The Amazing Blue Dot:

How Earth's Biology is Inspiring Engineering for the Stars

Christine Gregg
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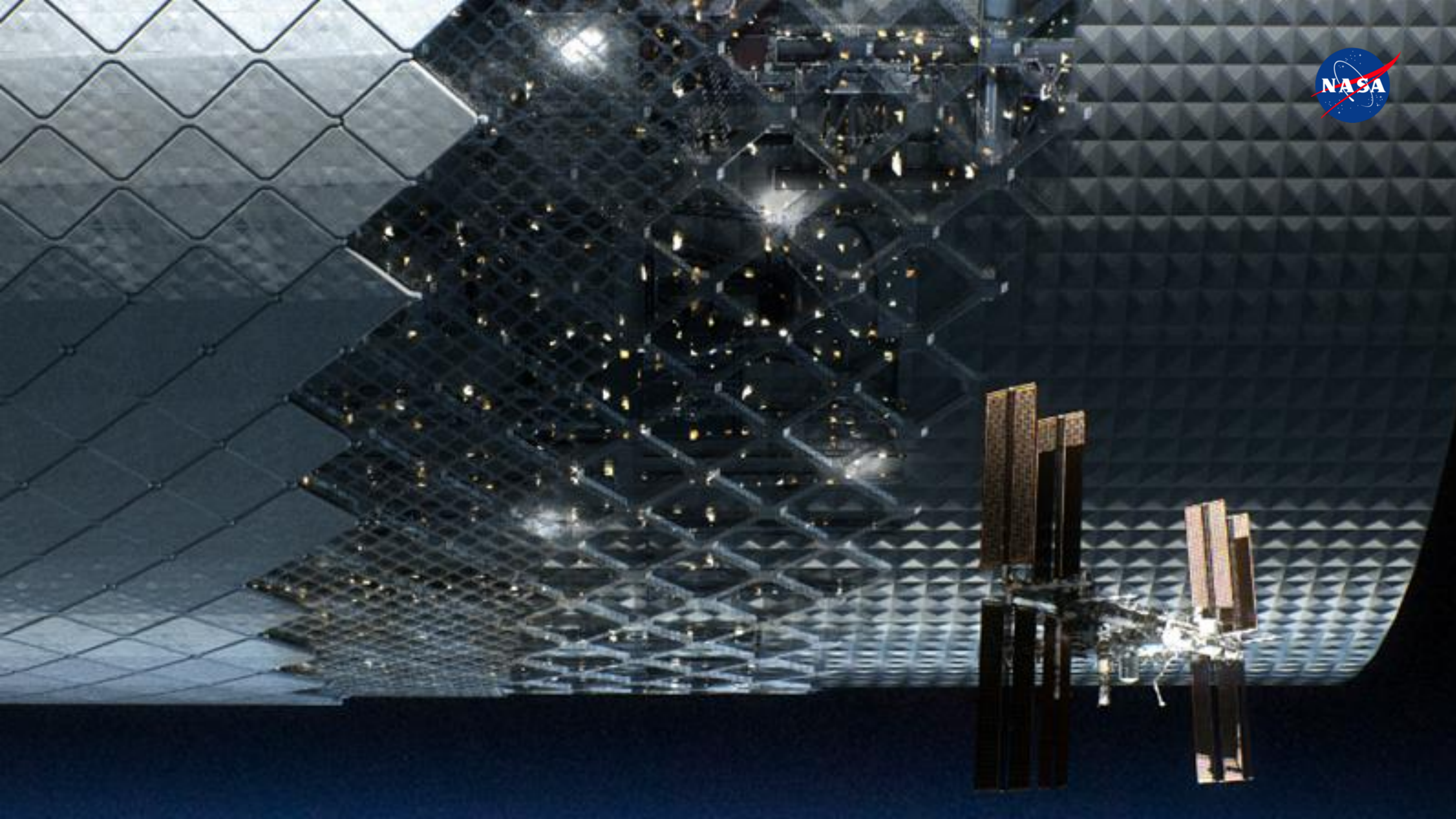
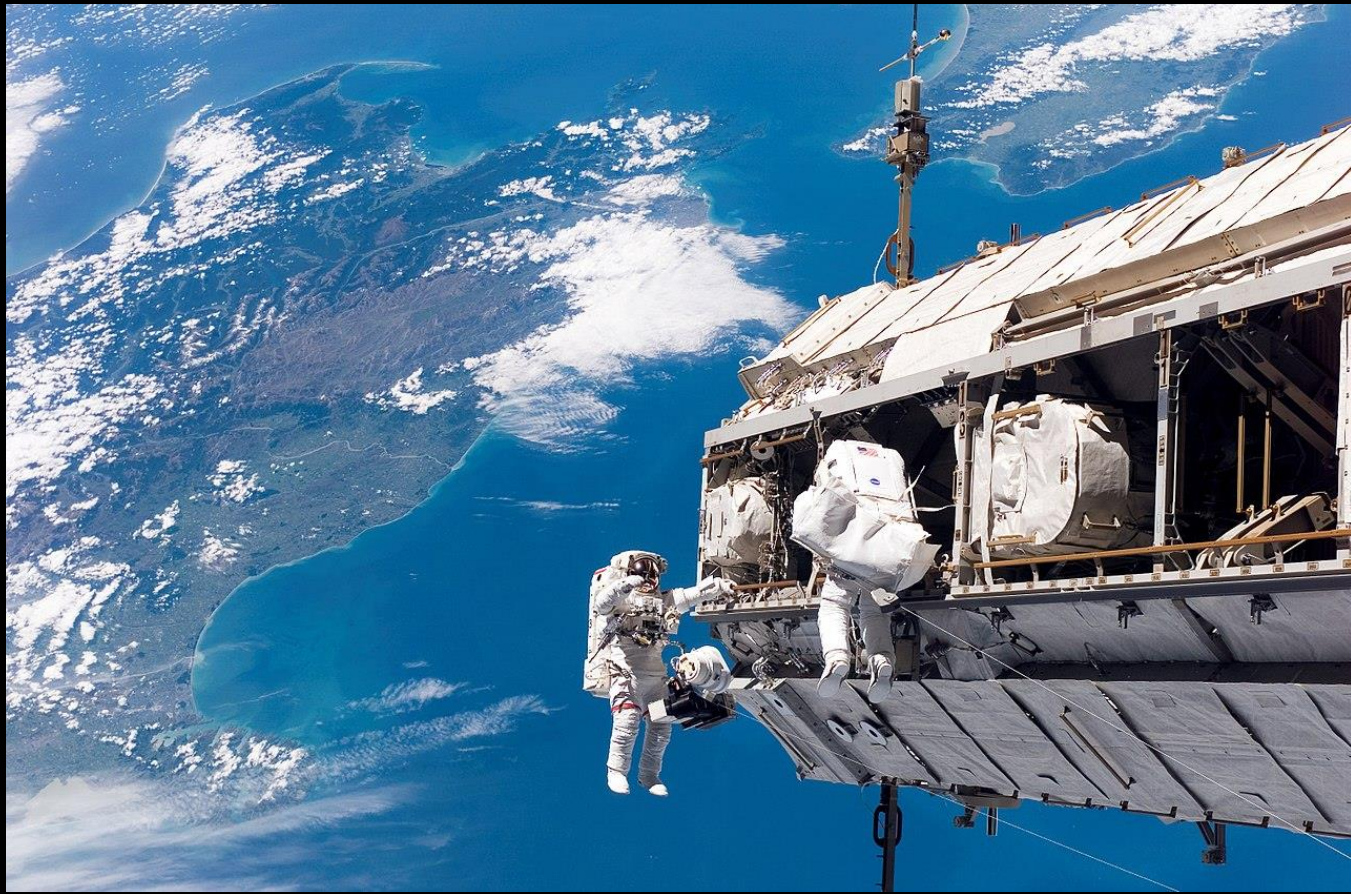
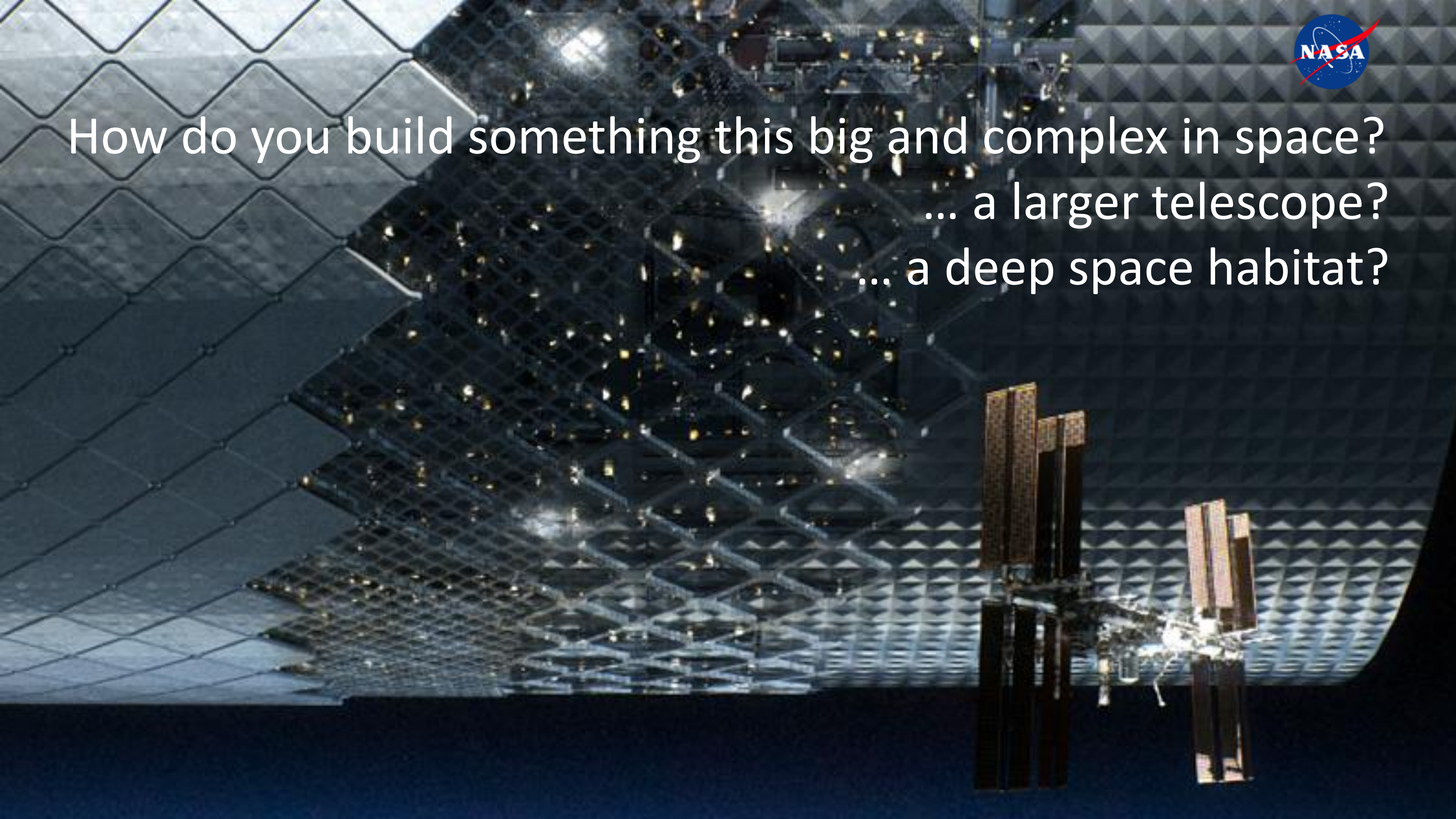

NASA


10 20 30 40 50 40 30 20 10
NASA
NASA



10+ years. 30+ Launches. X EVA. X EVR.

Astronaut Stephen K. Robinson anchored to the end of Canadarm2 during STS-114, 2005

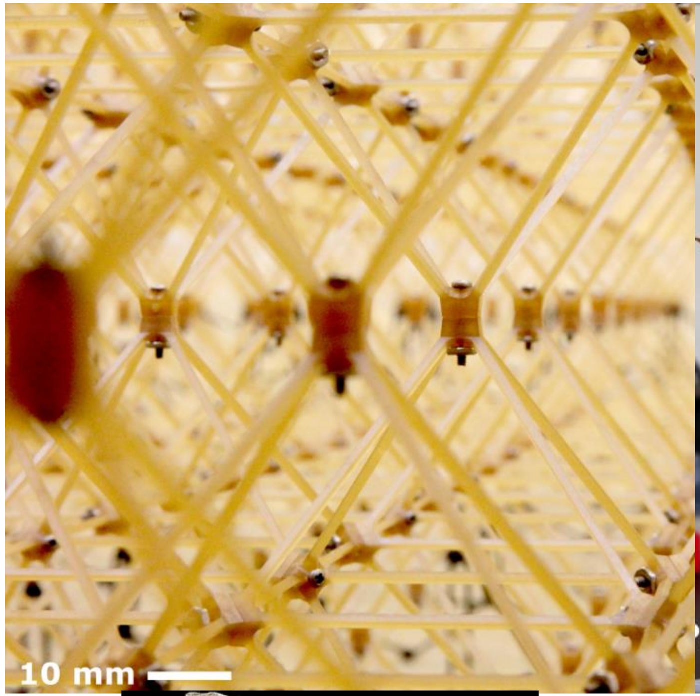


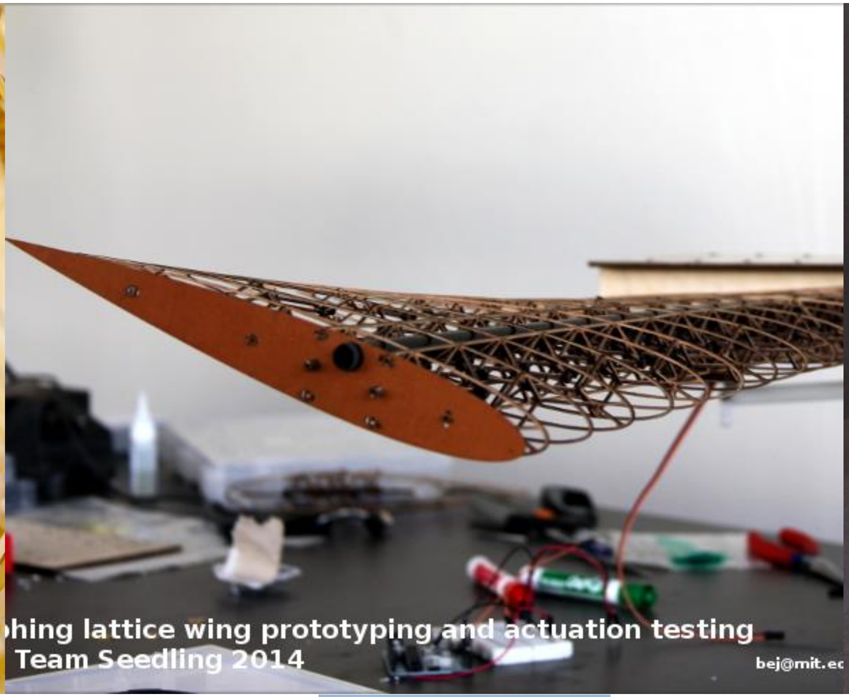
How do you build something this big and complex in space?

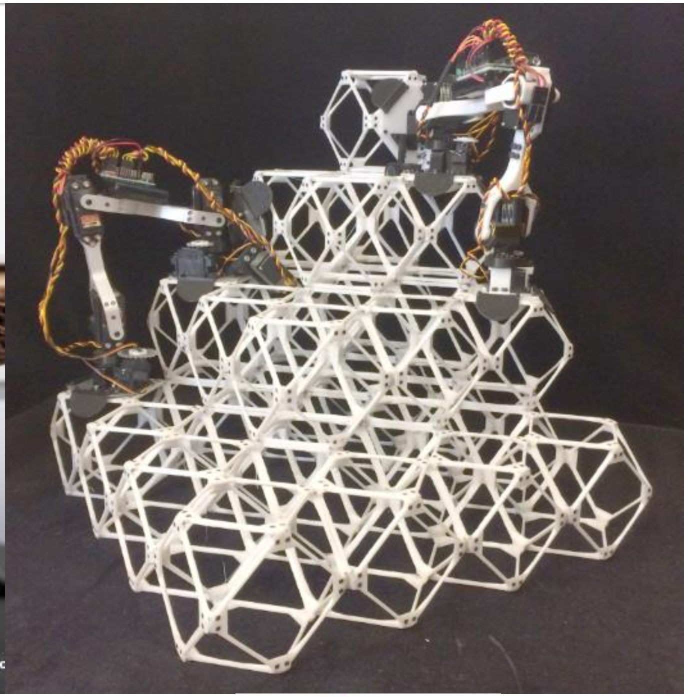
… a larger telescope?

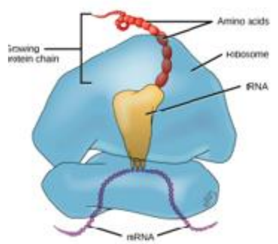
… a deep space habitat?

Biologically Inspired: Autonomously Assembling Programmable Lattice Materials









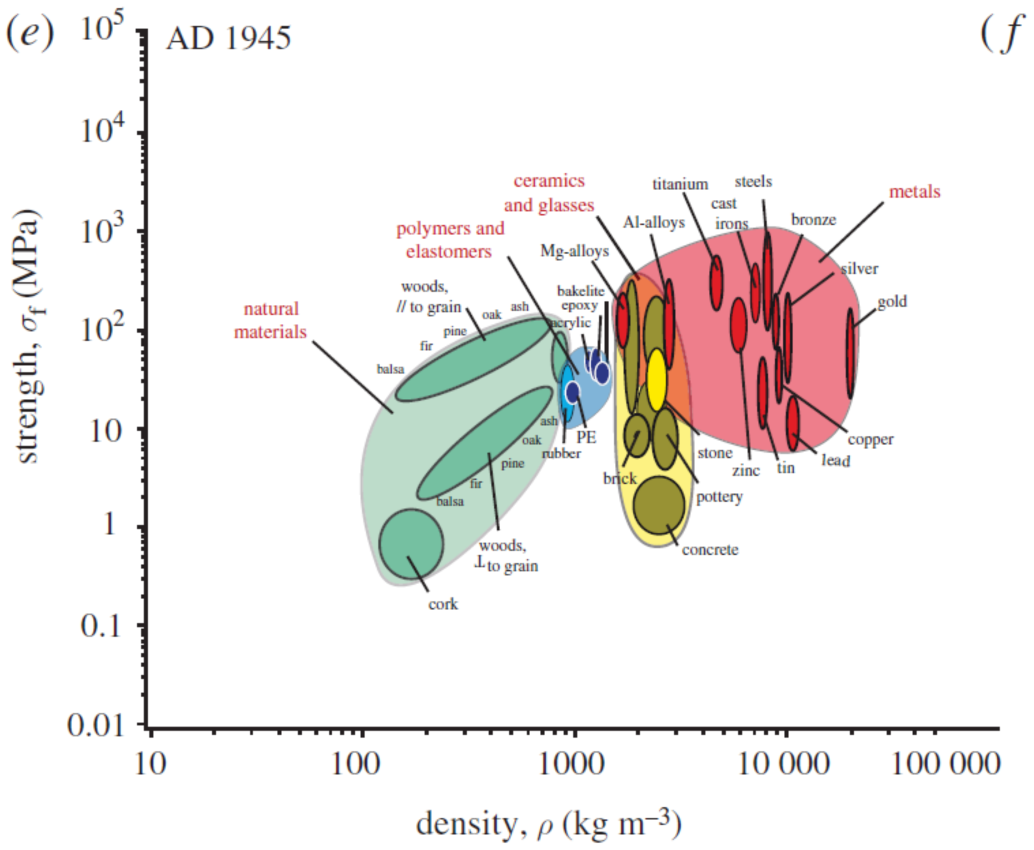
$4600/ kg

to Low Earth Orbit (SpaceX Falcon 9)

300kg fuel: 1 kg spacecraft

from Earth to Mars

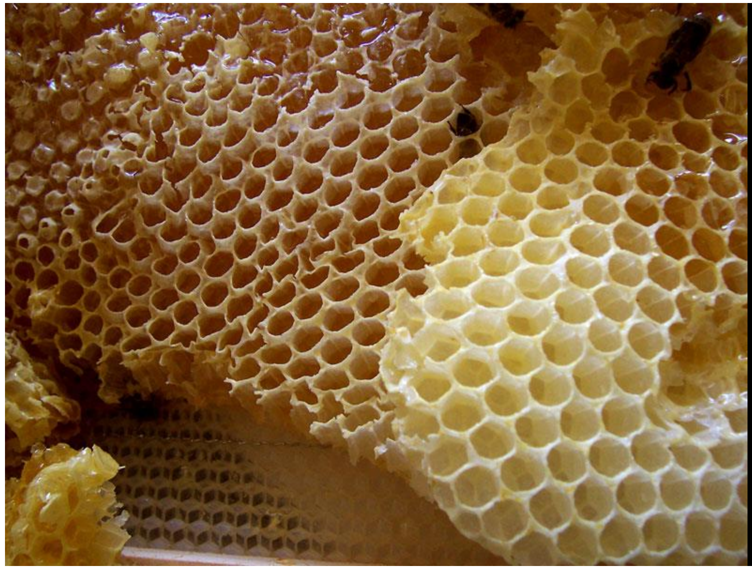
Historical Materials Development

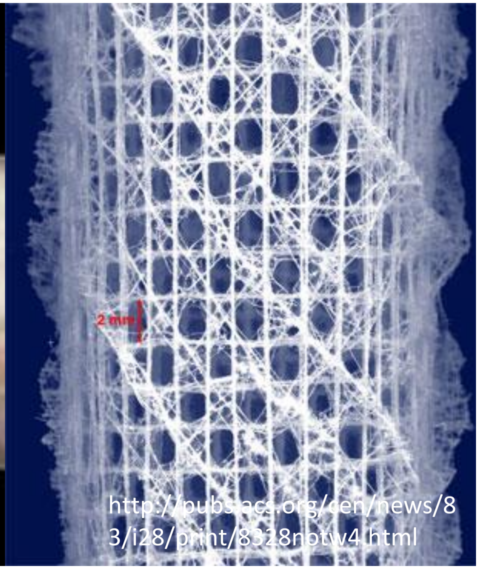


- N.A. Fleck, V. Deshpande, M. A. Ashby. “Micro-architected materials: past, present, and future.” *Proceedings of the Royal Society A: mathematical, Physical, and Engineering Sciences,* 2010.

Natural Material Structures

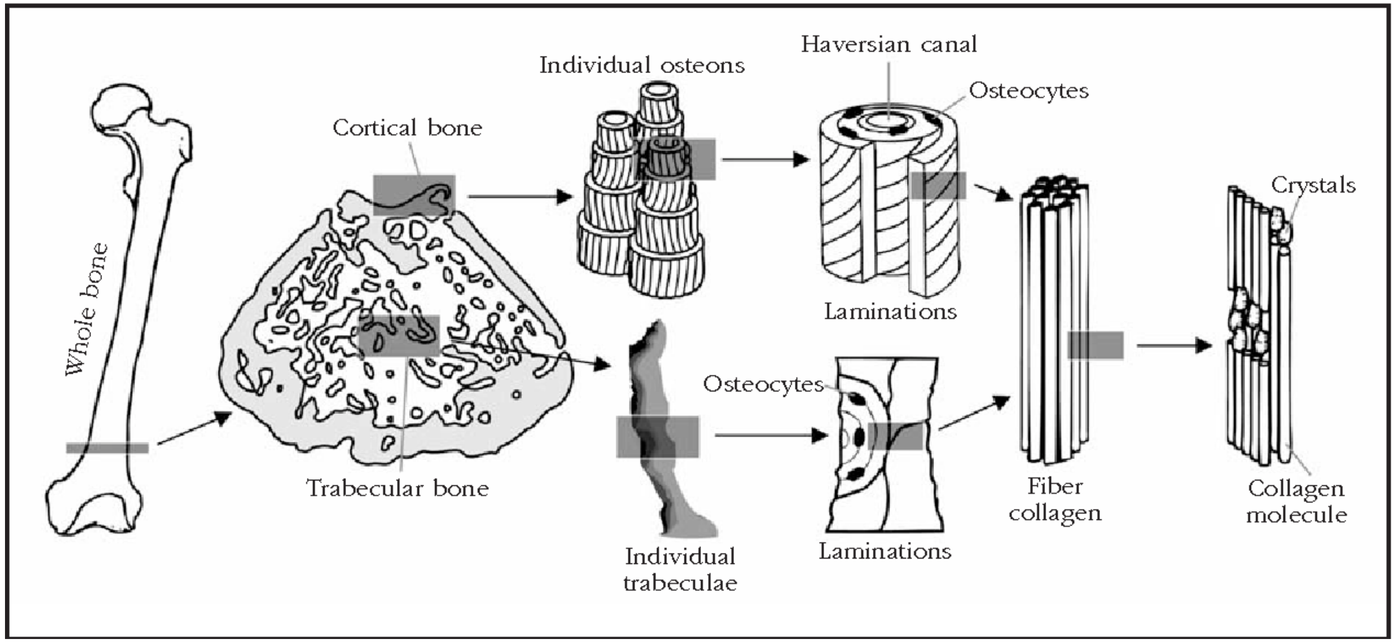
Cellular Materials





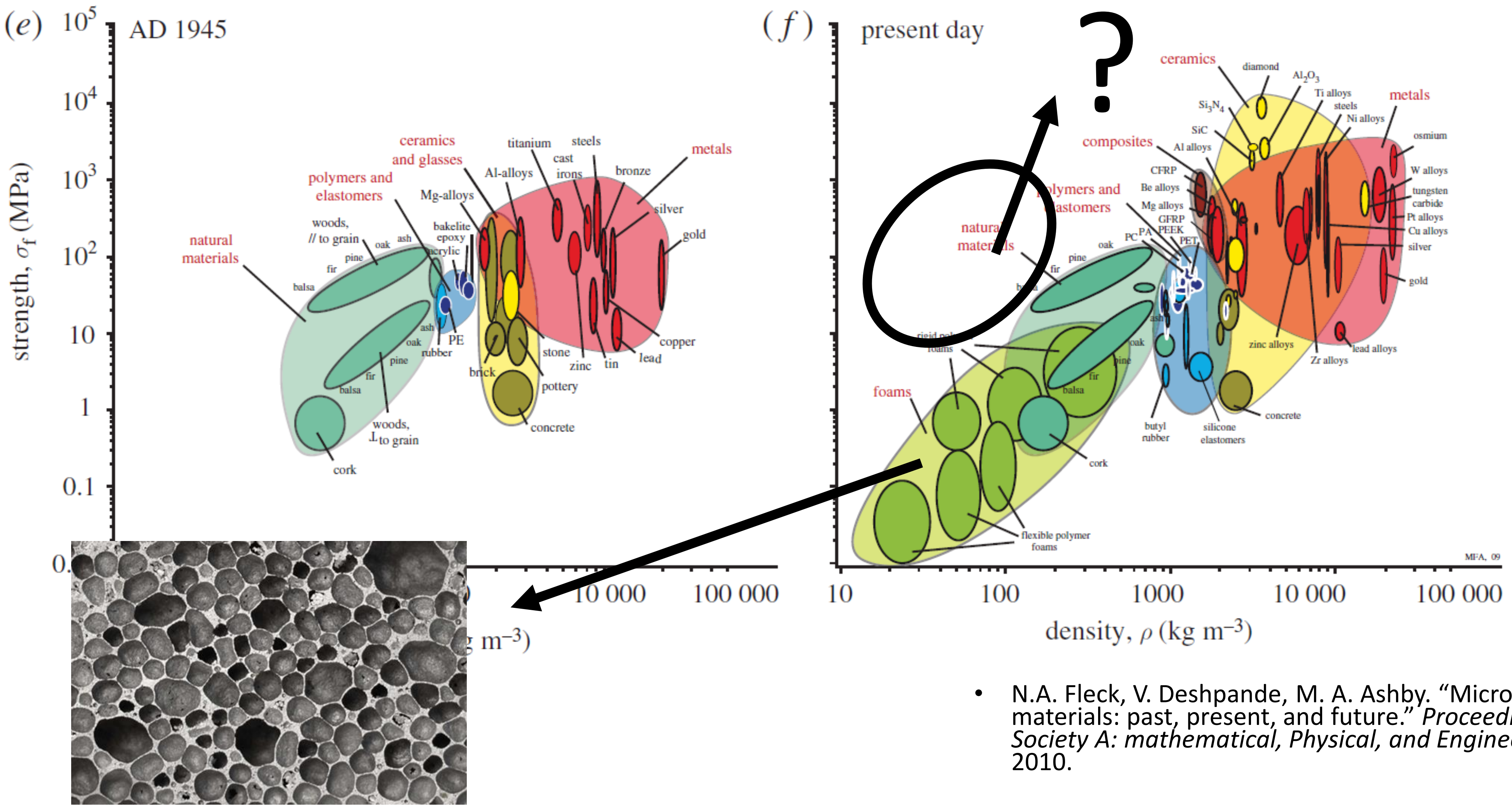
Natural Material Structures

Hierarchical Composite



Caeiro, JR, et al. “Biomechanics and bone (& II) : Trials in different hierarchical levels of bone and alternative tools for the determination of bone strength.” (2013).

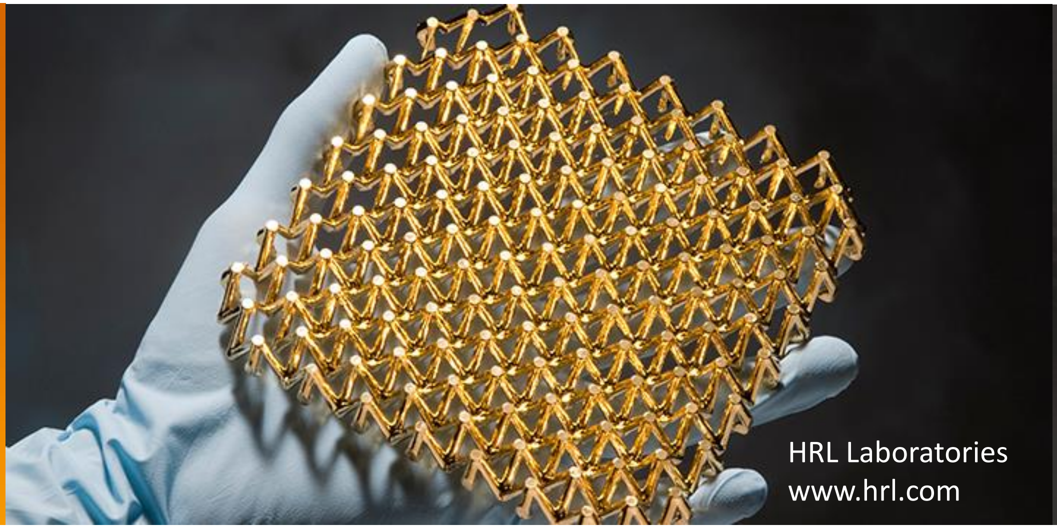
Historical Materials Development



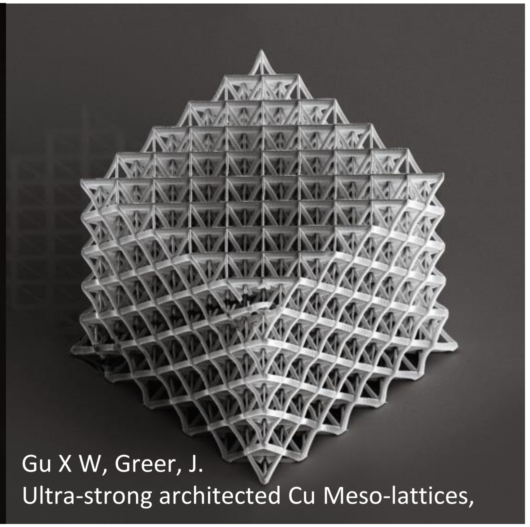
- N.A. Fleck, V. Deshpande, M. A. Ashby. "Micro-architected materials: past, present, and future." *Proceedings of the Royal Society A: mathematical, Physical, and Engineering Sciences*, 2010.

Architected Materials

HRL Laboratories
Image: www.wired.com



HRL Laboratories
www.hrl.com



Gu X W, Greer, J.
Ultra-strong architected Cu Meso-lattices,

Microstructural control → Improved Performance

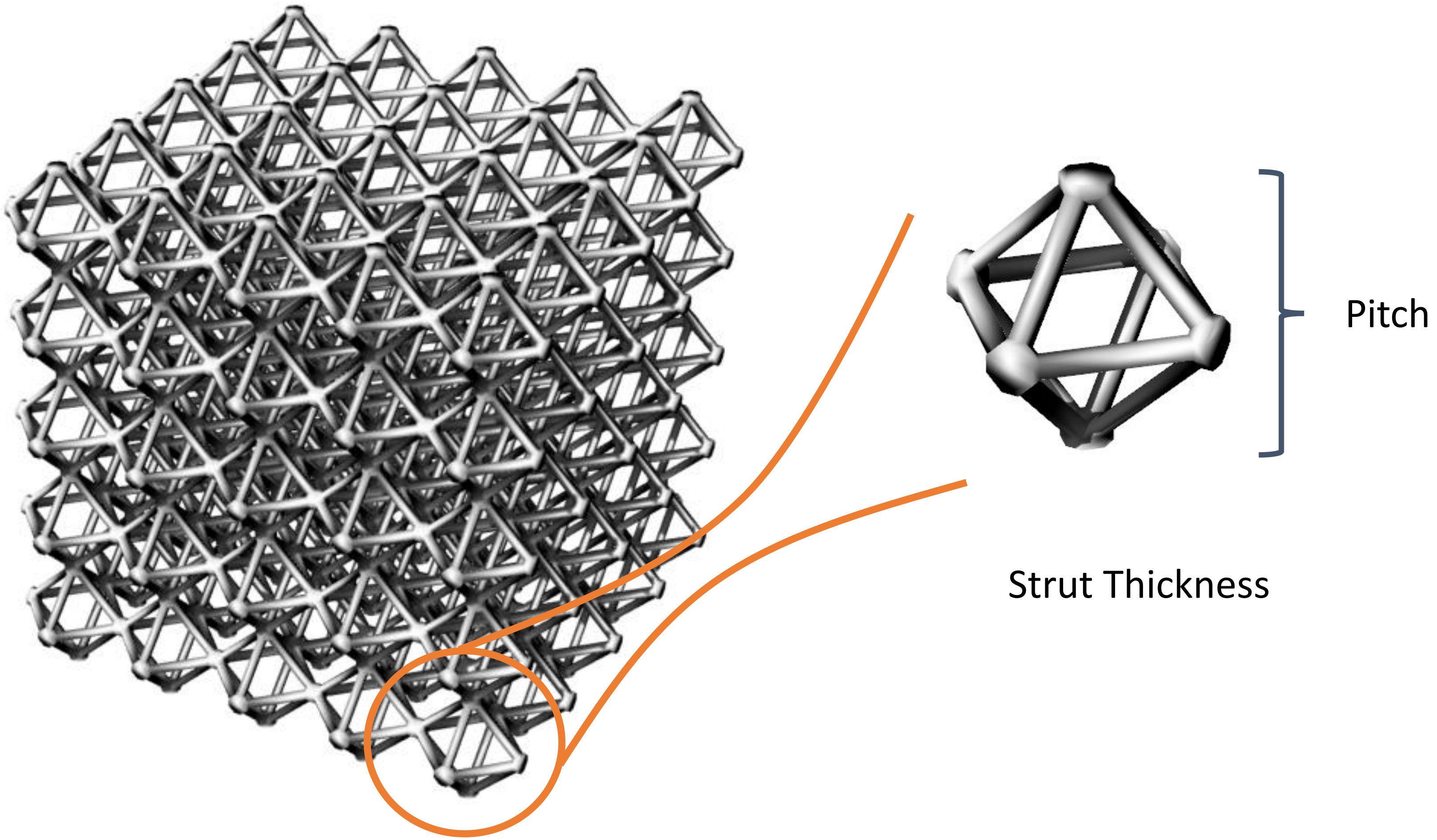
Take what you learn from nature, but don’t forget what we know about engineering!

Mechanics of Cellular Solids: Key Characteristics

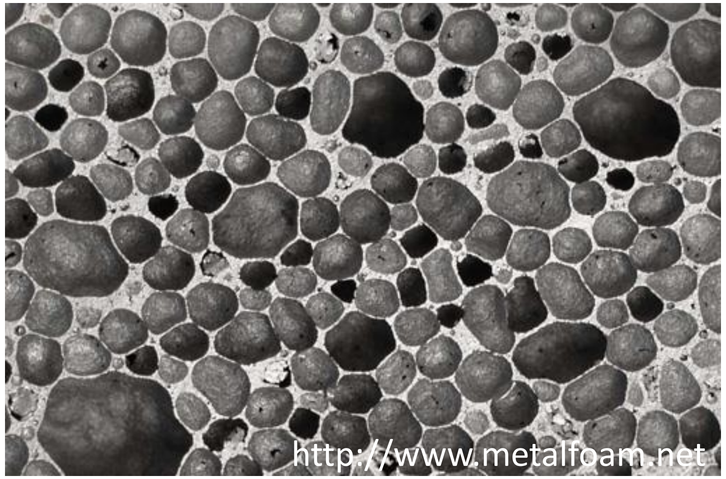
Geometry

Relative Density

Material



Ashby + Gibson: How to Predict Foam Material Behavior



Modulus of Foam →

Modulus of Foam Constituent Material (solid) →

$$\frac{E}{E_s} \propto \left(\frac{\rho}{\rho_s}\right)^2$$

← Scaling Factor

Relative Density (Volume Fraction)

Relative density scaling has been shown to accurately predict many relative material properties (strength, fracture toughness, etc.) for cellular materials

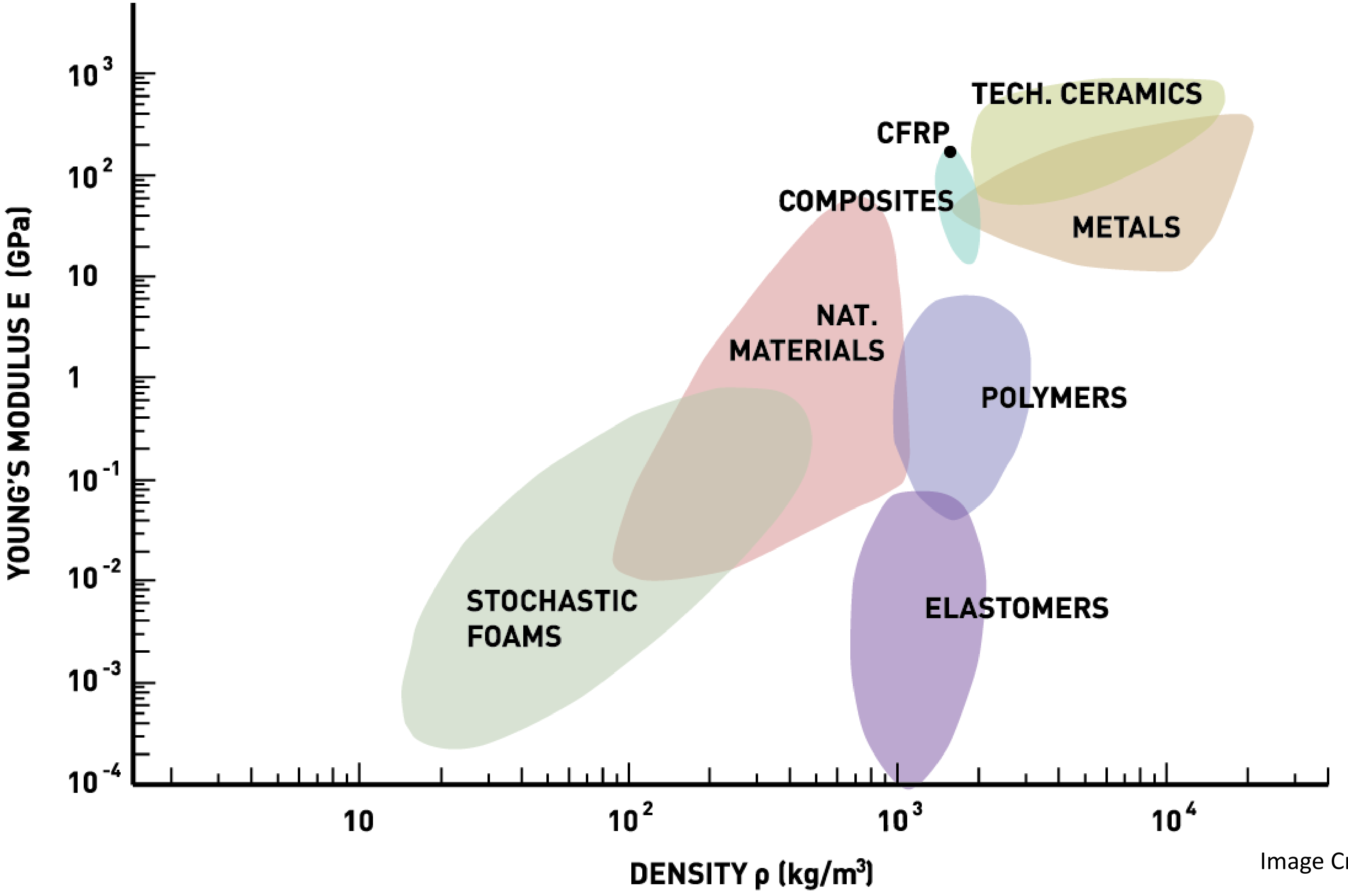
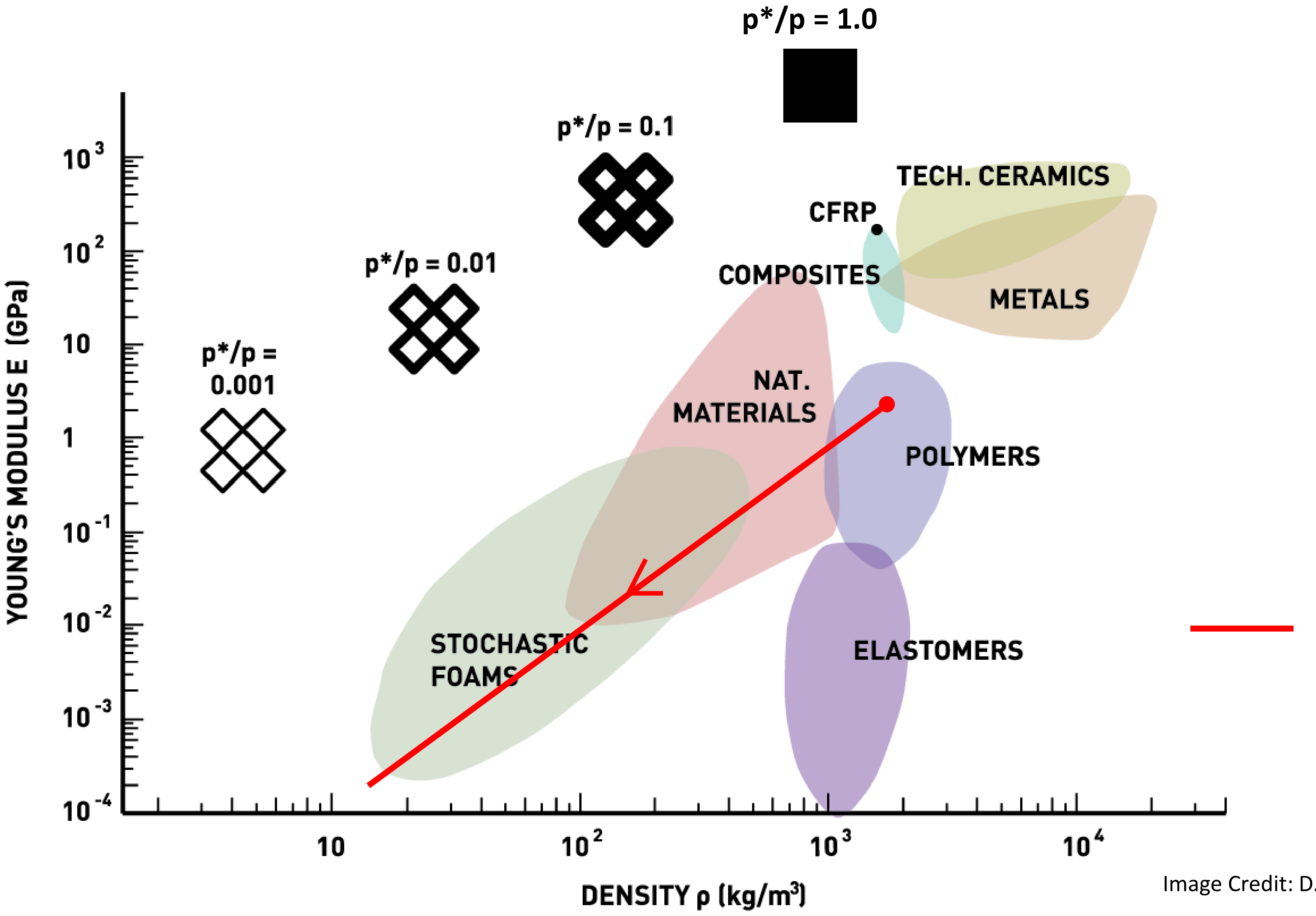


Image Credit: D. Cellucci (NASA ARC)



$$\frac{E}{E_s} \propto \left(\frac{\rho}{\rho_s}\right)^2$$

Image Credit: D. Cellucci (NASA ARC)

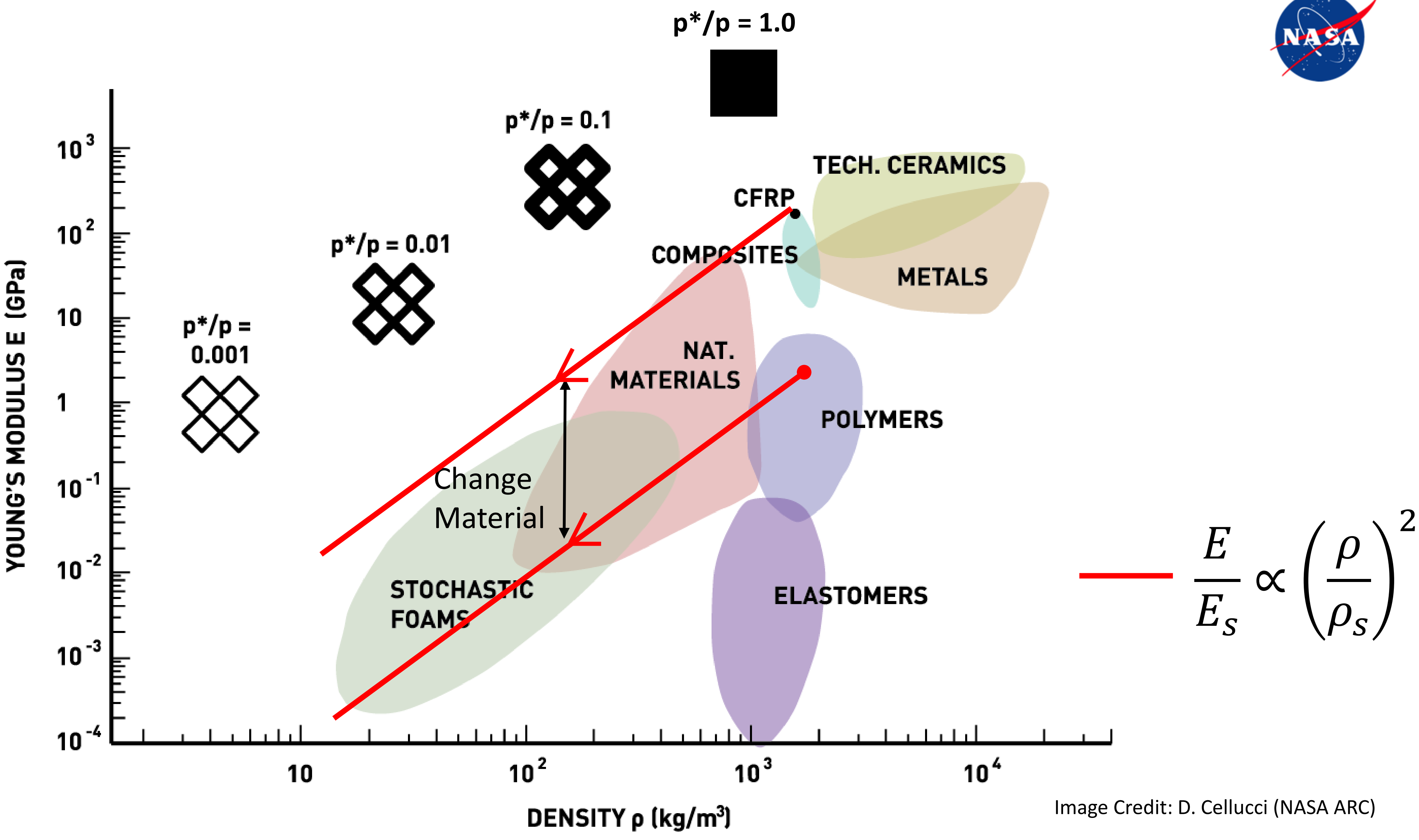


Image Credit: D. Cellucci (NASA ARC)

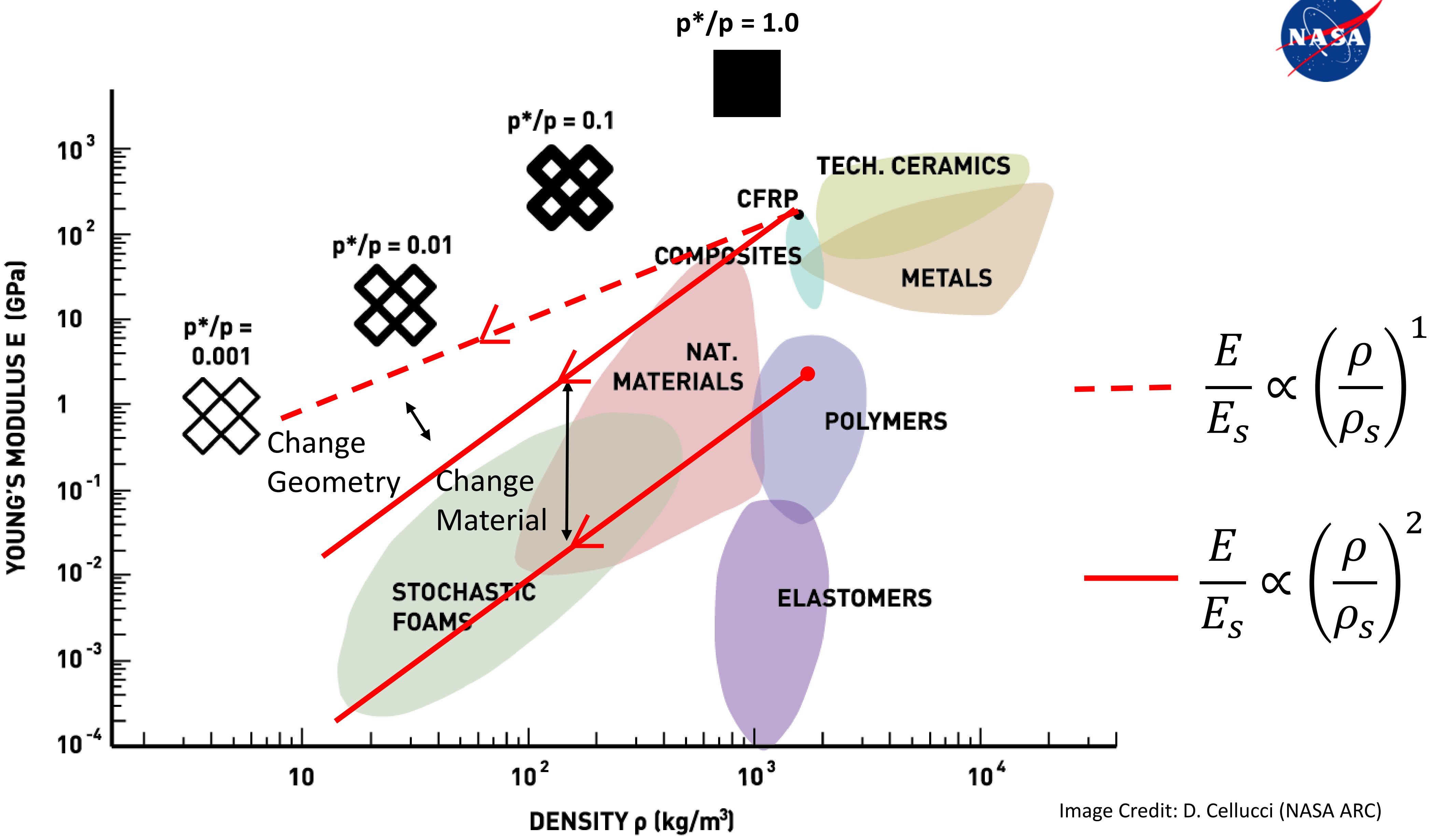
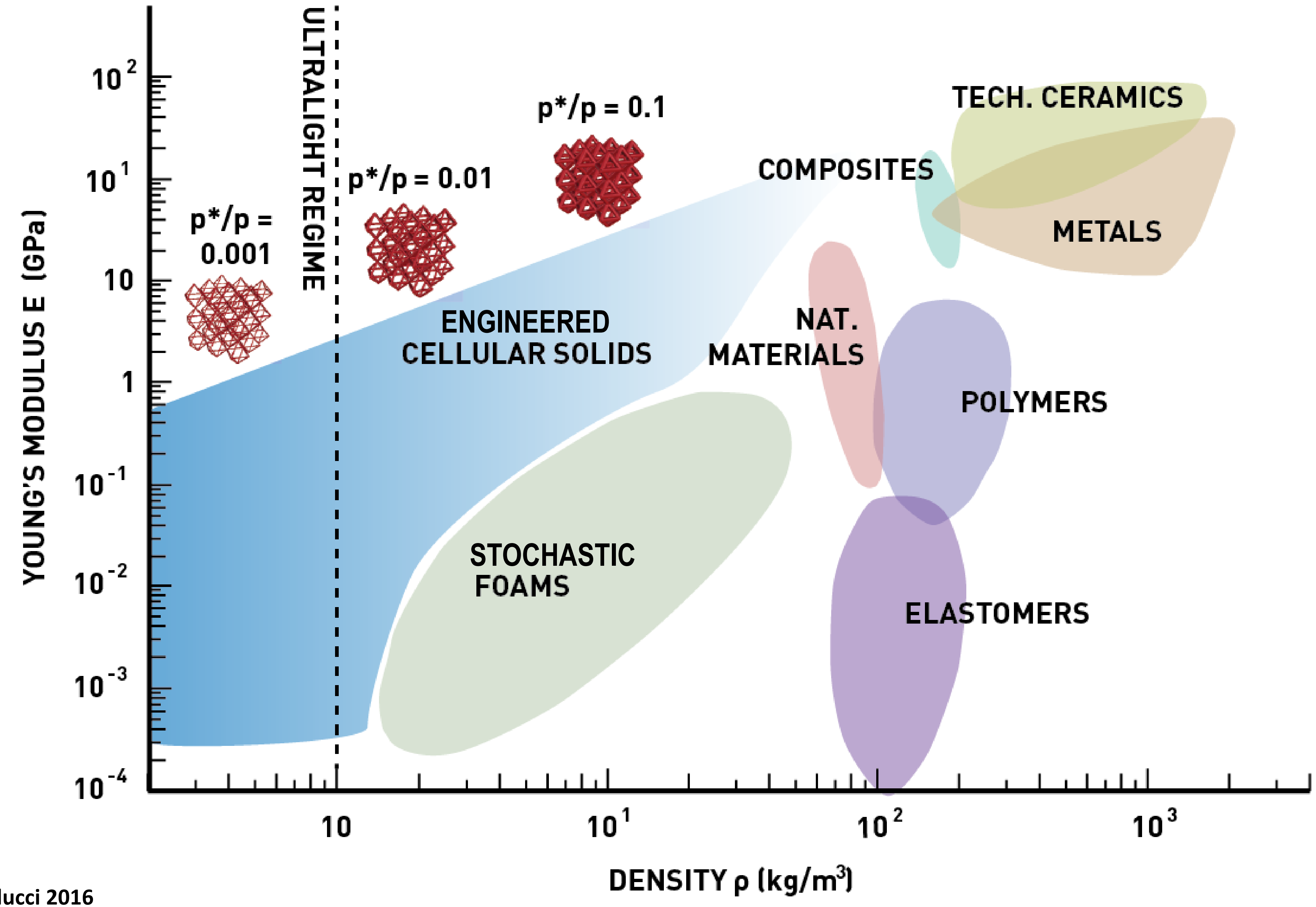
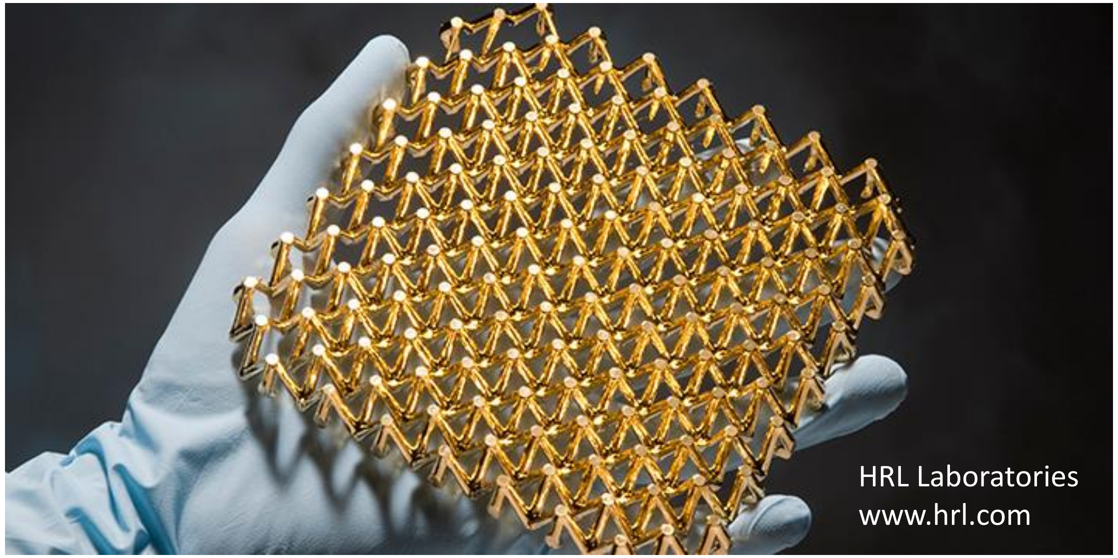


Image Credit: D. Cellucci (NASA ARC)



Cellucci 2016


HRL Laboratories
www.hrl.com

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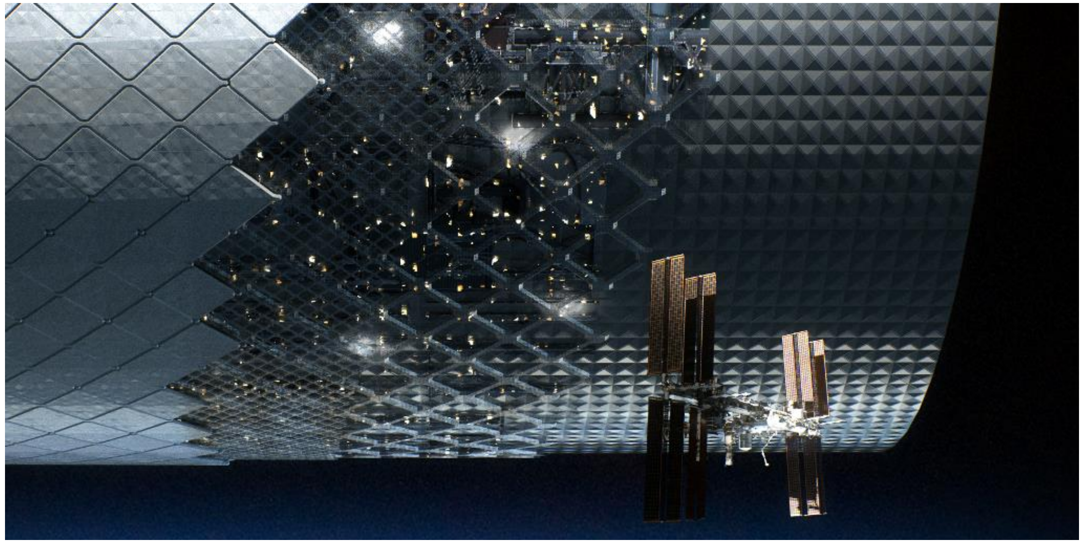
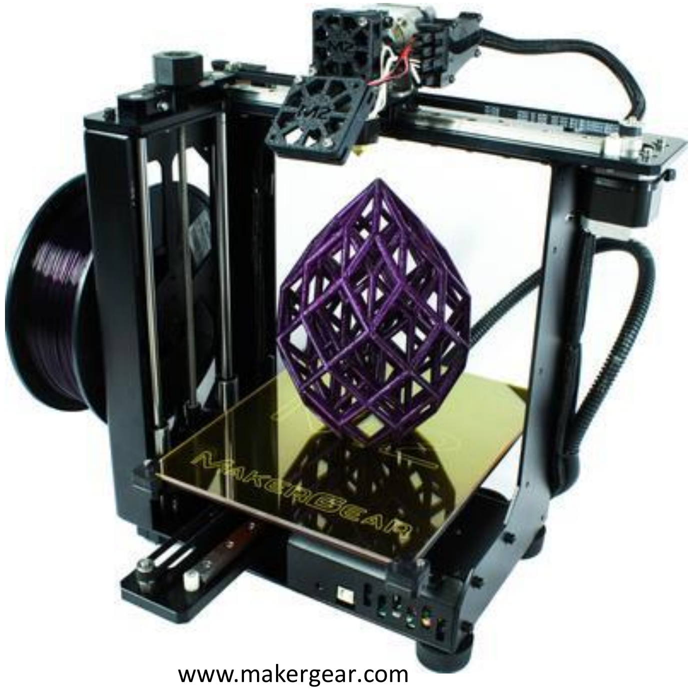
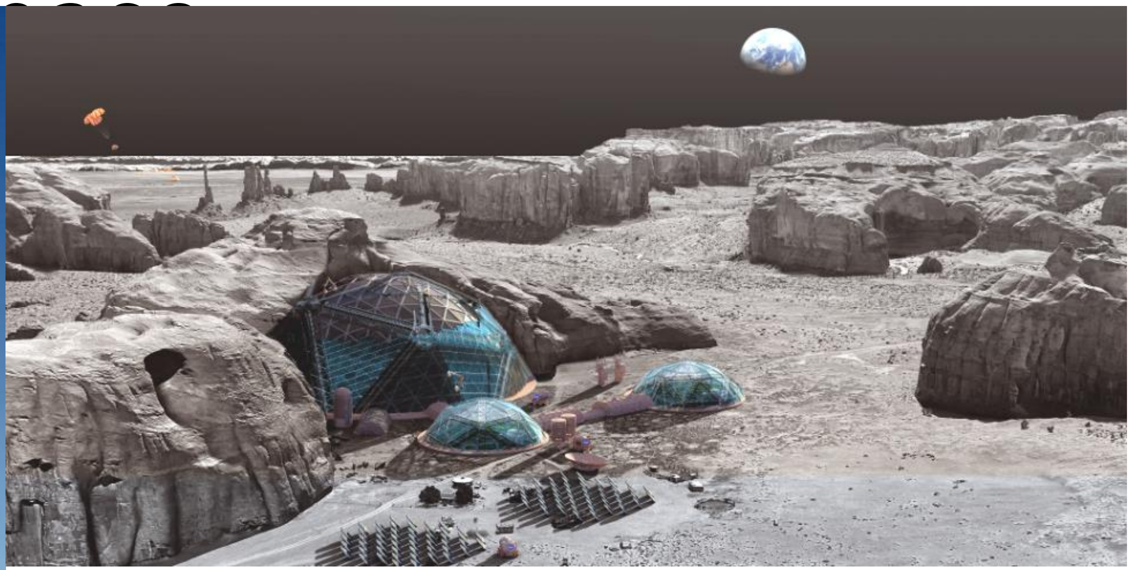


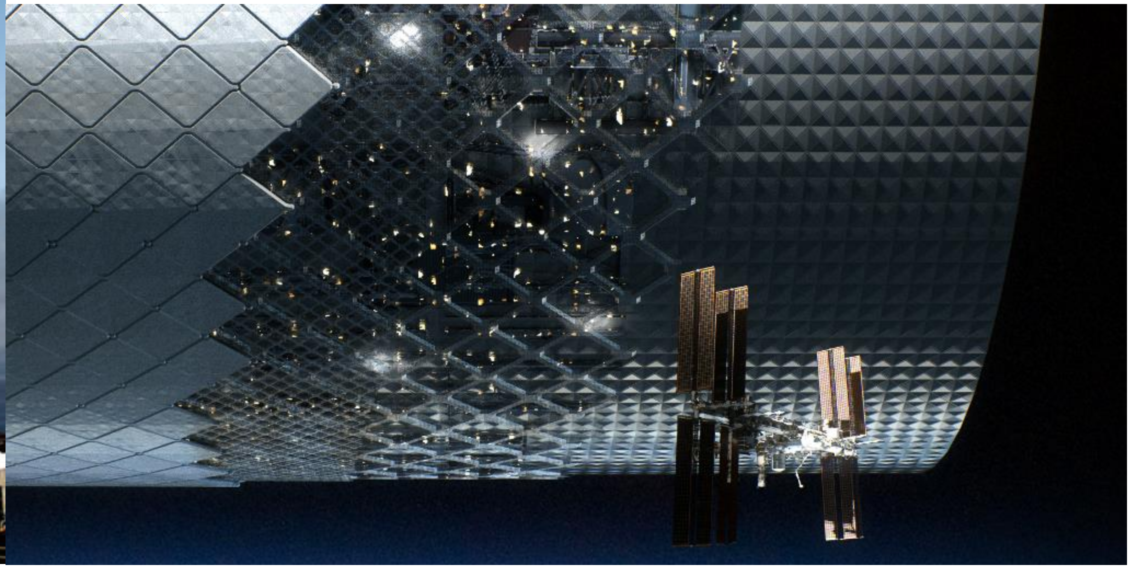


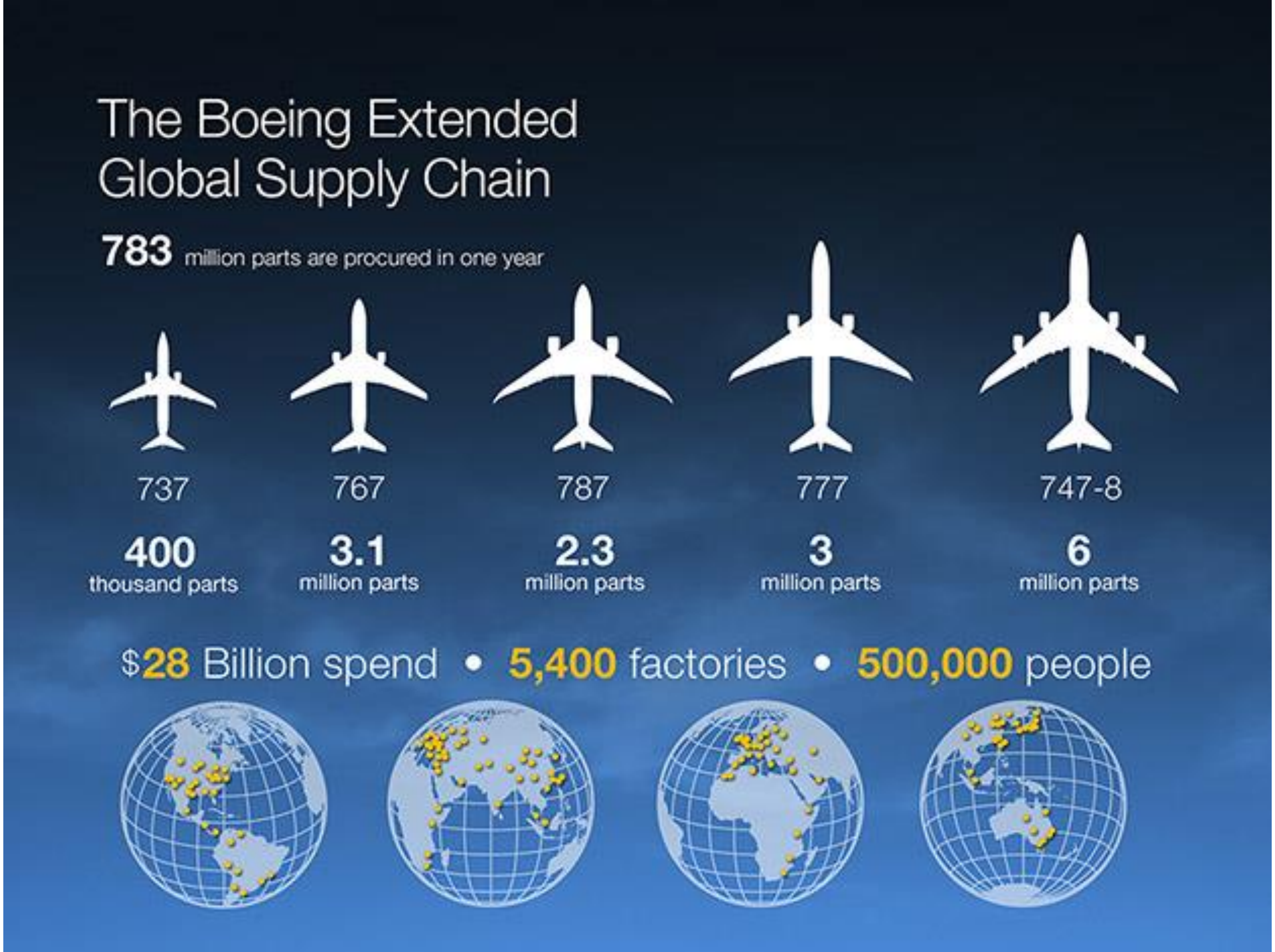
www.makergear.com

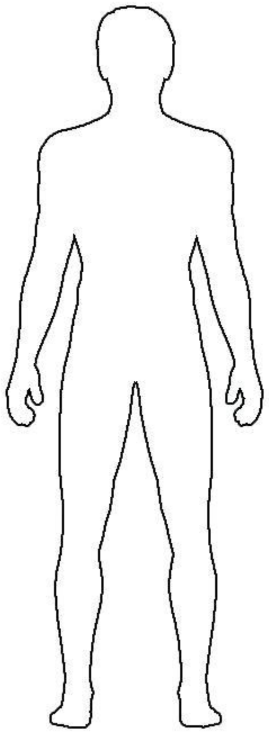
Machine must be bigger than the product

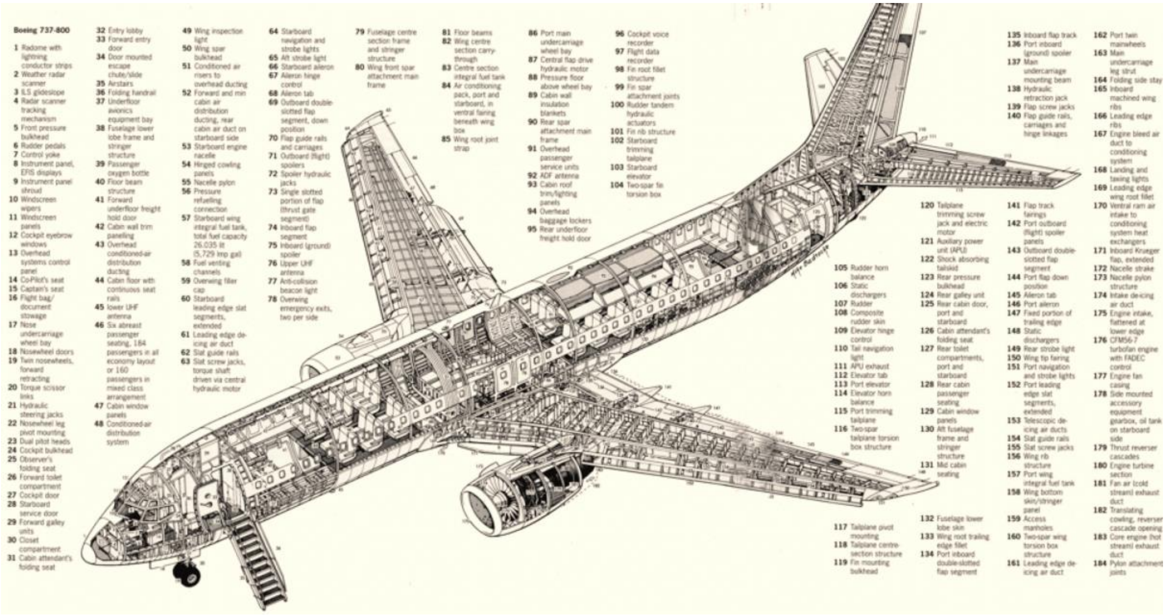
Manufacturing for Space






The Boeing Extended
Global Supply Chain
783 million parts are procured in one year
737
400
thousand parts
767
3.1
million parts
787
2.3
million parts
777
3
million parts
747-8
6
million parts
$28 Billion spend • 5,400 factories • 500,000 people





30-70 Trillion Cells

~200 types of Cells

$\Delta\ 10^{11}$

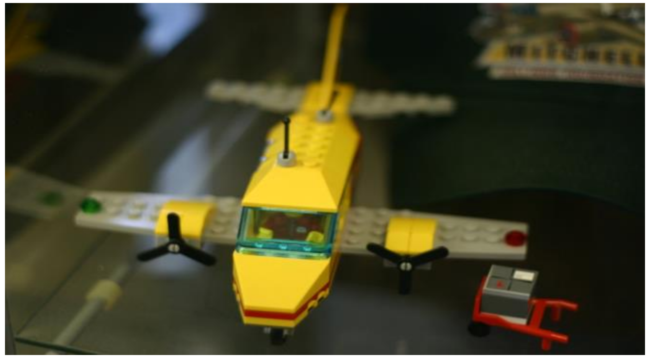
$\Delta\ 10^{1}$

~1 Million parts

~400,000 unique parts

Full Size LEGO® House, James May, 2011
~3.3e6 bricks

LEGO® City Limited Edition Set # 7747, 2009
444 bricks
image ©2009 The LEGO Group



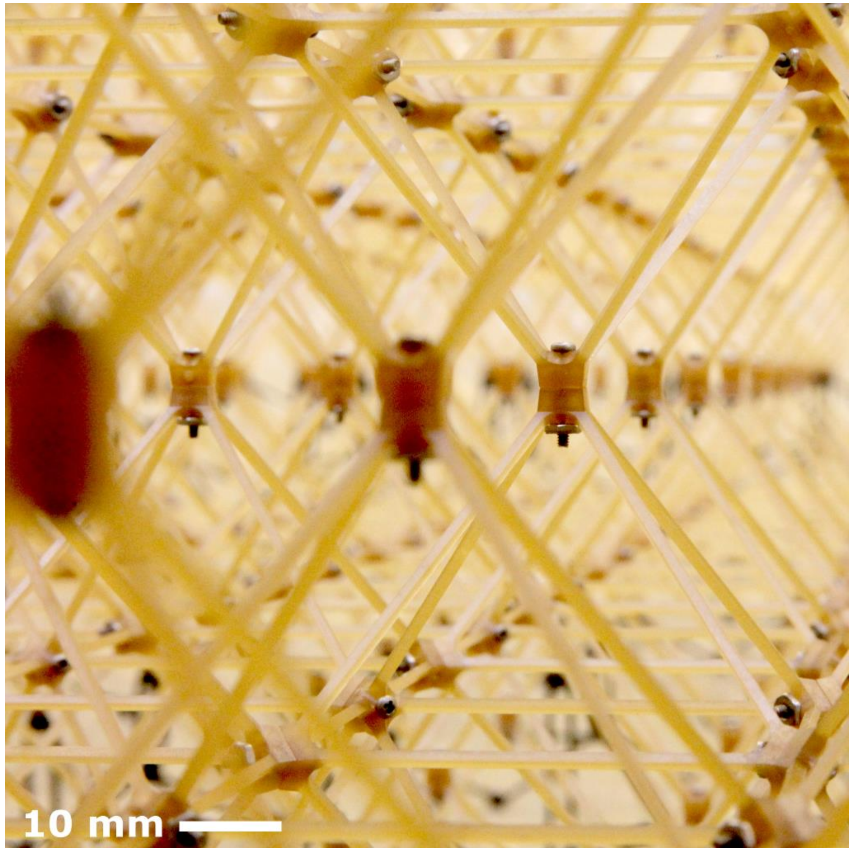
LEGO® Plane Set # 773x
~200 bricks
~100 different planes
~1e100 different things

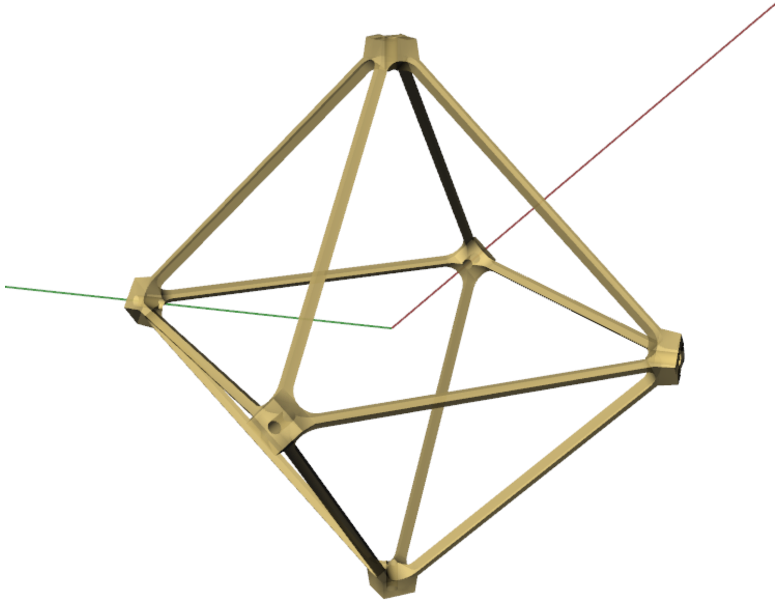
Discrete Lattice Materials

- **Unlimited build envelope**
- **Reconfigurable** (good for space!)
- **Economy of Scale**
- **Tunable properties** by mixing/matching parts
- Suited for **large-scale, automated assembly**
- **Simplified modeling**

“Ultra-light and Scalable Composite Lattice Materials”

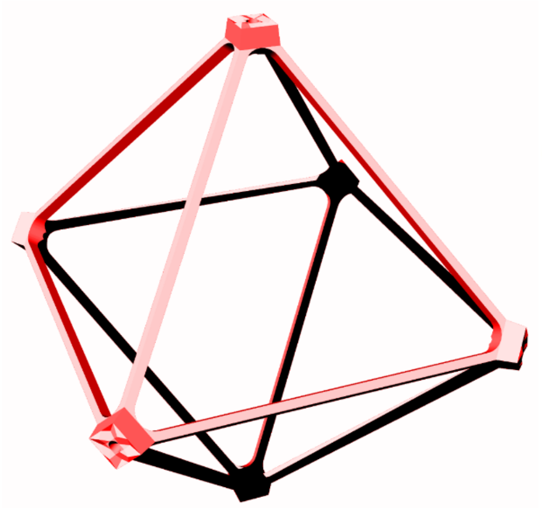
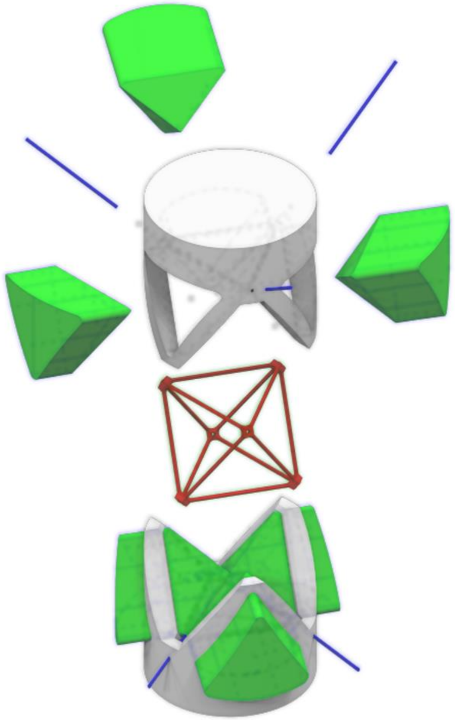
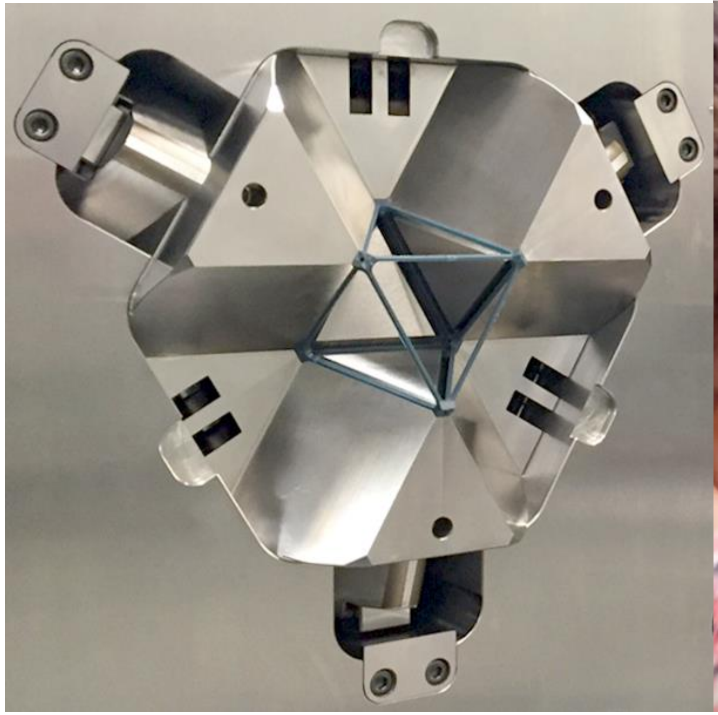
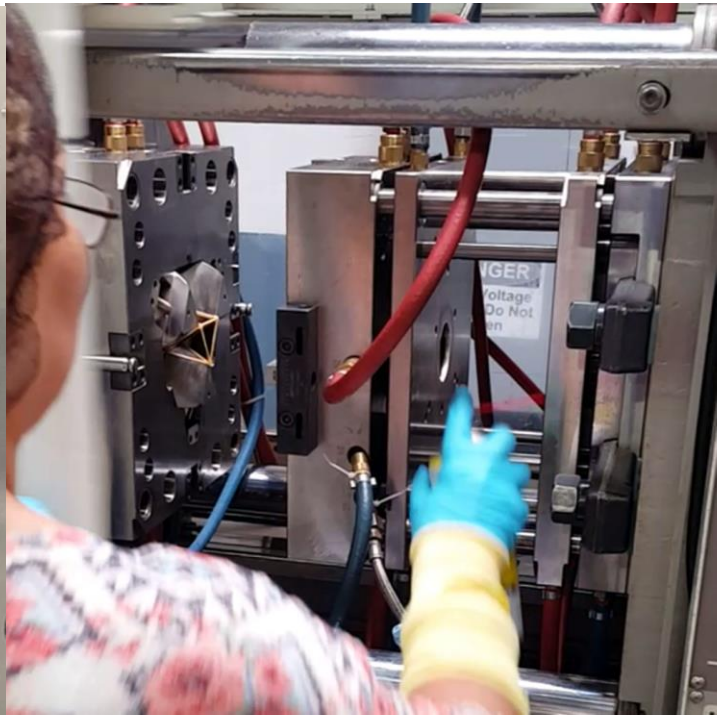
Combining **Cellular Materials** + **Building-Block Assembly**





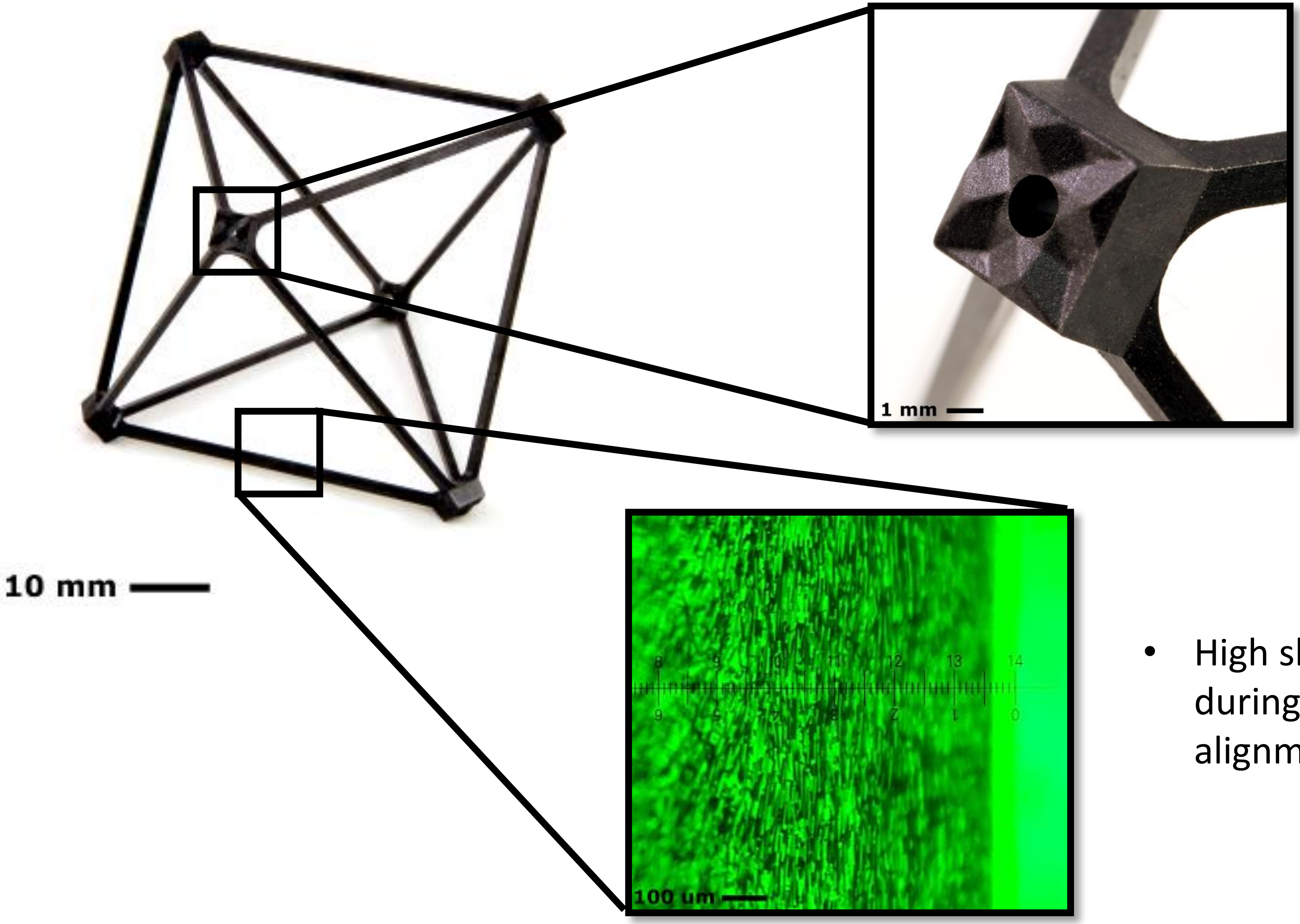
C.E. Gregg, J. H. Kim, K. C. Cheung. “Ultra-light scalable composite lattice materials.” *Advanced Engineering Materials.* 2018.

Unit Cell Manufacturing: Injection Molding

17 seconds/ part • highly repeatable • multi-material

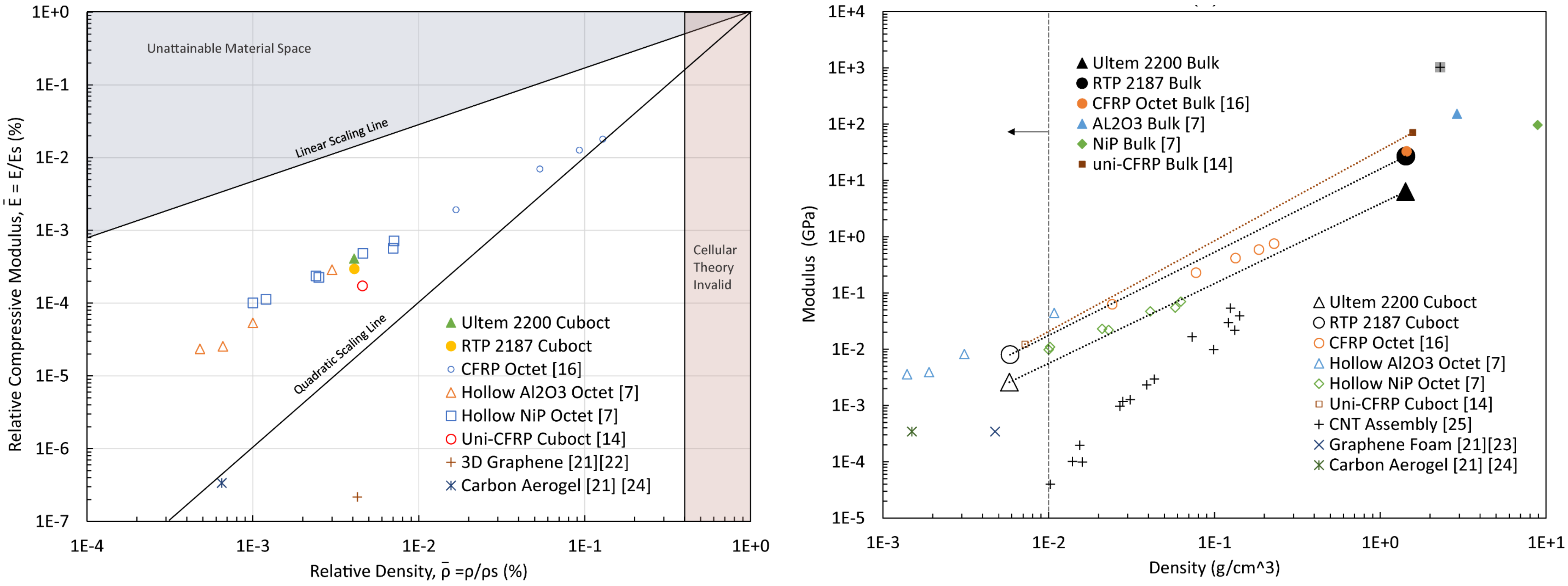
Resulting Unit Cell or “Voxel”



- Hirth joint ensures alignment during assembly
- Through-hole for pre-loaded bolted connection

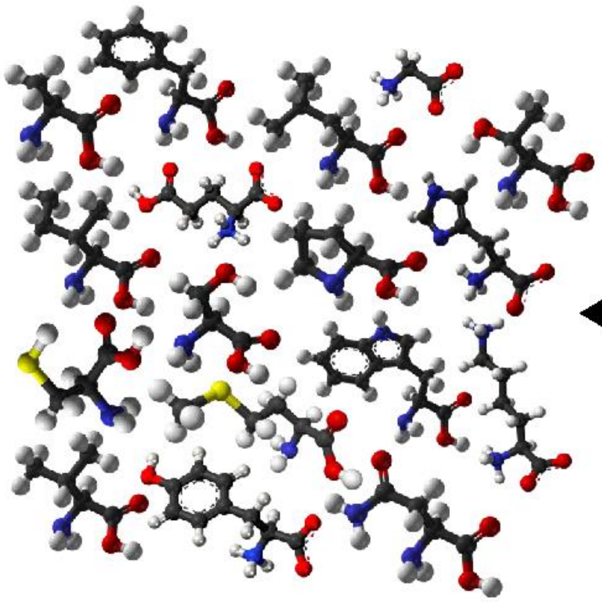
- High sheer in thin features during molding produces fiber alignment

Comparison to SOA



C.E. Gregg, J. H. Kim, K. C. Cheung. "Ultra-light scalable composite lattice materials." *Advanced Engineering Materials.* 2018 (accepted, in press)

Can we use building-block assembly to get tunable, programmable structures?



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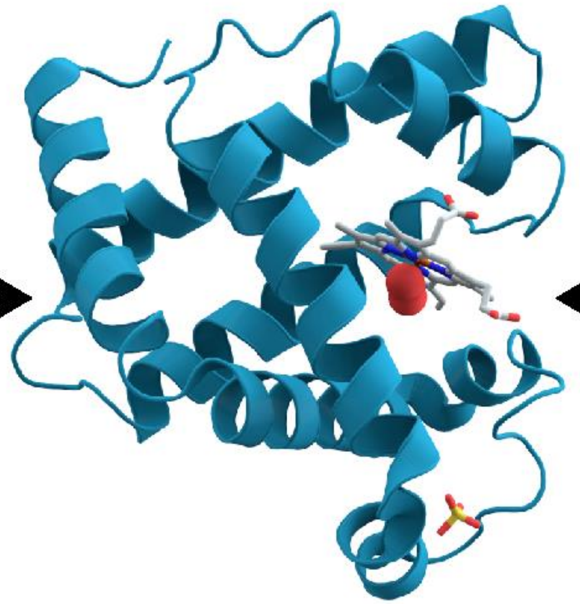

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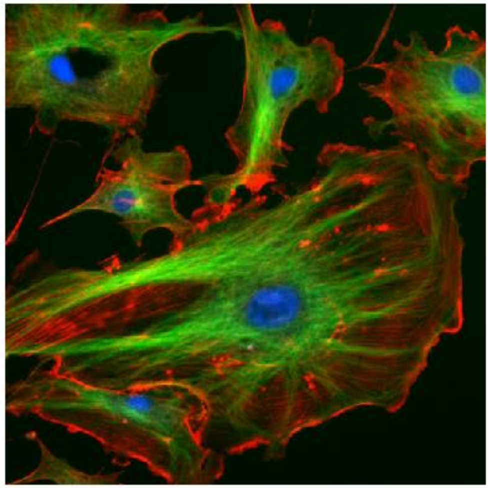
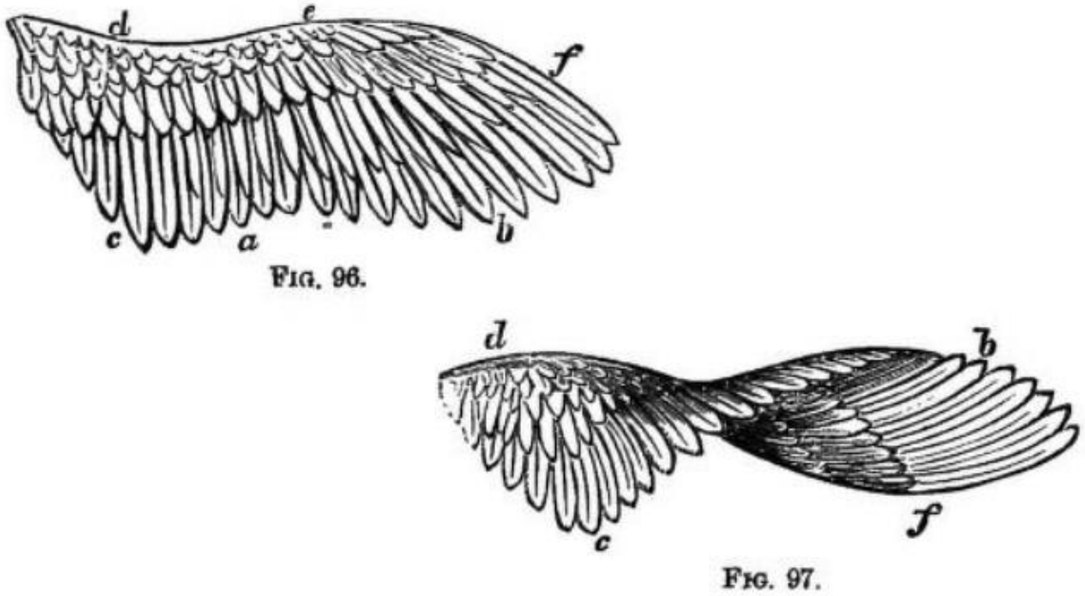
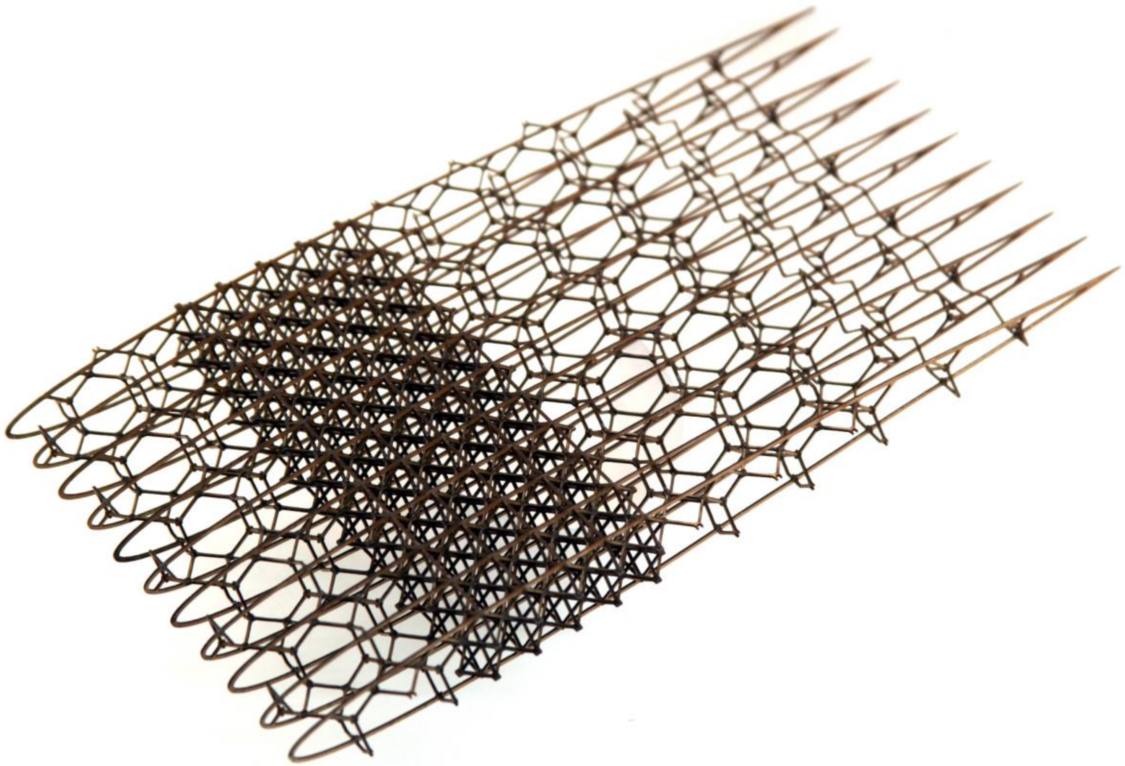


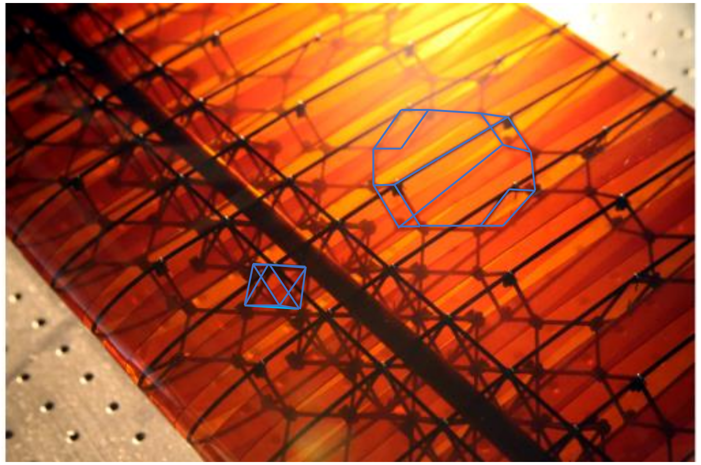
rsb.info.nih.gov/ij/images/

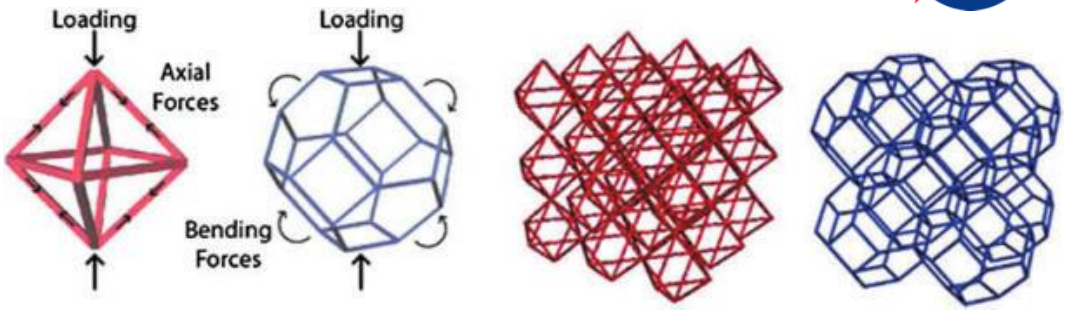
Bio-inspired flight

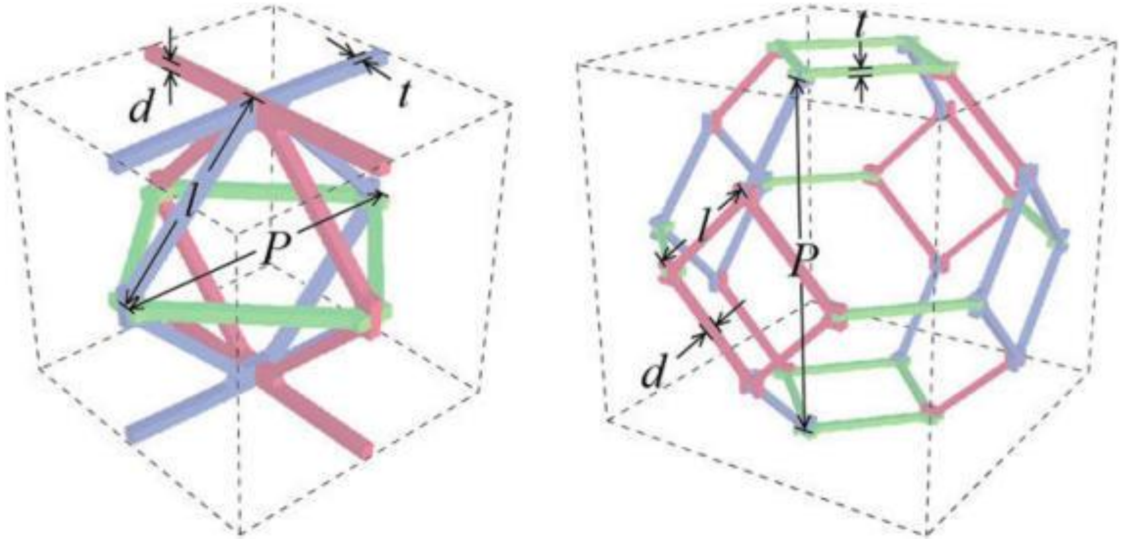


Animal locomotion; or, Walking, swimming, and flying, with a dissertation on aëronautics
By Pettigrew, James Bell, 1834-1908

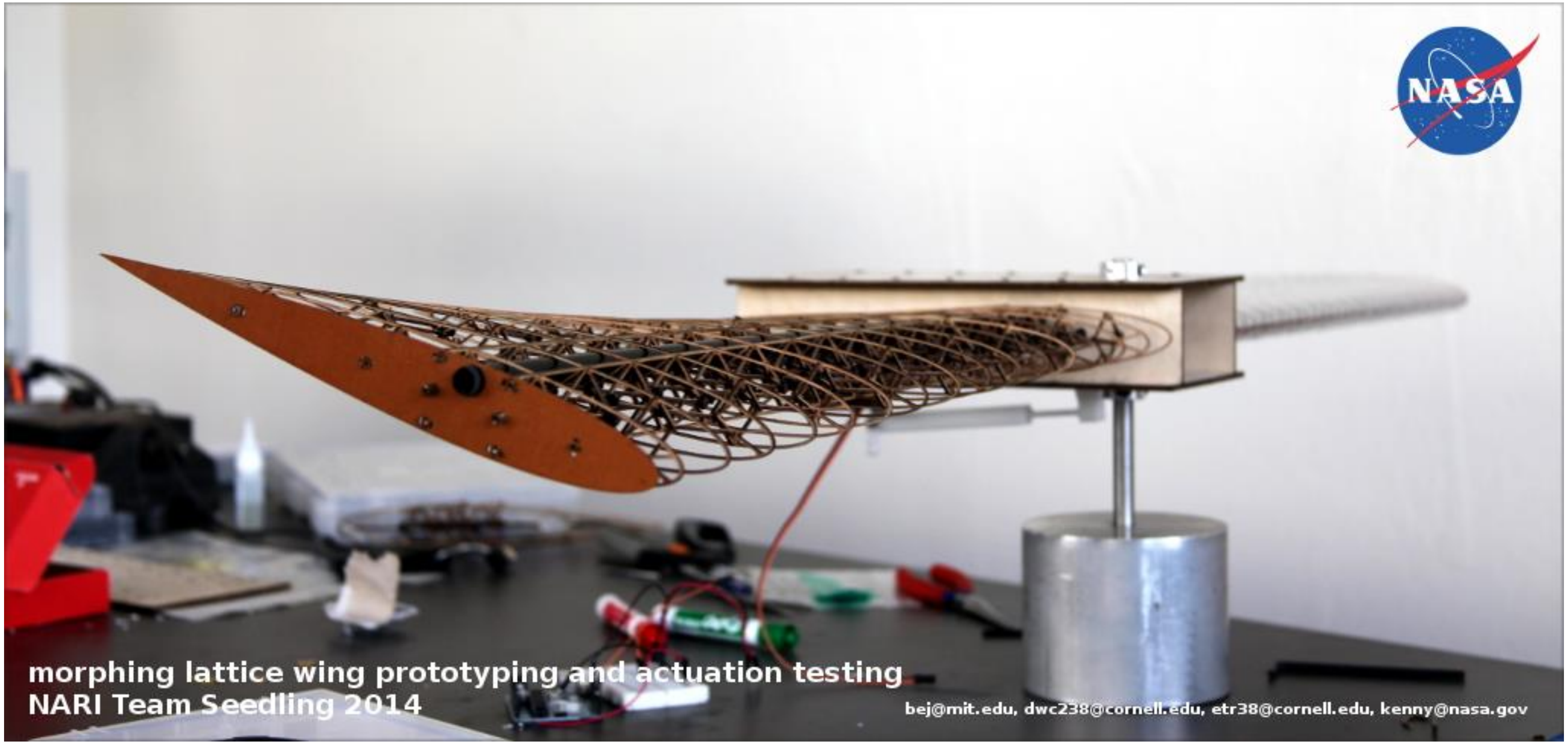








Jenett Benjamin, Calisch Sam, Cellucci Daniel, Cramer Nick, Gershenfeld Neil, Swei Sean, and Cheung Kenneth C.. Soft Robotics. March 2017, 4(1): 33-48. https://doi.org/10.1089/soro.2016.0032



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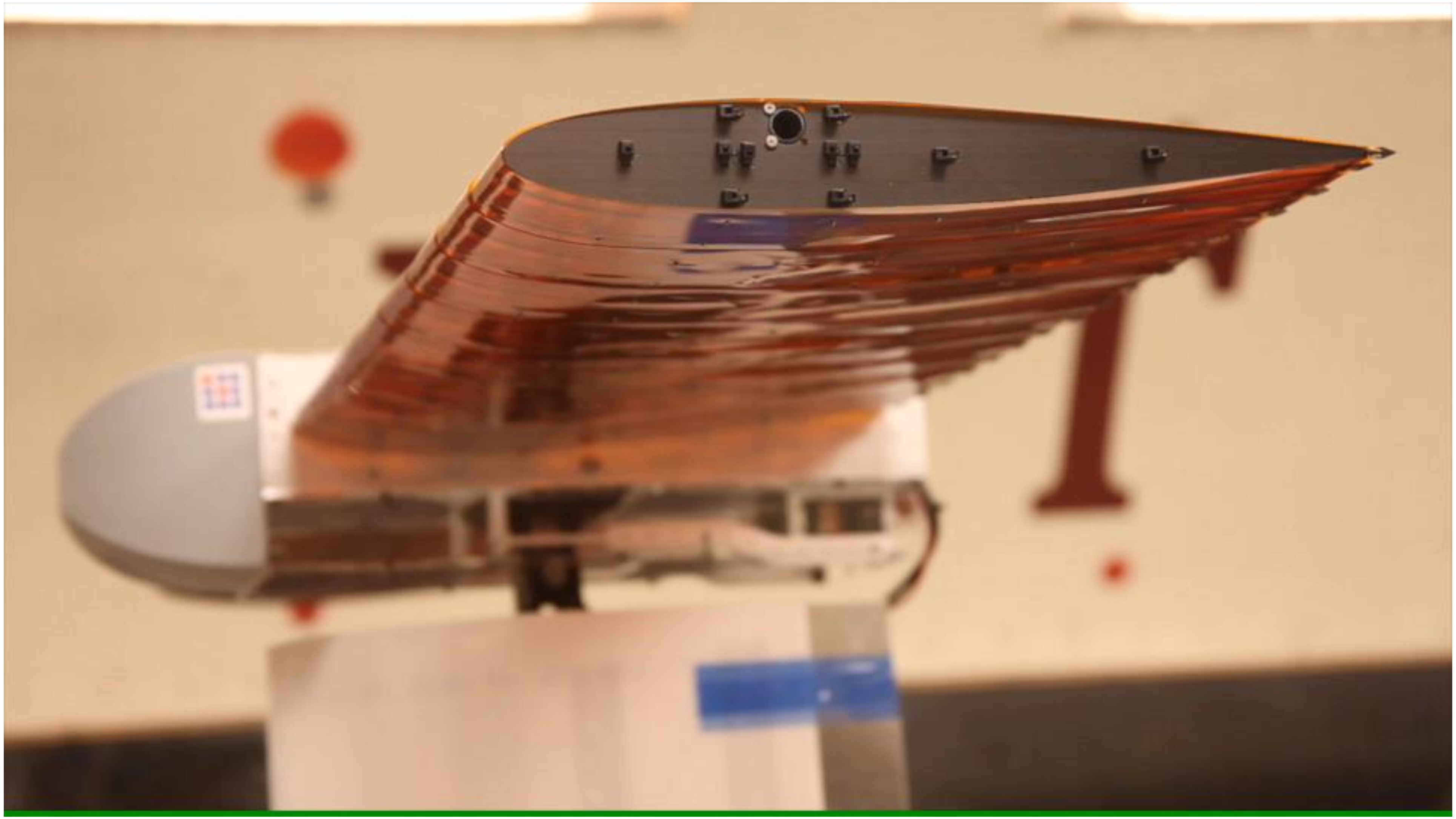
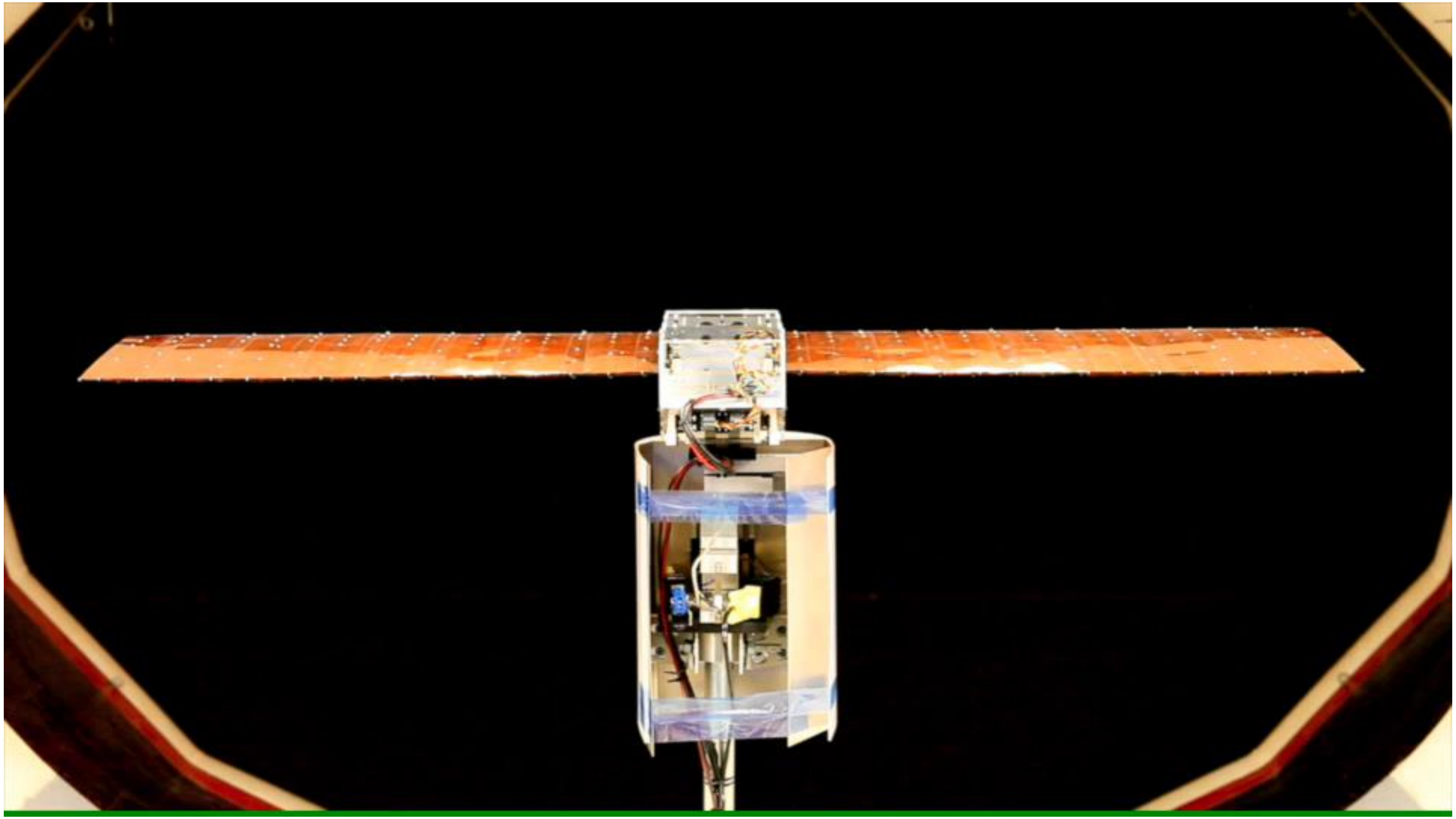


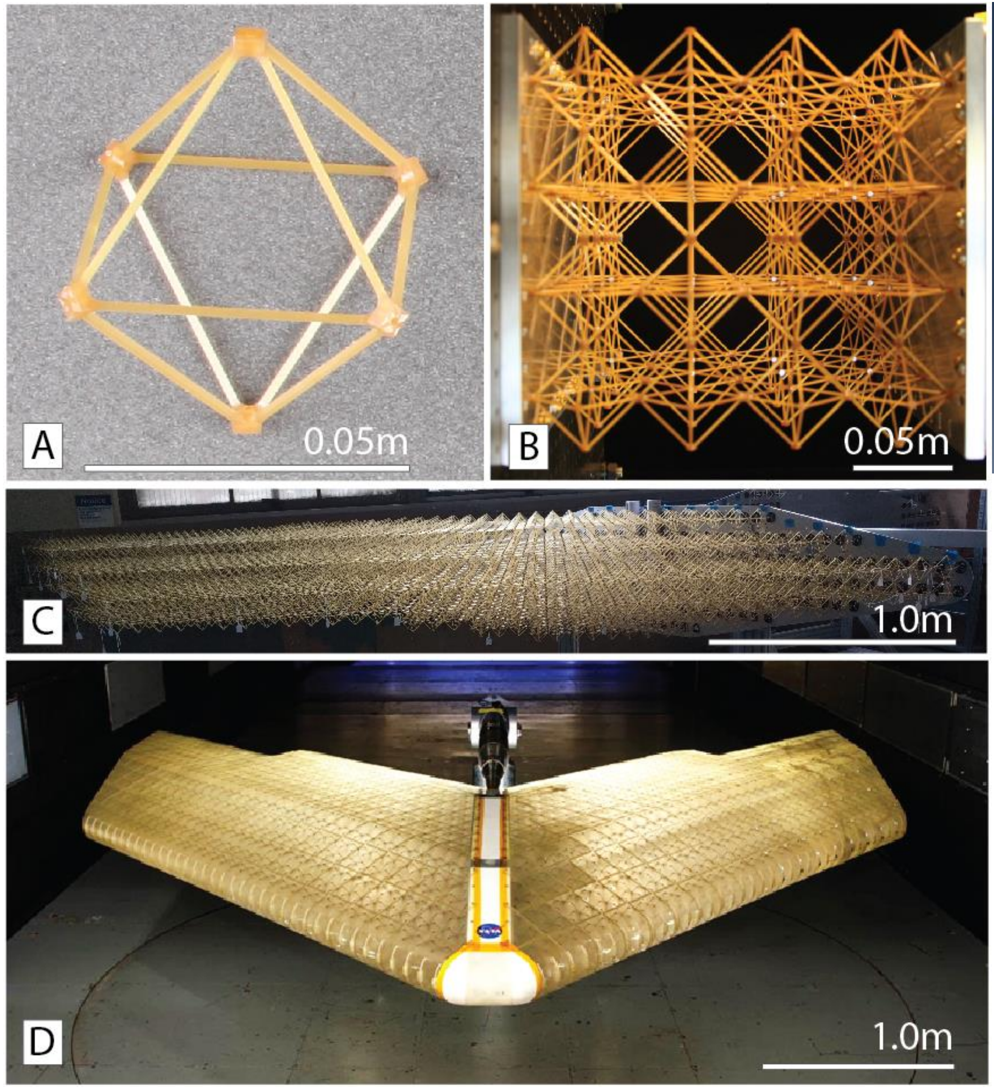
Jenett Benjamin, Calisch Sam, Cellucci Daniel, Cramer Nick, Gershenfeld Neil, Swei Sean, and Cheung Kenneth C.. Soft Robotics. March 2017, 4(1): 33-48. https://doi.org/10.1089/soro.2016.0032

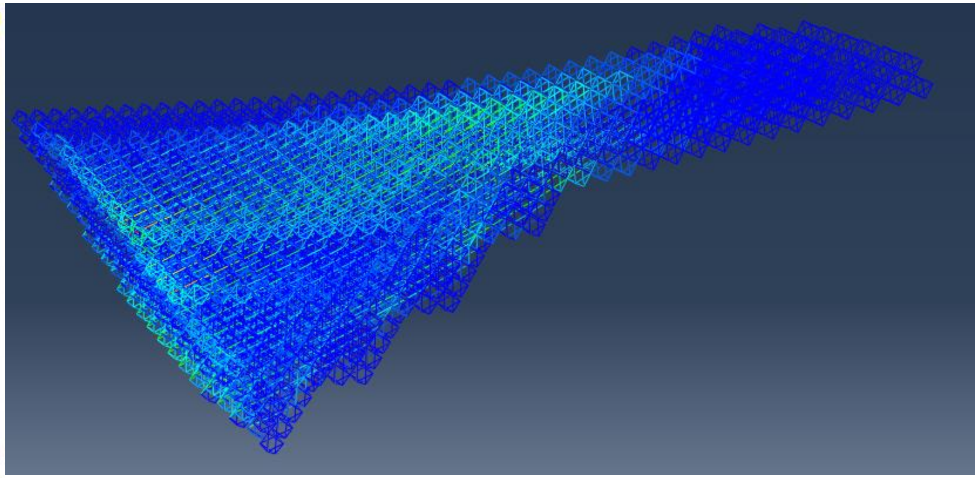


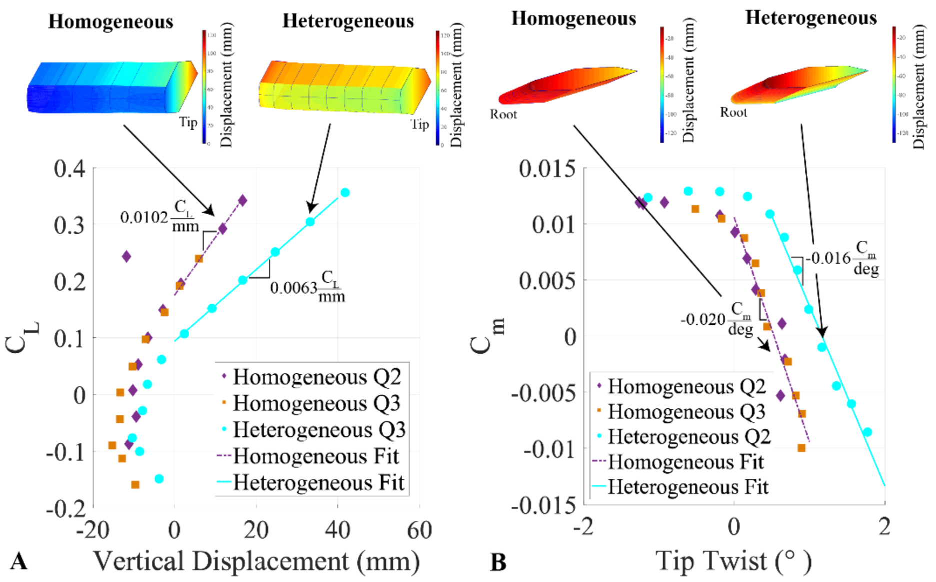
Jenett Benjamin, Calisch Sam, Cellucci Daniel, Cramer Nick, Gershenfeld Neil, Swei Sean, and Cheung Kenneth C.. Soft Robotics. March 2017, 4(1): 33-48. https://doi.org/10.1089/soro.2016.0032


MADCAT
N719NU
Ames Research Center

programmable soft materials





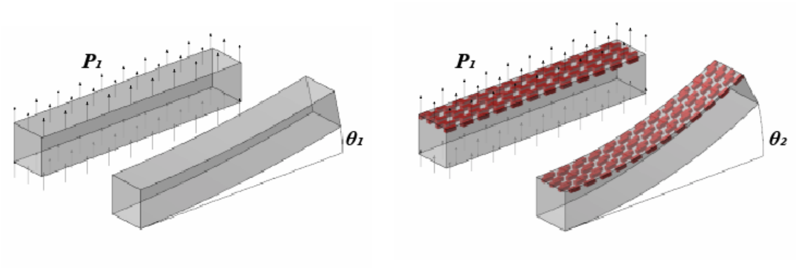
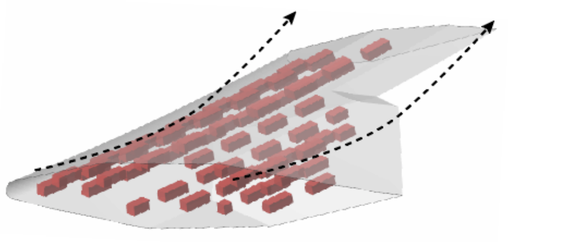
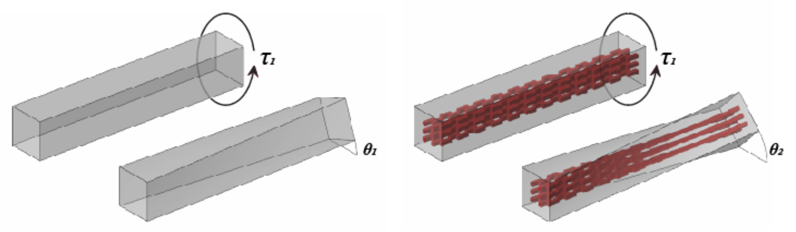
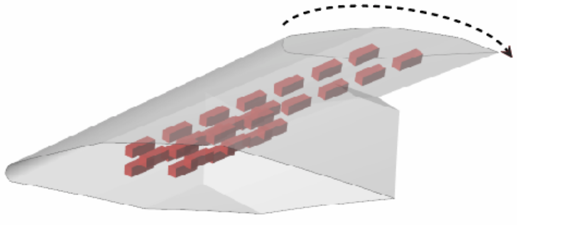
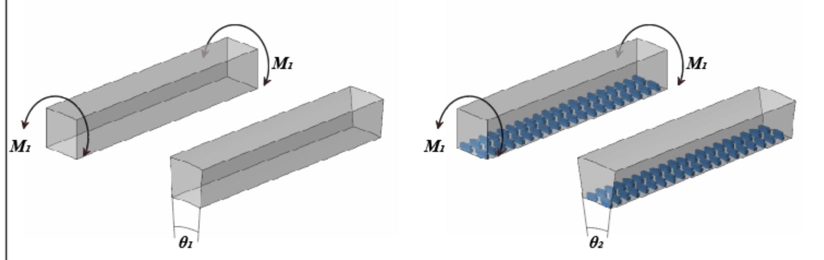
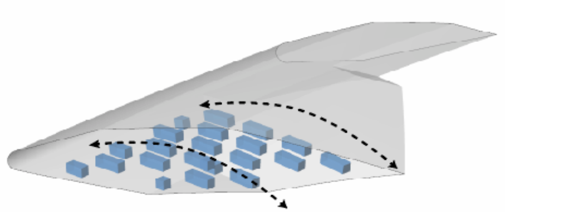


(1) Cramer, N., Jenett, B., Kim, J., Trinh, G., Formoso, O., Gregg, C., Trinh, K., Swei, S., Cheung, K. (in review)

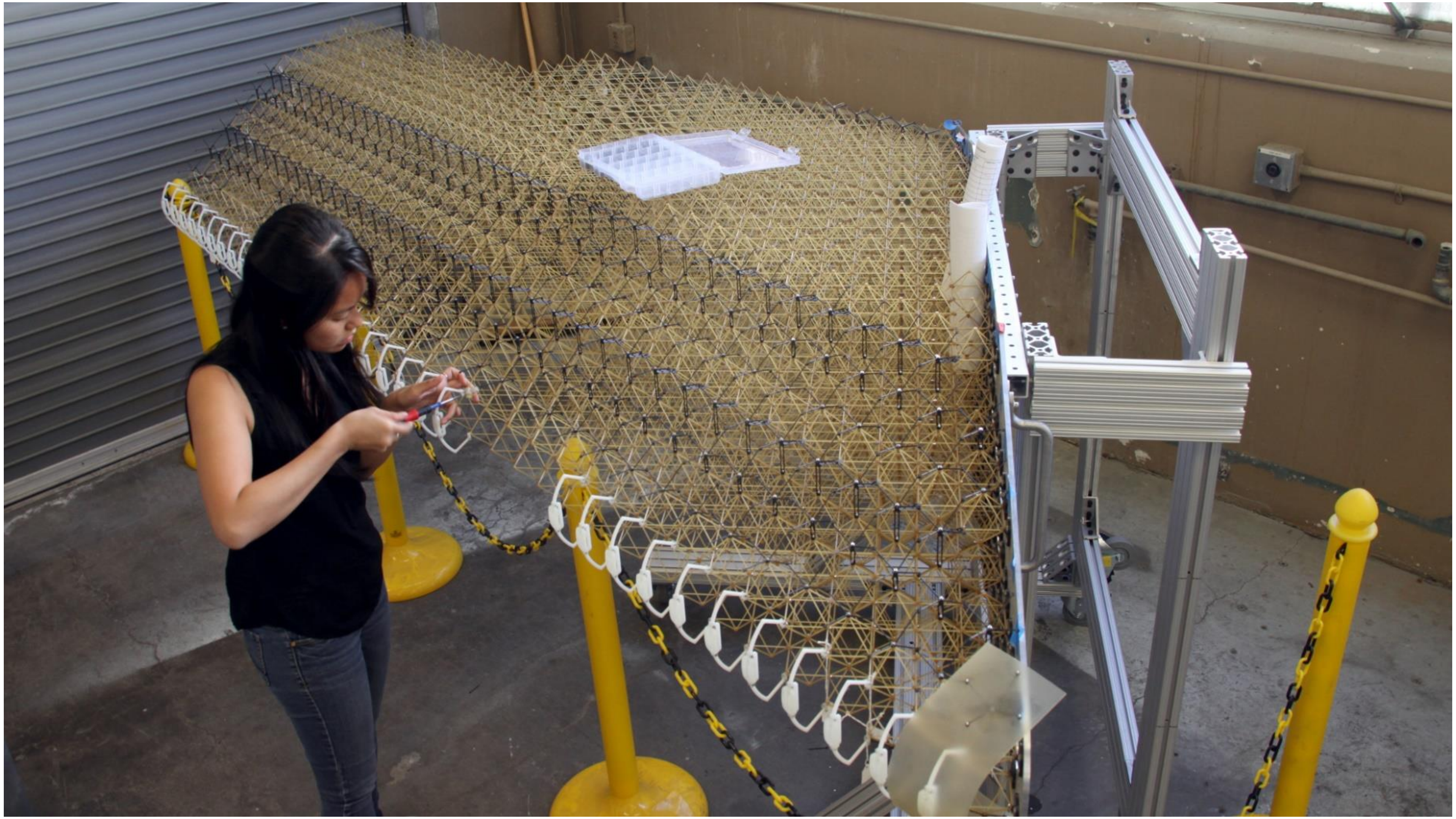
Tunability through component placement

Ultem 2200 Glass Reinforced Stiffer

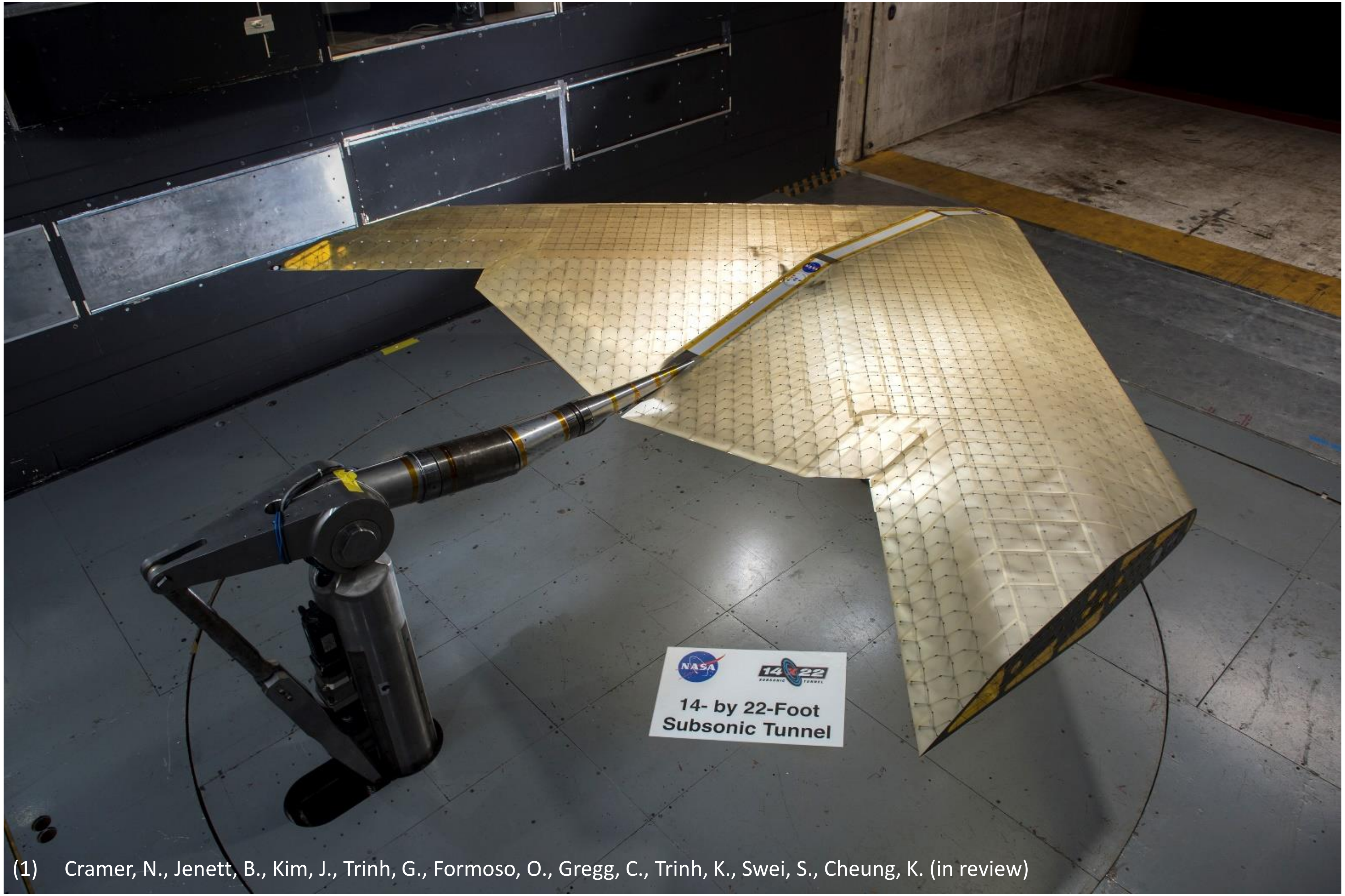
Ultem 1000 Softer

Guideline	*Behavior*	*Application*
(*iv-a*) Lengthwise anisotropy at boundary for decreased bending stiffness		 *Spanwise dihedral morphing*
(*iv-b*) Lengthwise anisotropy for decreased torsional stiffness		 *Outboard twist morphing*
(*v*) Widthwise anisotropy at boundary for decreased cross sectional shape rigidity		 *Inboard camber morphing*

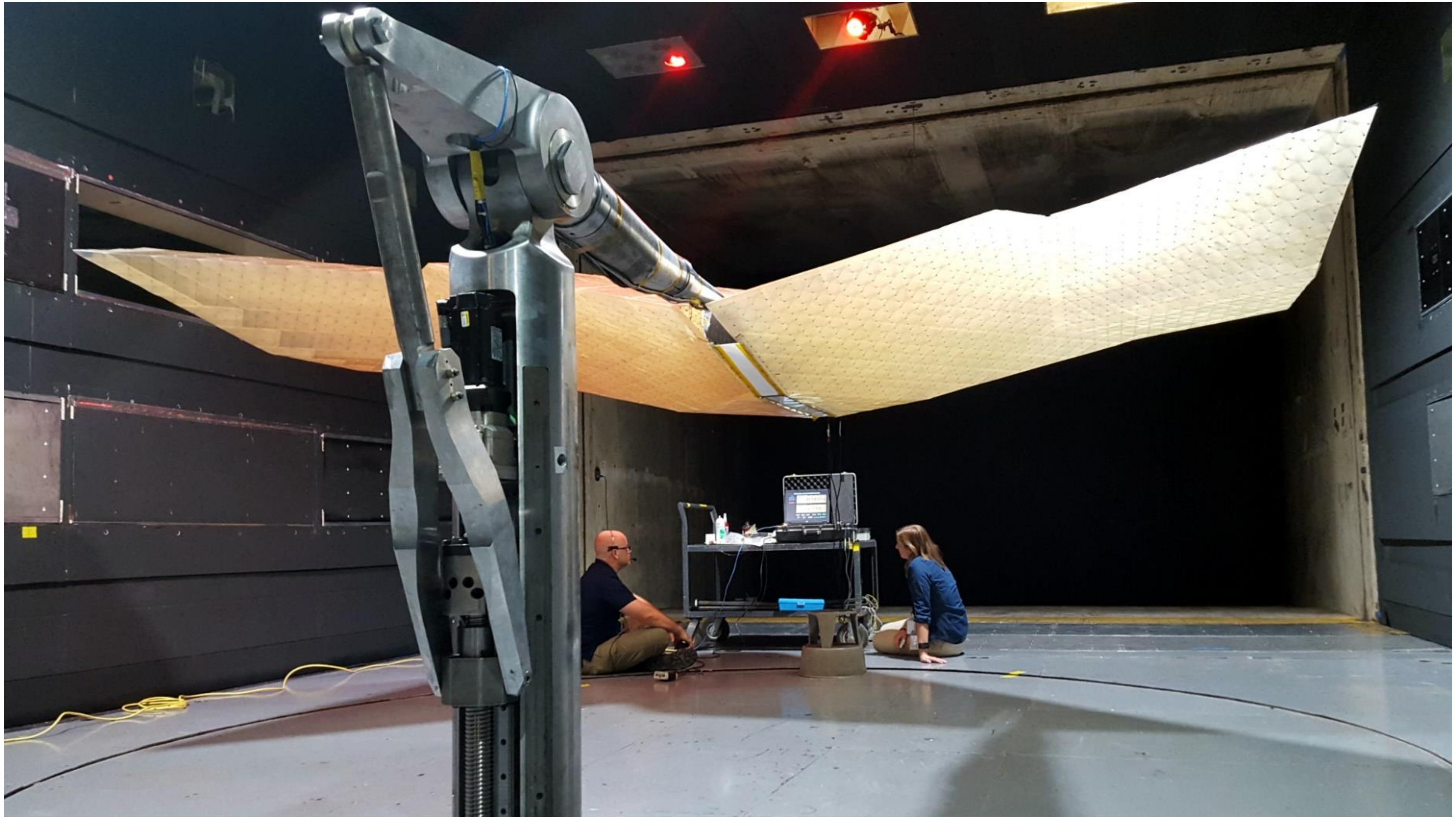
Cramer, Nick, et al. "Elastic Shape Morphing of Ultralight Structures by Programmable Assembly." *Smart Materials and Structures* (2019).



Cramer, Nick, et al. "Elastic Shape Morphing of Ultralight Structures by Programmable Assembly." *Smart Materials and Structures* (2019).

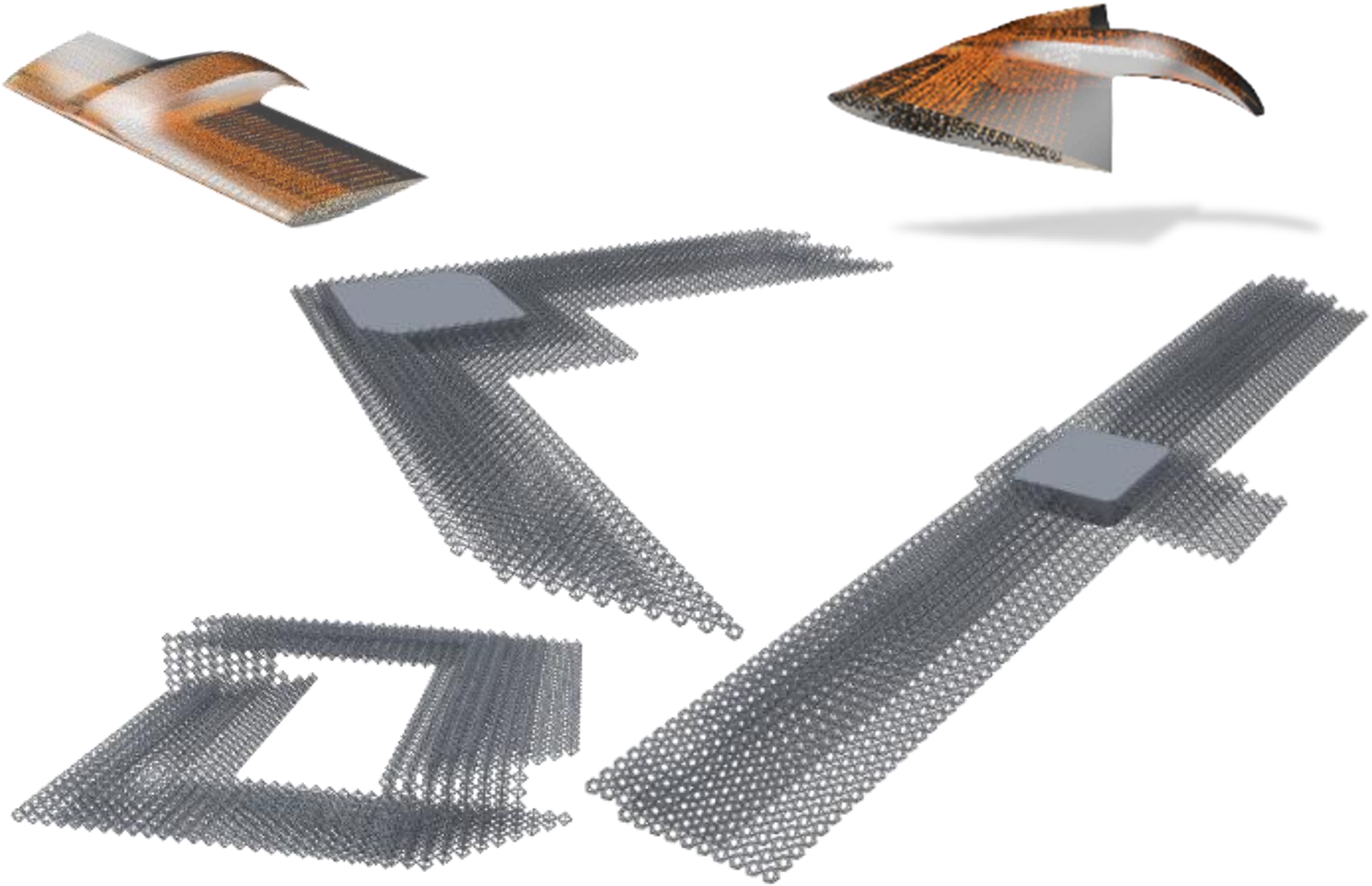


(1) Cramer, N., Jenett, B., Kim, J., Trinh, G., Formoso, O., Gregg, C., Trinh, K., Swei, S., Cheung, K. (in review)

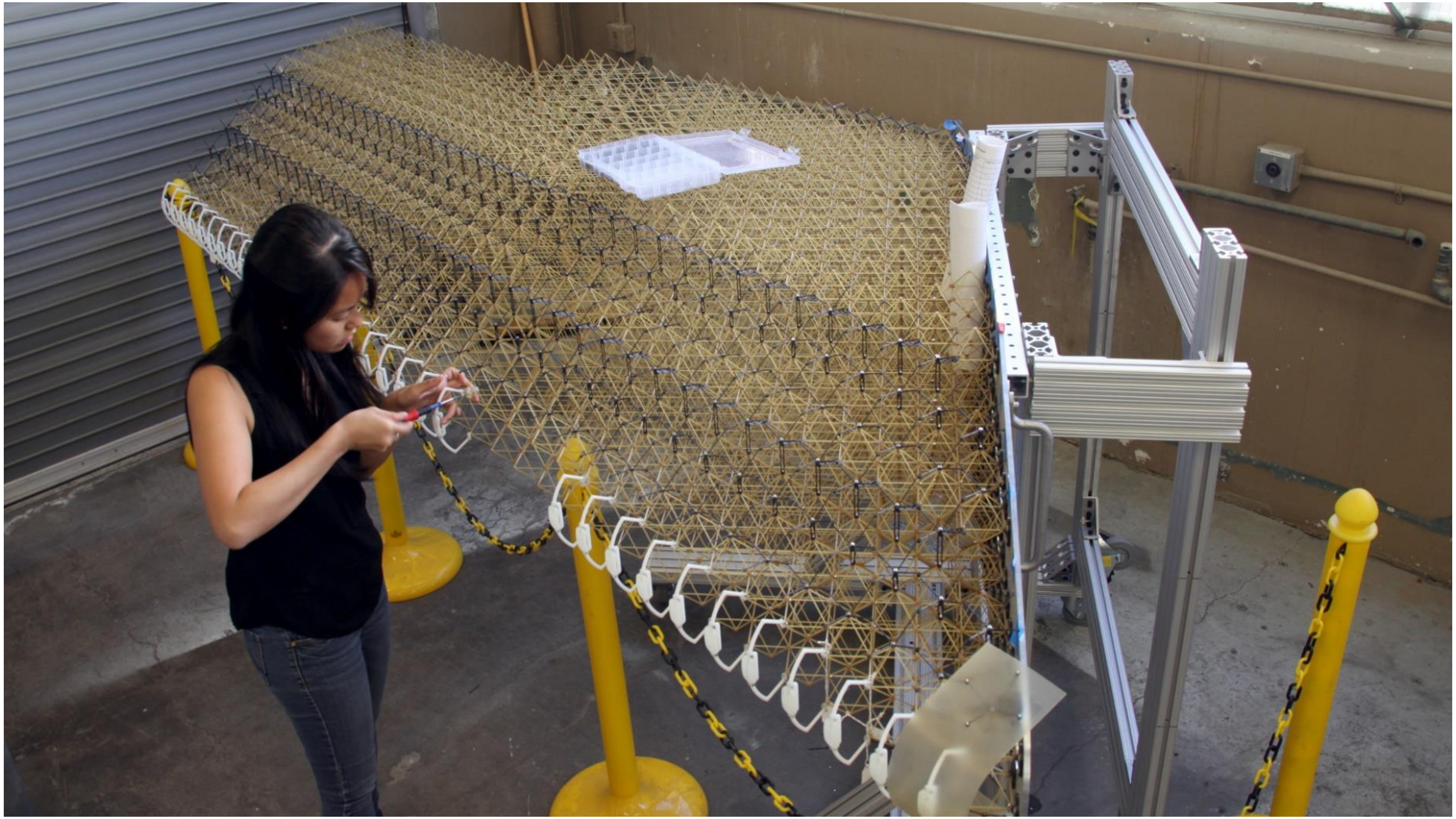


Cramer, Nick, et al. "Elastic Shape Morphing of Ultralight Structures by Programmable Assembly." *Smart Materials and Structures* (2019).

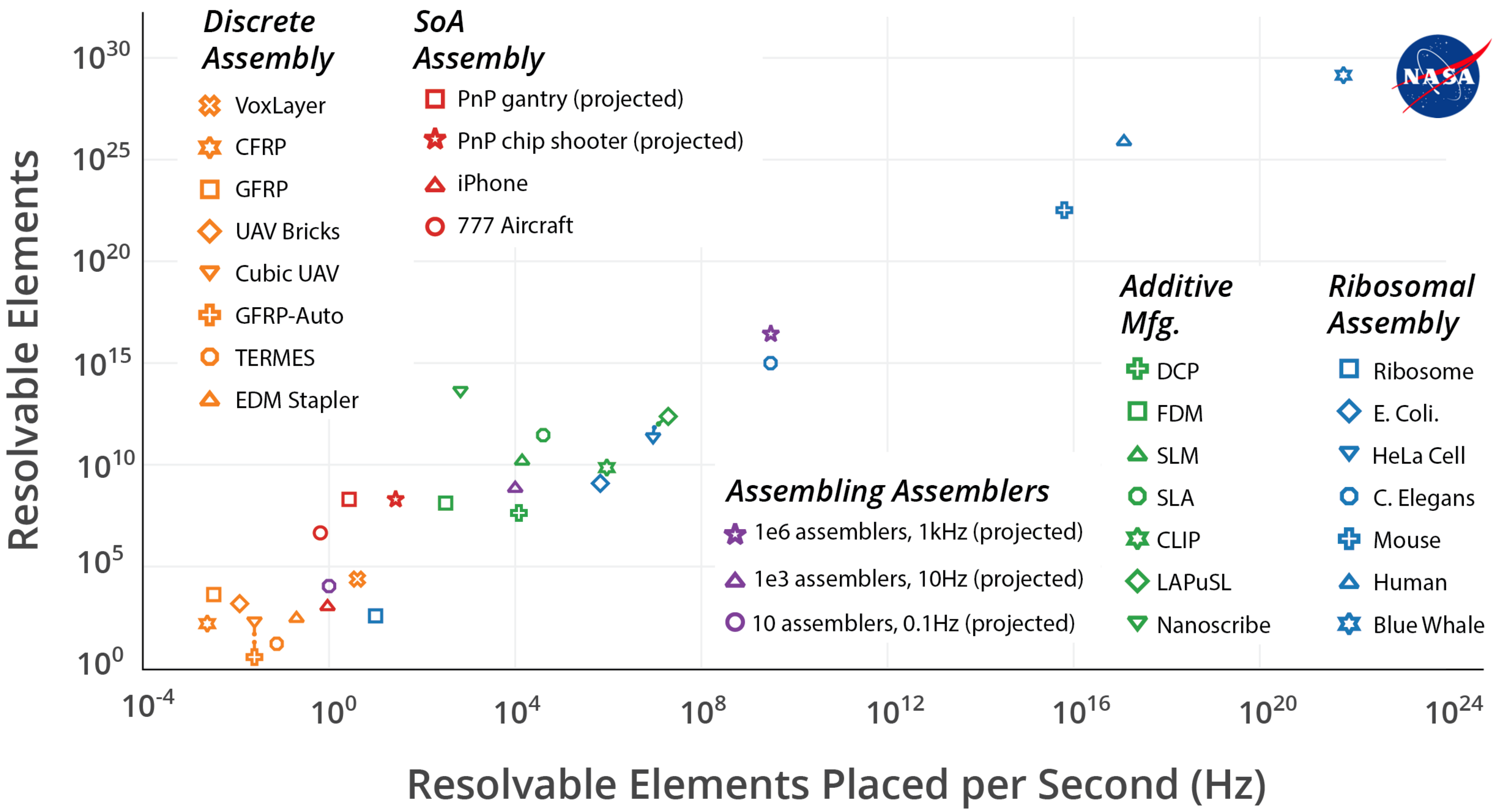
X^n planes



programmable soft materials



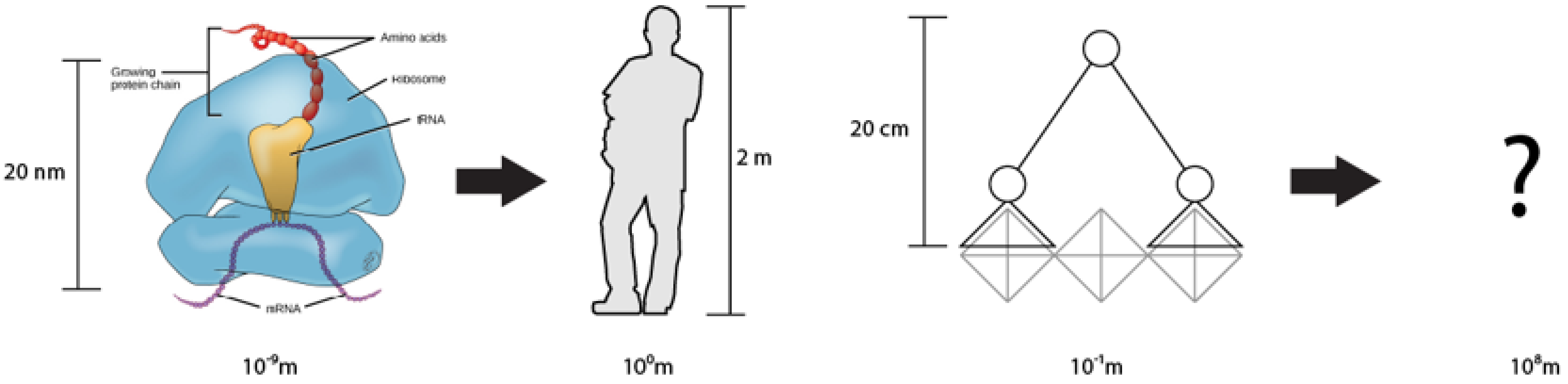
Cramer, Nick, et al. "Elastic Shape Morphing of Ultralight Structures by Programmable Assembly." *Smart Materials and Structures* (2019).



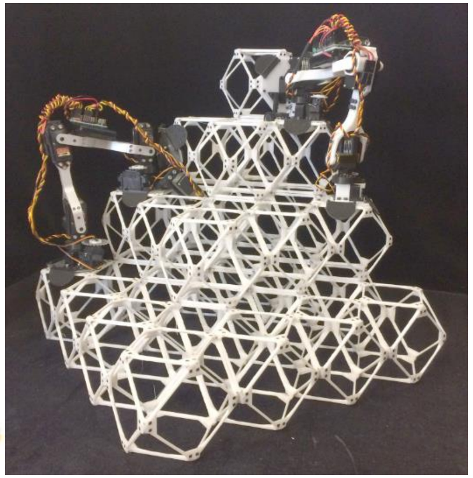
Langford, Thesis, MIT 2019

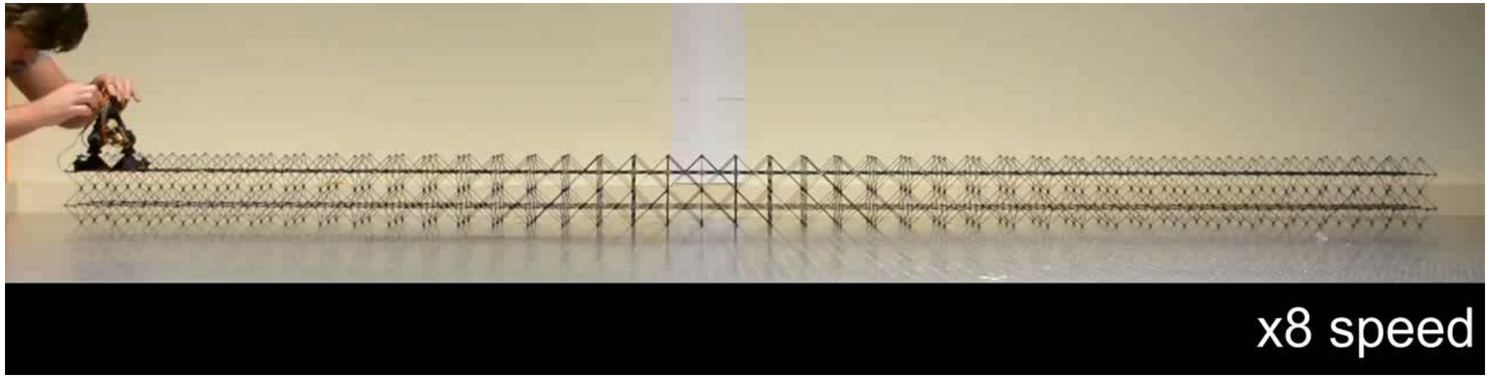
Machine	Speed Operation		Time per cycle (s)	Frequency (Hz)
Inkjet Printer	150	m/min (@ 300 dpi)	0.0001	10,000
High Speed Straight Stitch Sewing Machine	5500	stitches/min	0.011	91
Commercial High-Speed Straight Stitch Sewing Machine	1500	stitches/min	0.04	25
Bottle Capping Machine	80,000	parts/hr	0.045	22
M16 Rifle, automatic fire	800	rounds/min	0.075	13
CNC Turret Press Punching	400	punches/min	0.15	7
Pick and Place machine	300	parts/min	0.2	5
Nail gun	4	nails/sec	0.25	4
Ribosome	200	amino acids/min	0.3	3.3
Global Robotic Assembler (GR)	6	parts/min	10	0.10
Mobile Robotic Assembler (MR)	4	parts/min	15	0.07
Extravehicular Activity Strut Assembly (EVA)	120	struts/hour	28	0.04
Extravehicular Robotic Strut Assembly (EVR)	97	struts/hour	37	0.03
Relative Robotic Assembler (RR)	1	parts/min	60	0.02
GSWT	0.2	Voxel/min	300	0.003

High throughput via parallelization



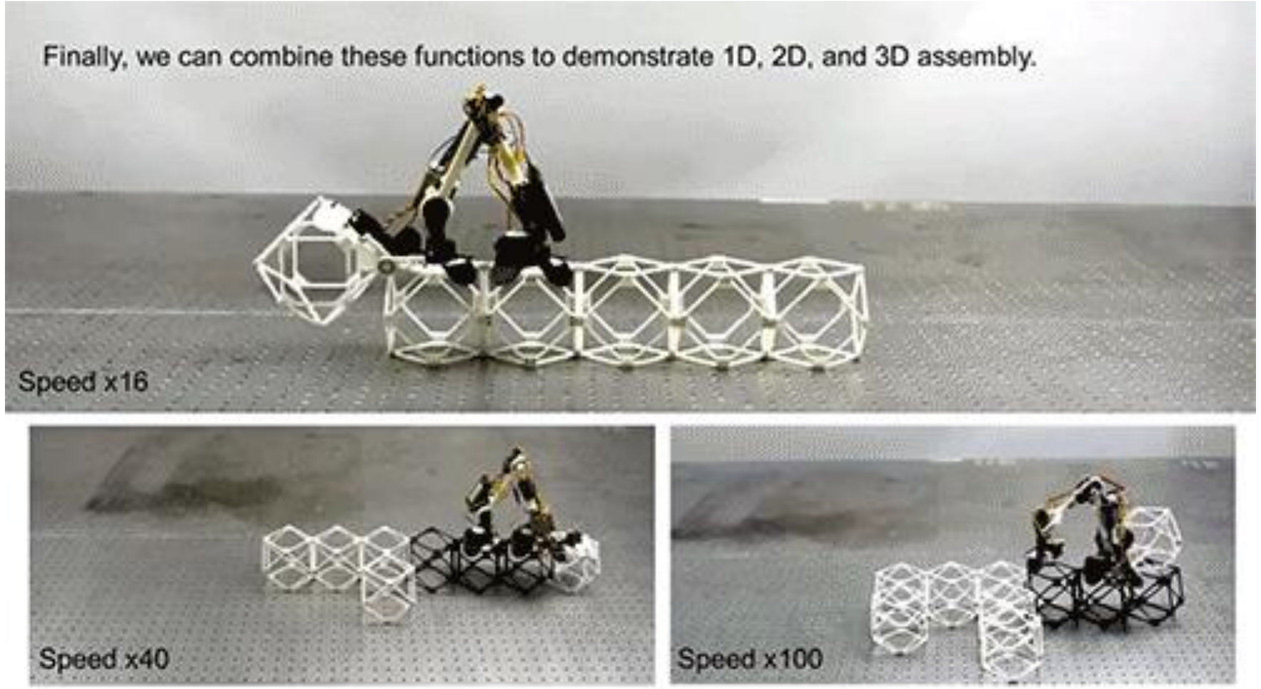
Relative Robot Assembly

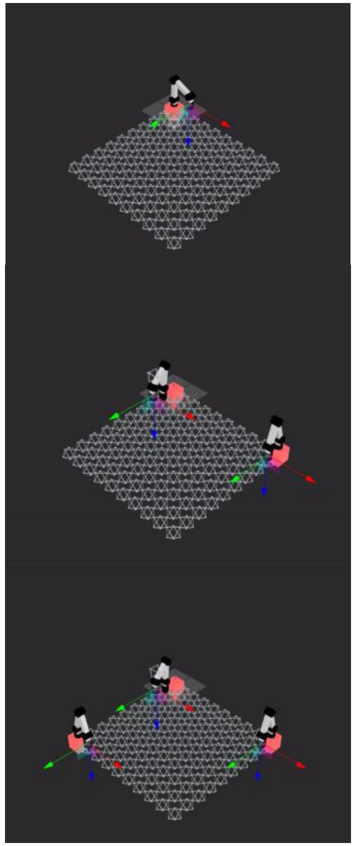




Jenett, Ben, and Kenneth Cheung. "Bill-e: Robotic platform for locomotion and manipulation of lightweight space structures." *25th AIAA/AHS Adaptive Structures Conference*. 2017.

Relative Robot Assembly

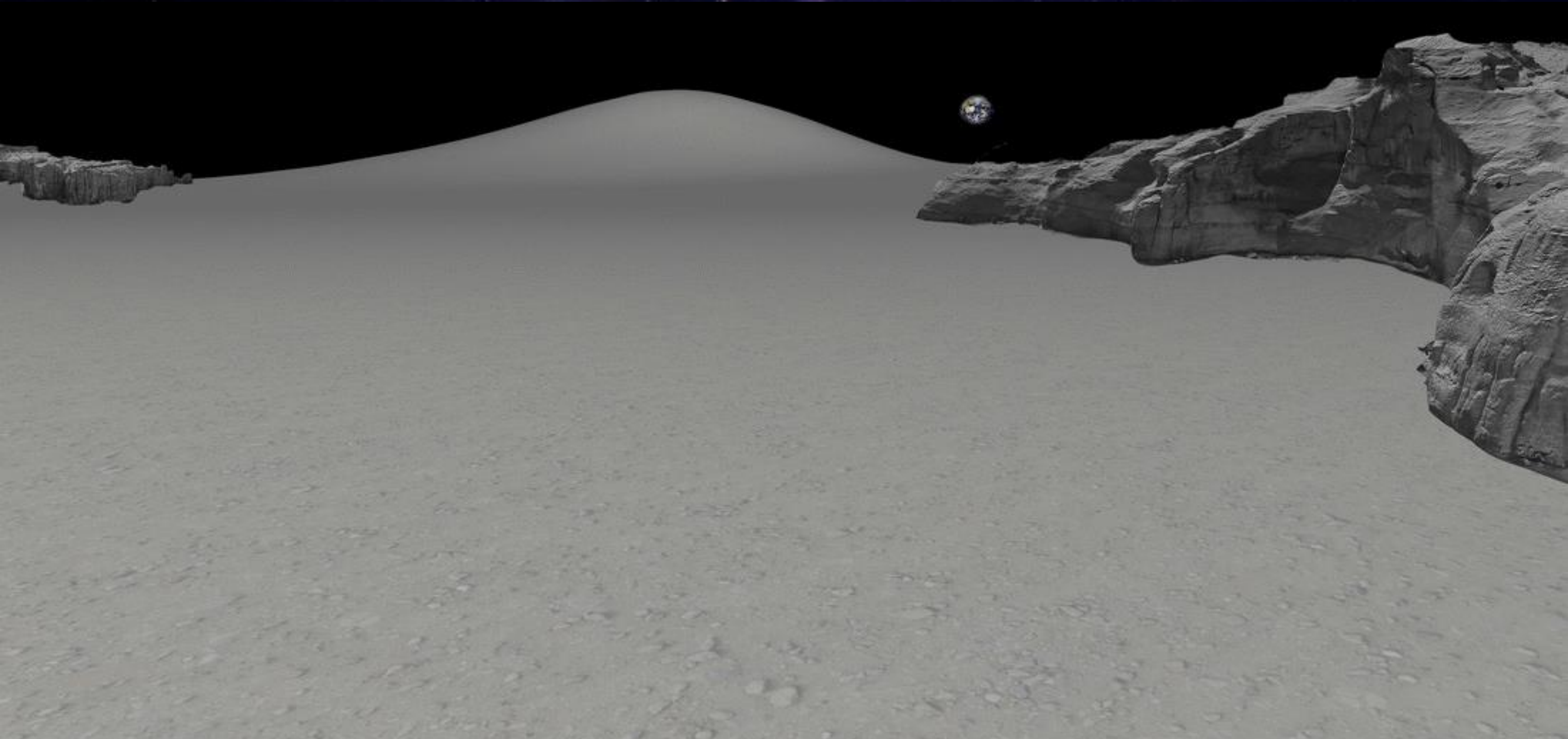




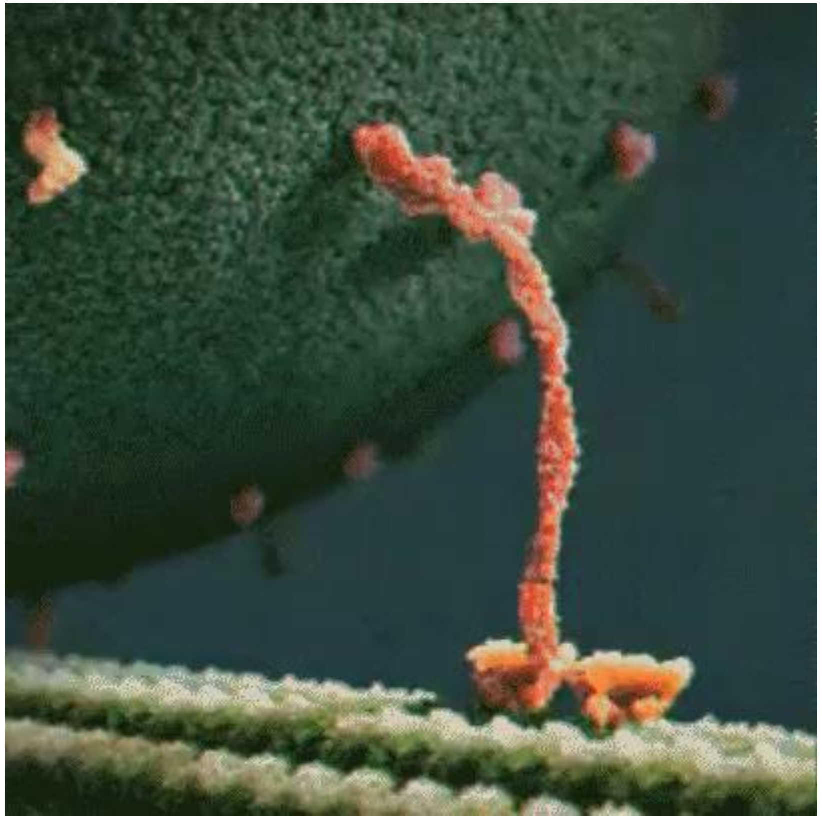
Jenett, Benjamin, et al. "Material–Robot System for Assembly of Discrete Cellular Structures." *IEEE Robotics and Automation Letters* 4.4 (2019): 4019-4026.

ARMADAS Technology Overview

Technology Product Capability



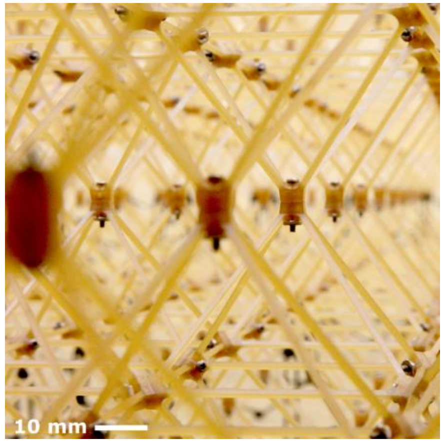
Molecular Motor: Kinesin

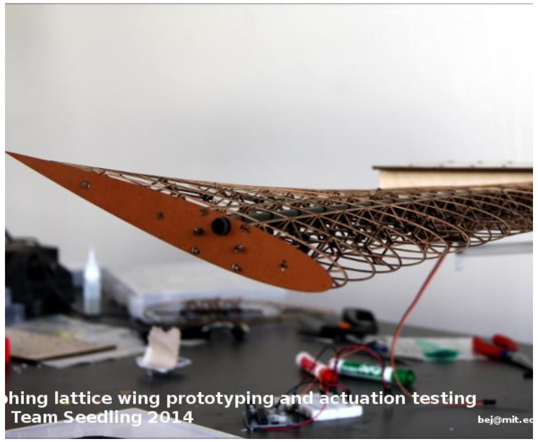


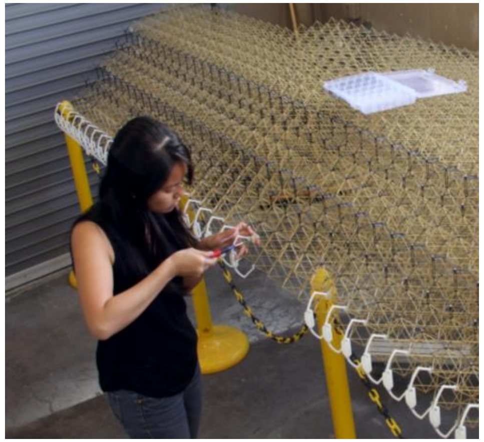
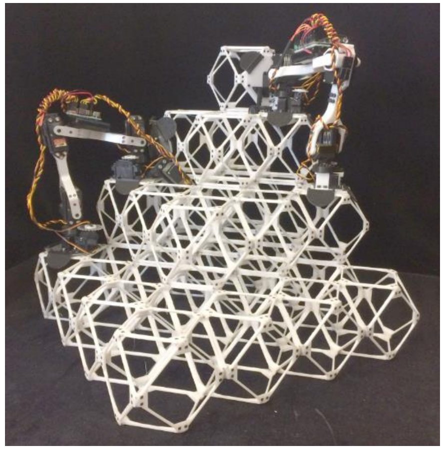
Animation from: “The Inner Life of a Cell” by Cellular Visions

- https://www.youtube.com/watch?v=y-uuk4Pr2i8

Cellular Materials
+ Programmable Structures
+ Building-Block Based Assembly
+ Autonomous 'Structure Specific' Robots
= **Autonomously Assembling Programmable Lattice Materials**





Current Team: Kenneth Cheung, Nicholas Cramer, Olivia Formoso, Christine Gregg, Benjamin Jenett, Inwon Park Sean Swei, Greenfield Trinh

Previous Team: 20+ Contributors!

Questions?

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christine.e.gregg@nasa.gov

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