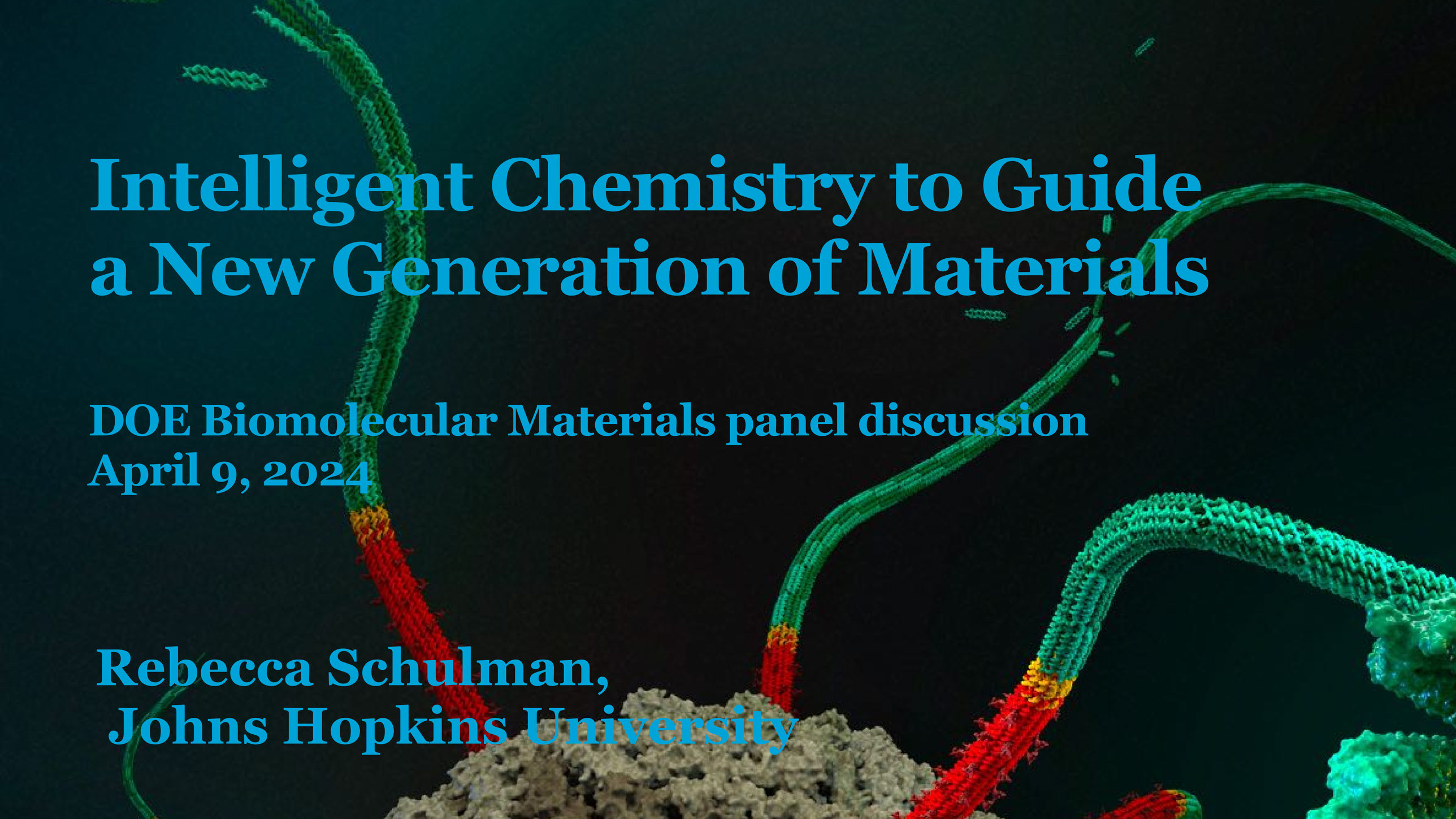
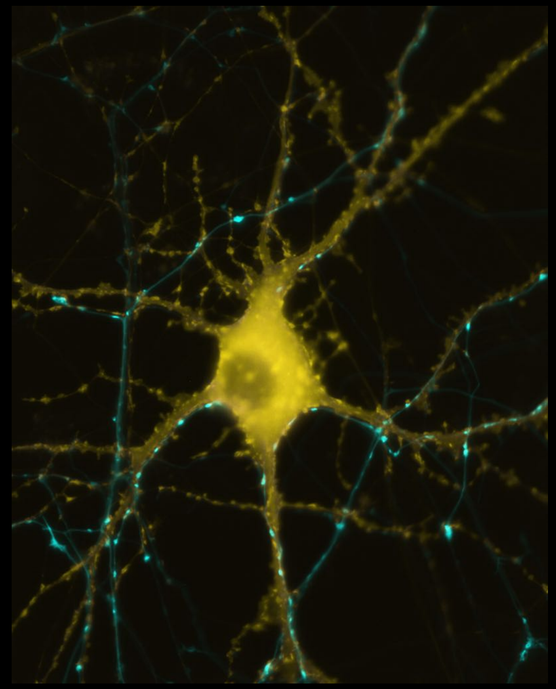


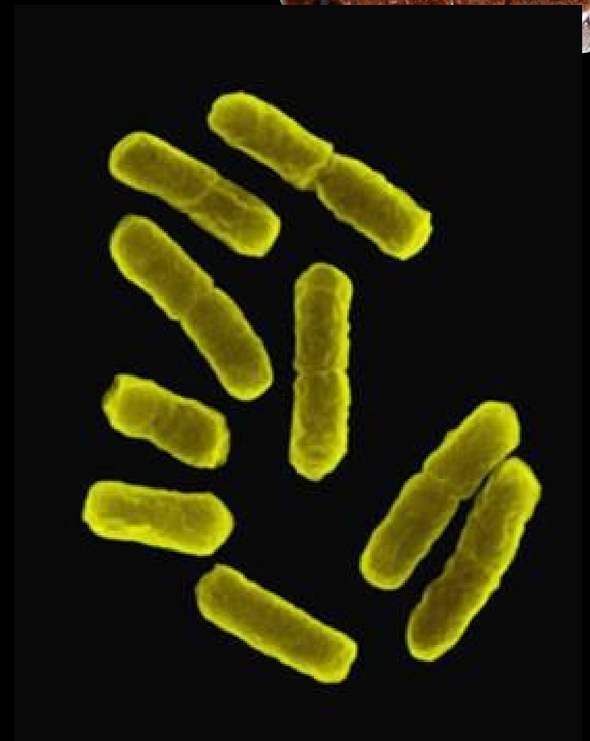
Intelligent Chemistry to Guide a New Generation of Materials

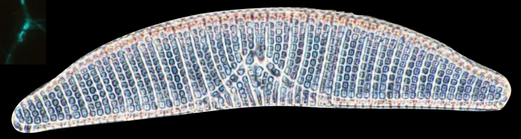
DOE Biomolecular Materials panel discussion
April 9, 2024

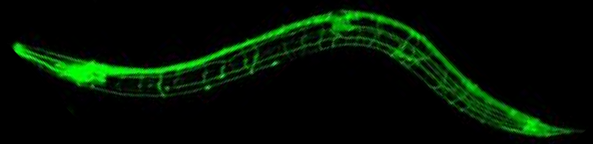
Rebecca Schulman,
Johns Hopkins University

Biological manufacturing and assembly remain a compelling proof of concept for versatility, precision, and functionality.



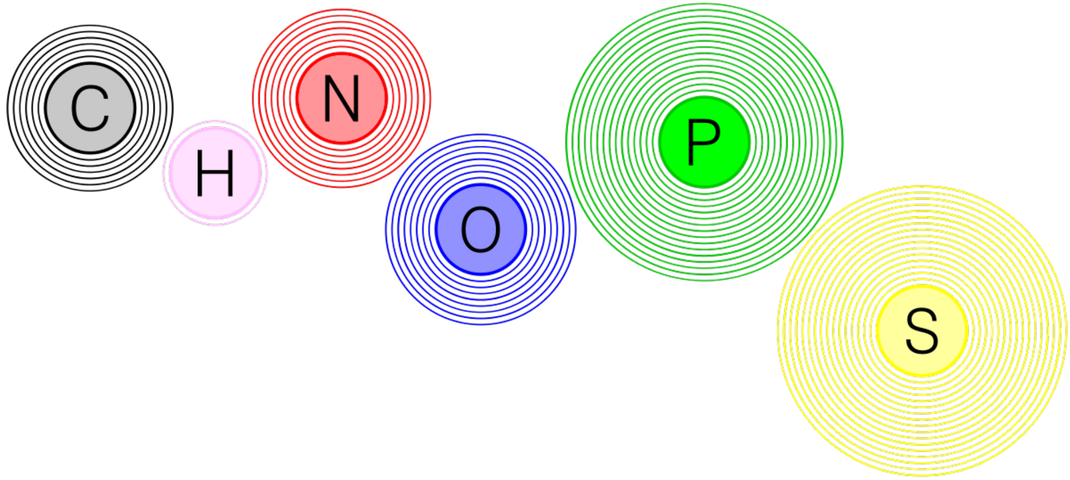






Biological materials have a range of powerful advantages.

Low capital equipment costs
Adaptability to a range of sites.



Universally available raw materials

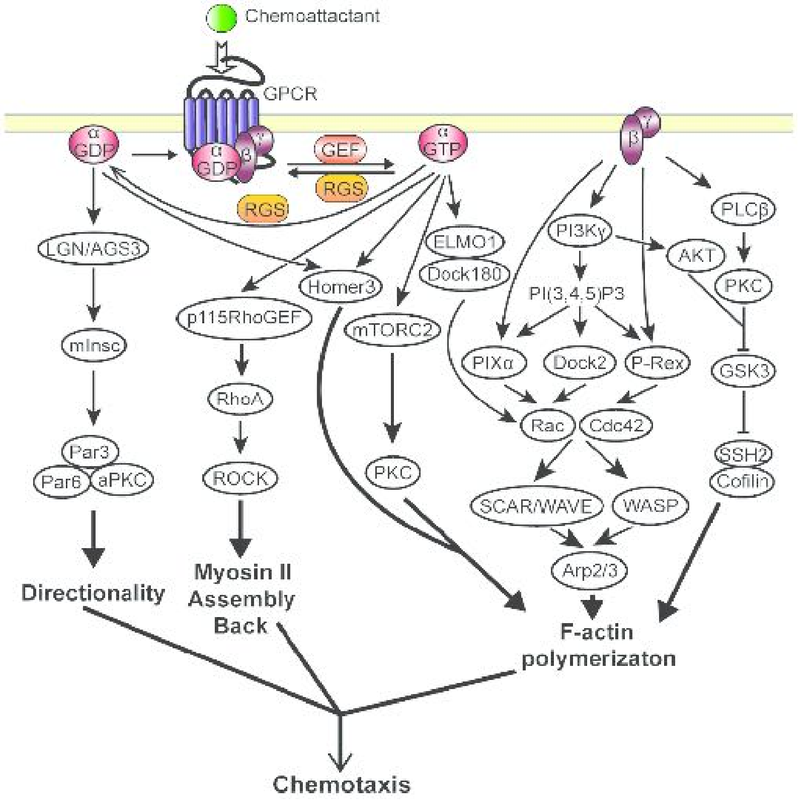

7164
7164
BNSF
7164
BNSF
BNSF


The biomolecular materials program allows the search that is needed, guided by fundamentals, in this vast space.

Thank you.

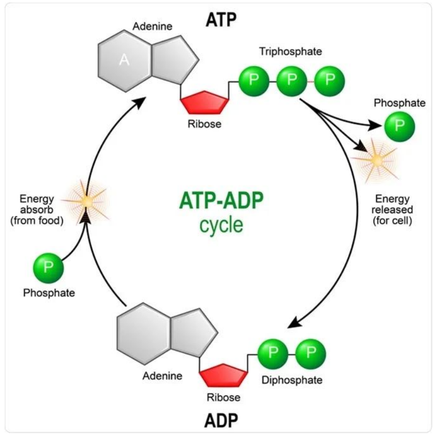
Distant mirror and inspiration: Biology use embedded “control circuits” to make materials do new things, and to improve their properties and efficiency.

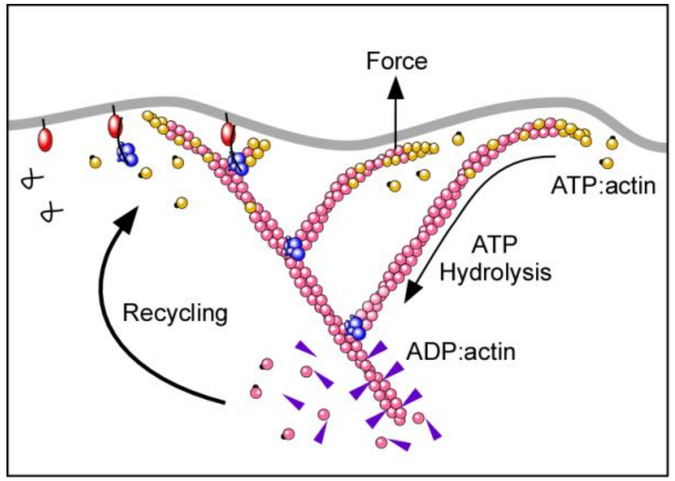
David Rogers ca 1950

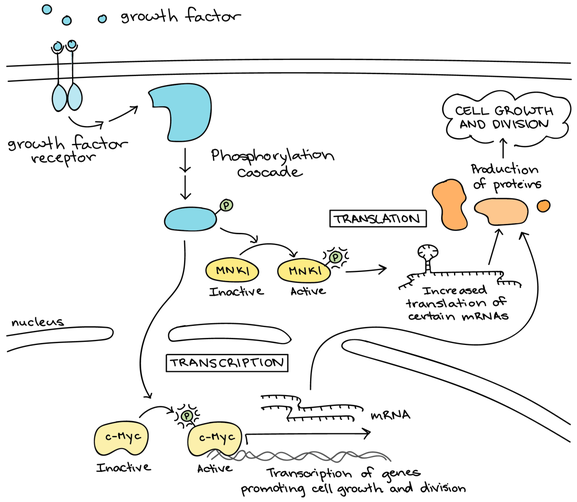


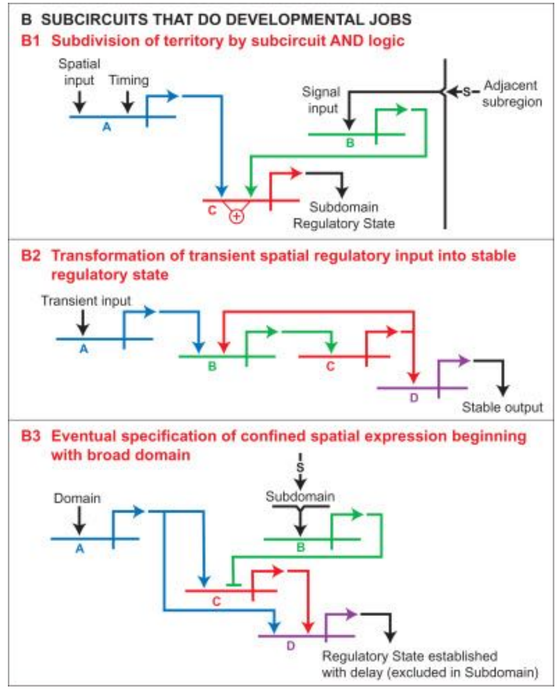
Kemp et al, JMS, 2016

Cells use biomolecular circuits for all sorts of tasks:









Energy flow

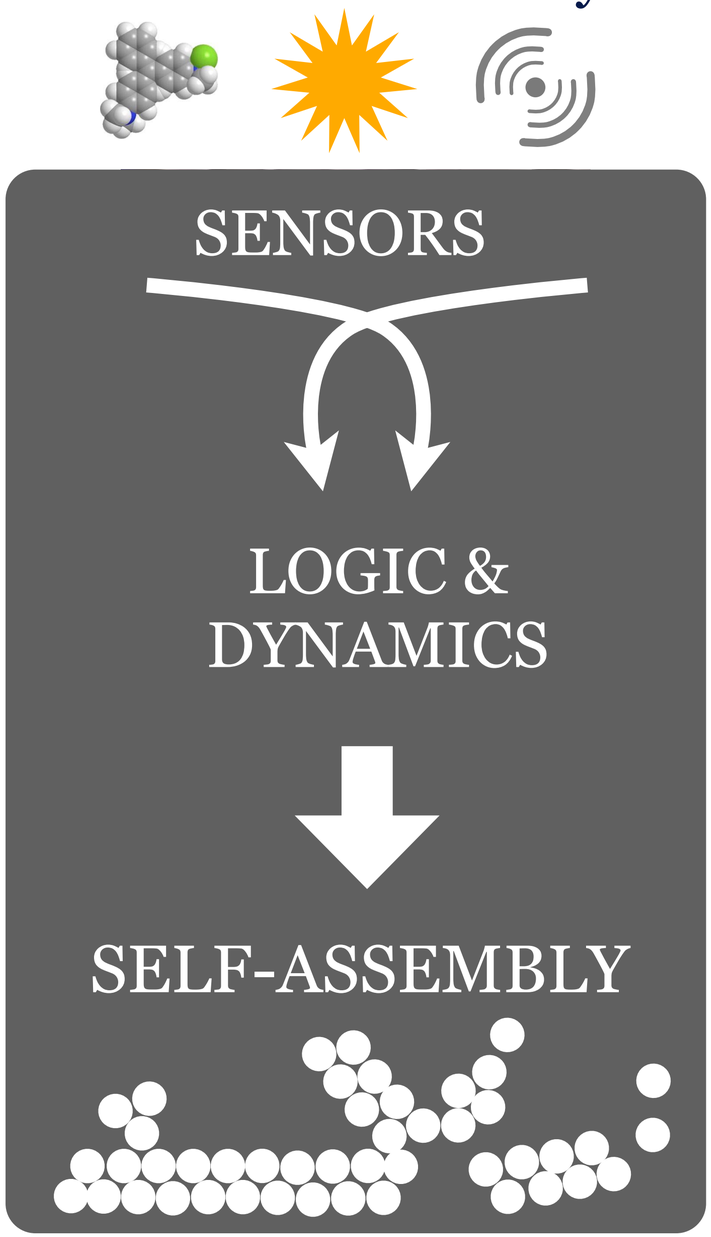
Motion

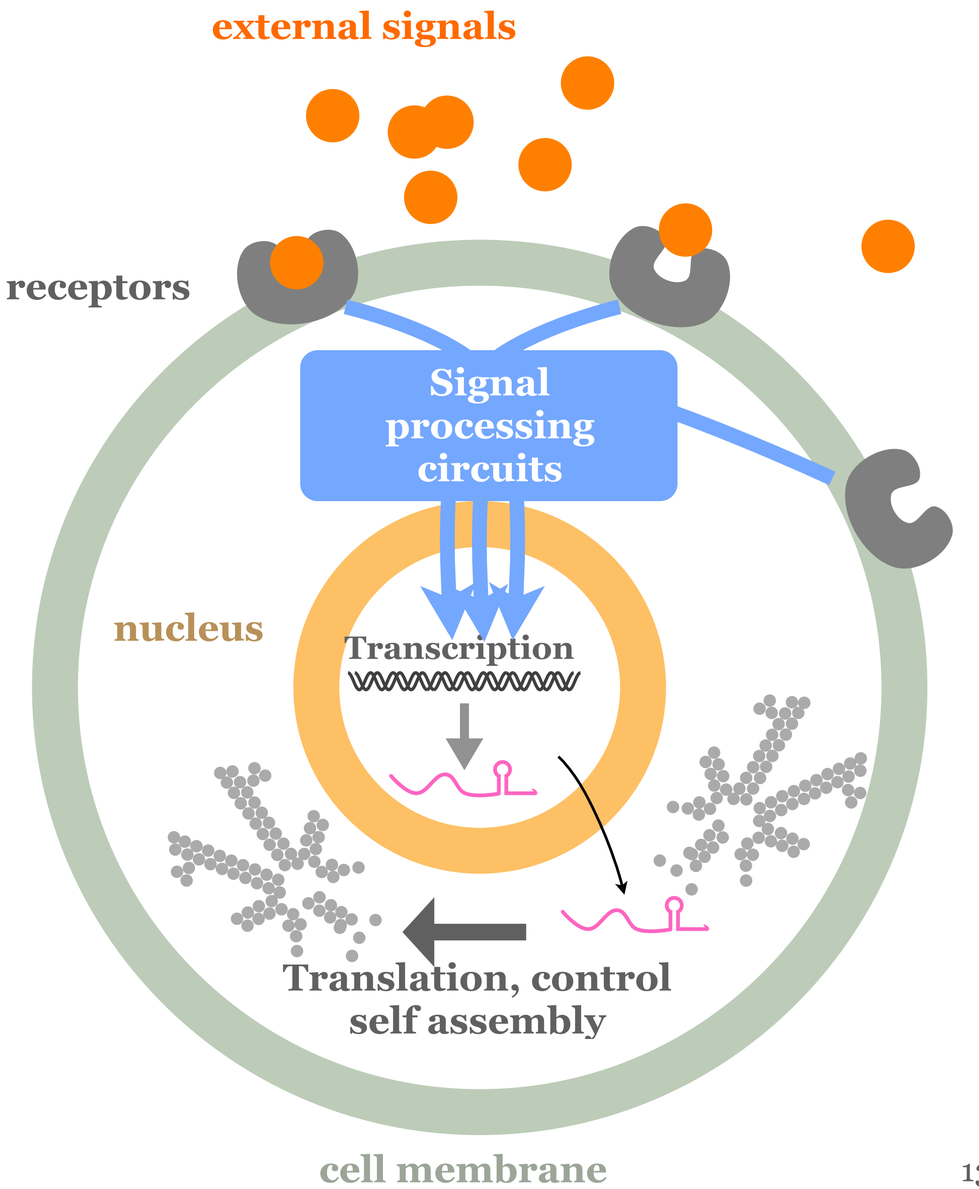
Regulation and control

Multistep protocols and assembly

Can we ***design*** complex biomolecular assembly dynamics similar to those observed in cellular systems?

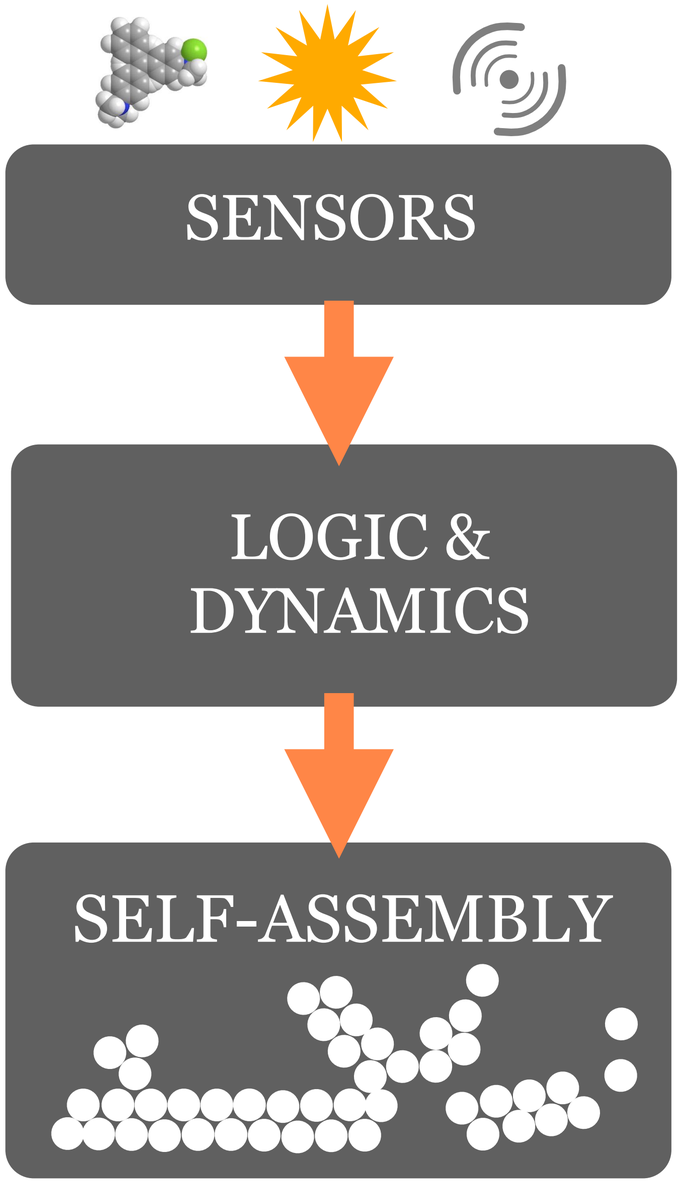
2015

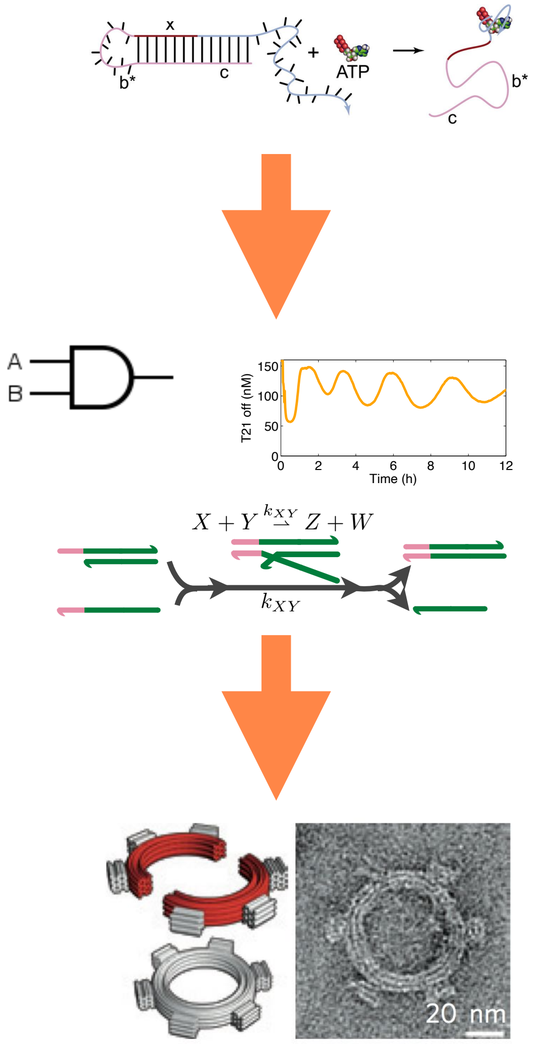




Specifically, we sought to build responsive biomaterials by integrating layers of nucleic acid devices

2015



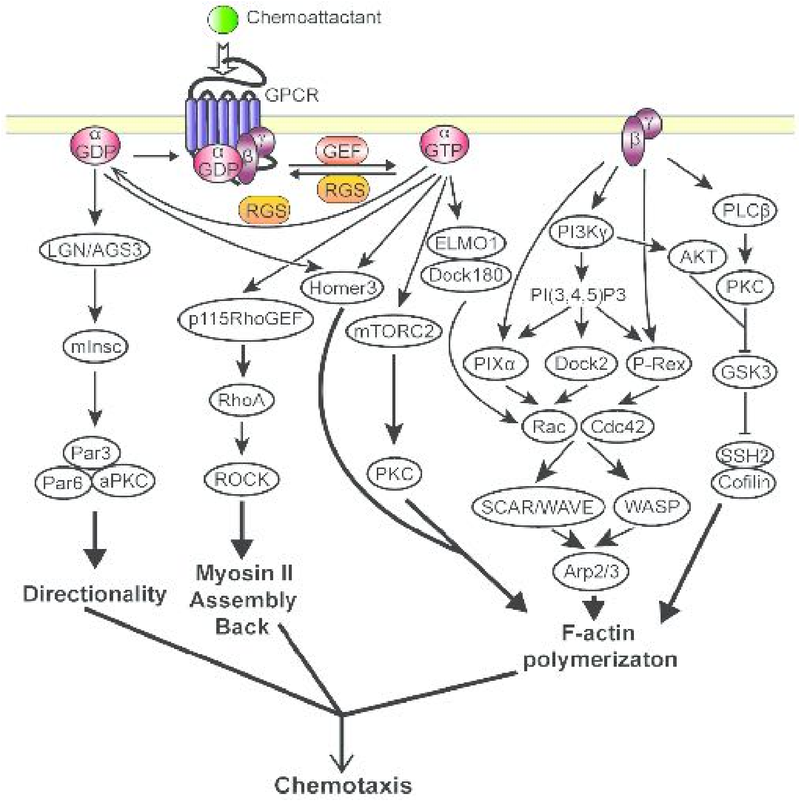


CHALLENGES

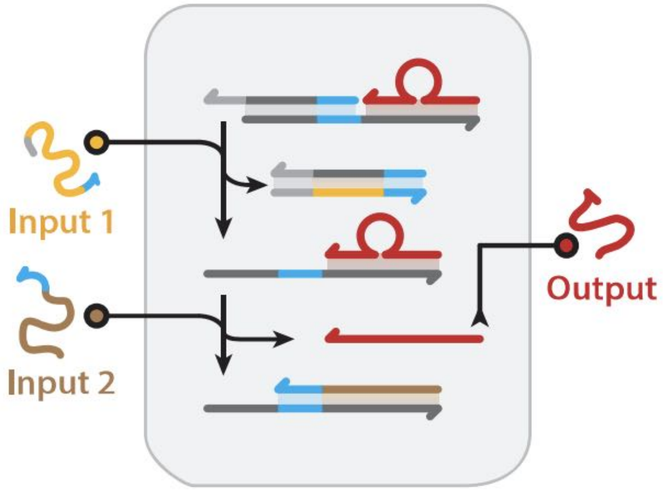
- Time scales
- Length scales
- Signal transmission
- Compatible environment

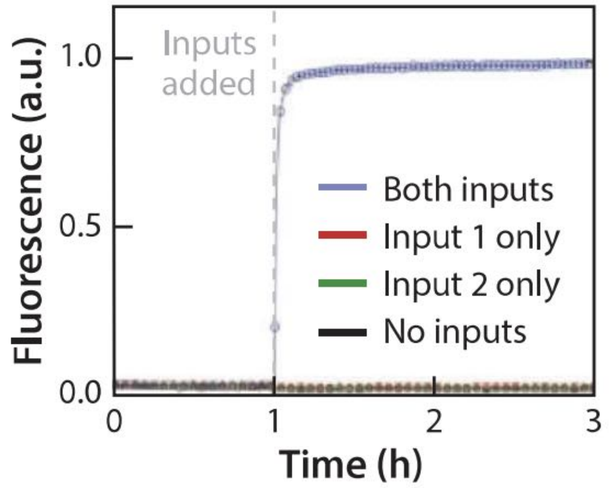
Solutions are portable to generic self-assembling, programmable matter

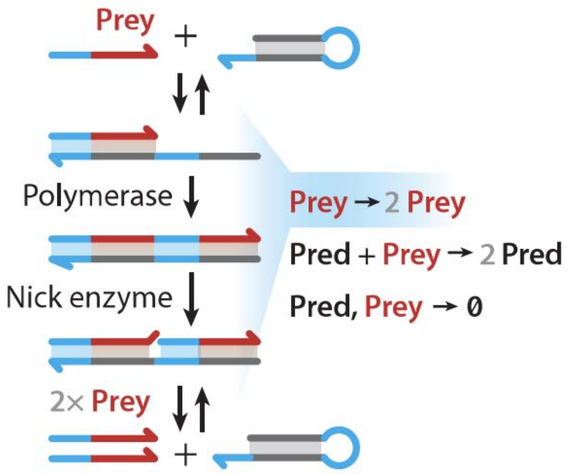
Biomolecular “circuits” provide biomolecular triggers as outputs.

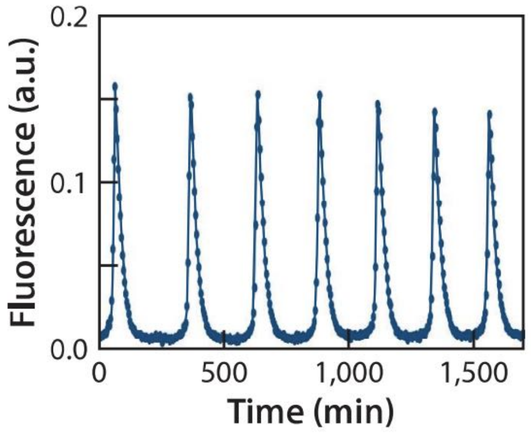


Kemp et al, JMS, 2016



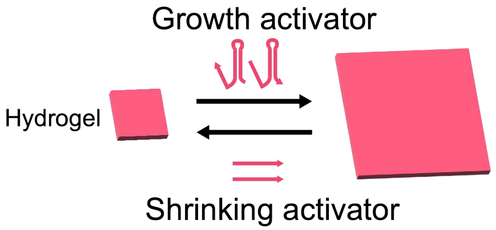




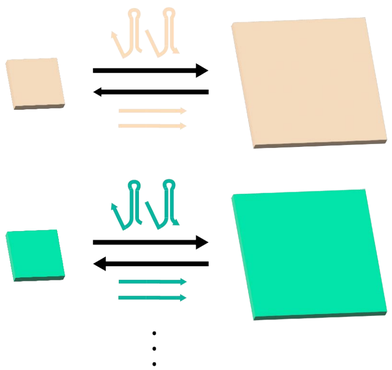


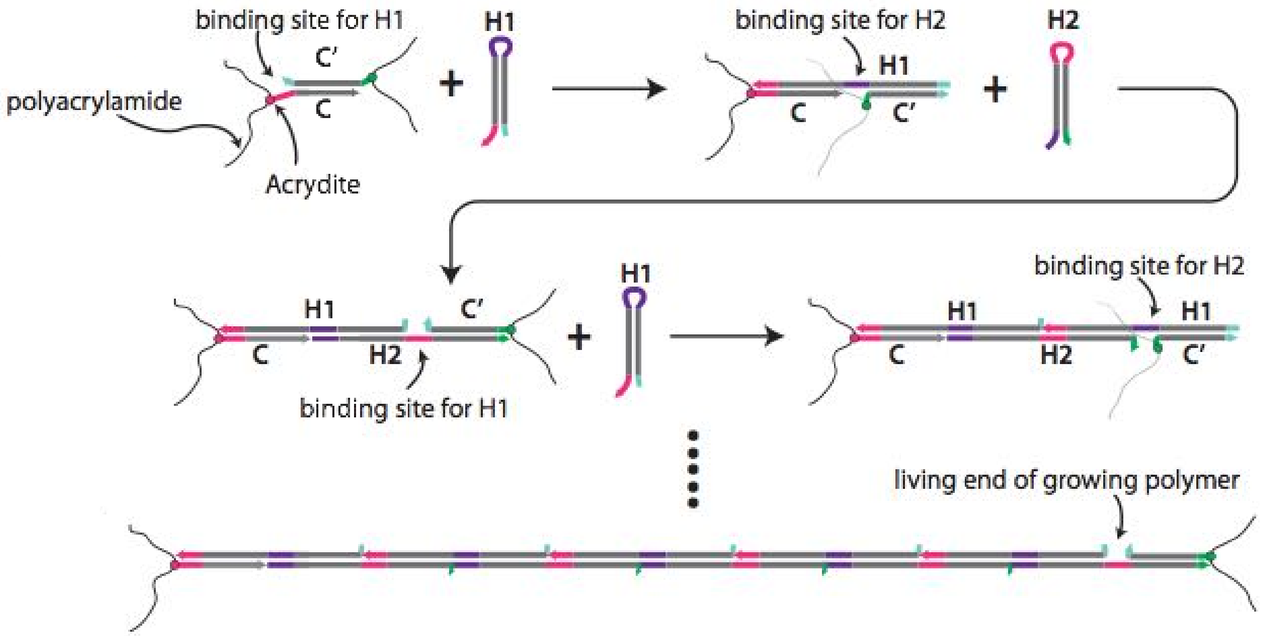
Scalise and Schulman, Ann. Rev. Biomed. Eng., 2018

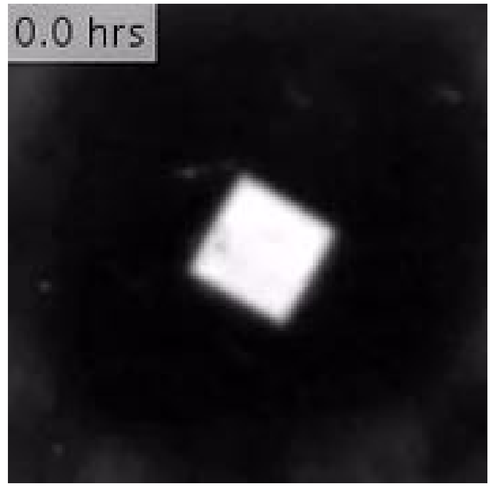
We therefore needed to ask how biomolecules could trigger changes in materials.

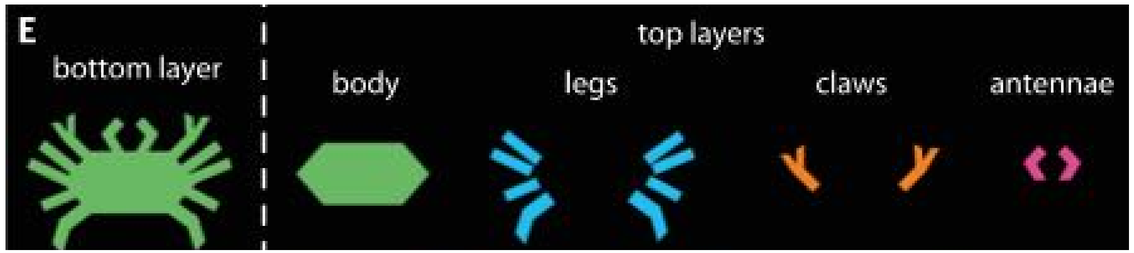


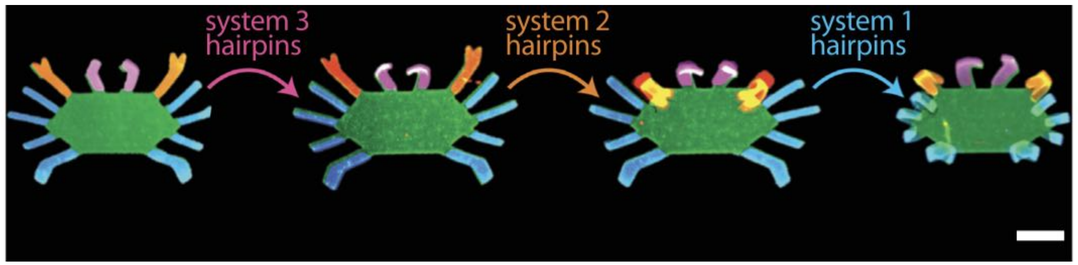
A library of orthogonal DNA actuators





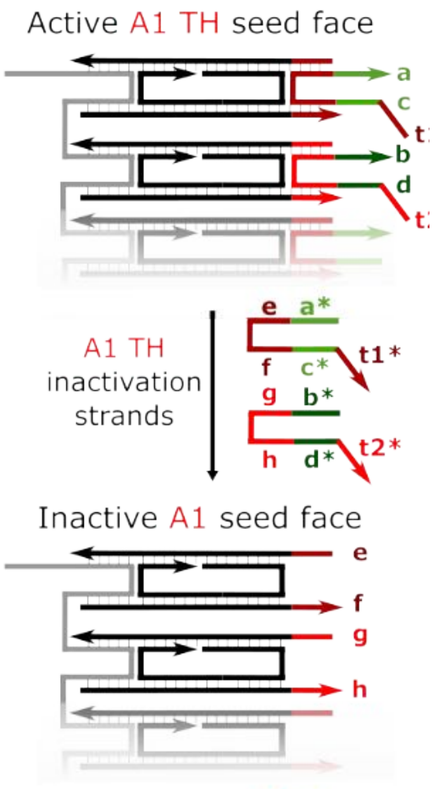


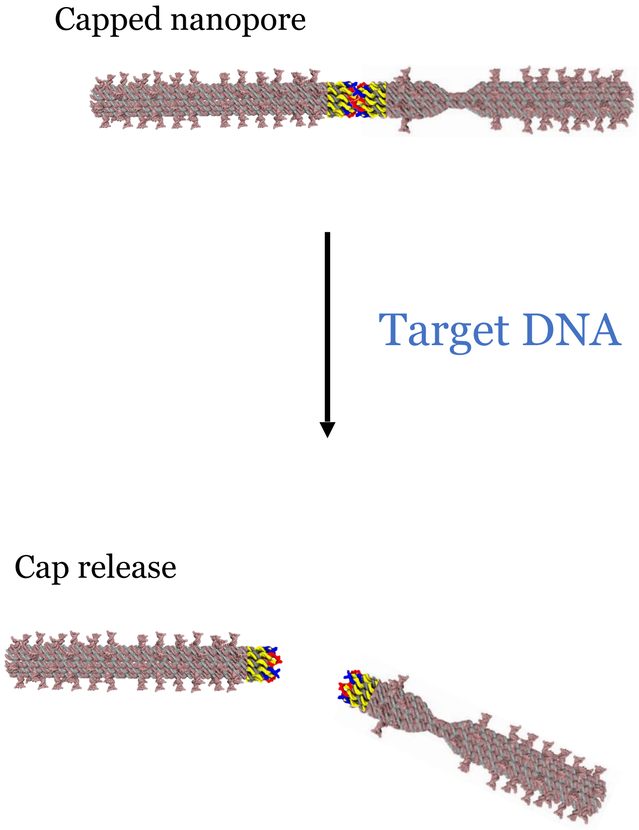


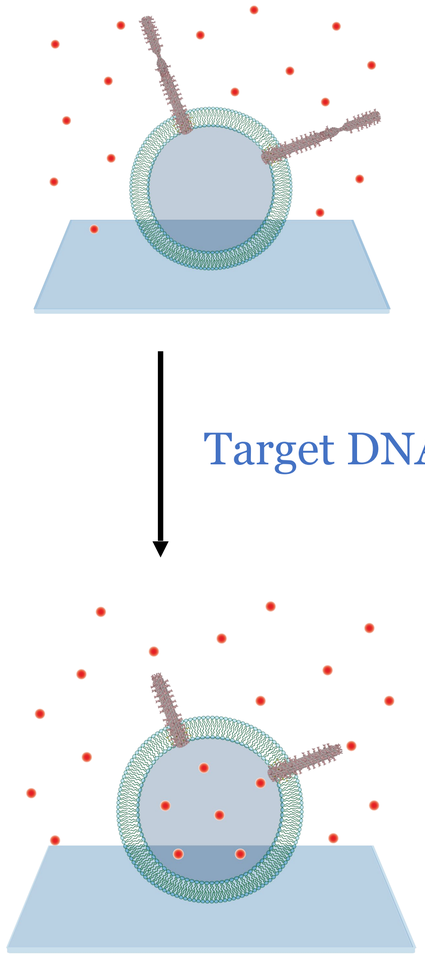


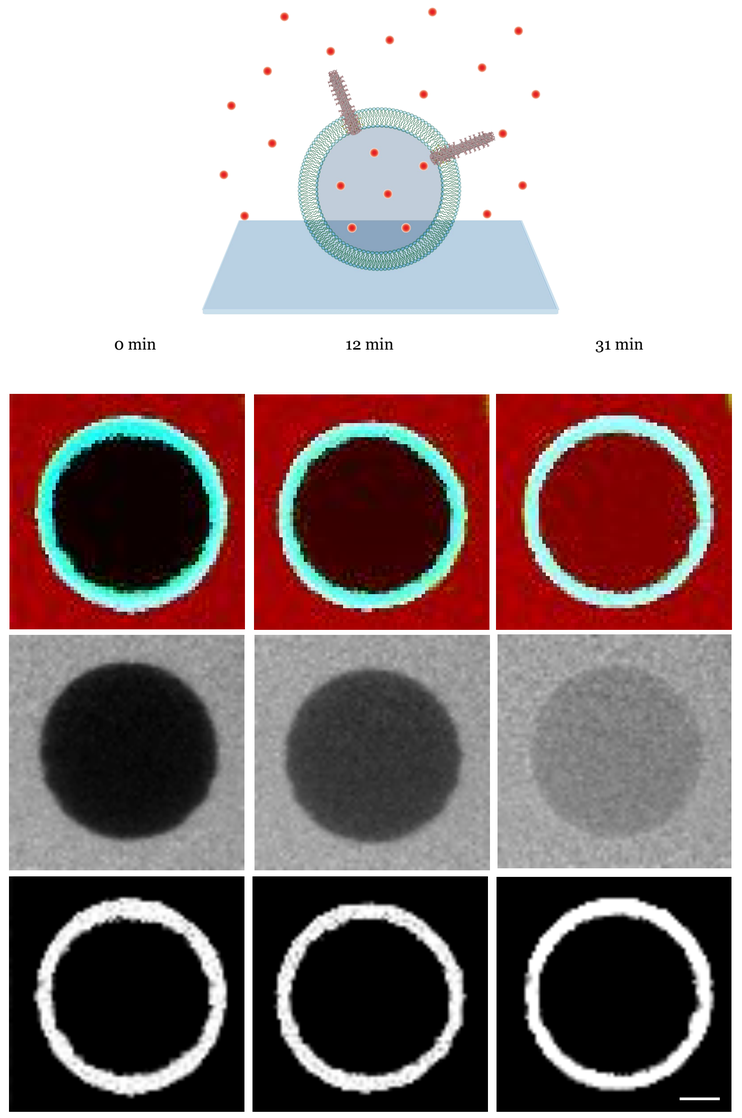
Cangialosi, Yoon, Liu, Huang, Guo, Nguyen, Gracias, Schulman, Science, 2017
Shi, Chen, Fern, Deng, Liu, Scalise, Huang, Cowan, Gracias, Schulman, biorxiv, 2022

We found, generally, how biomolecular signals can trigger conformational changes in materials using sequence-specific interactions.





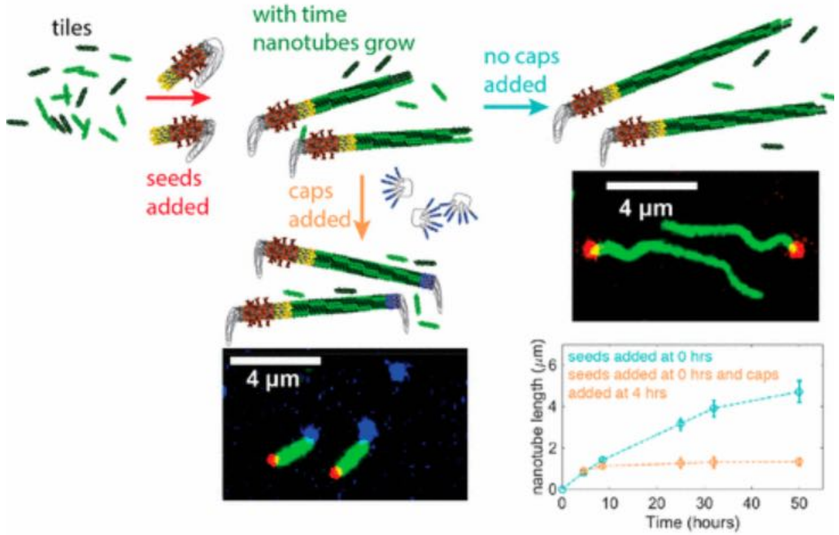




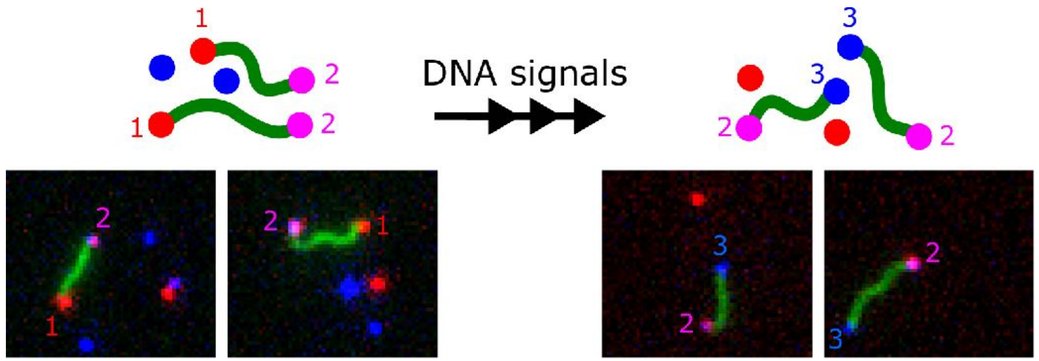
Li, Maffeo, Joshi, Aksimentiev, Menard, Schulman, Science Advances, 2022.

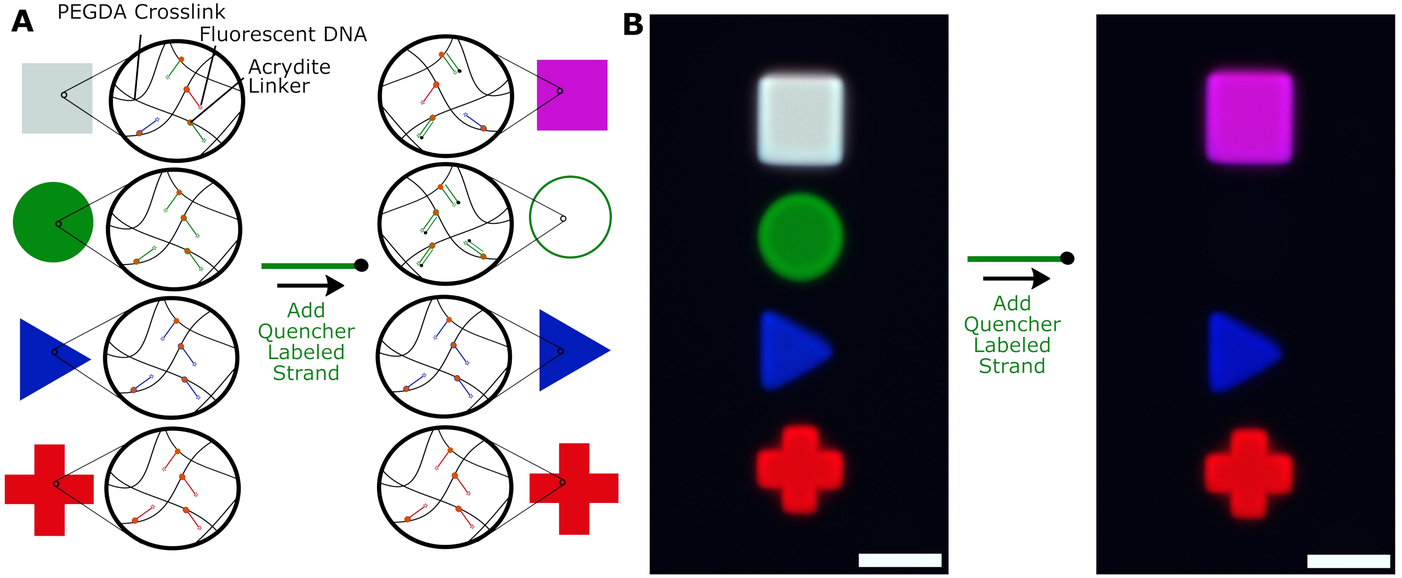
We found, generally, how biomolecular signals can trigger conformational changes in materials using sequence specific interactions.

Nucleated growth and capping of filaments



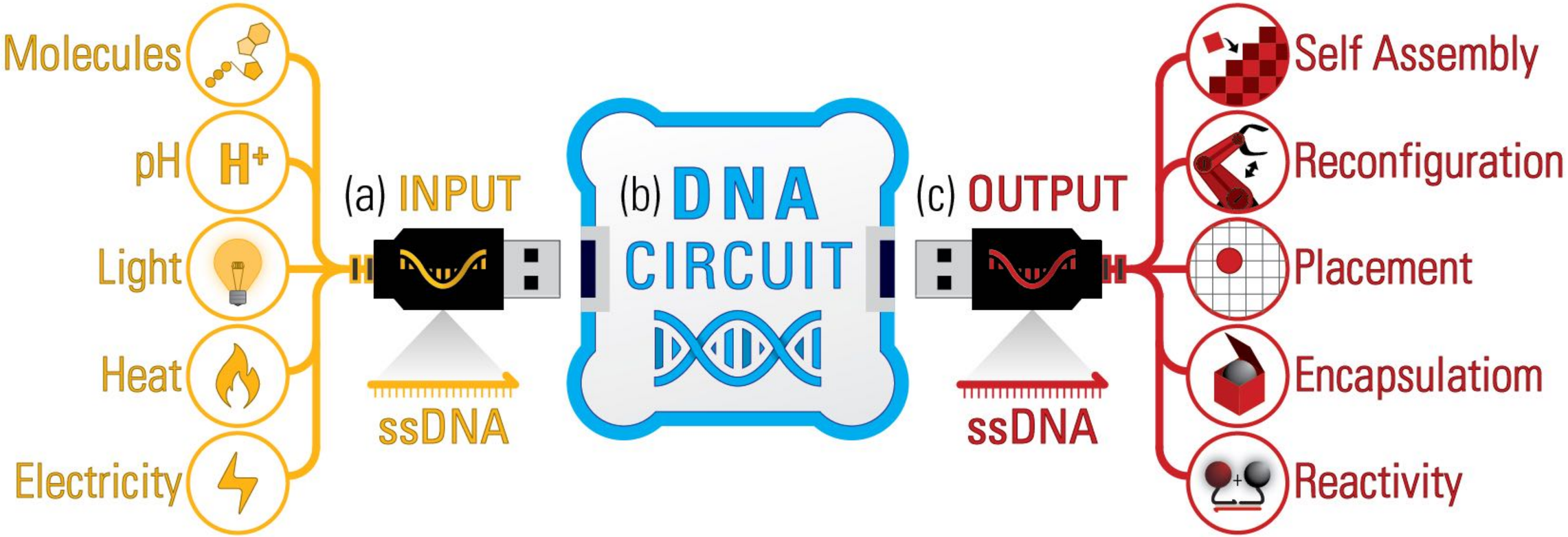
Reconfigurable nanotube architectures





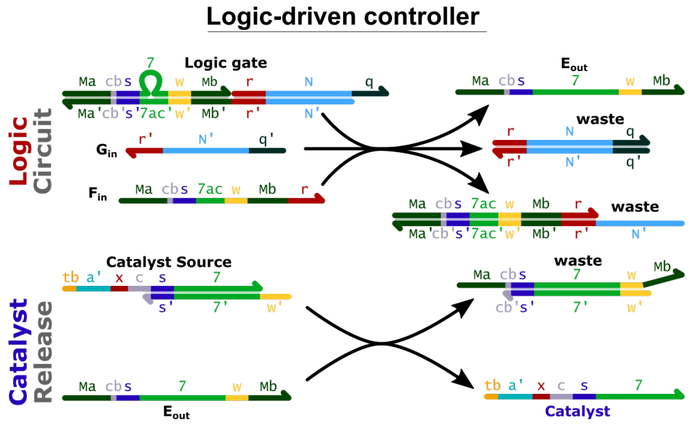
Mohammed and Schulman, Nano Letters, 2013
Agarwal, D. and Schulman, R., ACS Nano, 2017
Schaffter, Schneider, Agrawal, Pacella, Rothchild, Murphy, Schulman, ACS Nano, 2020
Rubanov, Cole, Lee, Soto Cordova, Chen, Gonzalez, Schulman, PLoS One, 2024
Cangialosi, Yoon, Liu, Huang, Guo, Nguyen, Gracias, Schulman, Science, 2017

These ideas led a general architecture for envisioning biomaterials with complex responses to a range of inputs.



Scalise and Schulman, Ann. Rev. Biomed. Eng., 2018

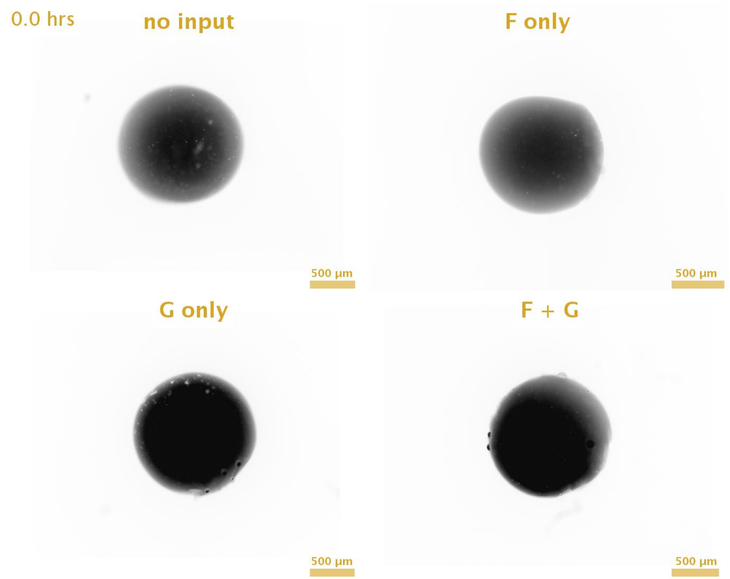
Molecular circuits can perform logic operation on inputs. For a desired result, the material amplifies the signal to direct and power a macroscopic material change.

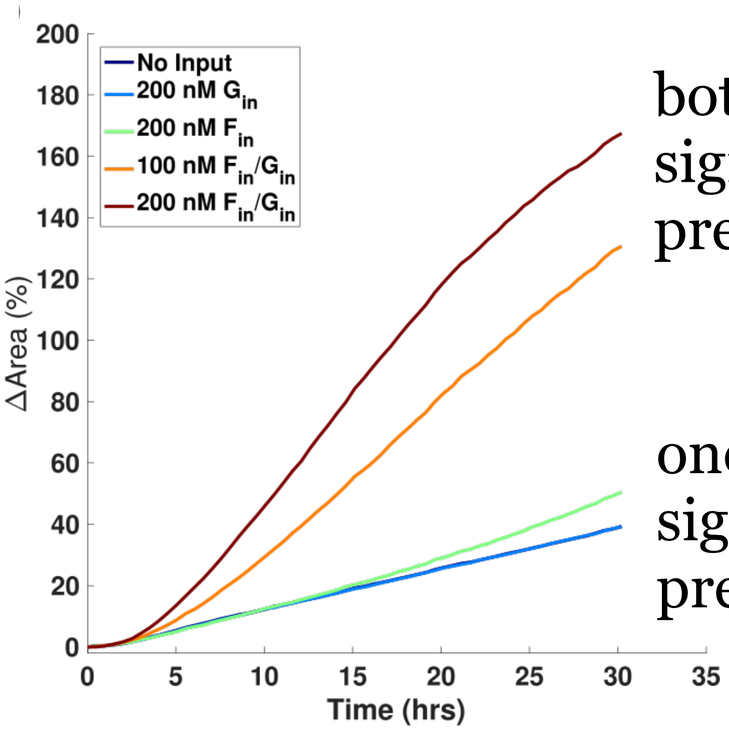


G low **G high**

F low

F high



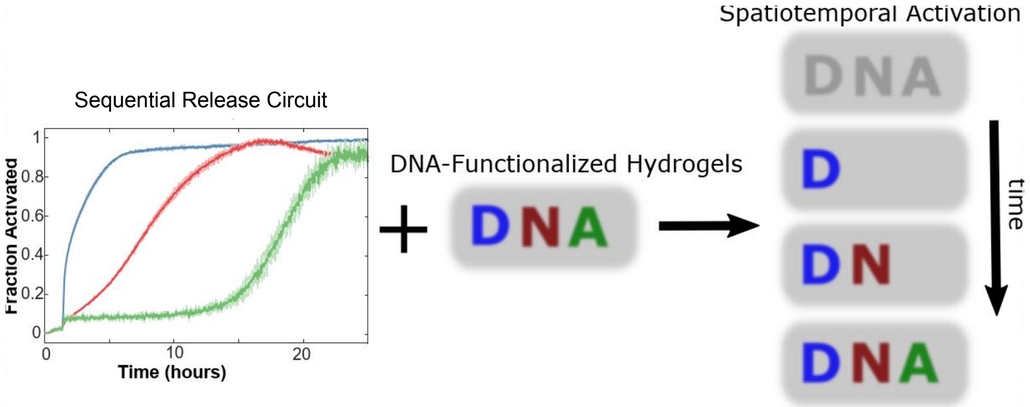


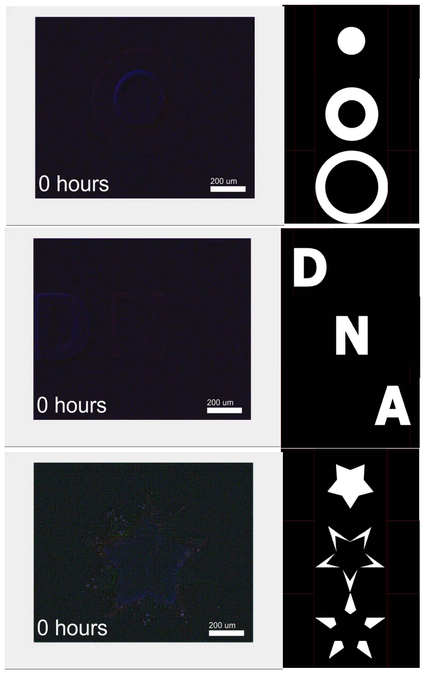
both signals present

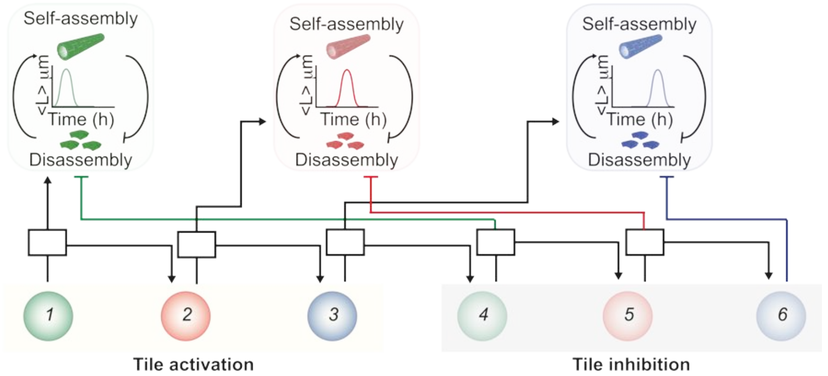
one or zero signals present

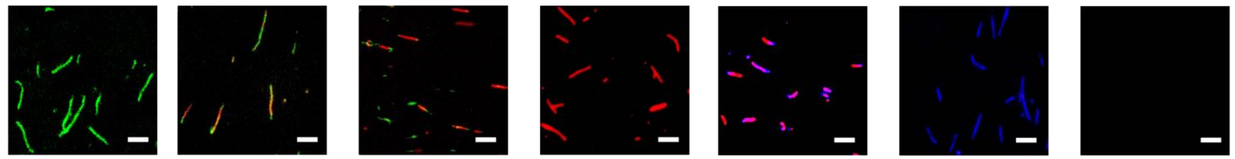
Fern and Schulman, Nature Comm.,2018

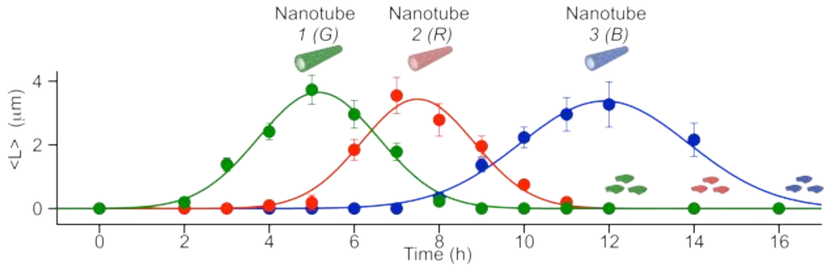
Biomolecular circuits can guide complex pathways of assembly by using multiple outputs.







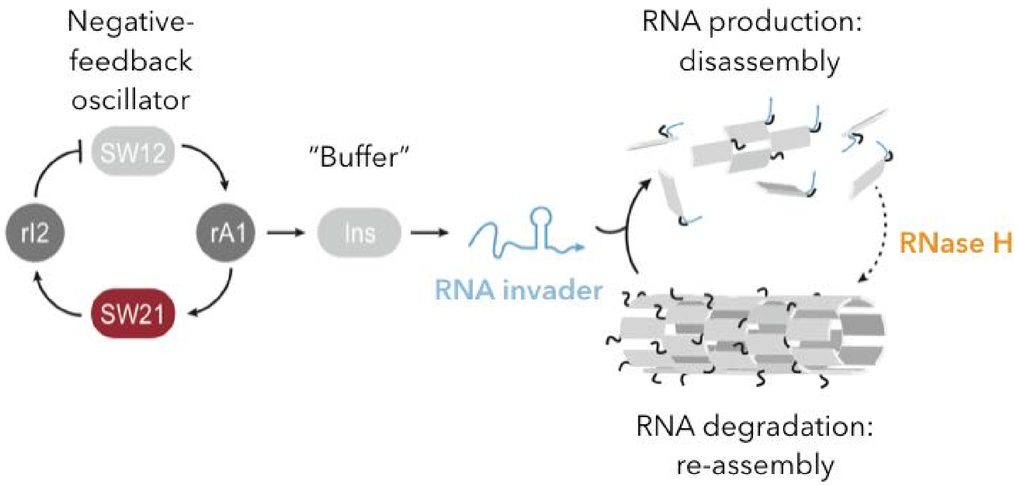


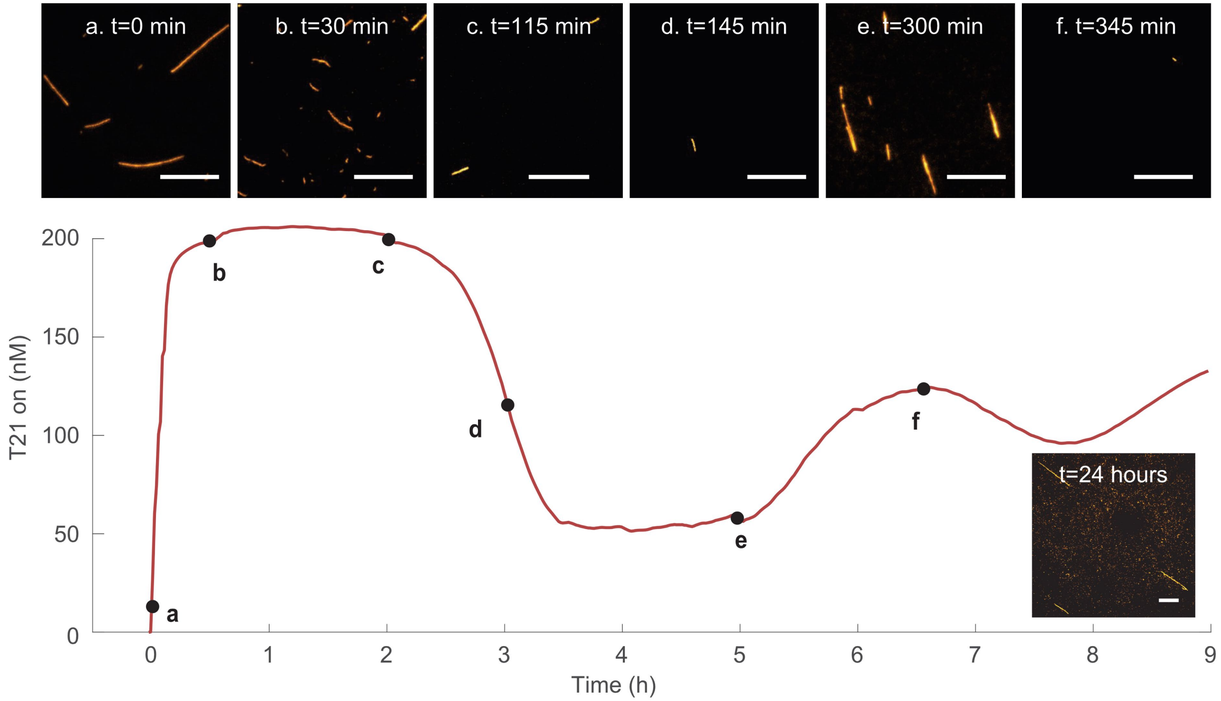


Rubanov, Dorsey, Scalise, Schulman, ACS Materials Letters, 2022

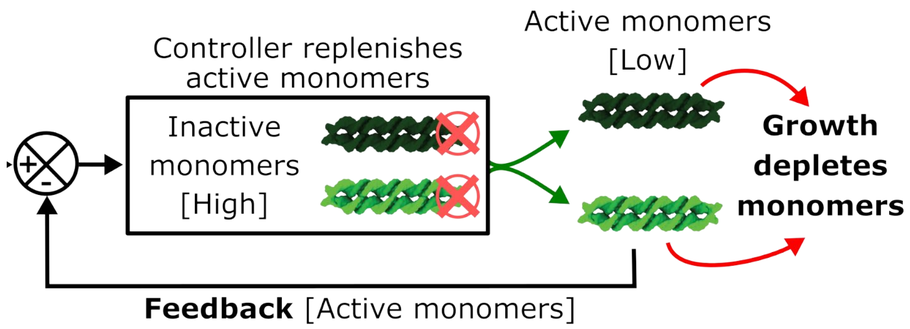
Sorrentino, Ranallo, Ricci, Franco, bioRxiv, 2024

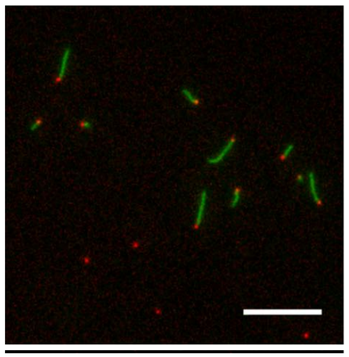
Complex circuits can orchestrate dynamic responses, and allow for feedback control.

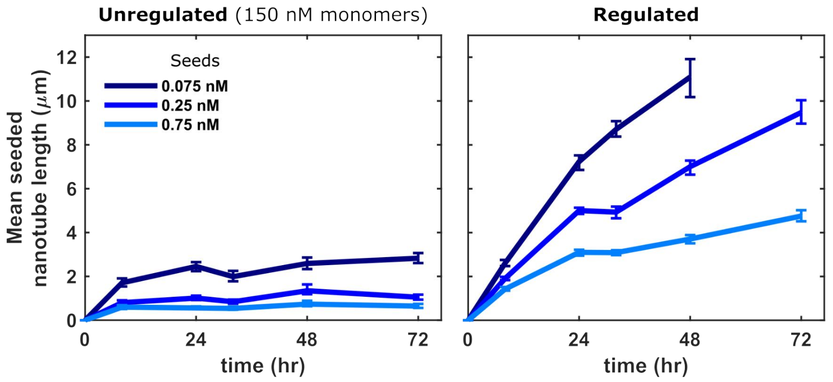


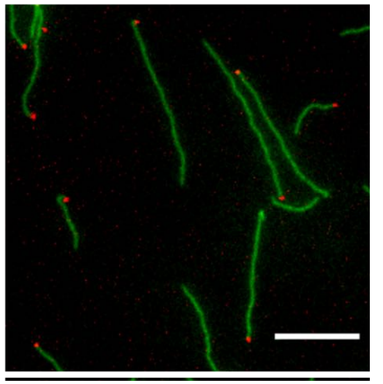


Green, Subrimanian, Franco, Nat. Chem., 2019





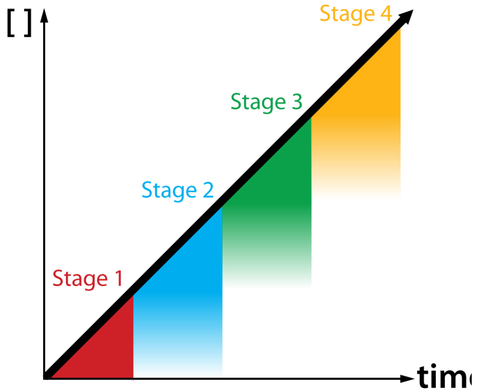


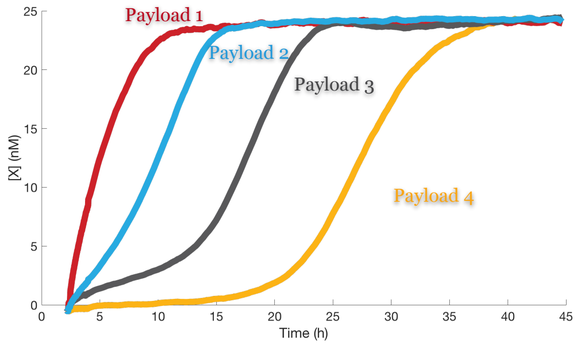


Schaffter, Scalise and Schulman, Nat. Comm., 2020

Creating “languages” of circuits can allow us to explore new material dynamics.

Sequential and conditional instructions





CHEMICAL PROGRAM:

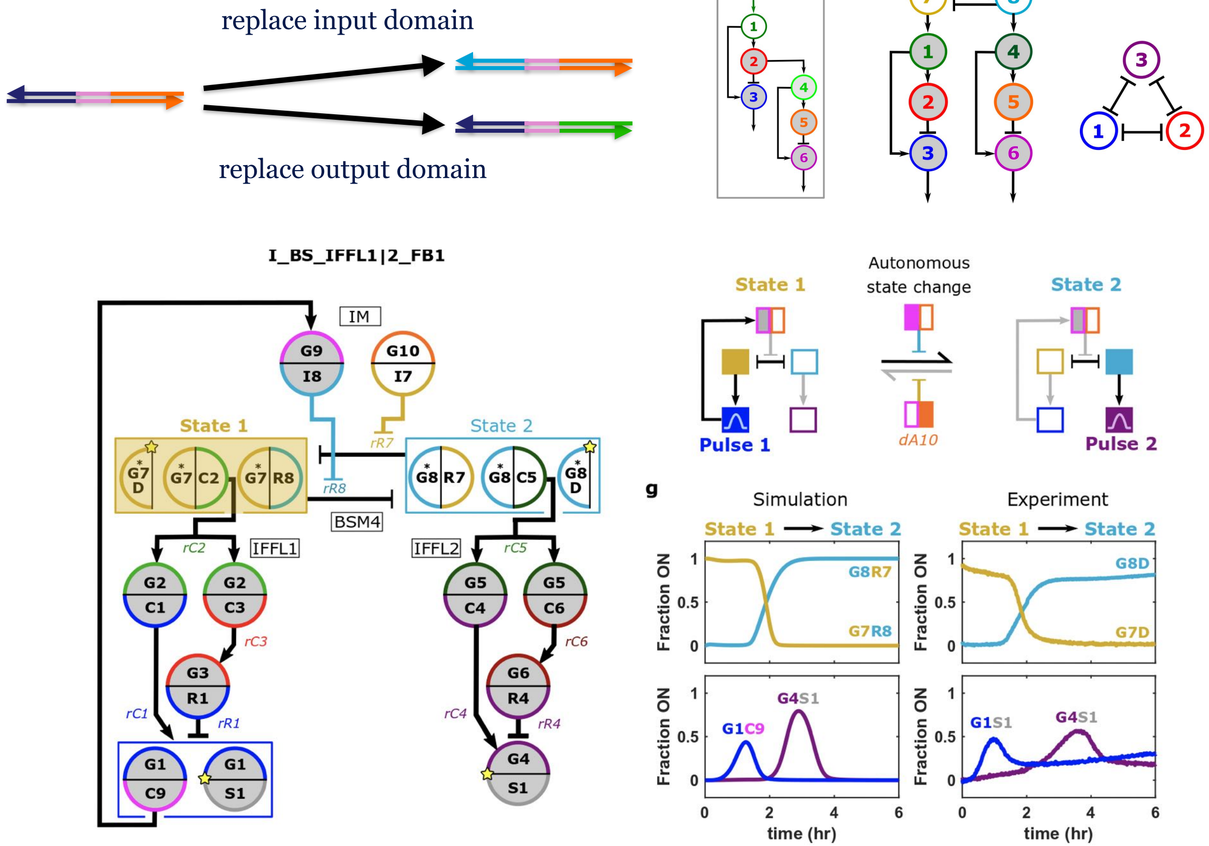
```
release(strandA);
release(strandB);
release(strandC);
release(strandD);
```

CHEMICAL PROGRAM:

```
release(payload1);
if([deprotect1,2]>0){
  release(payload2);
} elseif([deprotect1,3]>0){
  release(payload3);
}
```

Scalise, Rubanov, Miller, Potters, Noble and Schulman, ACS Syn. Bio., 2020

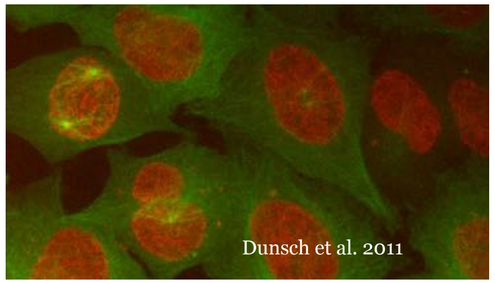
Regulatory (catalytic/excitable) networks

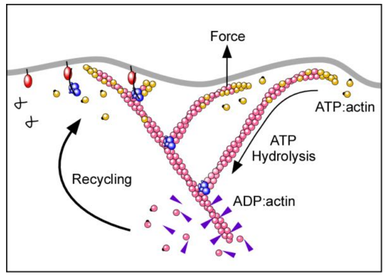


Schaffter and Schulman, Nature Chemistry, 2019
Schaffter, Chen, O’Brian, Noble, Murugan, Schulman, Nature Chemistry, 2022

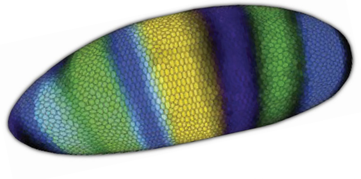
The idea of using biomolecular “agents” to control materials and chemistry could have broad implications.

Biomolecular circuits offer a means to program dynamics and machines.

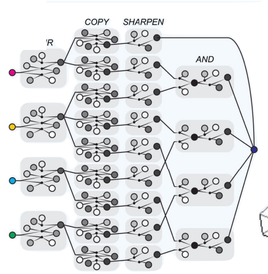


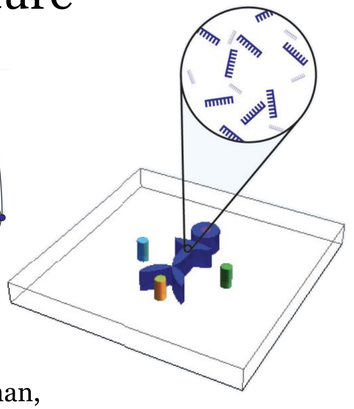


Biomolecular fields could structure and shape materials.



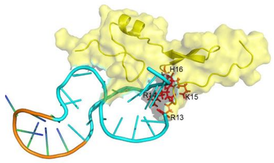
Fowlkes *et al.* (2008)

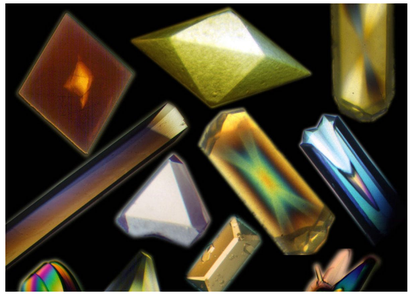


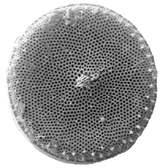


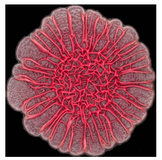
Scalise and Schulman, 2014

Biomolecular circuits could be the “brains” to regulate how many materials form and behave.

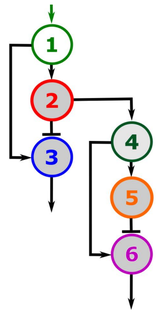


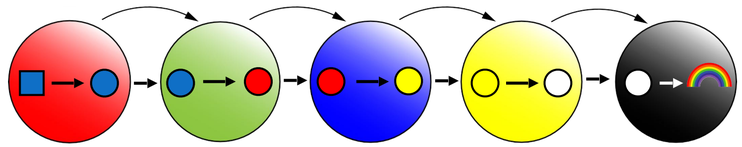






Biomolecular circuits could regulate synthesis.





Thank you!

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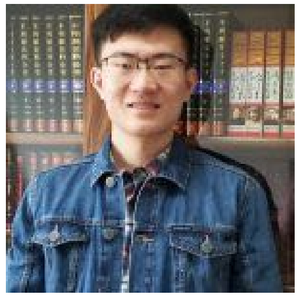

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