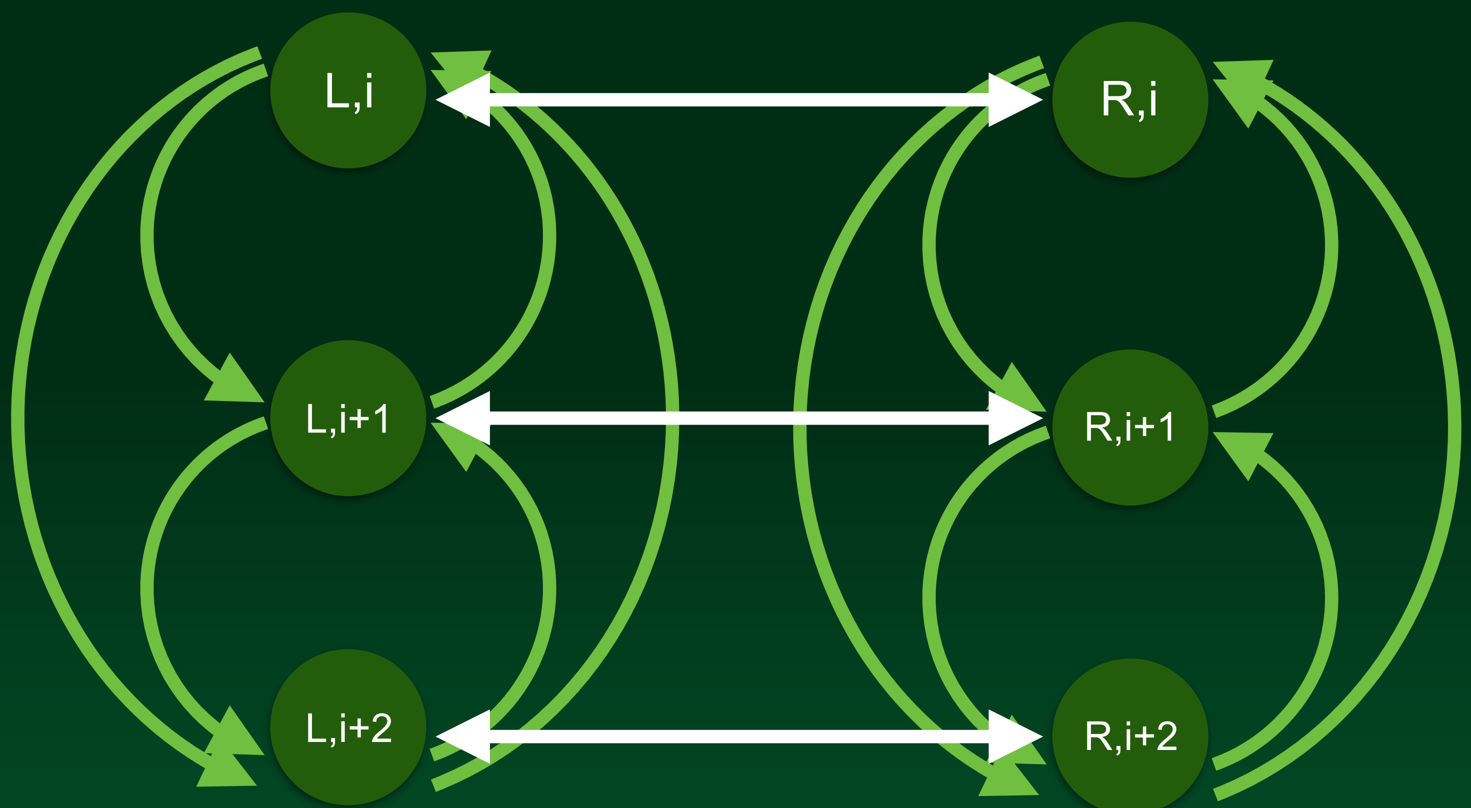


Couple oscillators to muscle segments



ODE model of coupled oscillators

$$\dot{\theta}_{k,i} = \omega + \alpha_c \sin\left(2\pi\left(\theta_{k*,i} - \theta_{k,i} + \varphi_s\right)\right)$$
$$+ \sum_{j=1}^{n} \alpha_{i-j} \sin\left(2\pi\left(\theta_{k,j} - \theta_{k,i} - \psi_{i-j}\right)\right)$$



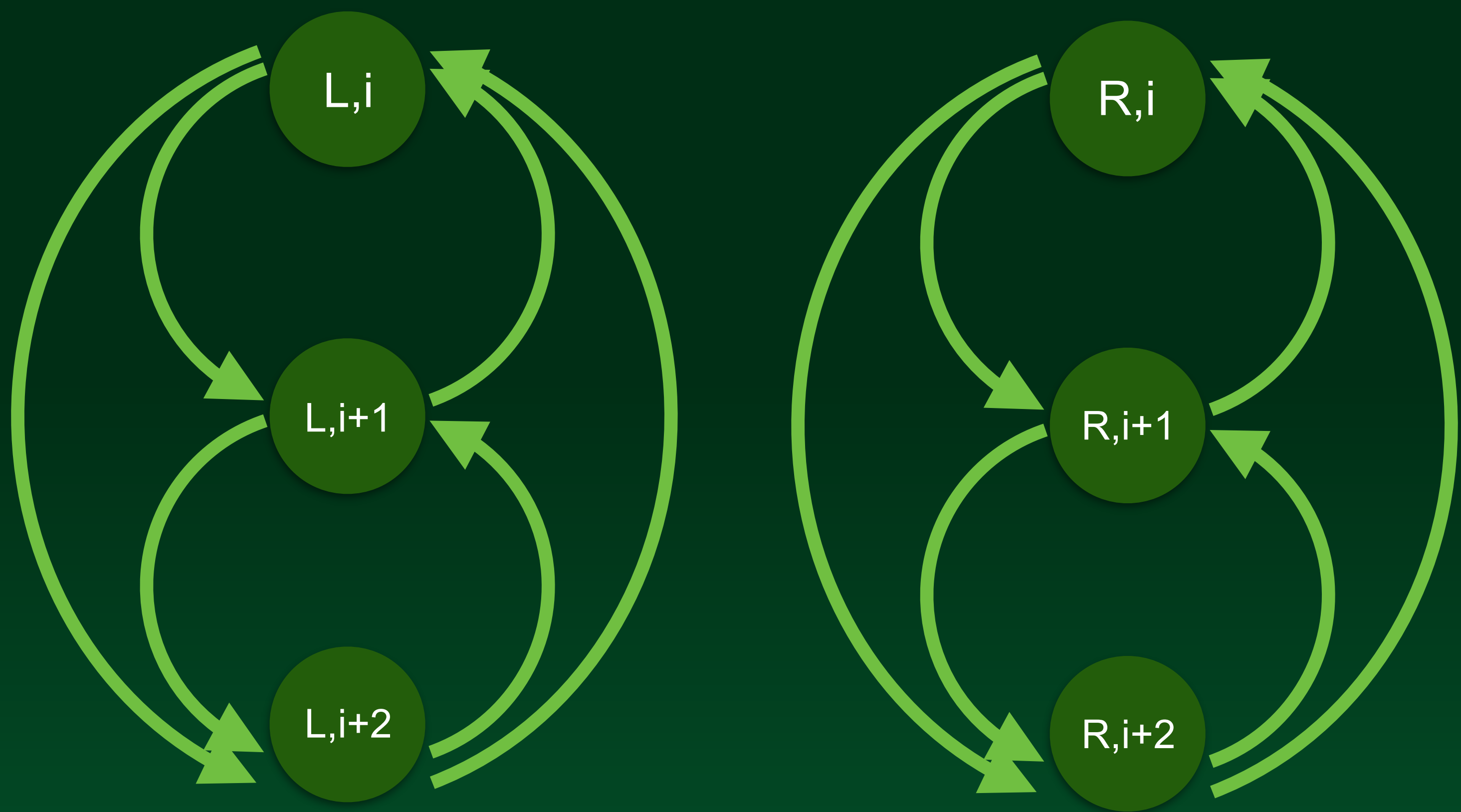
$\theta =$ phase

$\dot{\theta} =$ time derivative

$\omega =$ natural frequency

ODE model of coupled oscillators

$$\dot{\theta}_{k,i} = \omega + \alpha_c \sin\left(2\pi\left(\theta_{k*,i} - \theta_{k,i} + \varphi_s\right)\right) + \sum_{j=1}^{n} \alpha_{i-j} \sin\left(2\pi\left(\theta_{k,j} - \theta_{k,i} - \psi_{i-j}\right)\right)$$



Intersegmental connections

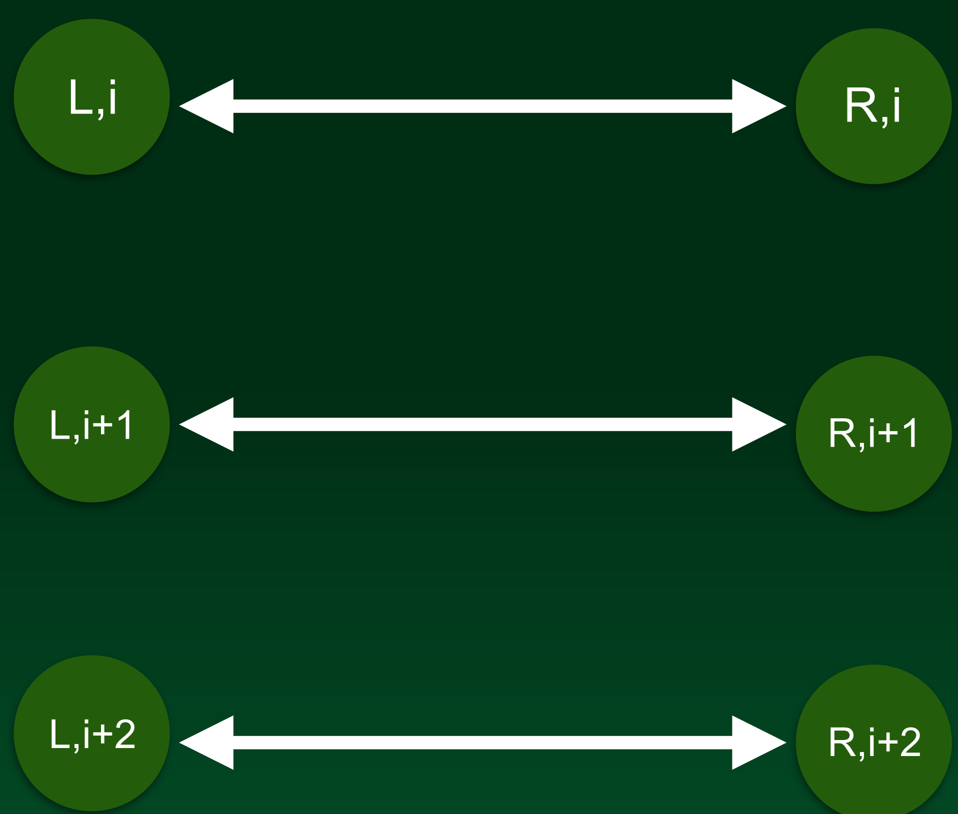
θ = phase

ψ_{i-j} = phase lag

ODE model of coupled oscillators

$$\dot{\theta}_{k,i} = \omega + \boxed{\alpha_c \sin\left(2\pi\left(\theta_{k*,i} - \theta_{k,i} + \varphi_s\right)\right)}$$
$$+ \sum_{j=1}^{n} \alpha_{i-j} \sin\left(2\pi\left(\theta_{k,j} - \theta_{k,i} - \psi_{i-j}\right)\right)$$

Cross connections



$\theta =$ phase

$\varphi_s =$ phase lag

Simulations show emergent swimming behavior

Vorticity plots, lamprey model immersed in fluid

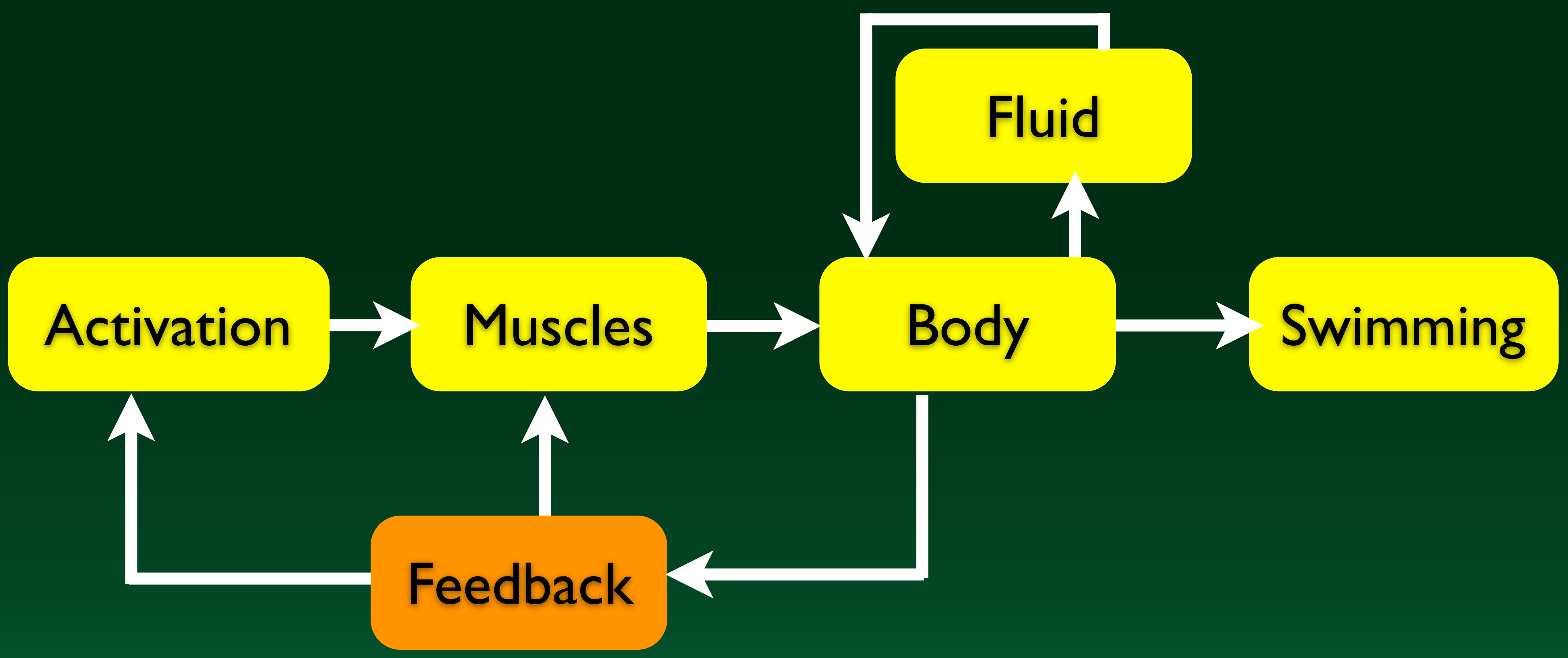
Red = counterclockwise vorticity

Blue = clockwise vorticity

Hamlet, Fauci, Tytell, J.Theo. Bio 2015

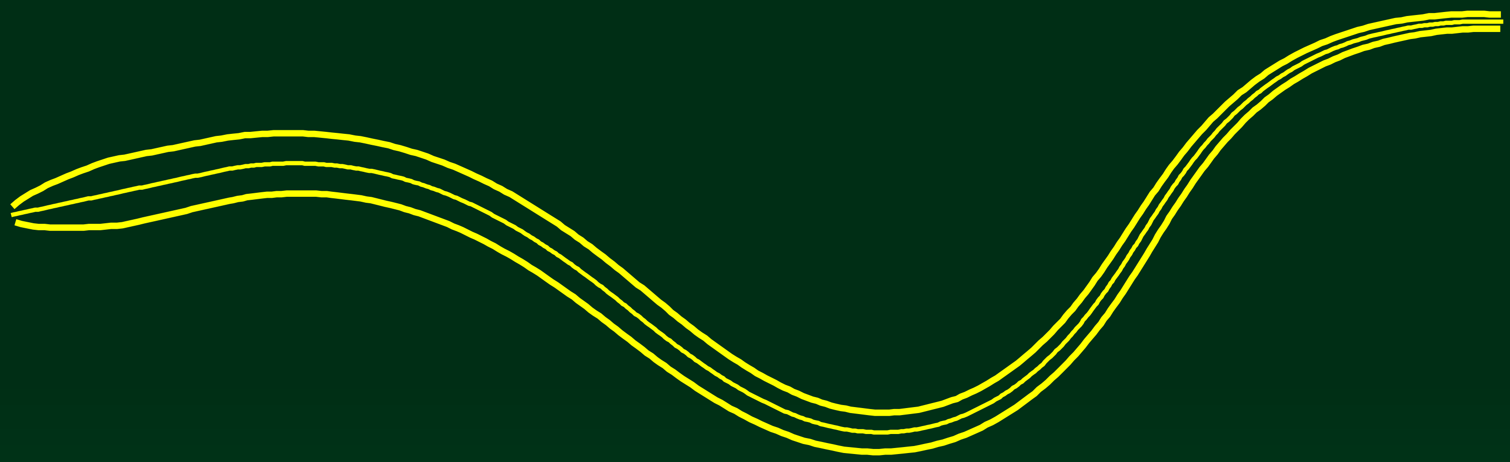
Sensory feedback closes the loop

- Proprioceptive (body-sensing) feedback affects activation
- Uses stretch receptors called edge cells

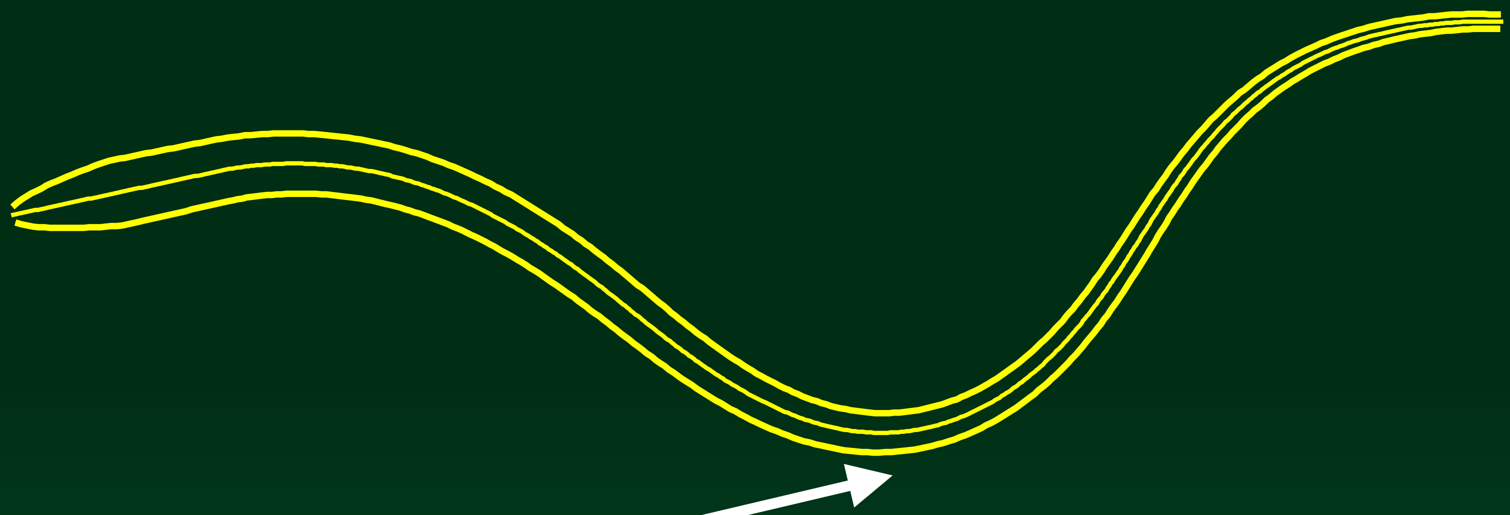


Edge cells and sensory feedback

- Edge cells give inhibitory and excitatory signals along the body

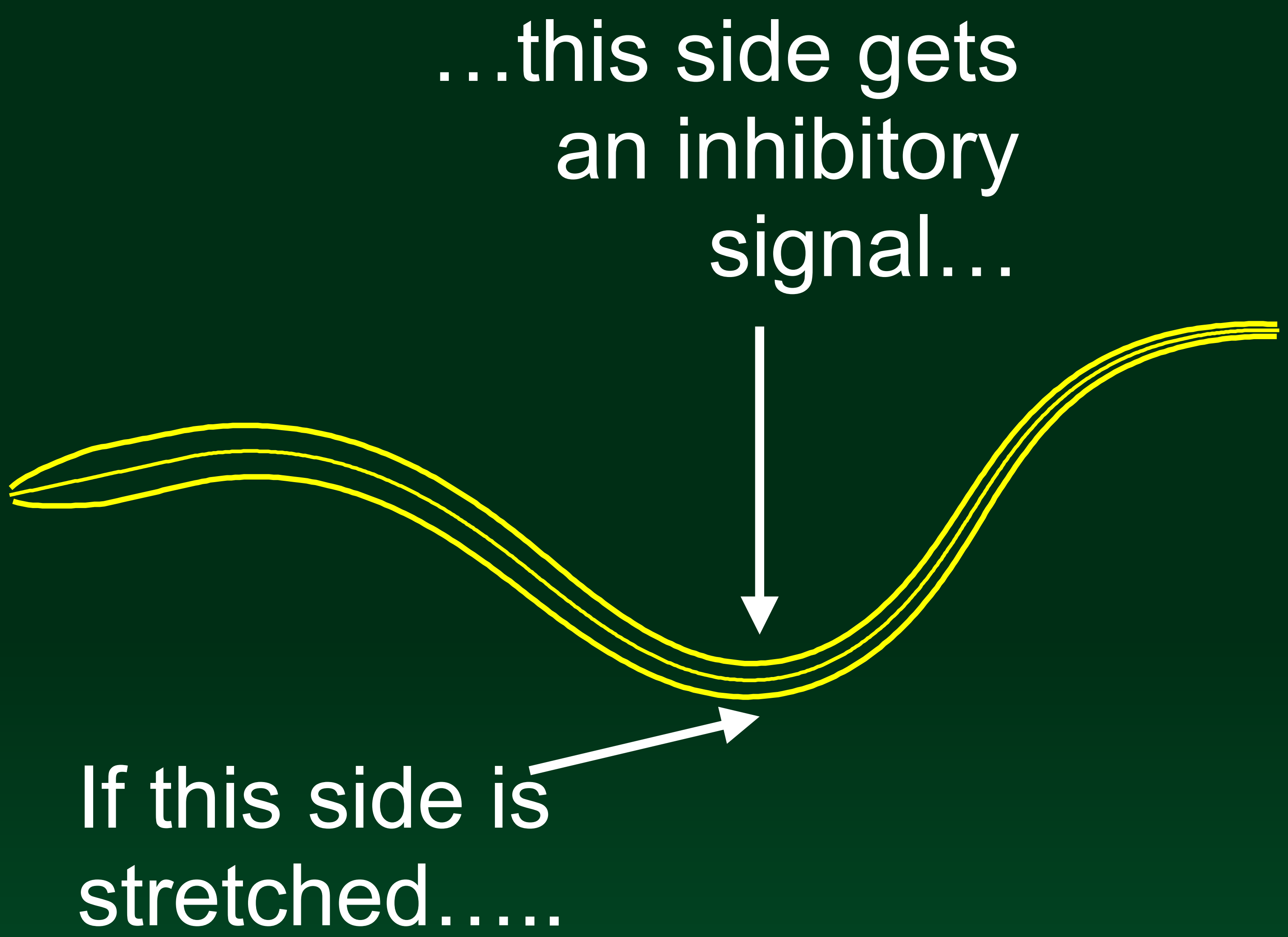


Edge cells and sensory feedback



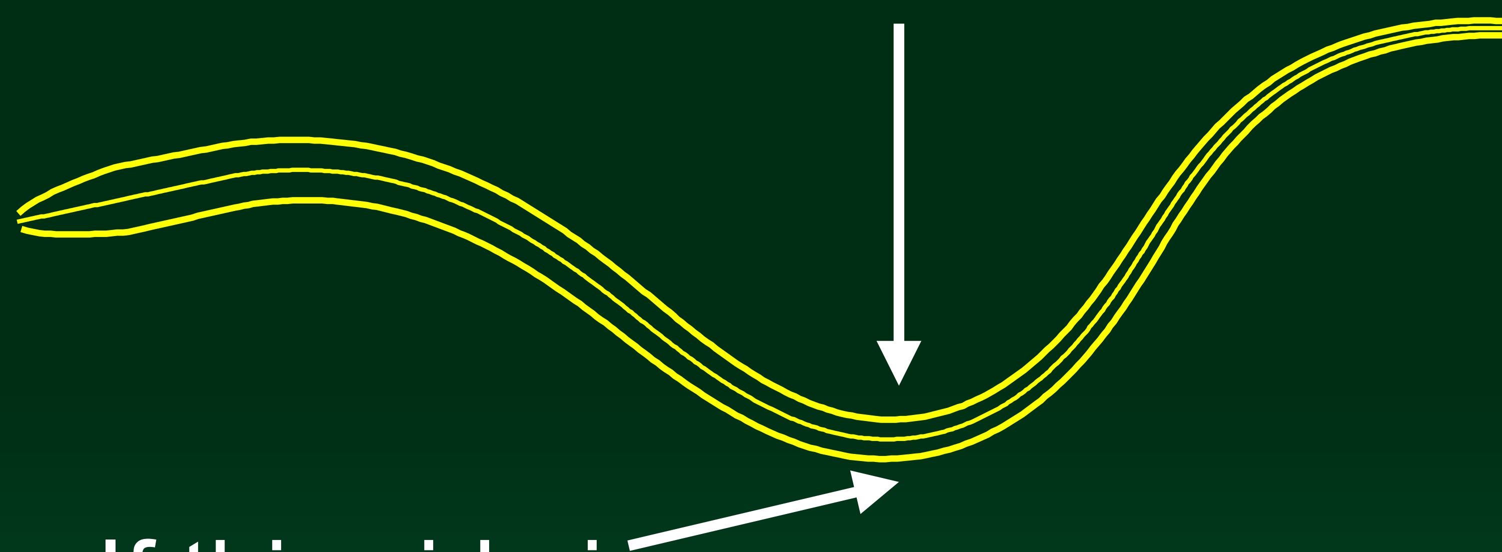
If this side is stretched…..

Edge cells and sensory feedback



Edge cells and sensory feedback

…this side gets
an inhibitory
signal…

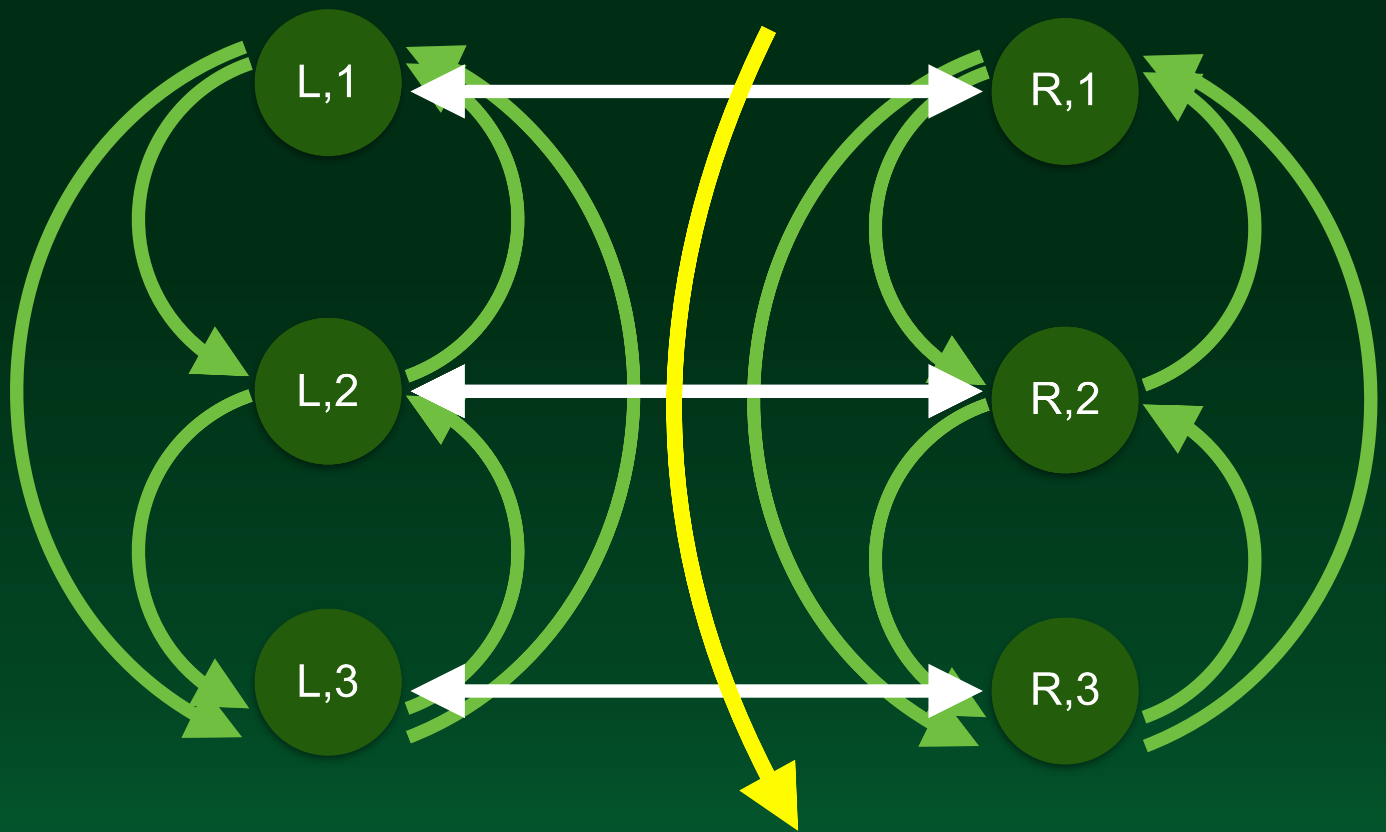


If this side is
stretched…..

…and this side
gets an excitatory
signal

Connect sensory feedback to oscillators

$$\dot{\theta}_{k,i} = \omega + \alpha_c \sin\left(2\pi\left(\theta_{k*,i} - \theta_{k,i} + \varphi_s\right)\right) + \sum_{j=1}^{n} \alpha_{i-j} \sin\left(2\pi\left(\theta_{k,j} - \theta_{k,i} - \psi_{i-j}\right)\right) + \eta_{k,i}\left(\kappa\right)$$

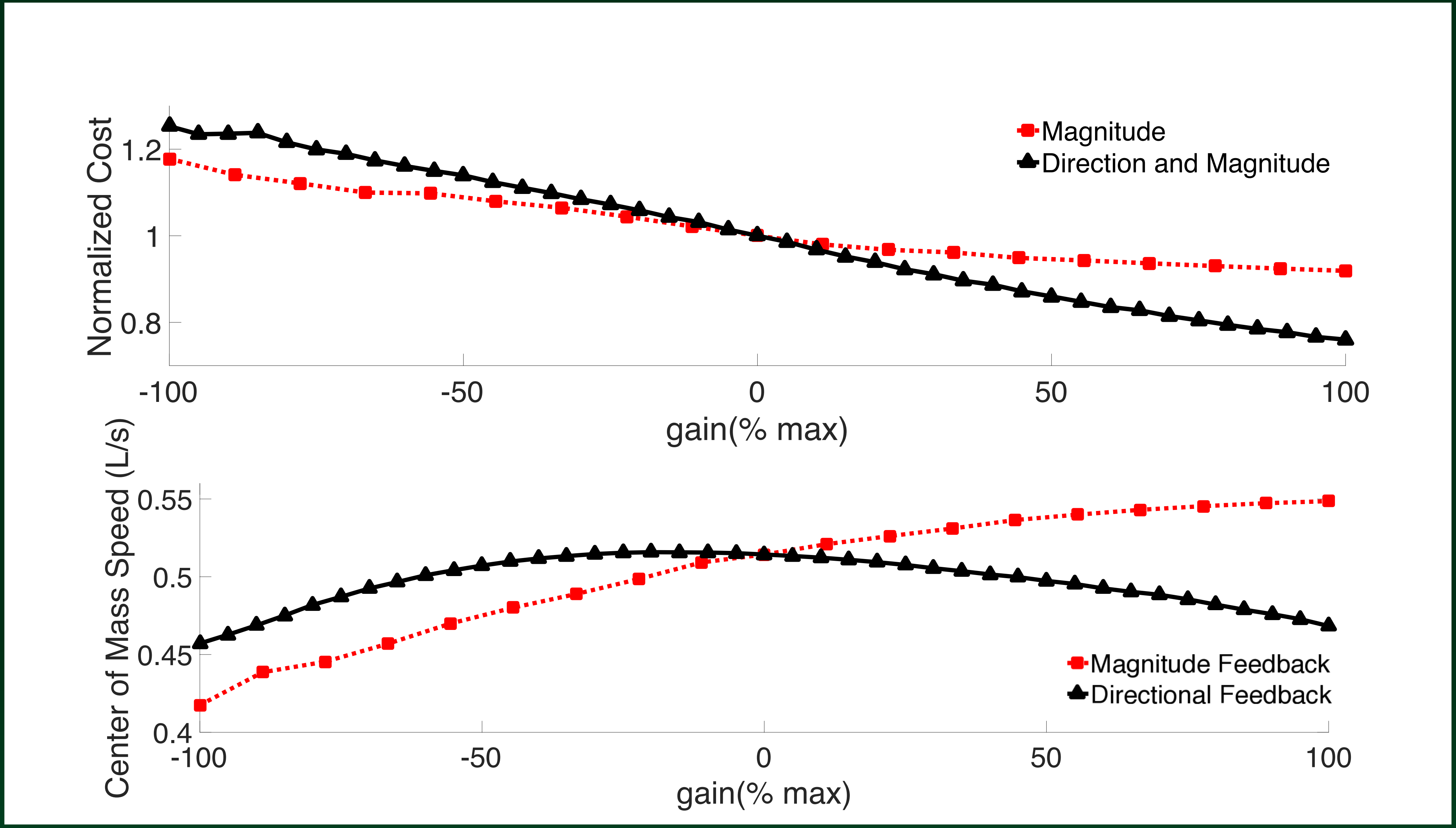


Curvature magnitude only

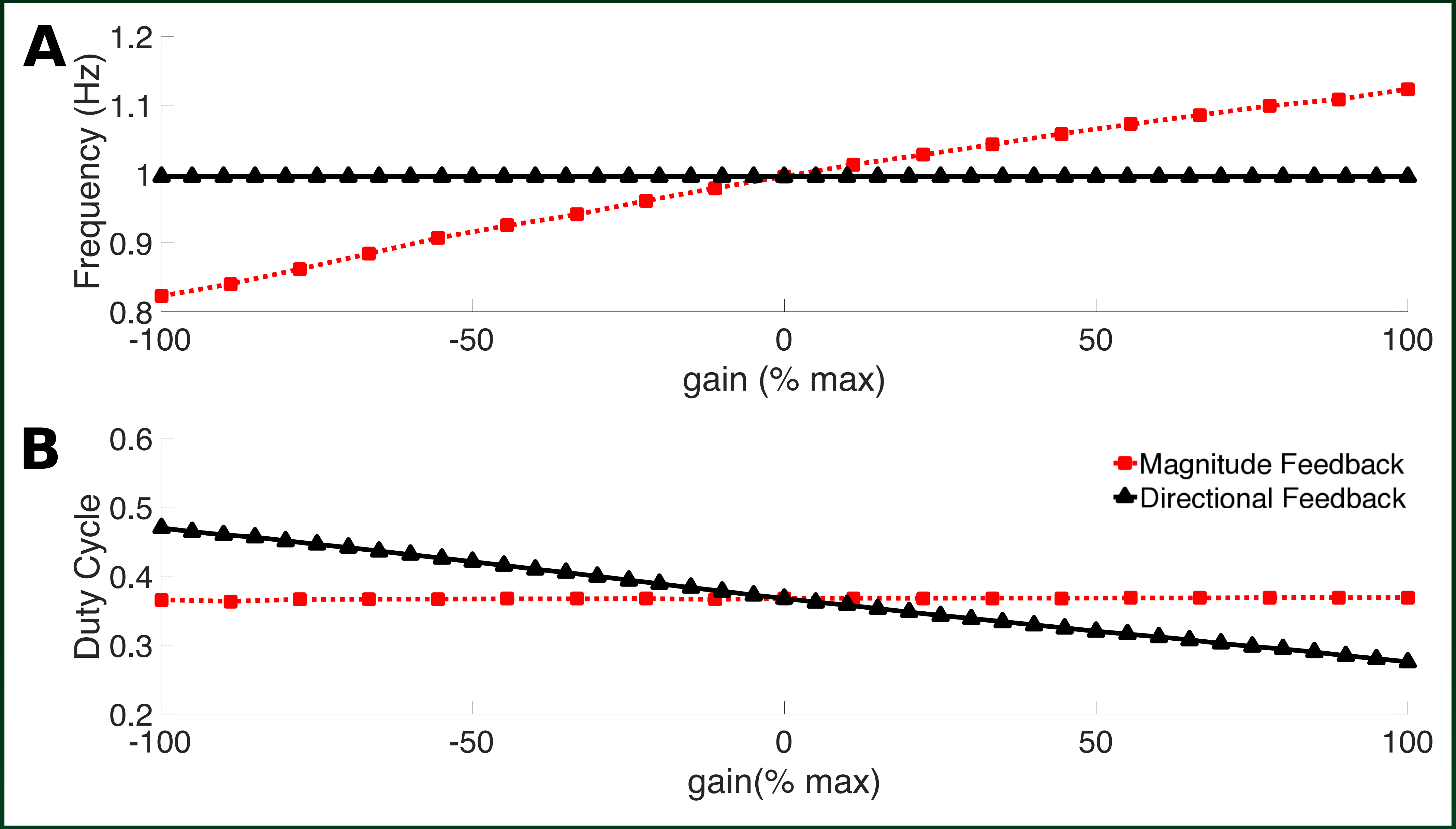
$$\eta_{k,i} = (-0.05)\,|\kappa|$$

$$\eta_{k,i} = (0.05)\,|\kappa|$$

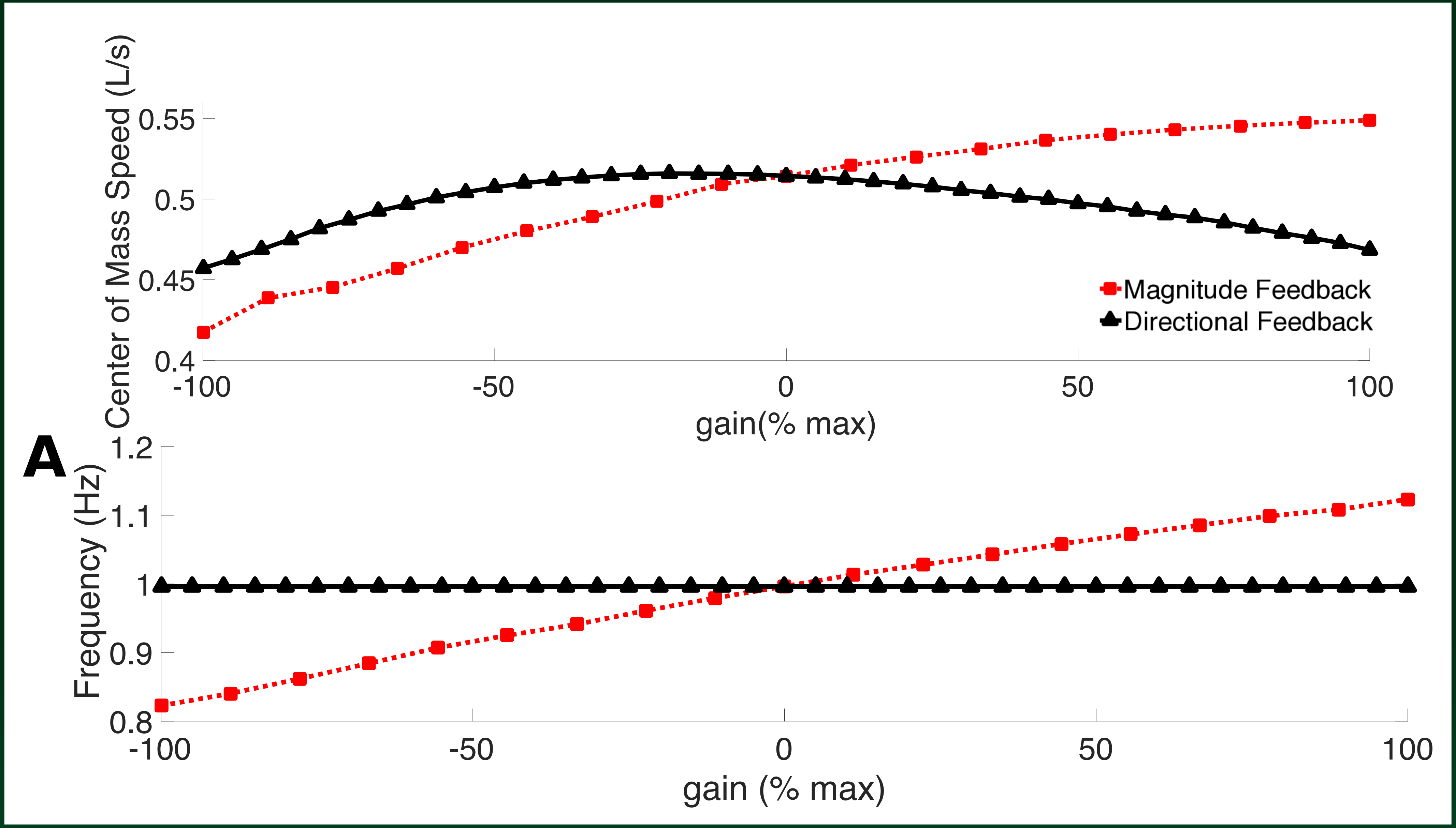
Curvature feedback results



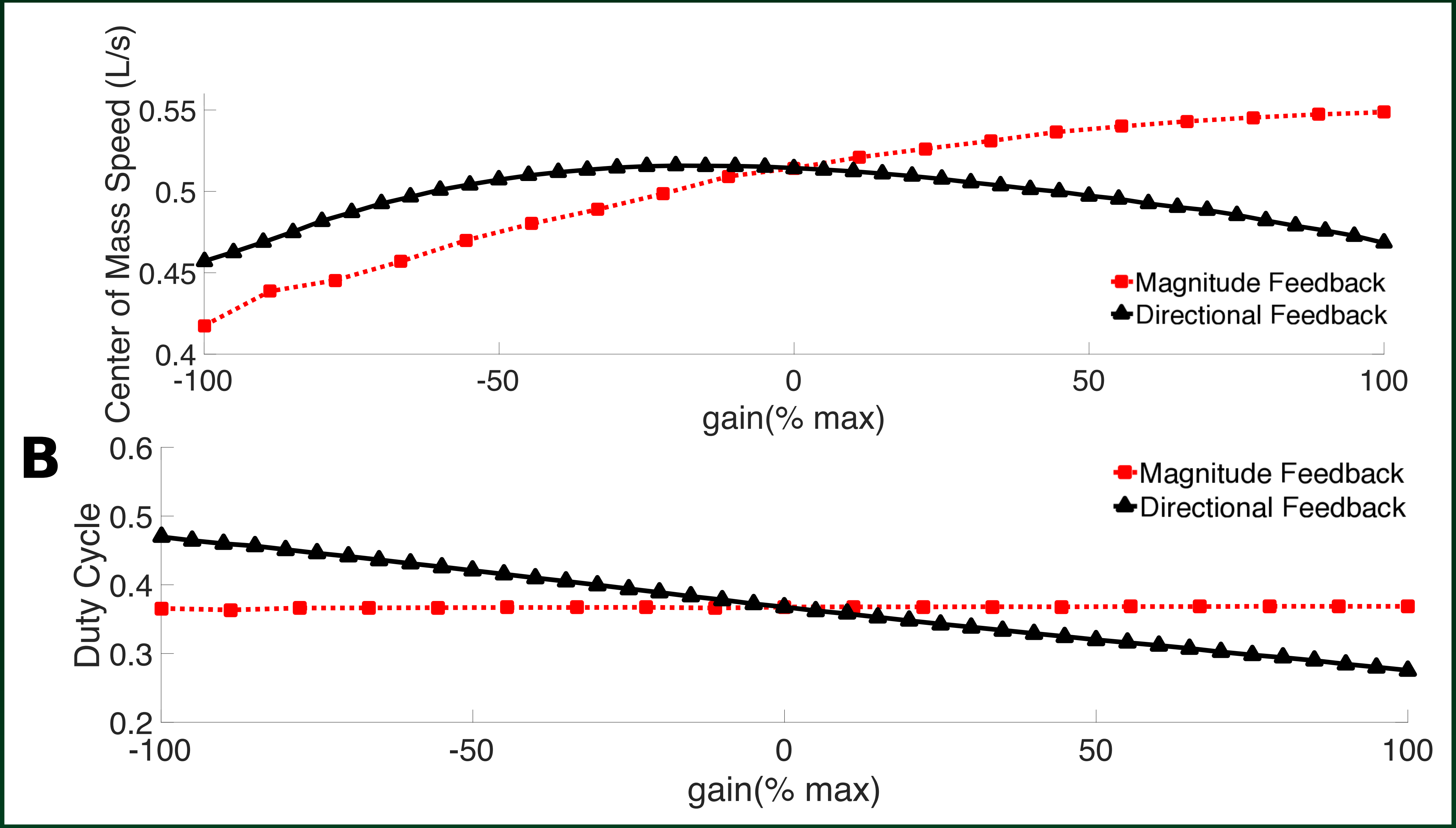
Curvature feedback results



Curvature feedback results



Curvature feedback results

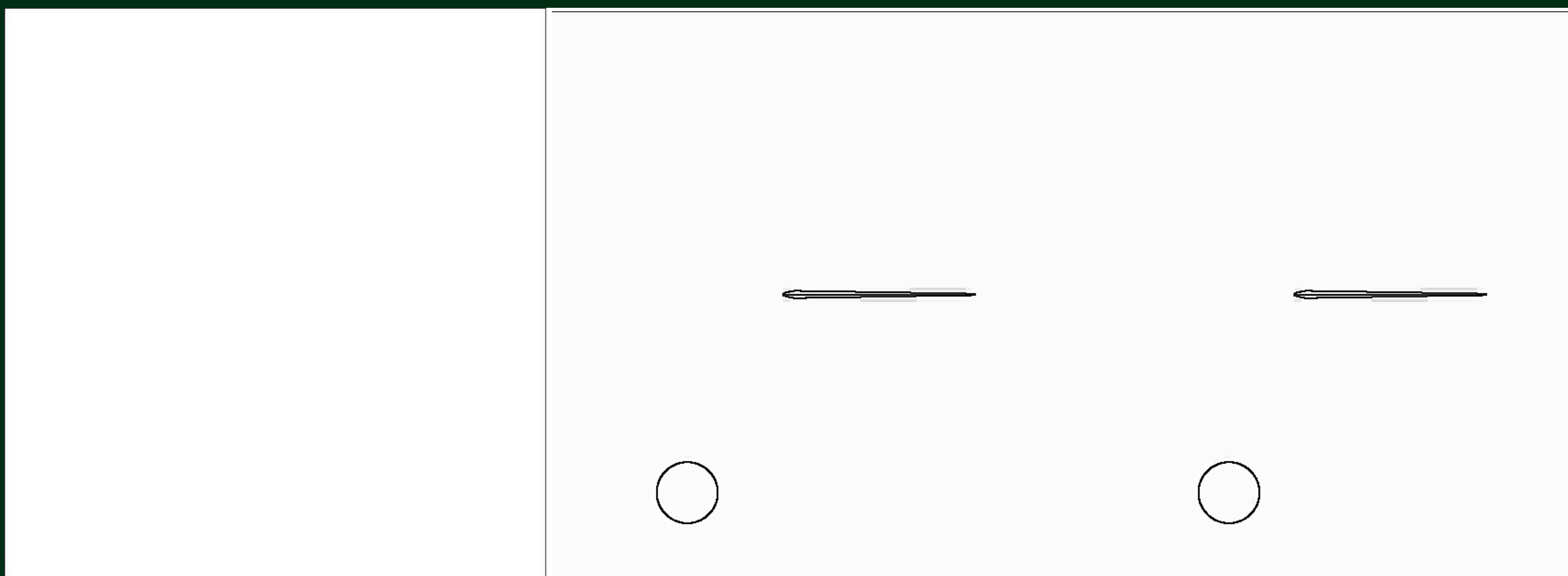


Current Work

curvature and state of phase

maximum curvature

Current Work



Summary

- CPG produces swimming behavior without sensory input in the computational swimmer
- Adding curvature feedback closes the physiological loop in the organism
- Examine the interacting systems and physiological effects of coordination
- Explore effects of different functional forms of feedback based on experimental studies

Current activities/next steps

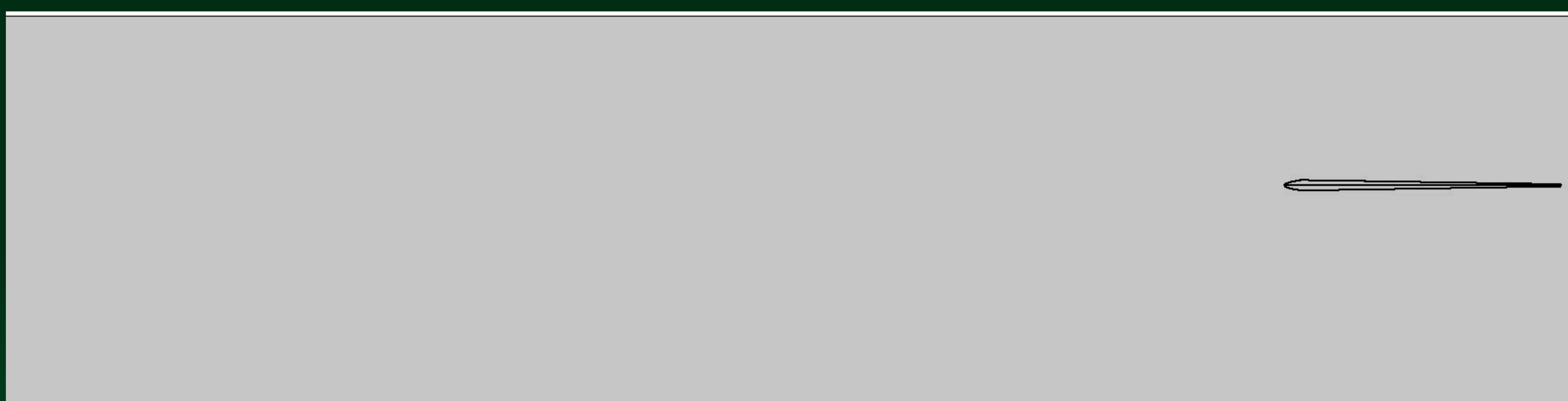
- Add perturbations to test ability of sensory feedback to stabilize swimming
- Add in time derivatives of curvature (rate of bending)
- Construct different functional forms of curvature driven feedback

Collaborators

Avis Cohen	University of Maryland, Biology
Eric Tytell	Tufts University, Biology
Chia-yu Hsu	National Taiwan University
Boyce Griffith	UNC Chapel Hill, CCIAM
Lisa Fauci	Tulane University, Center for Computational Science
Kathleen Hoffman	University of Maryland, B.C., Mathematics
Tim Kiemel	University of Maryland, Kinesiology
Thelma Williams	St. George's Univ. of London, Basic Medical Sciences
Phillip Holmes	Princeton University, Mathematics
Lex Smits	Princeton University, Mechanical Engr.
Megan Leftwich	George Washington University, Mechanical Engr.

Funding

- Army Research Office (W911NF-13-1-0289)
- National Science Foundation (NSF DMS-1312987 and NSF DBI-RCN-1062052)



Thank you!