ALAMEDA COUNTY
SCIENCE & ENGINEERING FAIR

HS-BCOM-145

Monte Carlo Simulation of Somatic Twist in Ancient Marine Worms

How the First Digital Organism in a Computer Evolves *In Silico* to Become the *First Fish*

OpenWorm

All graphics made by the student researcher unless otherwise cited.
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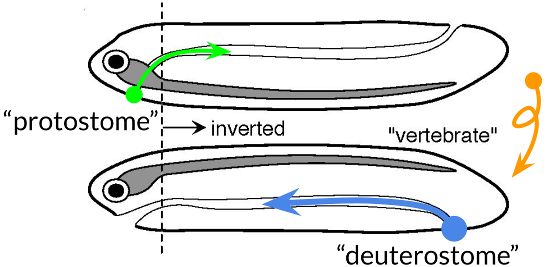
INTRODUCTION

Background

Kinsbourne (2013) had proposed **somatic twist theory** for the evolution of **decussation** in vertebrates, as a by-product of **dorsoventral inversion** during the invertebrate-to-vertebrate transition 550 million years ago. Comparative study of select **morphological models** (Cheong, 2025) inside an aquarium suggests a plausible evolutionary pathway for how this might have occurred in ancient marine worms, leading to corticospinal tracts decussation in *Pikaia*, the first fish.



Somatic Twist (Kinsbourne, 2013).

Research Question

The smallest worm will turn — but how? What force(s) could possibly drive the biomechanical tissues of ancient marine worms to perform a somatic twist?

Purpose

Run Monte Carlo simulation to recreate evolutionary events inside a computer; and *see* how the first digital *C. elegans* worm evolves *in silico* to become the 'first fish' — with a dorsoventrally inverted body plan after a somatic twist.

Hypothesis

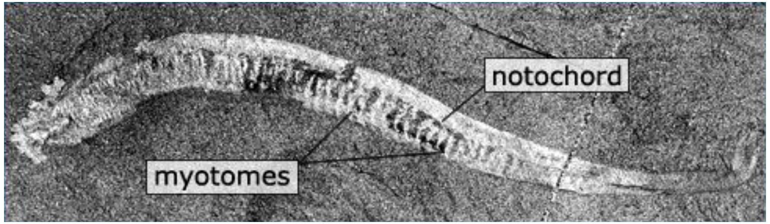
Underwater **buoyancy force** drove somatic twist of ancient marine worms.

Comparative study of morphological models from ancient marine worms to the first fish inside an aquarium (Cheong, 2025).

METHODS

1. Experimental Design

Starting with *C. elegans*, adjust model parameters for biomechanical matter and environment to evolve successive new generations of *marine worms* to see if any such instances, when given bountiful food sources: (a) turn into the **First Fish** after a somatic twist; or (b) grow into **Big Fat Annelids** without any somatic twist.



A fossil *Pikaia* (protochordate) has a visible notochord.
Photo: *Chip Clark, Museum of Natural History, Smithsonian Institution.*

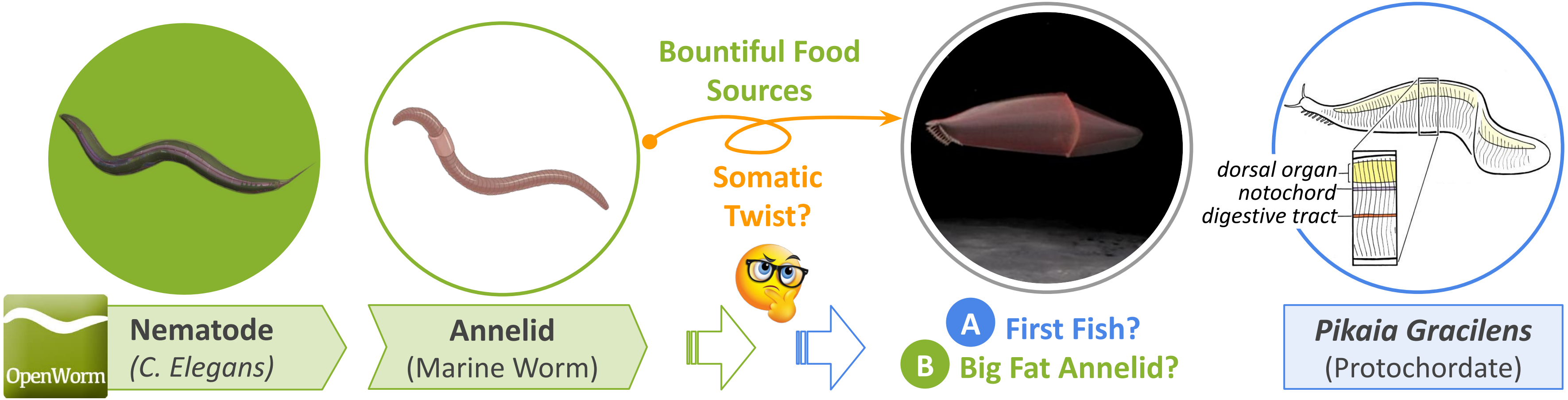
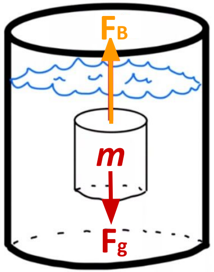


Image: *OpenWorm* | Image: *Biorender.com* | Image: *Phlesch Bubble* | Image: *Lacalli (2012)*

METHODS

2. Ask: “What Happens When Food Sources are Bountiful?”

- ❑ Intestinal gut expands with food and becomes heavier — also becomes denser.
- ❑ Excess fat plausibly stored alongside ventral nerve cord — mirroring the *Pikaia* dorsal organ.
- ❑ Or would *C. elegans* evolve to become more like an annelid along the way?
- ❑ Because hydrostatic coelomic fluid allows free movement and expansion of internal organs.
- ❑ Over geologic time, aquatic environment attains salinity — higher viscosity & density, too.
- ❑ Underwater **buoyancy force**, at or beyond turning point, drives somatic twist of marine worm.



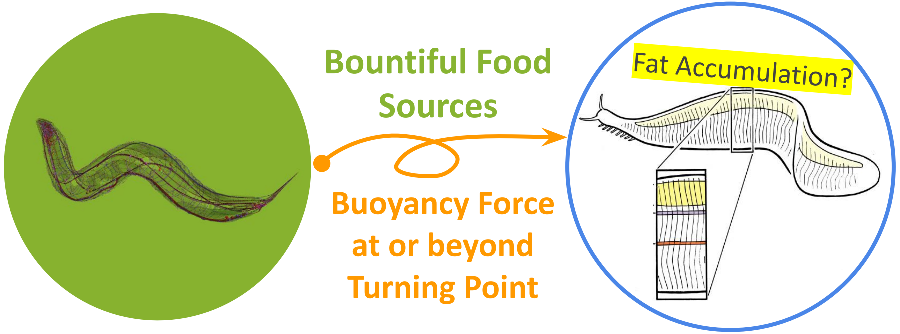
Archimedes Principle:

$$\boxed{F_B = \rho_w g V}$$

$$\boxed{F_g = mg}$$

$$\boxed{W = F_g - F_B}$$

Underwater buoyancy force, at or beyond turning point, drives somatic twist of marine worm.
Image: *James Charbonneau.*



Why *C. Elegans?* Start where data is most complete.
Image: *OpenWorm.*

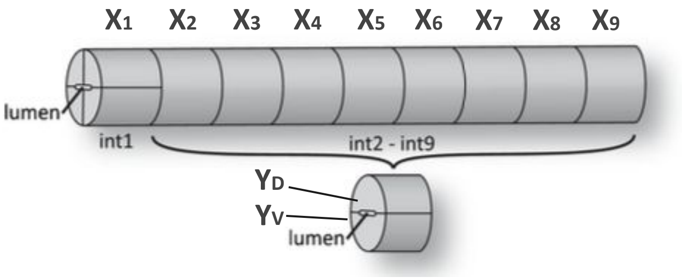
Pikaia as target reference and end point of simulation.
Image: *Lacalli (2012).*

METHODS

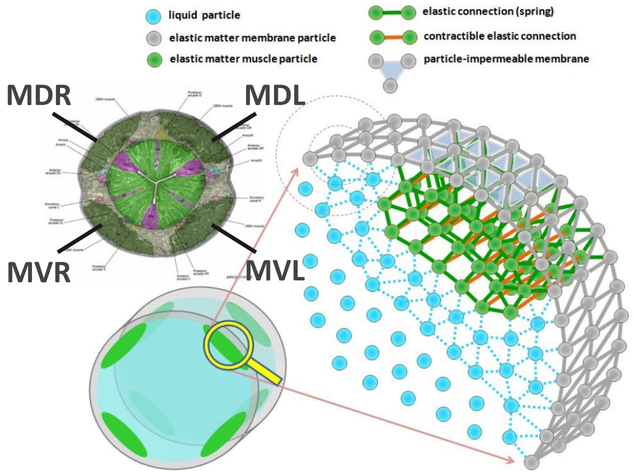
3. Gather Parameters for "Biomechanical Matter + Environment" Simulation

- *C. elegans* digestive tract: pharynx (57 + 38 cells), **intestine (20 cells)**, and rectum (11 cells).
- Intestinal cells: simple tube runs along **80% body length** and **1/3 of somatic mass** of organism.
- Model built with **biomechanical matter**: *contractile matter*, *elastic matter*, and *membranes*.

Intestine with 20 cells modeled as 9 rings



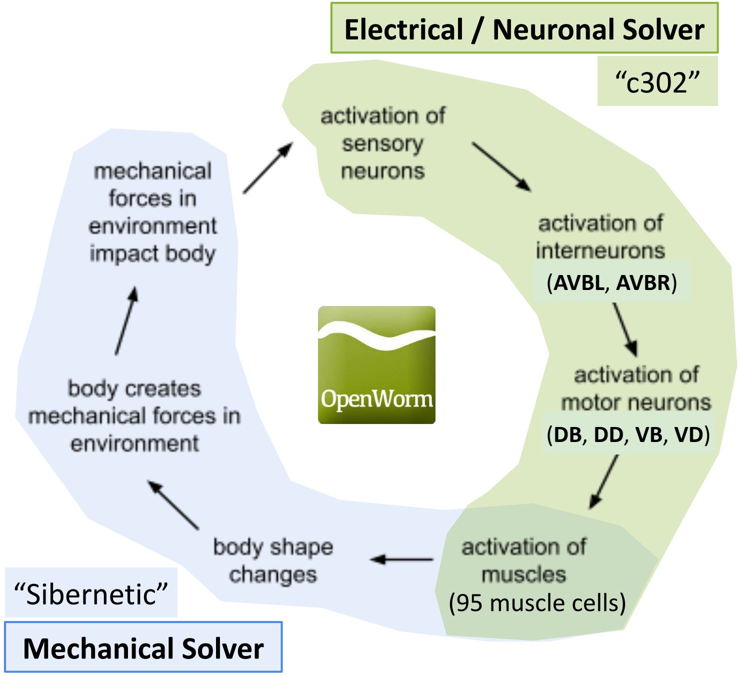
Basic structure of the intestine as a set of rings: four cells in the anterior-most $\mathbf{X_1}$ ring and two cells ($\mathbf{Y_D}$ and $\mathbf{Y_V}$) in each of the ring from $\mathbf{X_2}$ through $\mathbf{X_9}$. Dorsoventral inversion is detected from relative positions of $\mathbf{Y_D}$ and $\mathbf{Y_V}$. Image: *Dimov & Maduro (2019).*



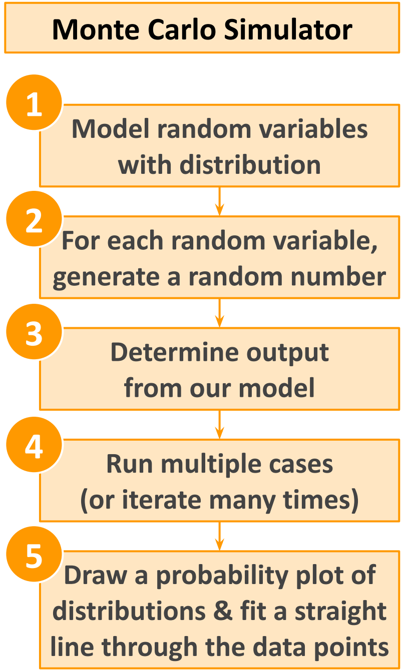
Types of particles used in the Sibernetic simulation framework for creating a model of the worm body with cuticle, **muscle quadrants** (**MDR**, **MVR**, **MVL**, and **MDL**) and internal liquid. Image: *Gleeson et al. (2023).*

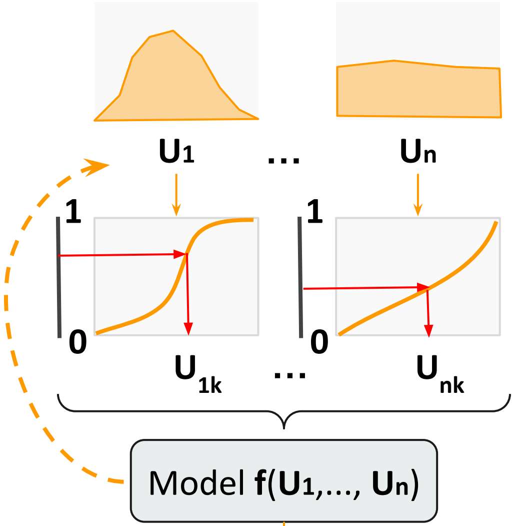
METHODS

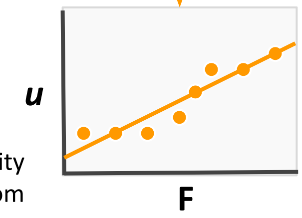
4. Extend Sibernetic & OpenWorm Software with Monte Carlo Simulator



Feedback control loop of simulation engine. Solvers for two systems of equations: smoothed particle hydrodynamics and Hodgkin-Huxley, overlap at the activation of muscle cells. Image: *OpenWorm.*



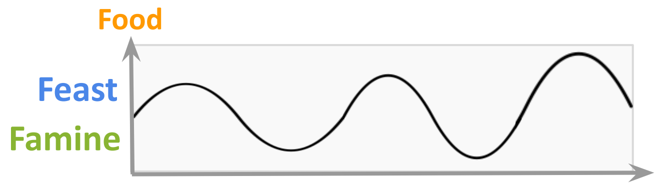




Adding Monte Carlo method so as to predict probability of various outcomes (e.g., somatic twist?) when random variables (e.g., feast or famine?) are present.

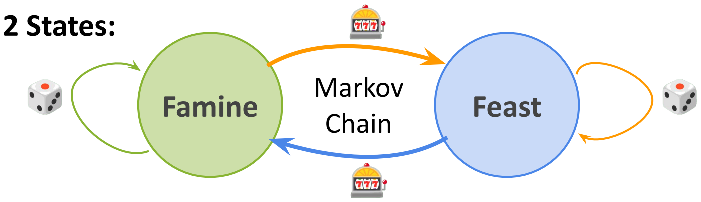
METHODS

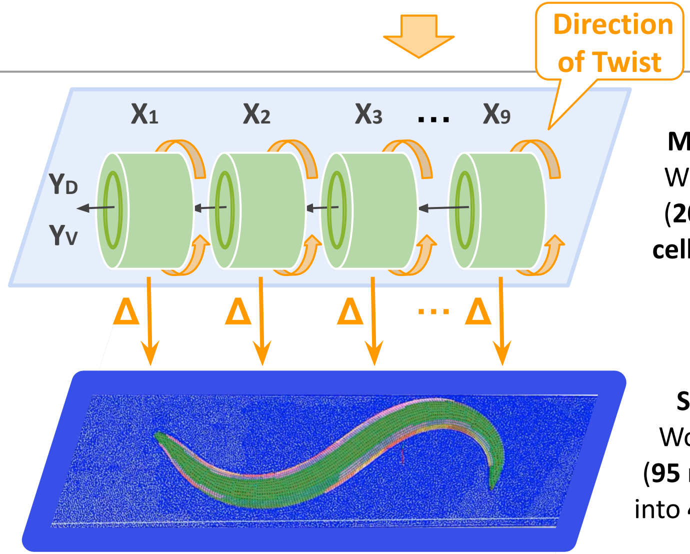
5. Run Monte Carlo Simulation — Until Somatic Twist Event Detected



Cycles of Feast & Famine

Simulation Time Steps





Monte Carlo Worm Model (**20 intestinal cells** as **9 rings**)

\+

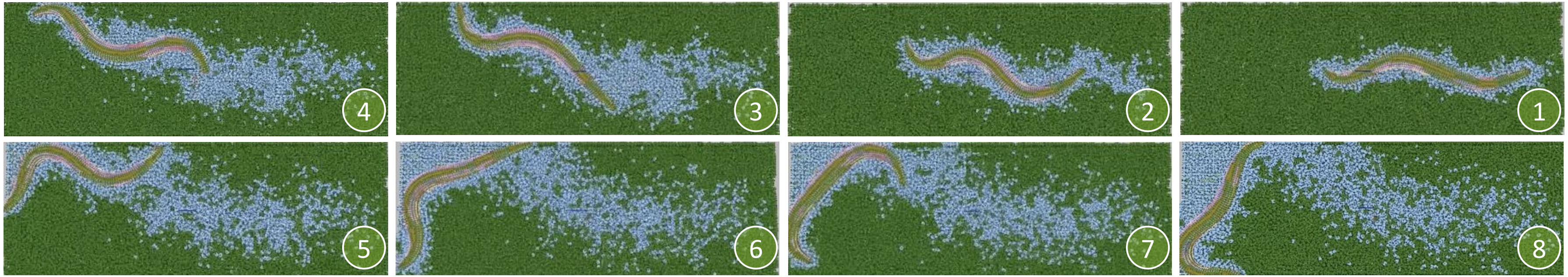
Sibernetic Worm Model (**95 muscle cells** into **4 quadrants**)

4 Quantities:	Δmass	Δvolume	Δdensity	Δweight
S FAMINE	Δm	ΔV	Δρ	Δ*W*
Y_D	⬇⬇	⬇	⬇	⬇
Y_V	⬇	⬇⬇	⬆	⬆
S FEAST	Δm	ΔV	Δρ	Δ*W*
Y_D	⬆⬆	⬆	⬆	⬆
Y_V	⬆	⬆⬆	⬇	⬇
Environ	⬆	-	⬆	⬆

RESULTS

1. Calibration: “The Smallest Worm Will Turn.” (Shakespeare, *“Henry VI”*, 1591)

Trial	Platform	Processor	GPU	Memory	Duration	Total Steps	Run Time	OK?
1A	MacBook Air	8-Core Apple M2	10-Core GPU	16 GB	15 ms	3000	2466 sec	❌
1B	MacBook Pro	8-Core Intel i9 2.4 GHz	Radeon Pro 8 GB	32 GB	15 ms	3000	199 sec	✅
2B	MacBook Pro	8-Core Intel i9 2.4 GHz	Radeon Pro 8 GB	32 GB	5000 ms	1000000	34.65 hrs	😬
2C	MacBook Pro	16-Core M4 Max	40-Core GPU	64 GB	5000 ms	1000000	*TBD*	🤷🏻‍♂️
2D	AWS Cloud	*TBD*	-	*TBD*	5000 ms	1000000	*TBD*	🤷🏻‍♂️

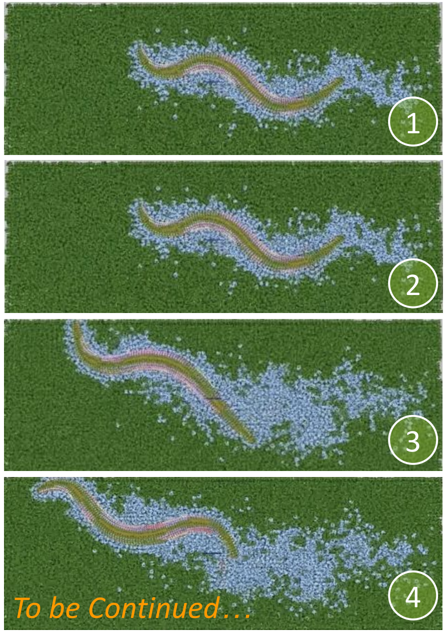


A simulated *C. elegans* makes three turns in five seconds inside a bounded aquatic environment. Different processor and memory configurations were benchmarked to estimate computing resources required for running repeated trials on OpenWorm + Sibernetic. Original Docker image and Python source code: *https://hub.docker.com/r/openworm/openworm*

RESULTS

2. Visualization: "The Worm Did Turn. It Turned on Itself." (Kinsbourne, 2013)

Future Work: Rendering



9 Intestinal Rings

Worm Model Mapping

4 Muscle Quadrants

Worm Model Parameter Space = 72 x 2 Parameters Total

Y_D	$X_1..X_9$
Δm	⬇ ⬇
ΔV	⬇
$\Delta \rho$	⬇
Δw	⬇

Y_V	$X_1..X_9$
Δm	⬇
ΔV	⬇ ⬇
$\Delta \rho$	⬆
Δw	⬆

Y_V	$X_1..X_9$
Δm	⬆
ΔV	⬆ ⬆
$\Delta \rho$	⬇
Δw	⬇

Y_D	$X_1..X_9$
Δm	⬆ ⬆
ΔV	⬆
$\Delta \rho$	⬆
Δw	⬆

$\Delta_{X,Y,Q}$ $\Delta_{X,Y,Q}$

	HEAD					NECK					BODY										TAIL					
MDR	1	2	3	4		5	6	7	8		9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Y_D											X_1	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9						
MVR	1	2	3	4		5	6	7	8		9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Y_V											X_1	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9						
MVL	1	2	3	4		5	6	7	8		9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	
Y_V											X_1	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9						
MDL	1	2	3	4		5	6	7	8		9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Y_D											X_1	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9						

Worm behavior emerges from simulation of empirical data, with tiny proportional changes: $\Delta_{X,Y,Q}$ applied to the worm body: **MDR** $_{9..18}$, **MVR** $_{9..18}$, **MVL** $_{9..18}$, and **MDL** $_{9..18}$ at each time step, driven by famine and feast cycles which successive worm generations must adapt to.

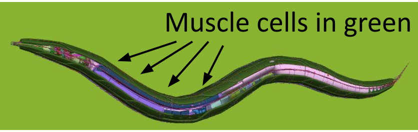
DISCUSSION

Validation *In Silico:* Monte Carlo Simulation of Somatic Twist

Theories Matching Simulation Results

- ❑ Simulation results provide *in silico* validation for **somatic twist theory** of Kinsbourne (2013).
- ❑ That means **dorsoventral inversion** (St. Hilaire, 1882), a long-held hypothesis in the field, has also been validated.
- ❑ **"From Worm to Man"**: underwater **buoyancy** is the force that drives somatic twist, which in turn cause dorsoventral inversion that ultimately led to **decussation** in vertebrates.

Review of Known Facts About *C. Elegans*



- ❑ Four bands of muscles run the length of the body enable locomotion.
- ❑ Head moves freely — all four muscle quadrants independently wired.
- ❑ *Dorsal* or *ventral* bending for body movements — never left or right.
- ❑ **Locomotion**: lie on *left or right side* when crossing horizontal surface.

Possible Errors

- ❑ All models are *wrong*, but some are *useful*.
- ❑ More than one way to map 9 intestinal rings onto 95 muscle cells for Sibernetic simulation.
- ❑ *Geometric progression* from tiny proportional changes to model parameters at each time step.

Unexpected Challenges

- ❑ OpenWorm simulation very compute intensive.
- ❑ 2 ½ days on MacBook simulates 5-sec duration.
- ❑ Run future repeated simulations on AWS cloud?
- ❑ Highlighting worm body for visual confirmation
- ❑ Somatic twist is bottom-up emergent behavior
- ❑ Design considerations of somatic twist detector

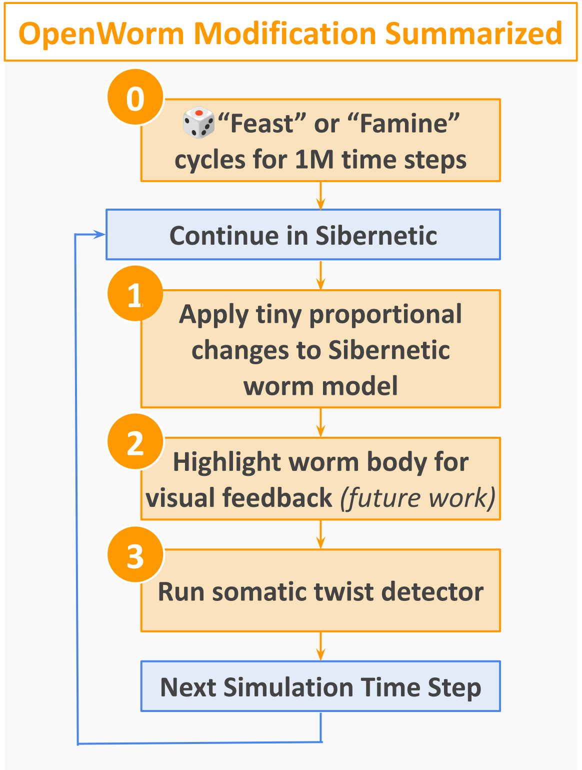
Repeated Trials

- ❑ Repeated Monte Carlo trials expensive to run!

CONCLUSIONS

Underwater Buoyancy Drives Somatic Twist of Marine Worm

- ❑ Somatic twist theory of Kinsbourne (2013) offers a testable hypothesis for how corticospinal tracts became decussated as by-product of dorsoventral inversion in ancient marine worms.
- ❑ My results validated somatic twist theory by simulating underwater buoyancy force that drives somatic twist in marine worms during times when food was bountiful.
- ❑ My contribution: novel design of a **somatic twist detector** that can track relative cell positions during Sibernetic simulation to identify when dorsoventral inversion has just occurred.
- ❑ A biomechanical worm model has greater reproducibility *in silico* compared with mechanical ‘twistable body plan structures’ submerged inside an aquarium (Cheong, 2025).
- ❑ Monte Carlo simulation shows great promise as a practical new approach to conducting evolutionary biology experiments *in silico* when combined with Sibernetic and OpenWorm.



REFERENCES

1. Allentoft-Larsen, M. C., Gonzalez, B. C., Daniels, J., Katija, K., Osborn, K., & Worsaae, K. (2021). Muscular adaptations in swimming scale worms (Polynoidae, Annelida). *Royal Society Open Science*, *8*(10). https://doi.org/10.1098/rsos.210541
2. Cheong, A. (2025). *Why Do Vertebrates Have Decussated Corticospinal Tracts?*
3. Dimov, I., & Maduro, M. F. (2019). The C. elegans intestine: organogenesis, digestion, and physiology. *Cell and Tissue Research, 377*(3), 383–396. https://doi.org/10.1007/s00441-019-03036-4
4. Gleeson, P., Alicea, B., Cantarelli, M., Idili, G., Lee,C.W., Palyanov, A., Khayrulin, S., Portegys, T., Ghayoomie, V. & Larson, S. (2023, June 24–28). Updates from the OpenWorm project: incorporating NeuroPAL data and ASH neuron electrophysiological recordings [Poster session]. 24th International C. elegans Conference, Glasgow, Scotland.
5. Gleeson, P., Cantarelli, M., Currie, M., Hokanson, J., Idili, G., Khayrulin, S., Palyanov, A., Szigeti, B., & Larson, S. (2015). The OpenWorm Project: currently available resources and future plans. *BMC Neuroscience*, *16*(S1). https://doi.org/10.1186/1471-2202-16-s1-p141
6. Kinsbourne, M. (2013). Somatic twist: A model for the evolution of decussation. *Neuropsychology, 27*(5), 511–515. https://doi.org/10.1037/a0033662
7. Lacalli, T. (2012). The Middle Cambrian fossil Pikaia and the evolution of chordate swimming. *EvoDevo*, *3*(1), 12. https://doi.org/10.1186/2041-9139-3-12
8. OpenWorm. (n.d.). Openworm Website. https://openworm.org/ & https://github.com/openworm/OpenWorm
9. Palyanov, A., Khayrulin, S., & Larson, S. D. (2016). Application of smoothed particle hydrodynamics to modeling mechanisms of biological tissue. Advances in Engineering Software, 98, 1–11. https://doi.org/10.1016/j.advengsoft.2016.03.002
10. *Pikaia gracilens*. (n.d.). The Burgess Shale. https://burgess-shale.rom.on.ca/fossils/pikaia-gracilens/
11. Szigeti, B., Gleeson, P., Vella, M., Khayrulin, S., Palyanov, A., Hokanson, J., Currie, M., Cantarelli, M., Idili, G., & Larson, S. (2014). OpenWorm: an open-science approach to modeling Caenorhabditis elegans. *Frontiers in Computational Neuroscience*, *8*. https://doi.org/10.3389/fncom.2014.00137