White Lies about Biology: Programming Deformable Surfaces

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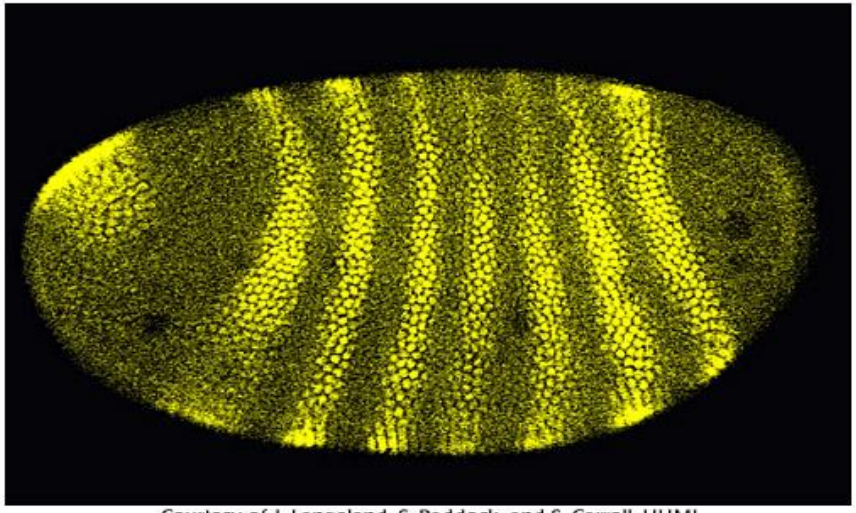
ICCS 2011

Fields vs. Geometry

Spatial patterning:



Courtesy of J. Langeland, S. Paddock, and S. Carroll, HHMI,
Dept. of Molecular Biology, University of Wisconsin. Noncommercial, educational use only.

Geometric patterning:

- Dynamic, nonlinear substrate
- Complex, overlapping actuation mechanisms

(copyrighted picture – drosophila embryo during germ band extension)

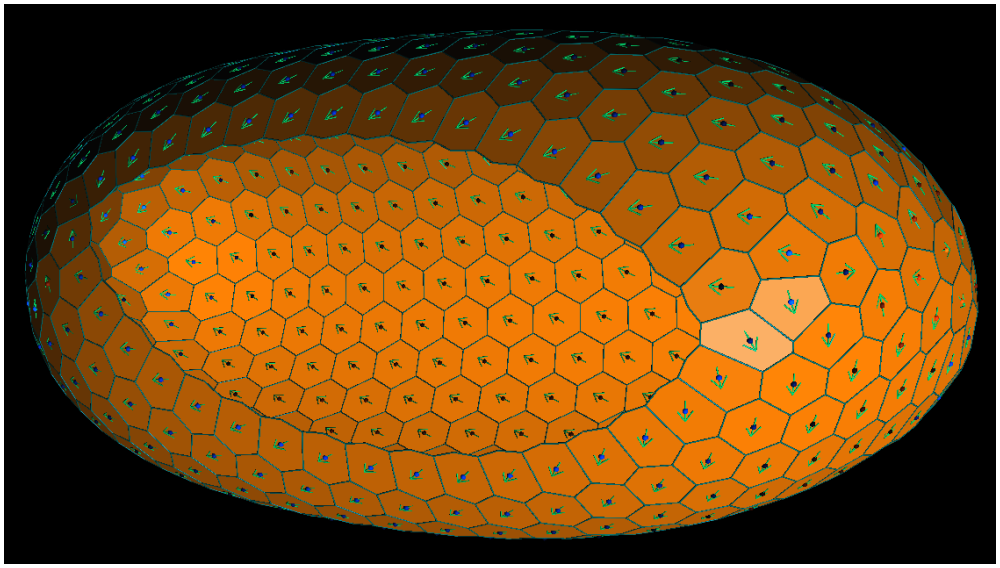
Parkhurst lab, Fred Hutchinson CRC

A Simplified Laboratory?

- Goal:
  - Capture essential physical / computational problems
  - …Without quantitatively mimicking details of any particular system
- Must confront deformation, 3D

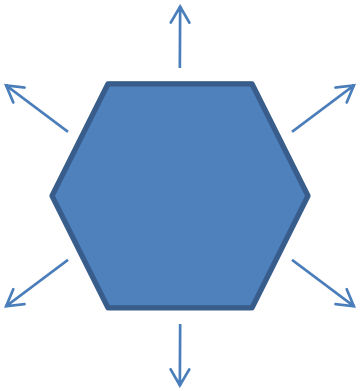
Low-Fidelity “2½-D” Modeling

- Surfaces instead of volumes
- Discrete cellularization
- Transparent control parameters

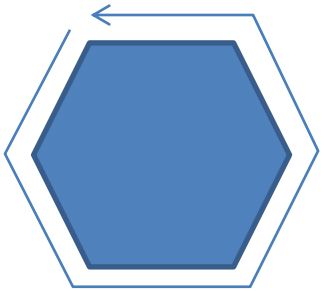


Cell Control

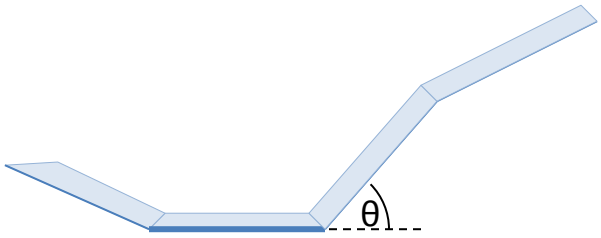
- Area ($A_{0,}$ k_A)



- Surface tension ($\sigma_{p,q}$)



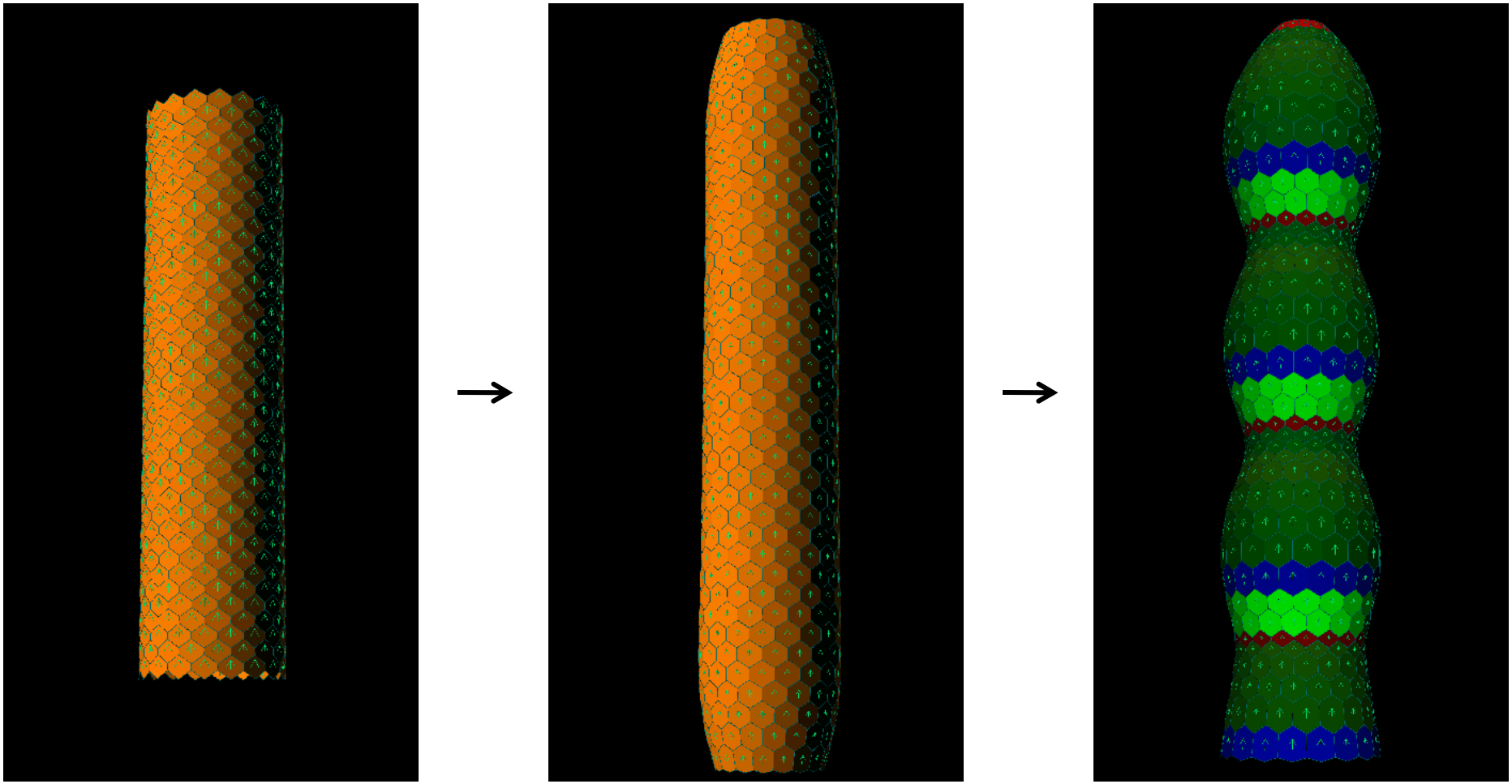
- Bending (θ_0, $\Delta\theta_{ij}$, k_θ)



(and a few more minor ones)

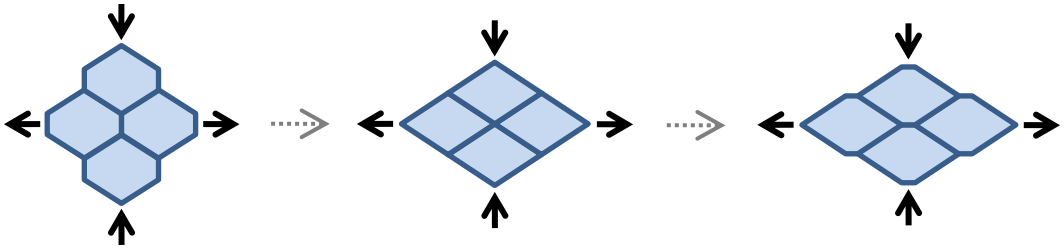
Collective Behaviors (I)

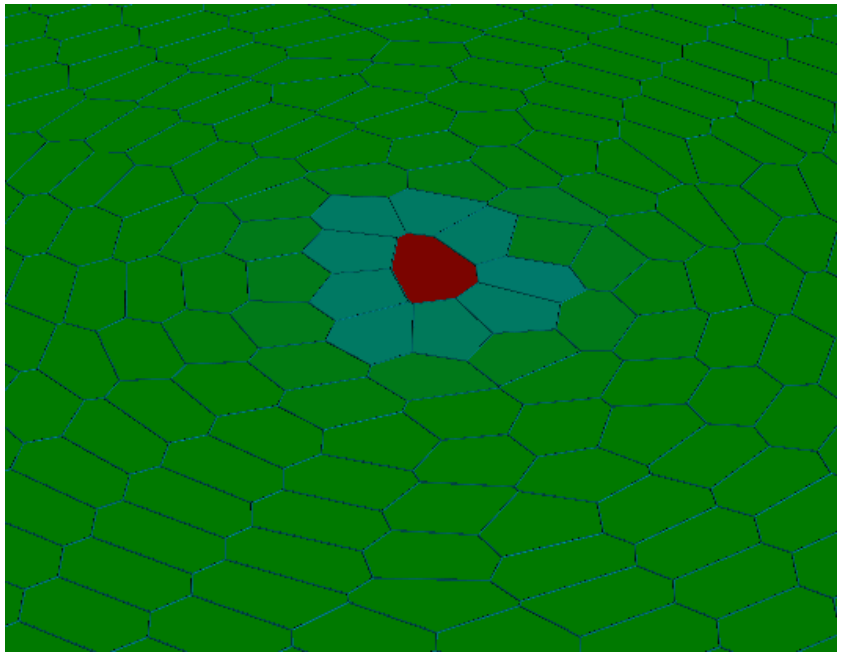
- Elastic convergence

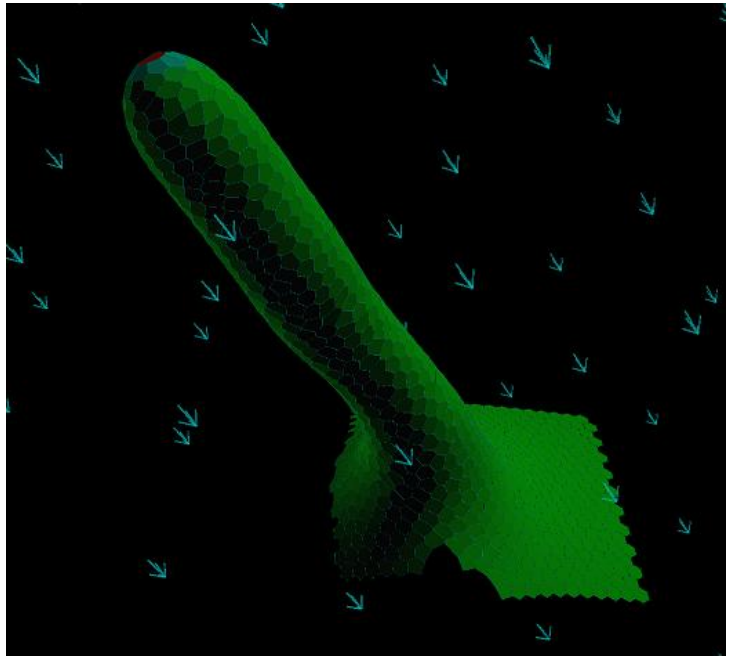


Collective Behaviors (II)

- Plastic yielding:







Implementation

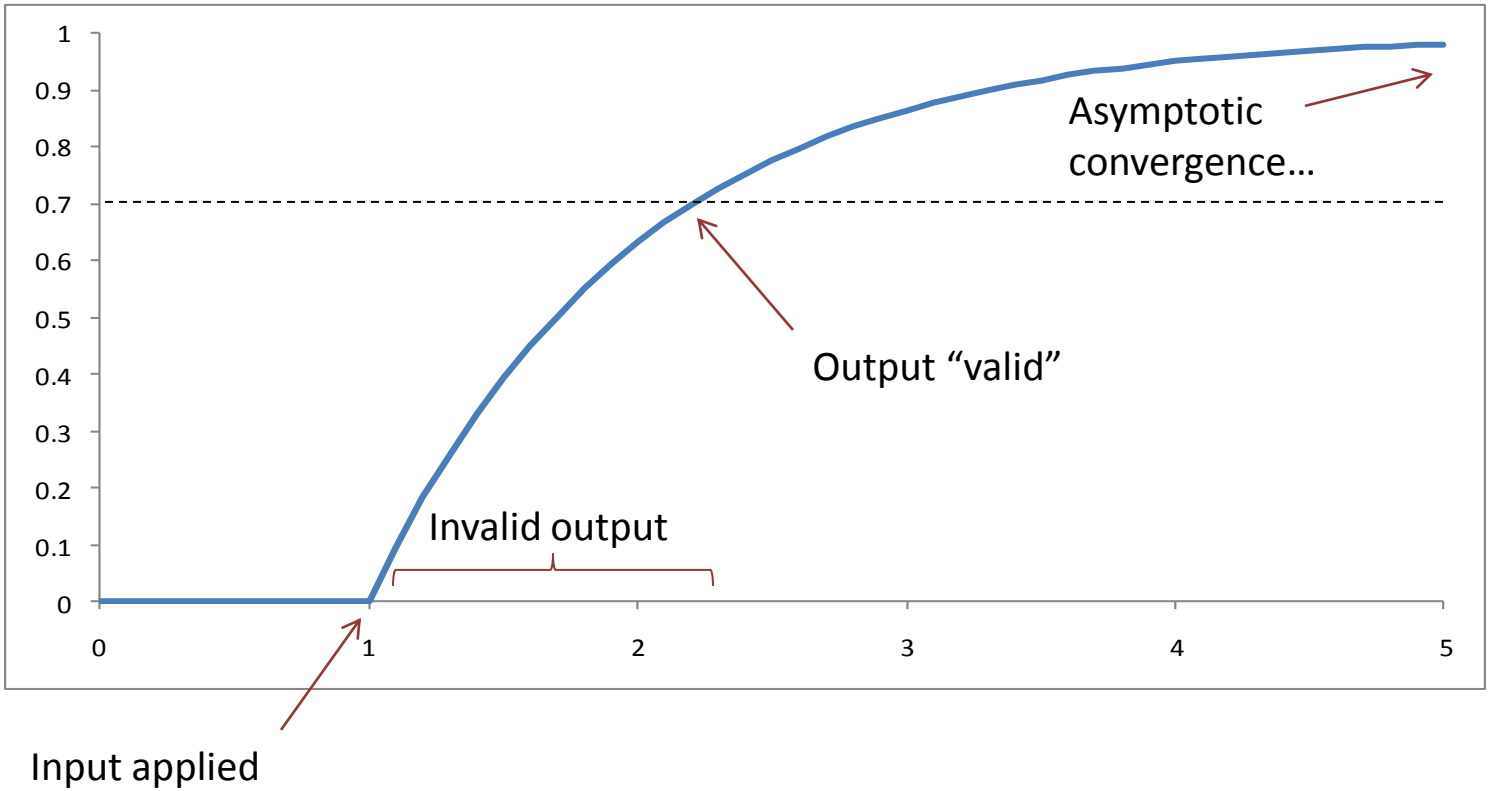
- ~10kLoC C++
  - Pthreads / Windows threads
- Adaptive gradient descent

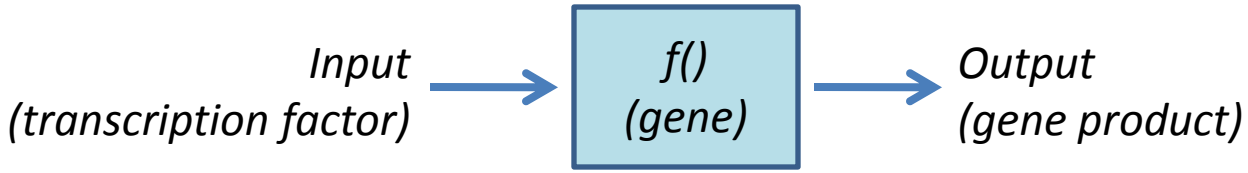
Challenges and Possible Solutions

- Convergence Timing
- Forming and Fighting the Material
- Spatial-Mechanical Leakage

Convergence Timing (I)

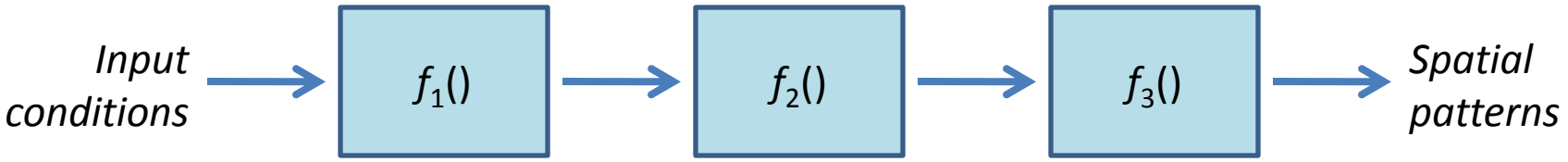
Regulatory networks take time to converge:



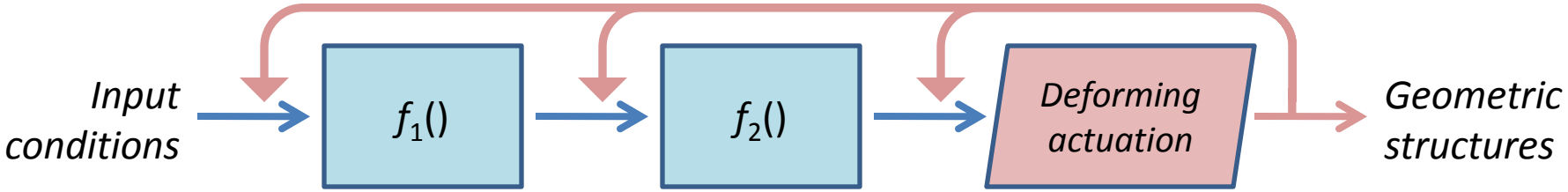


Convergence Timing (II)

- Spatial patterning can be feed-forward (or self-stabilizing)
  - Here, temporary input glitches don't matter



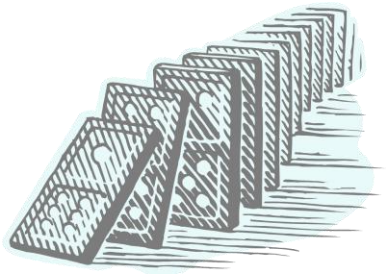
- But, deformation causes spurious feedback loops



- And, plastic deformation is irreversible
- Now what?

Convergence Timing: Solutions?

- Safety margins
  - Cons: Development speed is precious
- Self-stabilizing geometry
  - (E.g. hydra?)
  - Cons: Really hard, especially with plastic yielding?
- Self-timed circuits
  - Cons:
    - Has anyone ever seen this?
    - How do you do self-timed gradients???



Forming and Fighting the Material

- Material response is complicated
  - Too many sensitive dependencies

    ⇒ Not robust or evolvable
- Solutions?
  - Feedback control
  - Multi-modal actuation

Spatial-Mechanical Leakage

- Stress & strain are non-local
  - Deformation in one place affects the whole structure

    ⇒ Not very robust or evolvable
- Solutions?
  - Feedback isolation
  - Self-stabilization
  - Mechanical restraints

Conclusions

- Lightweight “2½-D” surface modeling captures many key developmental phenomena
- Developmental theory is missing answers to deep questions raised by deformation
- Got any good hypotheses? ☺

Questions?

Related Work

- Amorphous computing
  - Origami Shape Language [Nagpal01]
  - Growing Points Language [Coore99]
  - Modular robotics work…
- Mechanical hypothesis modeling
  - [Odell81], [Jacobson86], [Davidson95], …
  - Taber et. al.
  - …
- Multi-scale, data-driven modeling
  - Brodland et. al. ([Brodland06], [Chen08])
- Robustness in developmental systems biology
  - [Eldar04], …
- Classical developmental patterning theory
  - Meinhardt et. al., …