Lightweight Digital Materials for NASA Infrastructure

ICRA 22, Philadelphia, PA, May 27, 2022

Christine Gregg
NASA Ames Research Center



ICRA 2022
IEEE International Conference on Robotics and Automation

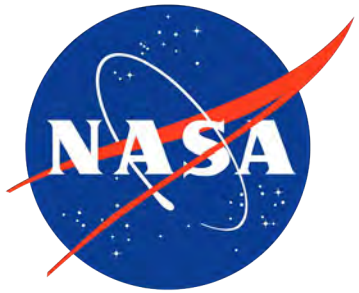




Image Credit: NASA

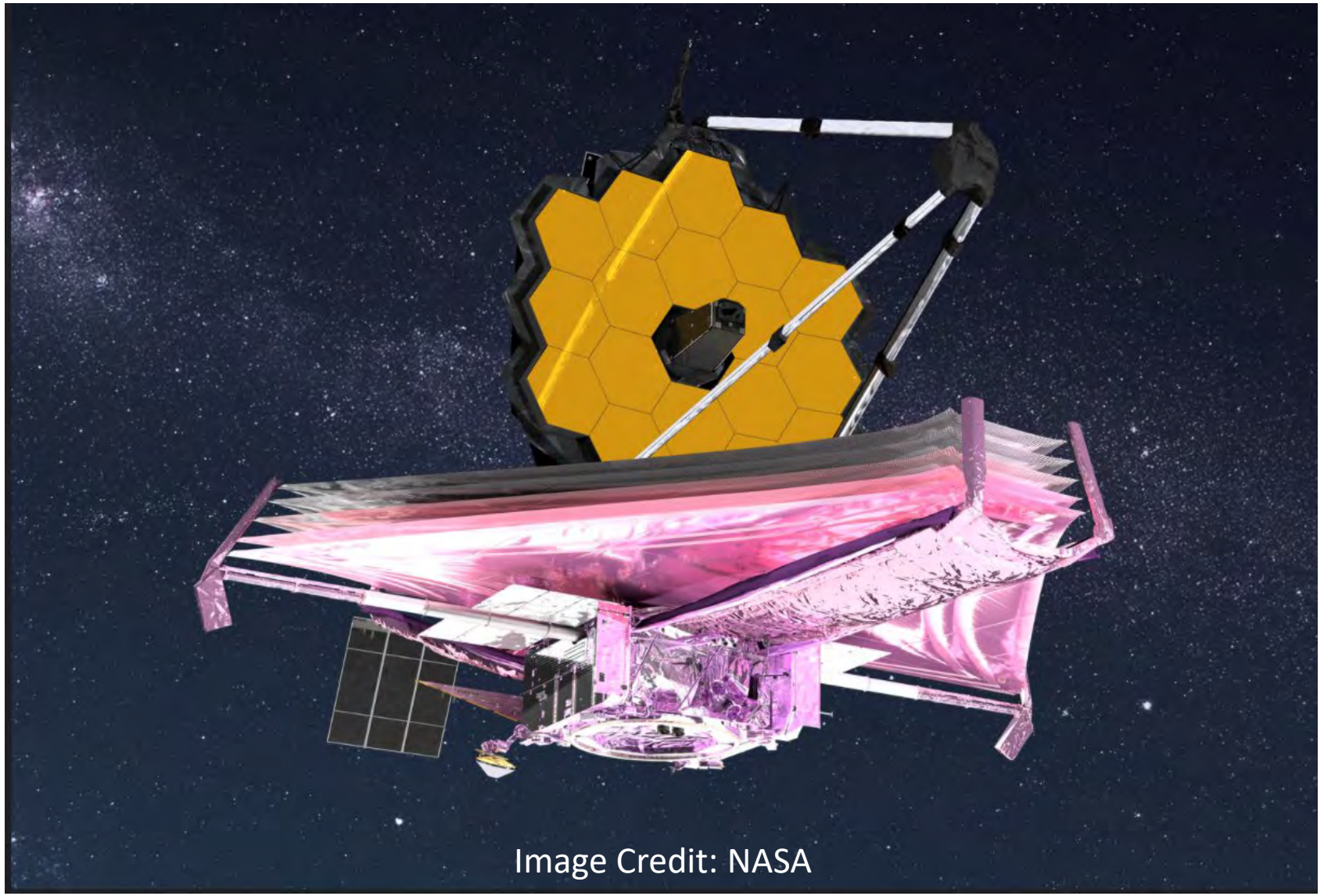


Image Credit: NASA

This won’t fold into a rocket.

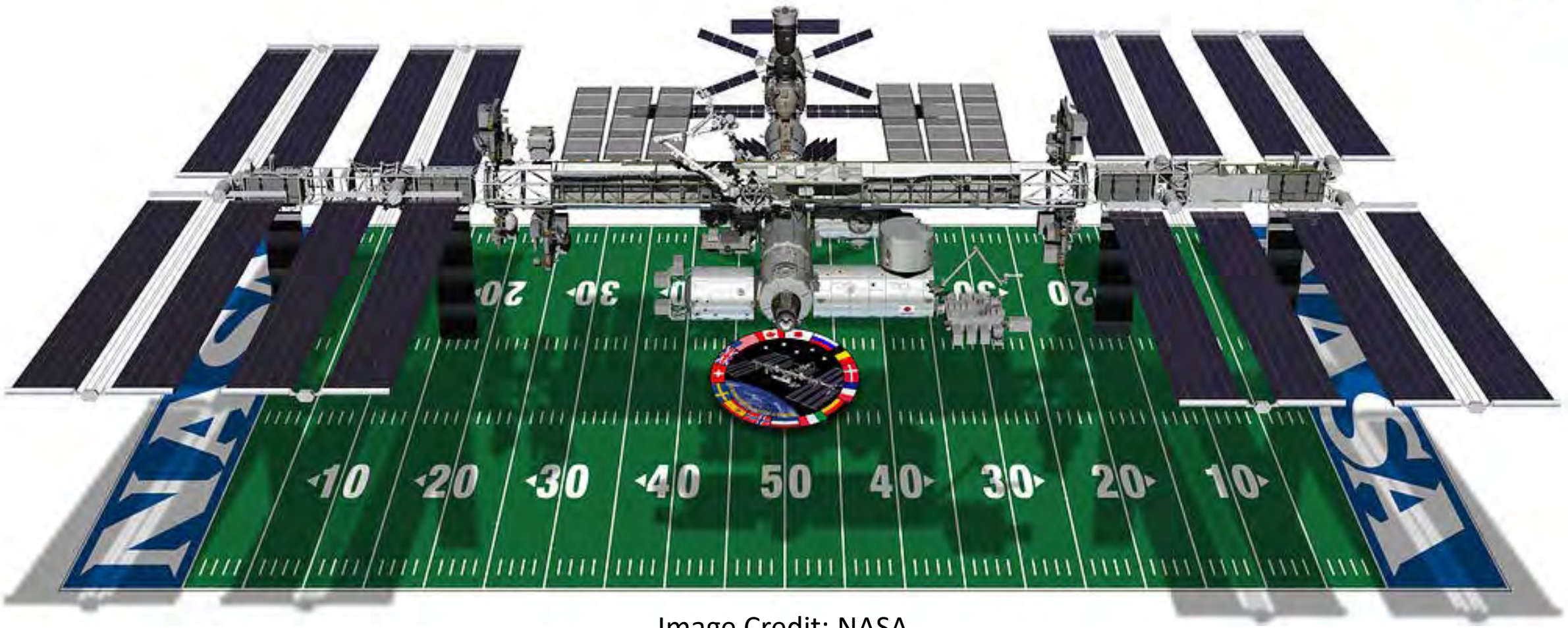


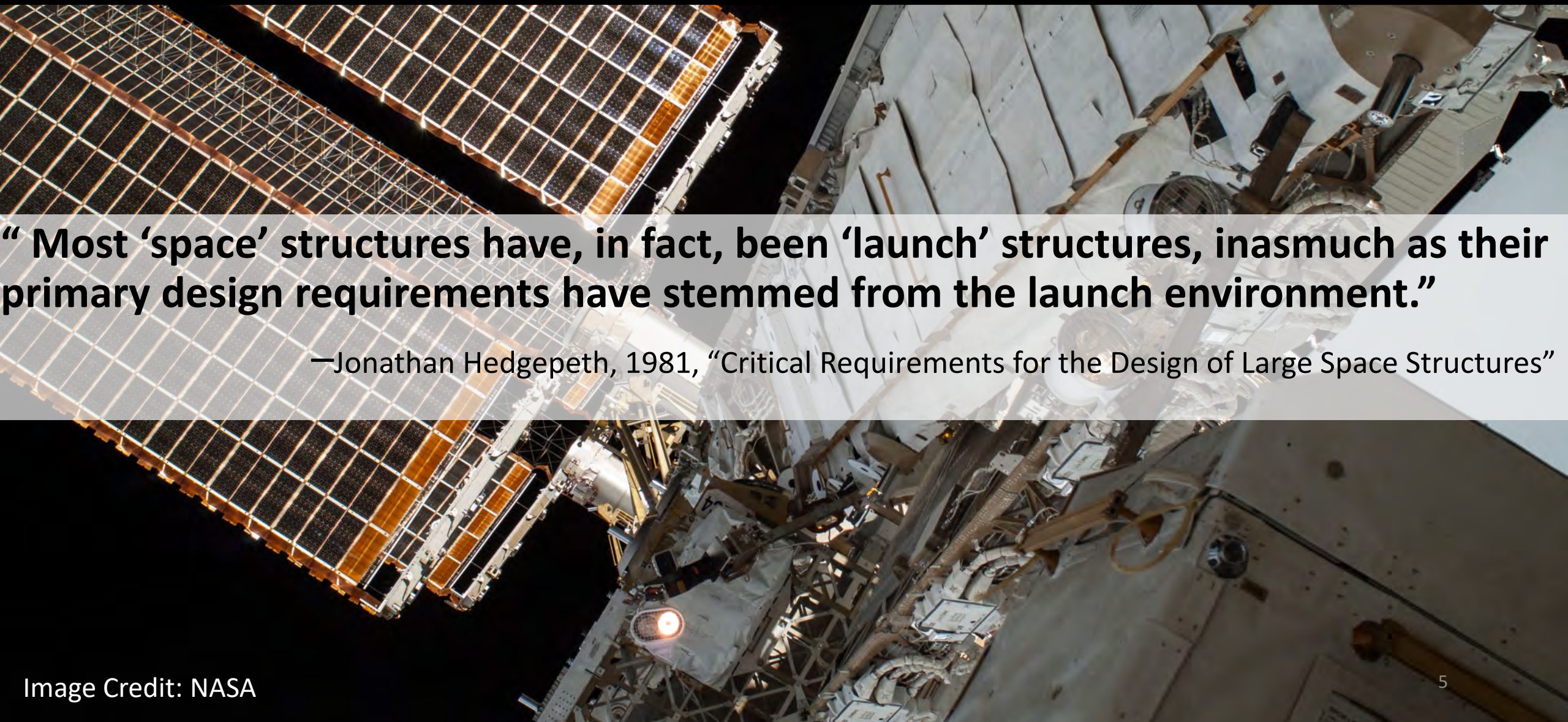
Image Credit: NASA



Image Credit: NASA

10+ years. 30+ Launches.

Why not build everything like JWST or ISS?



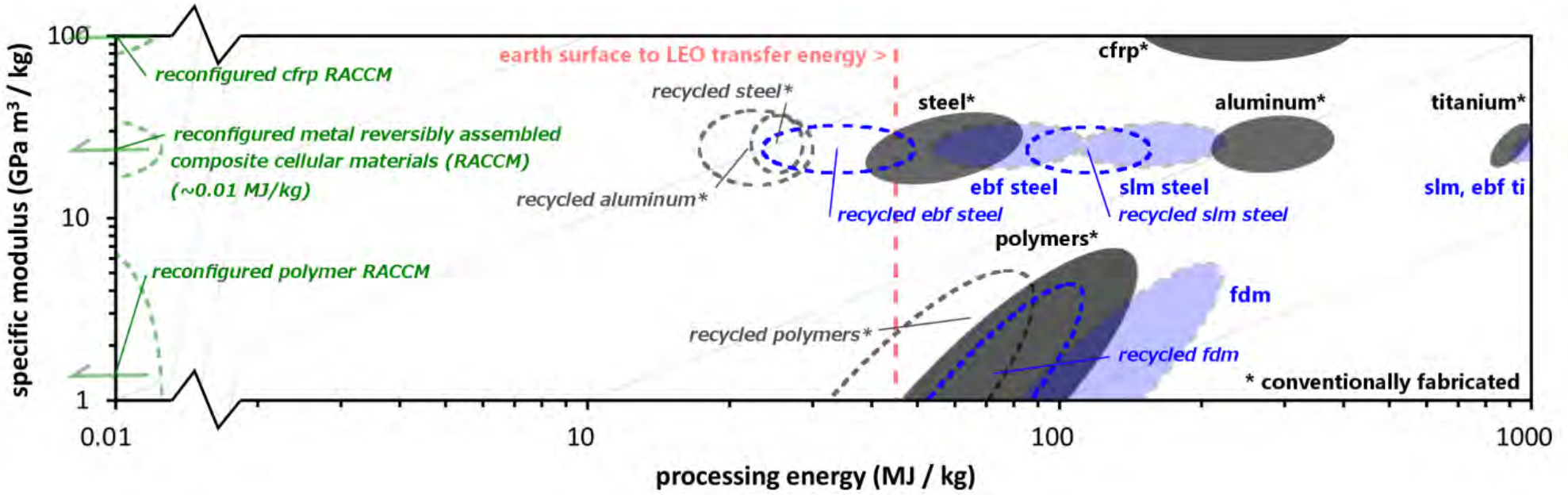
“ Most ‘space’ structures have, in fact, been ‘launch’ structures, inasmuch as their primary design requirements have stemmed from the launch environment.”

—Jonathan Hedgepeth, 1981, “Critical Requirements for the Design of Large Space Structures”

Image Credit: NASA

Investing in ‘re-usable’ material systems pays off

- Comparison of processing energy for various engineering materials (none include launch energy) shows that even recycling aluminum is the same order of magnitude as launch to LEO
- Reconfiguration (via mechanical assembly) is orders of magnitude lower energy



Gregg, C., et al. “Assembled, Modular Hardware Architectures - What Price Reconfigurability?” IEEE Aeroconference, Big Sky, Montana, 2019.

NASA CP 2255 (1982) NASA/ASEE Study

Advanced Automation for Space Missions

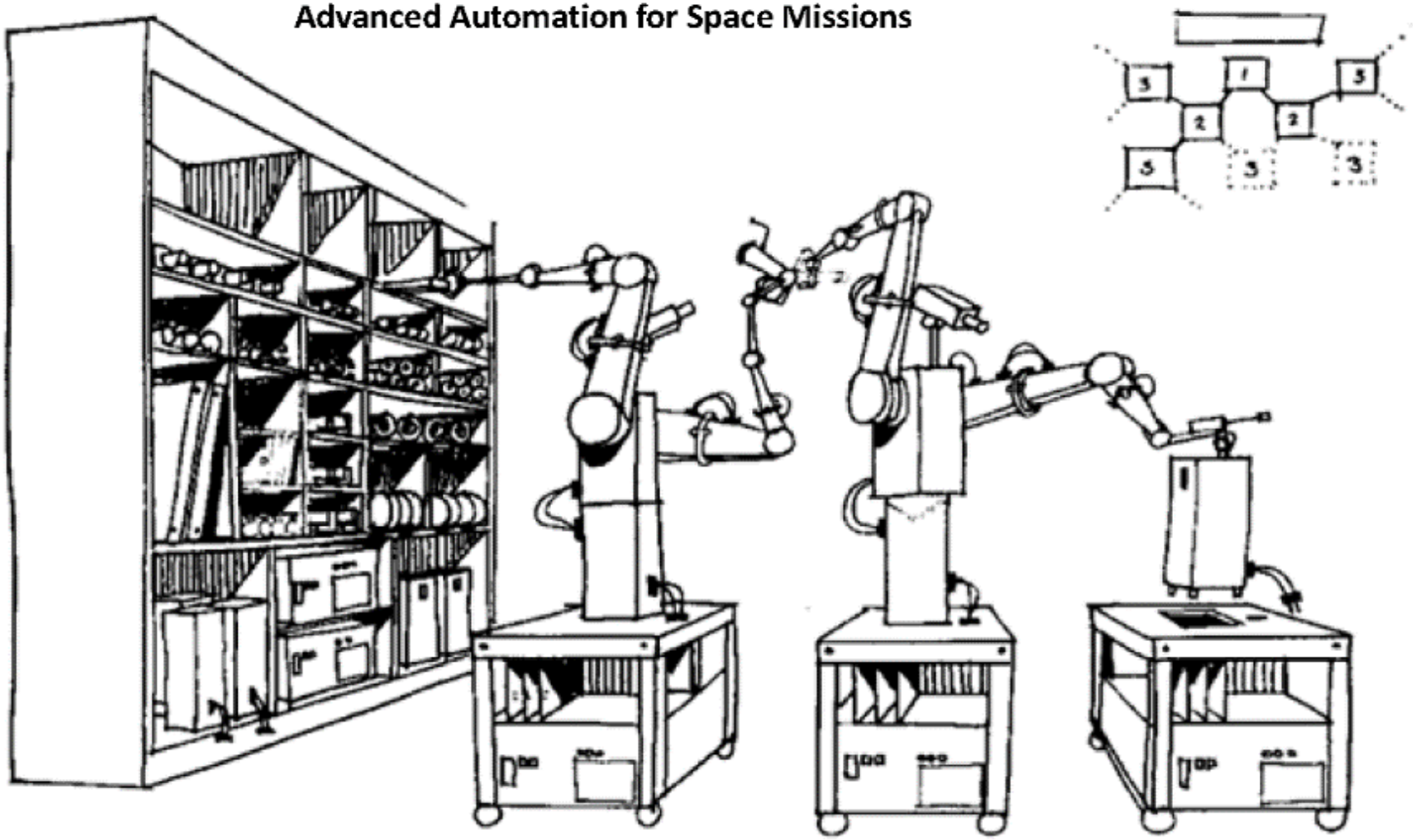


Image Credit: NASA

We are still chasing (but getting much closer!) scalable, reliable, component level robotic assembly that will unlock new science, new exploration, more efficient space operations (see NASA demonstration missions OSAM-1, OSAM-2, etc.)

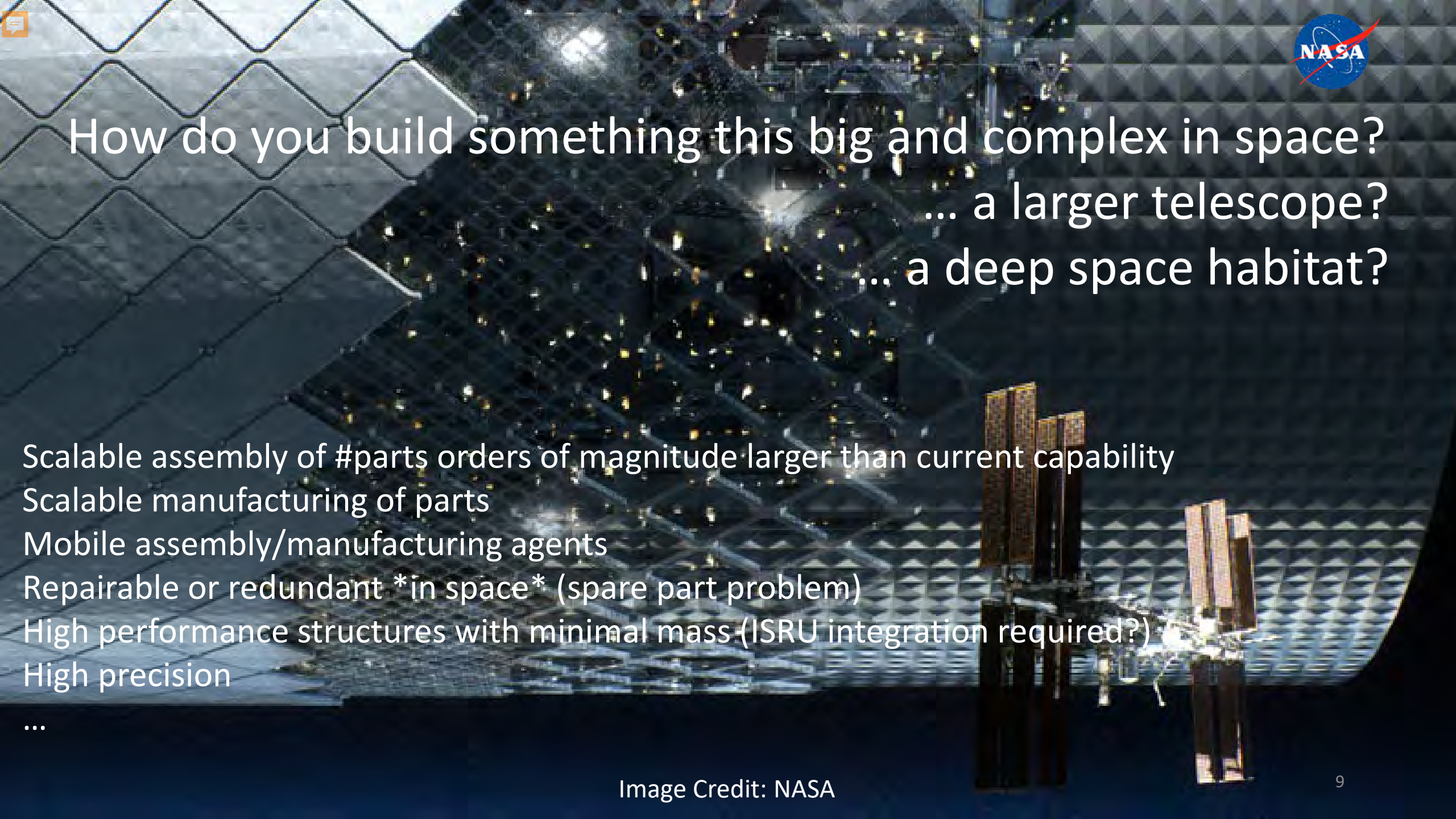


How do you build something this big and complex in space?

… a larger telescope?

… a deep space habitat?

Image Credit: NASA

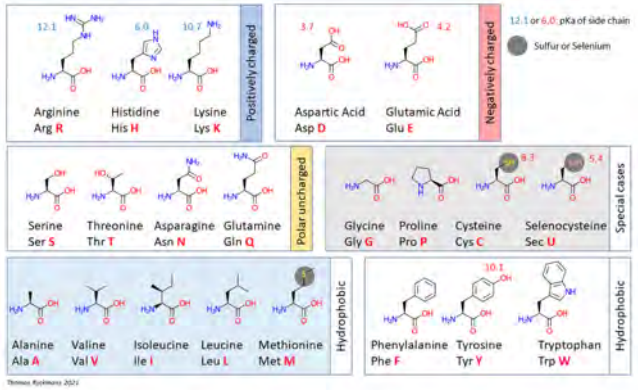


How do you build something this big and complex in space?
… a larger telescope?
… a deep space habitat?

Scalable assembly of #parts orders of magnitude larger than current capability
Scalable manufacturing of parts
Mobile assembly/manufacturing agents
Repairable or redundant *in space* (spare part problem)
High performance structures with minimal mass (ISRU integration required?)
High precision
…

Image Credit: NASA

Biological Hierarchical Construction



Thomas Ryckmans, 2021 Creative Commons License

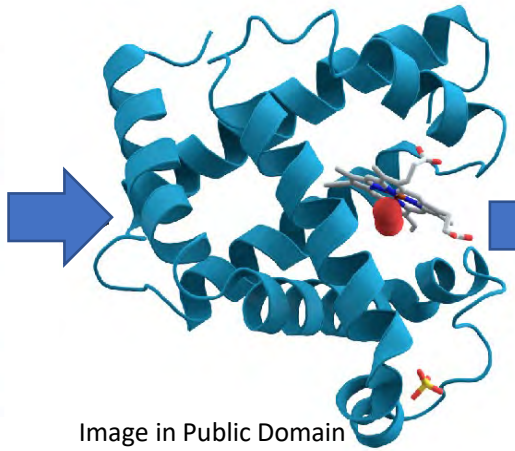
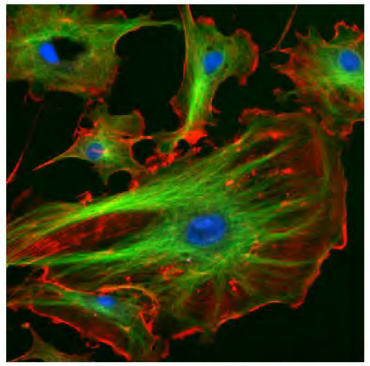


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rsb.info.nih.gov/ij/images/

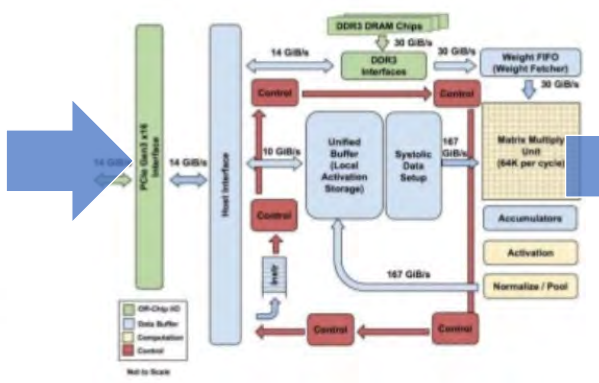
Digital Computation and Communication

Digital Systems:

- resilient to noise
- scalable and general
- repeatable and exact (computing when compared to analog computers)
- small set of parts optimized
- error correction

```
/*
 * Generating PI Value Using Nilakantha Infinite Series
 */
flag = 1;
PI = 3;
for (int i = 2; i < 100; i+=2)
{
    if (flag)
    {
        PI += (4.0 / (i*(i + 1)*(i + 2)));
    }
    else
    {
        PI -= (4.0 / (i*(i + 1)*(i + 2)));
    }
    flag = !flag;
}
printf("The value of PI (Using Nilakantha Series) is : %0.5f\n\n", PI);
```

0/1





Biology and digital electronics both achieve extreme scale and functional complexity by combining building-blocks into hierarchical structures.



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

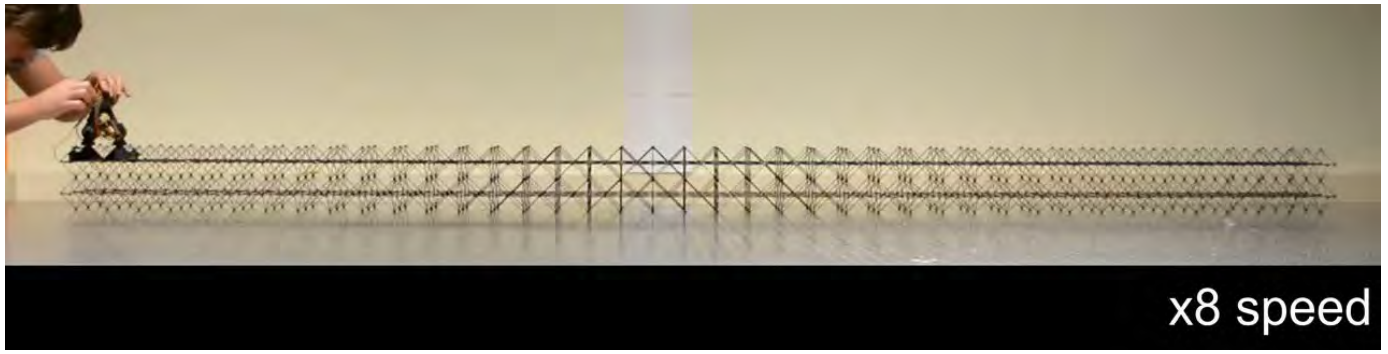
Of course, digital/ discrete structural systems are available…

Automated Reconfigurable Mission Adaptive Digital Assembly Systems (ARMADAS) Project

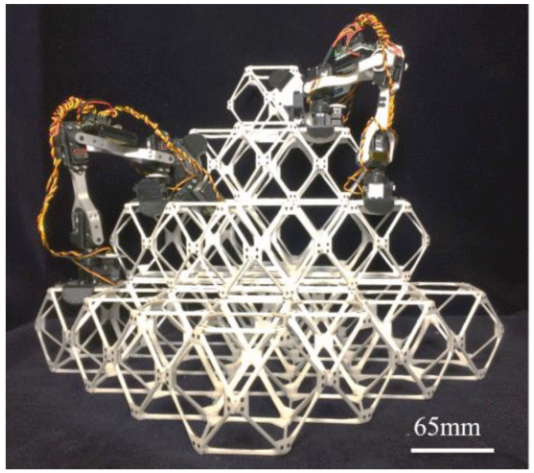
- Assembly system based on a programmable matter approach
  - **Discrete lattice building blocks** with high performance mechanical connections
  - **Relative robots** that locomote on the structure and leverage the **highly structured periodic environment** for error correction, indexing, and metrology

Automated Reconfigurable Mission Adaptive Digital Assembly Systems (ARMADAS) Project

- Prior Art Lattice/Relative Robot Systems:
  - Prior art demonstrated robust bipedal locomotion with minimal sensing, material transport/placement, assembly algorithms, **decoupled robotic and structural precision (global precision from parts)**
  - Expected ARMADAS Contribution: large-scale assemblies with autonomous transport, placement, and high-performance mechanical connections between building blocks to form high strength/stiffness structures



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



B. Jenett, A. Abdel-Rahman, K. Cheung and N. Gershenfeld, "Material–Robot System for Assembly of Discrete Cellular Structures," in *IEEE Robotics and Automation Letters*, vol. 4, no. 4, pp. 4019-4026, Oct. 2019, doi: 10.1109/LRA.2019.2930486.



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



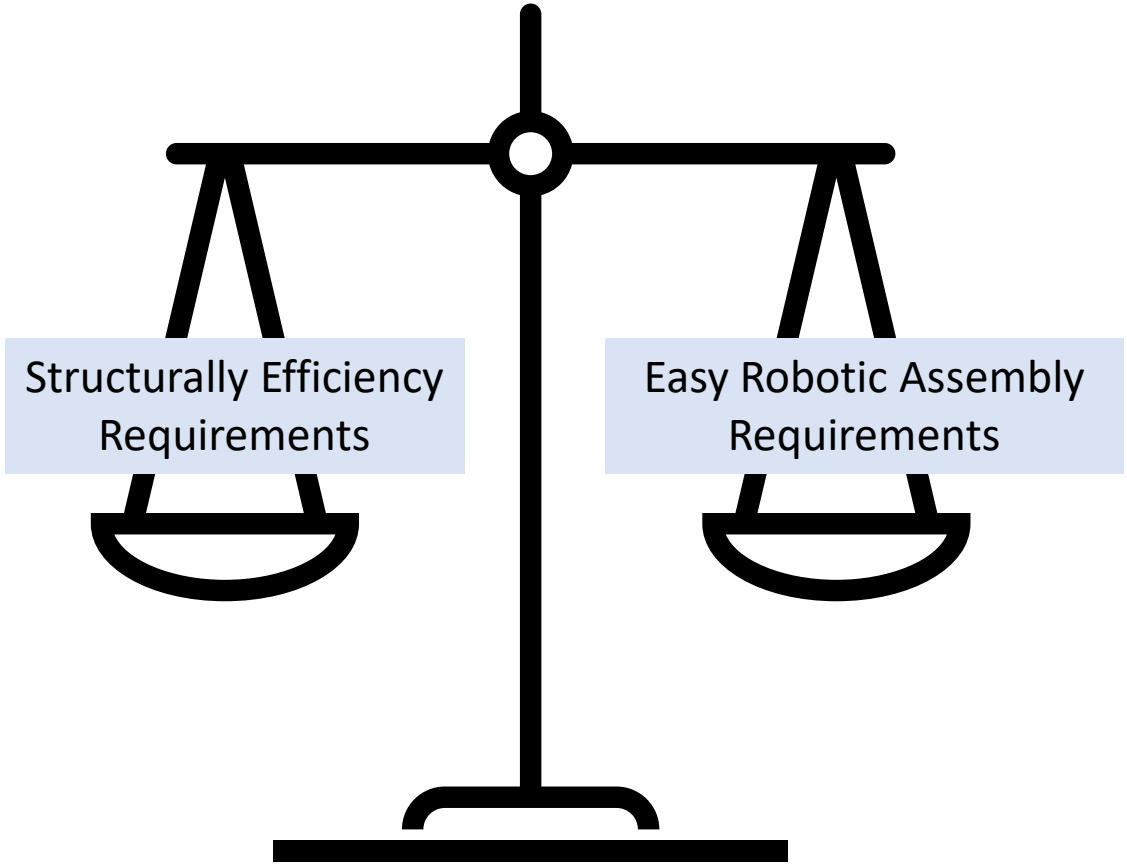
LEGO® City Limited Edition Set # 7747, 2009
444 bricks
image ©2009 The LEGO Group



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

What should building blocks look like for demanding NASA structural applications?

What should building blocks for robotic assembly look like for demanding NASA structural applications?





$4600/ kg

to Low Earth Orbit (SpaceX Falcon 9)

300kg fuel: 1 kg spacecraft

from Earth to Mars

Image Credit: NASA

Applications demand high performance structures and materials

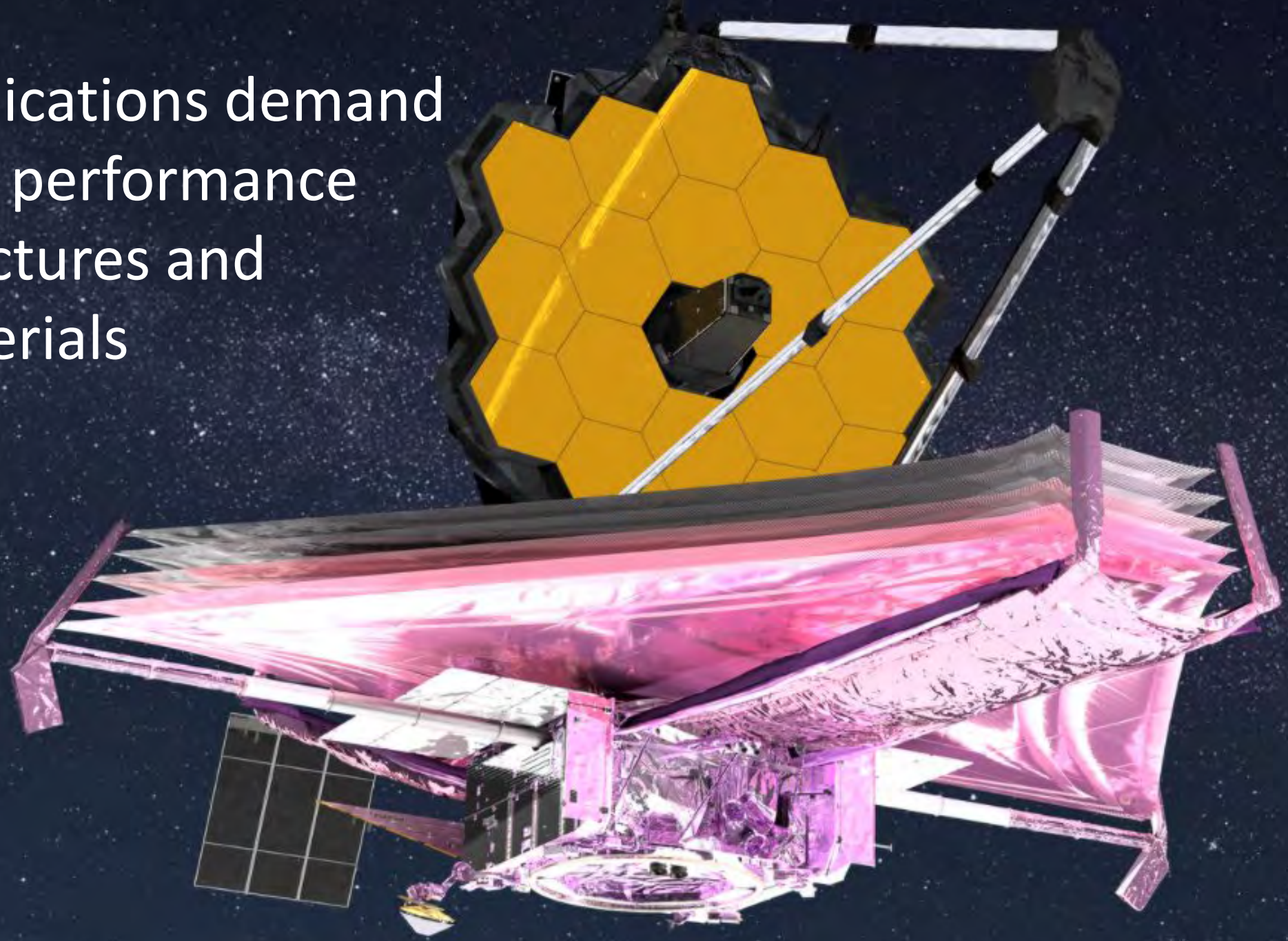
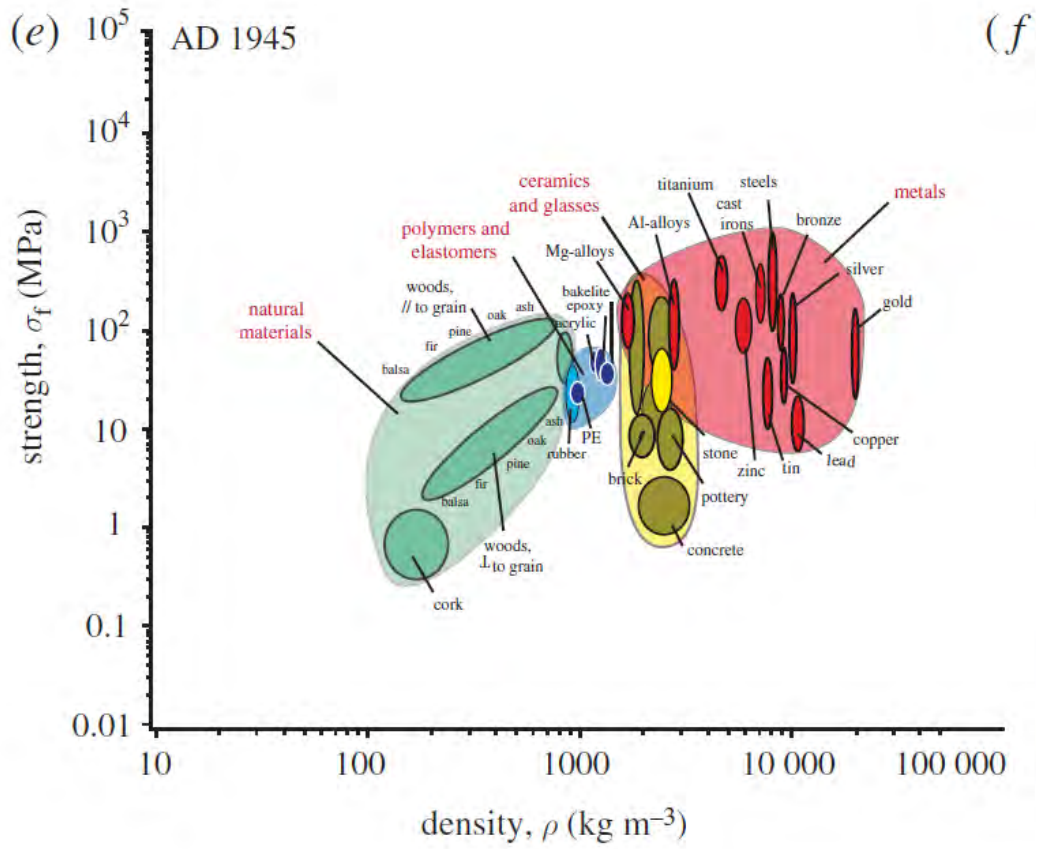


Image Credit: NASA

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

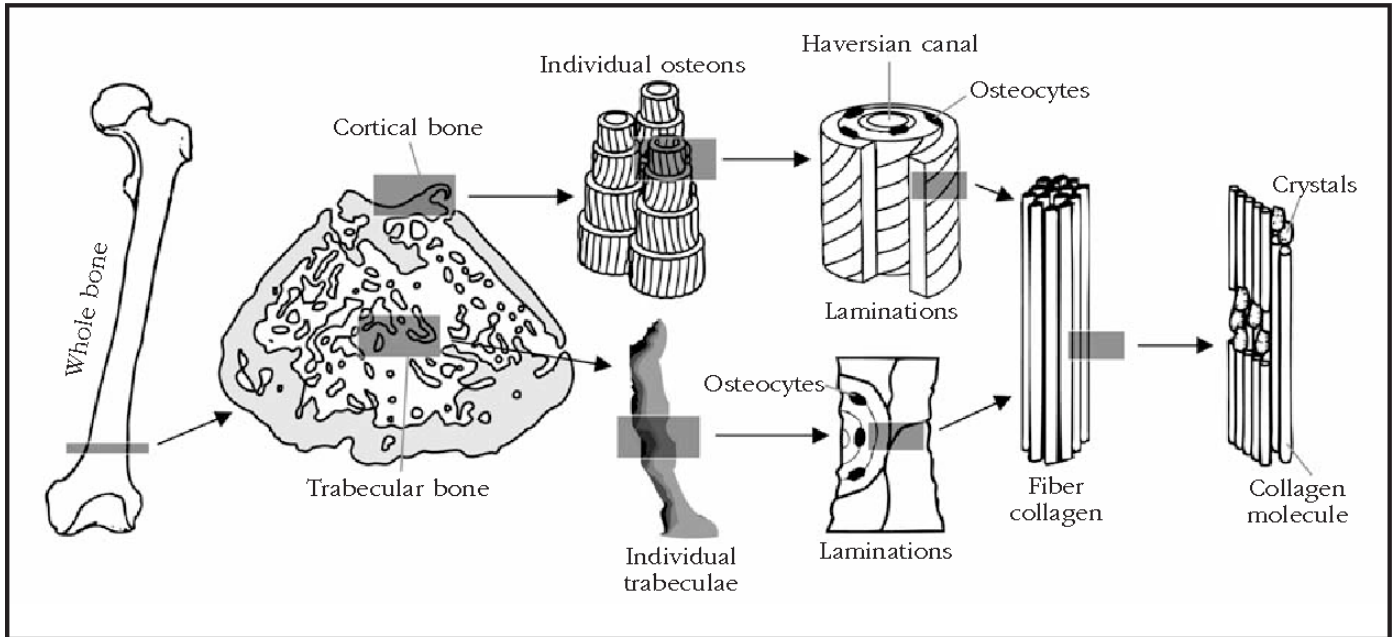
Cellular Materials





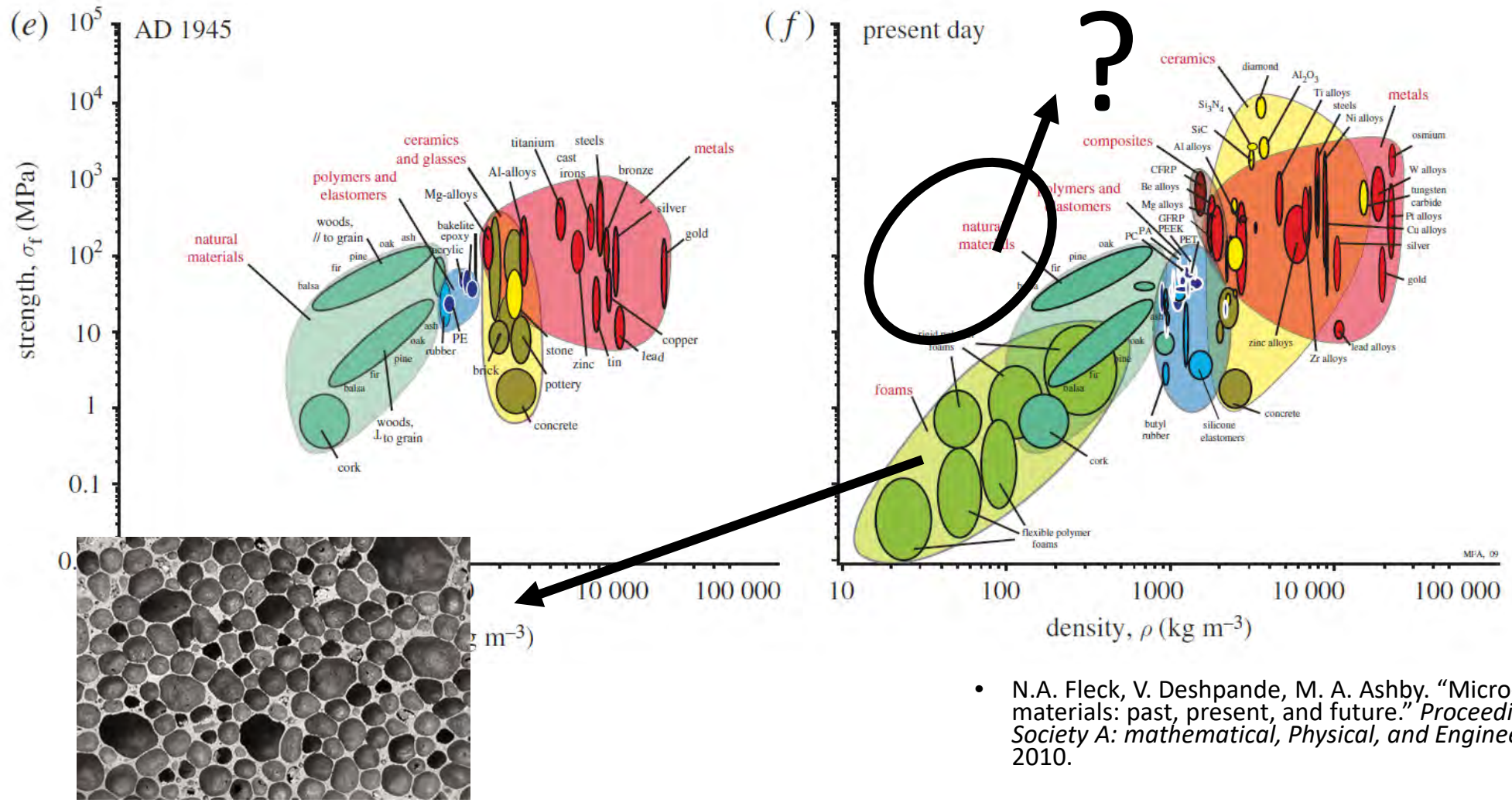
Natural Material Structures

Hierarchical Composite



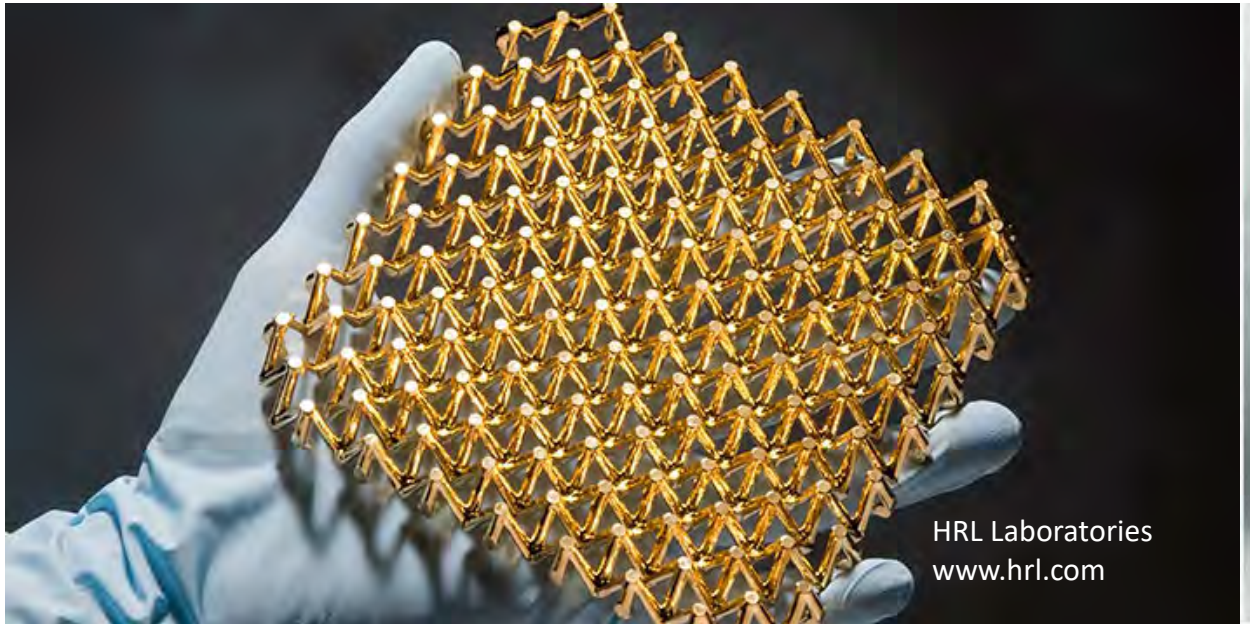
Caeiro, JR, et al. "Biomechanics and bone (& II) : Trials in different hierarchical levels of bone and alternative tools for the determination of bone strength." (2013).

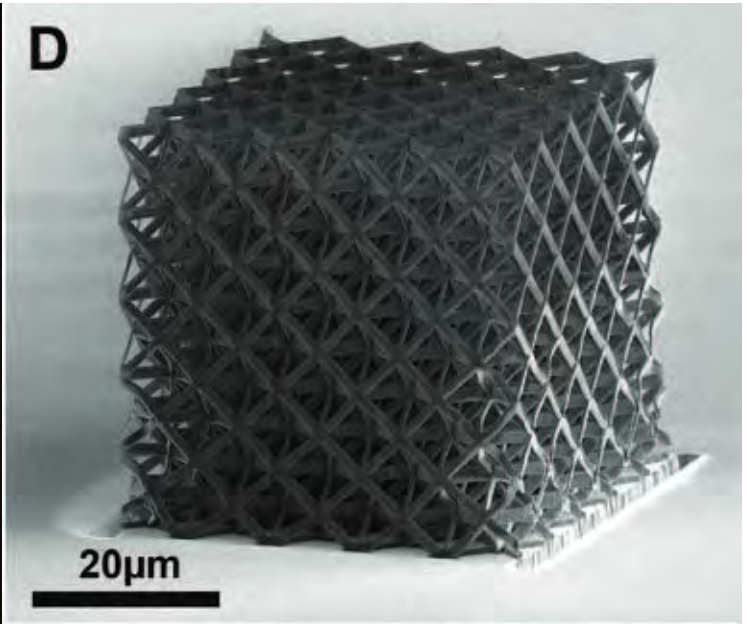
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Architected Materials





Meza, L., Das, S., and Greer, J. “Strong, lightweight, and recoverable three-dimensional ceramic nanolattices.” *Science* (2014).

Microstructural control → Improved Performance

Mechanics of Cellular Solids: Key Characteristics

Geometry

Relative Density

Material

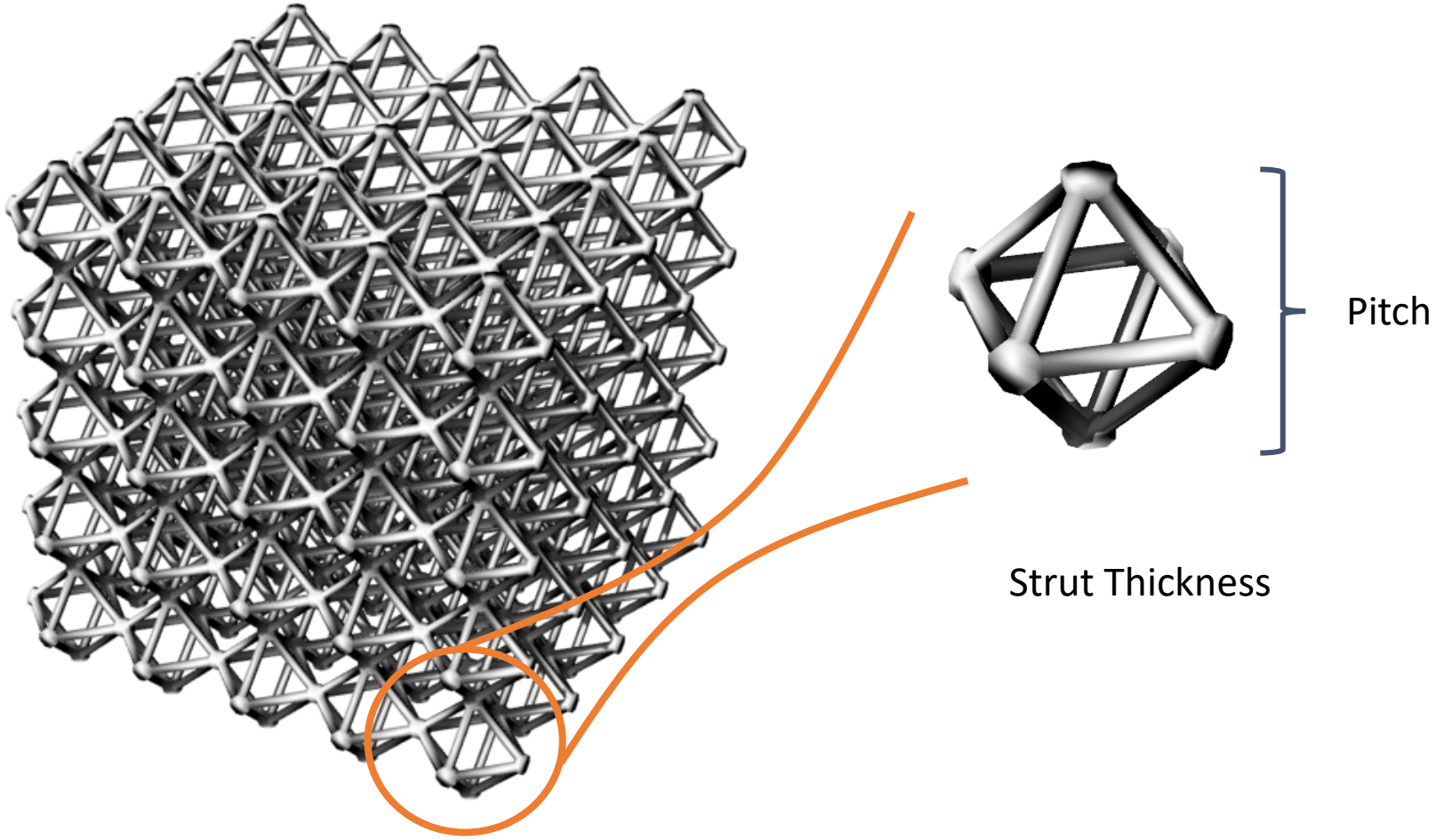
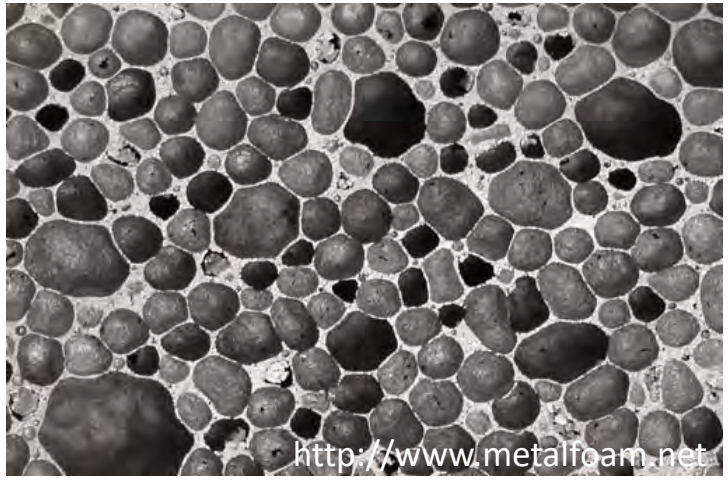


Image Credit: C. Gregg

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

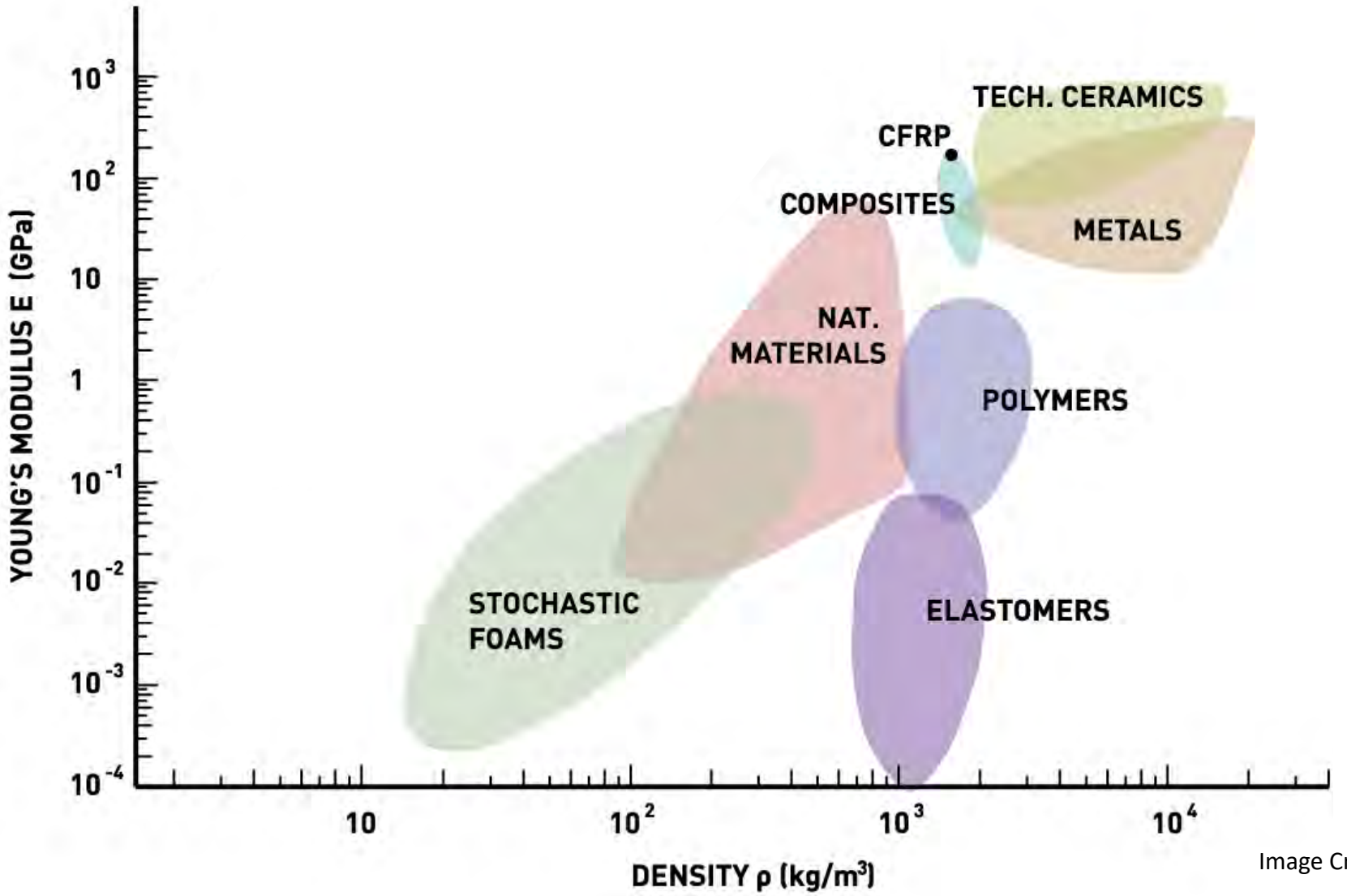
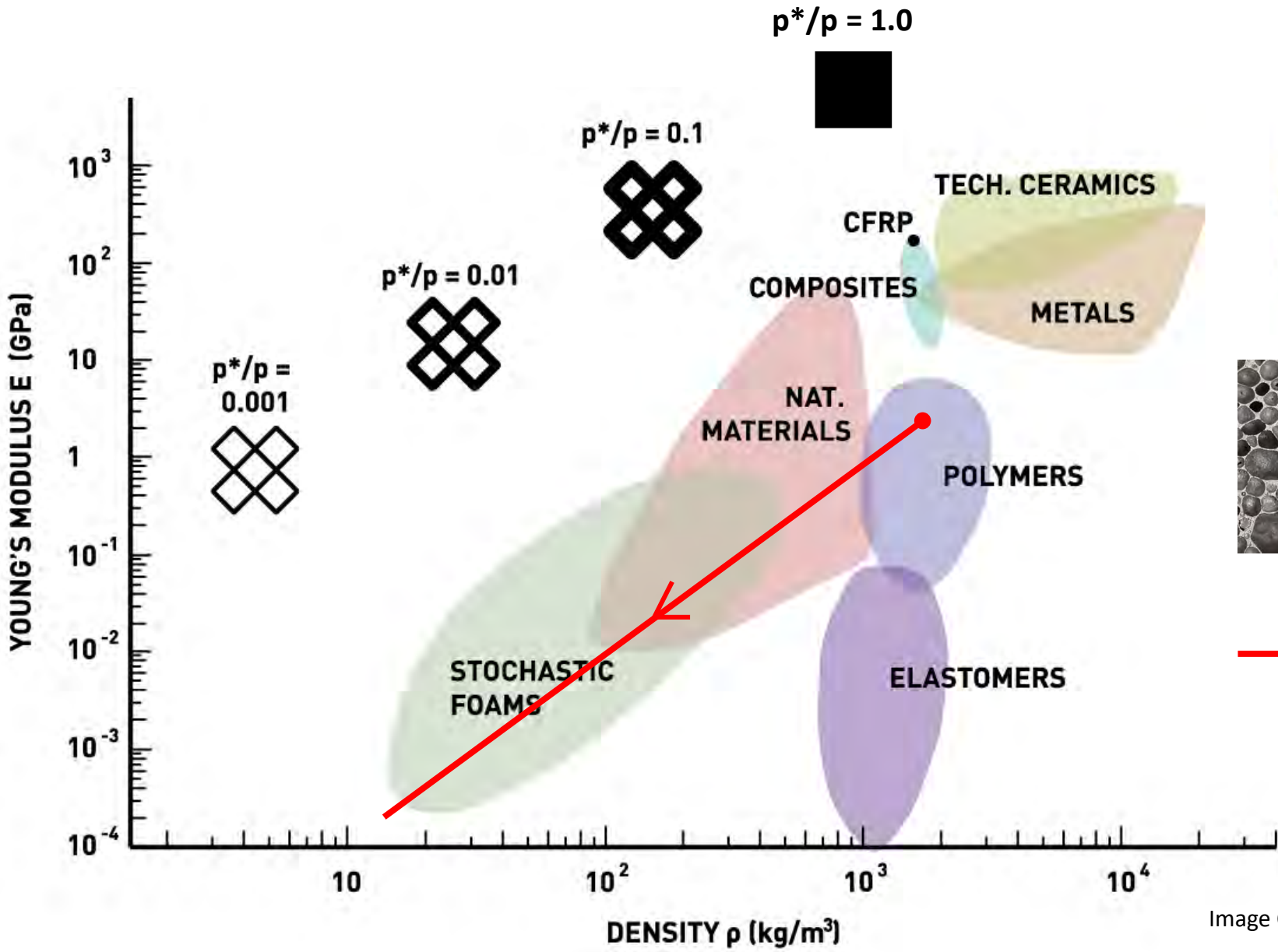
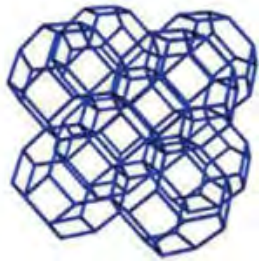
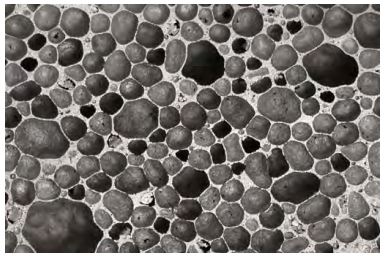


Image Credit: D. Cellucci (NASA ARC)



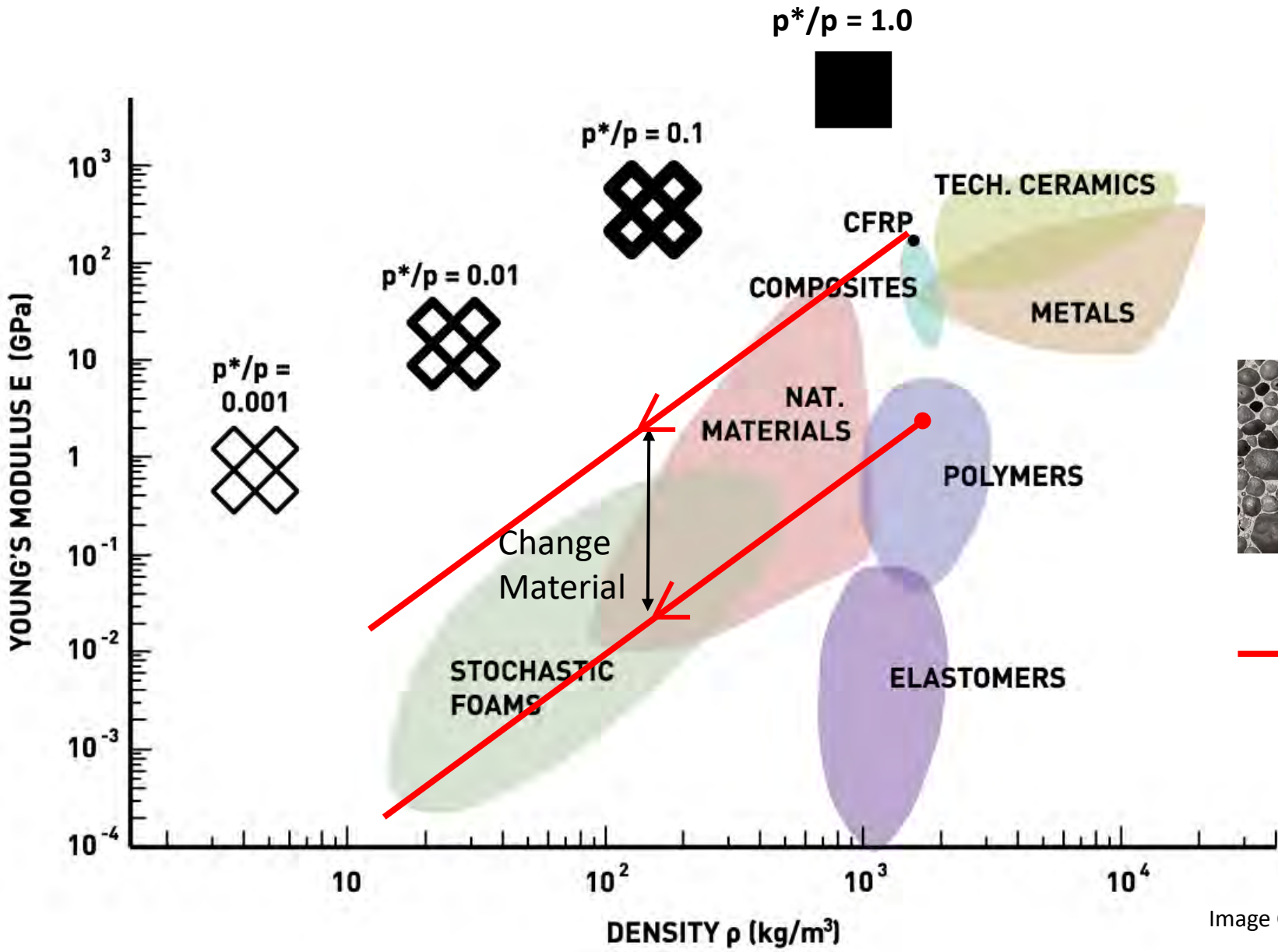


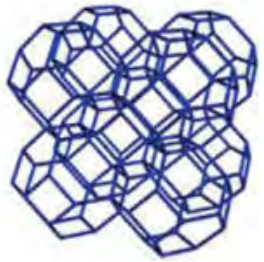


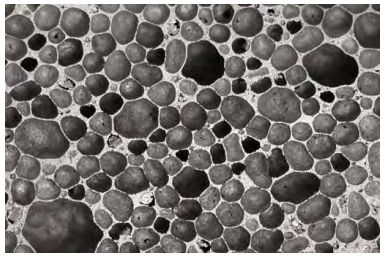
$$\frac{E}{E_s} \propto \left(\frac{\rho}{\rho_s}\right)^2$$

Image Credit: D. Cellucci (NASA ARC)

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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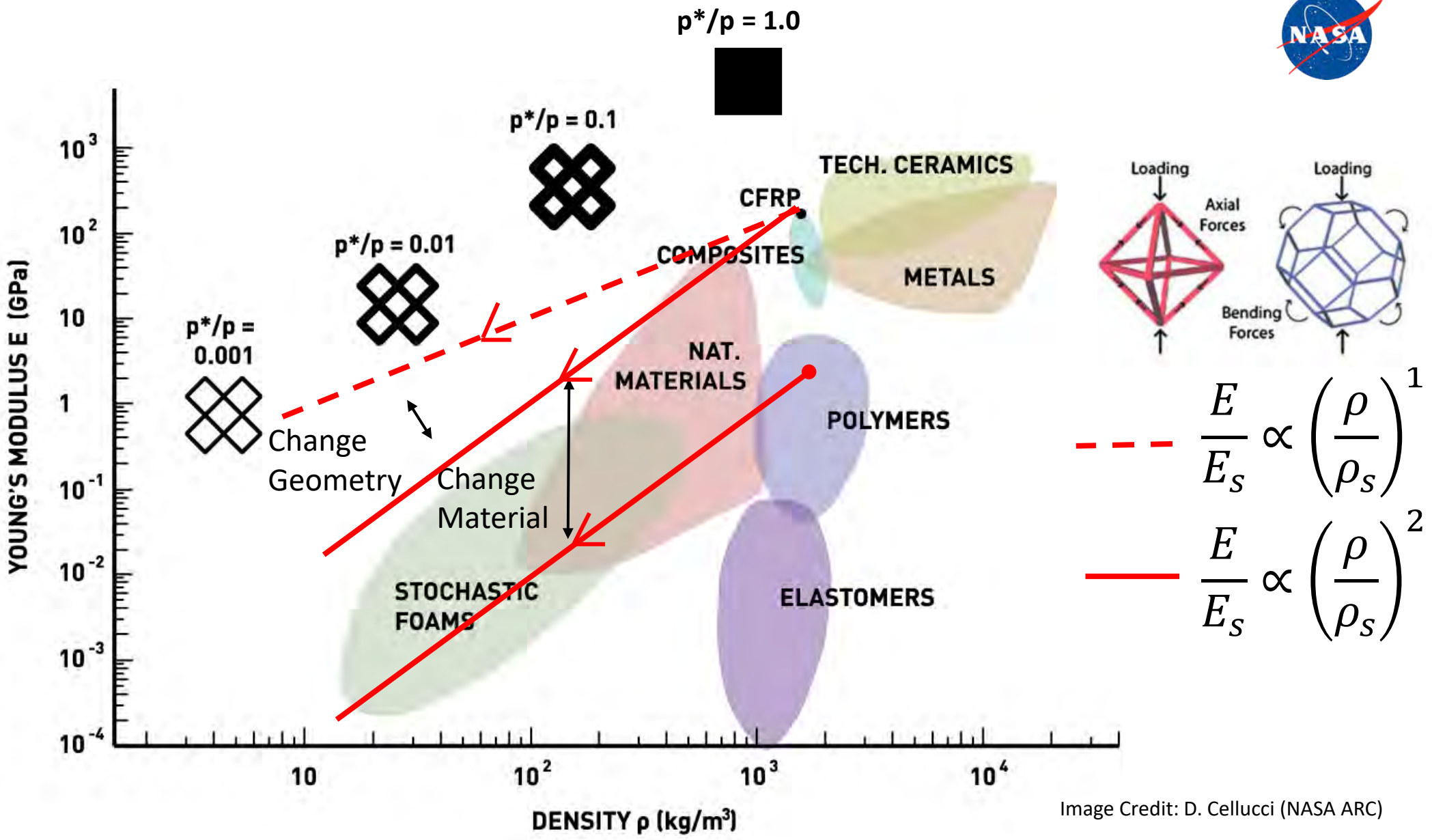
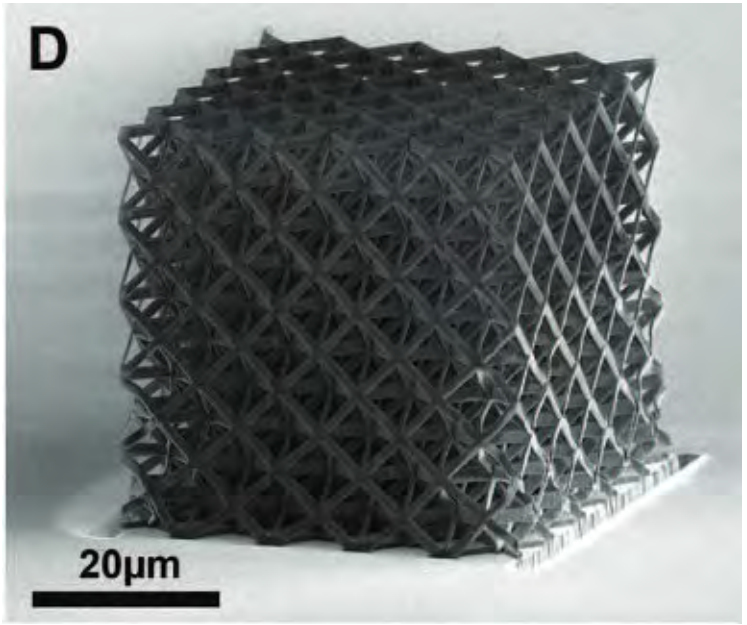


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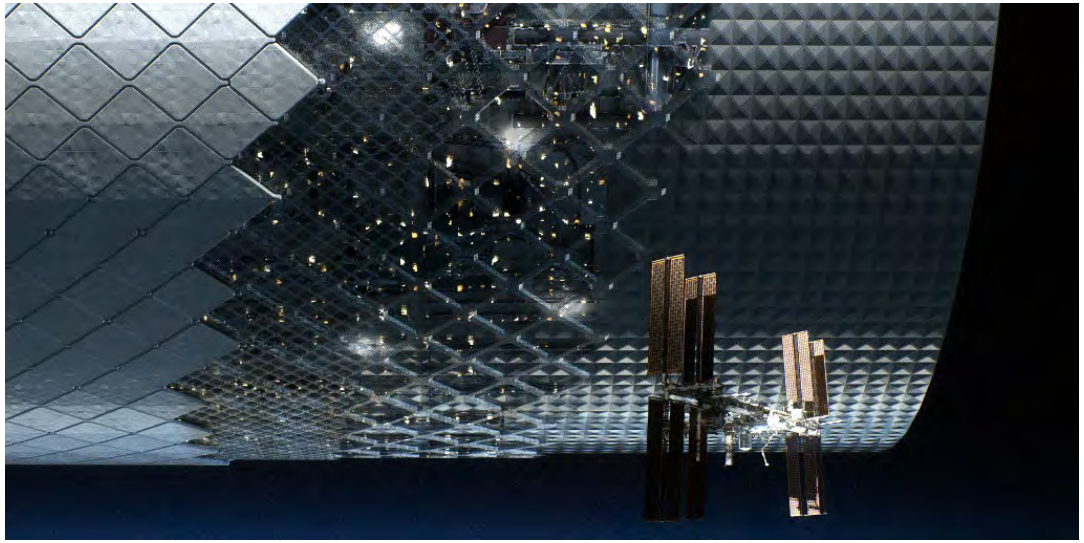


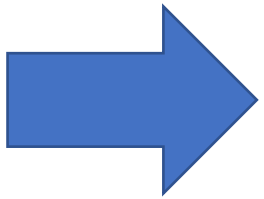
Image Credit: NASA

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**





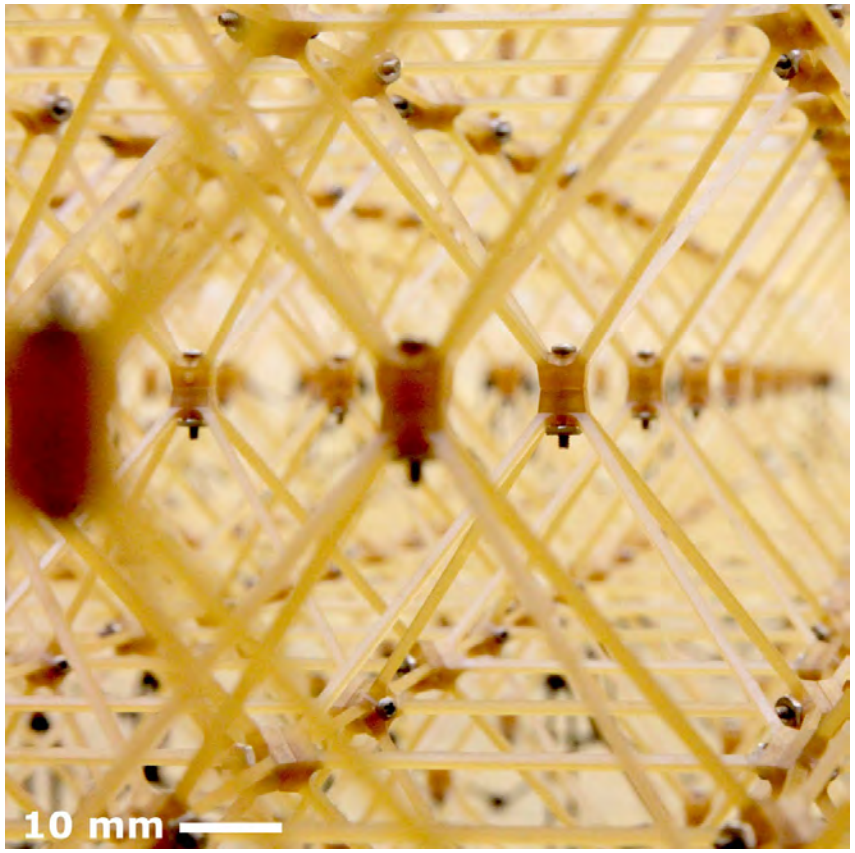


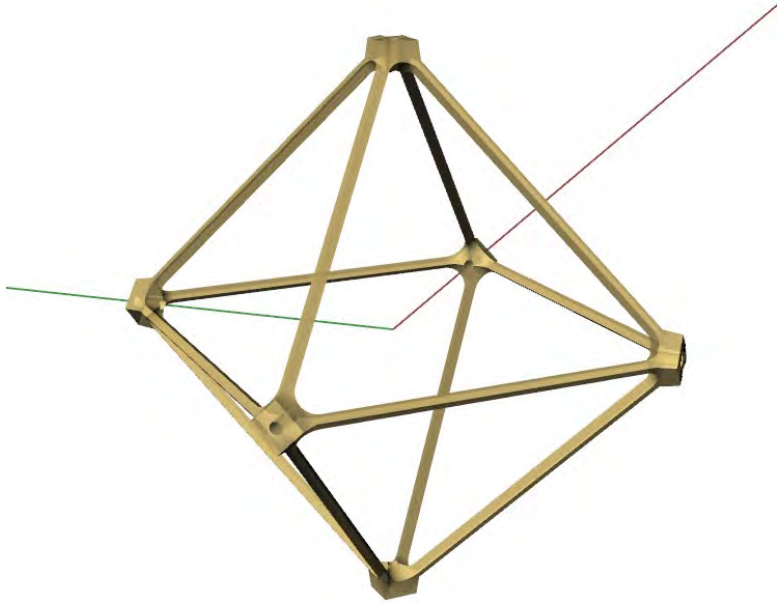


Images in Public Domain

Trinh, G. et al. “Robotically Assembled Aerospace Structures: Digital Material Assembly using a Gantry-Type Assembler.” IEEE Aeroconference, Big Sky, Montana. 2017.

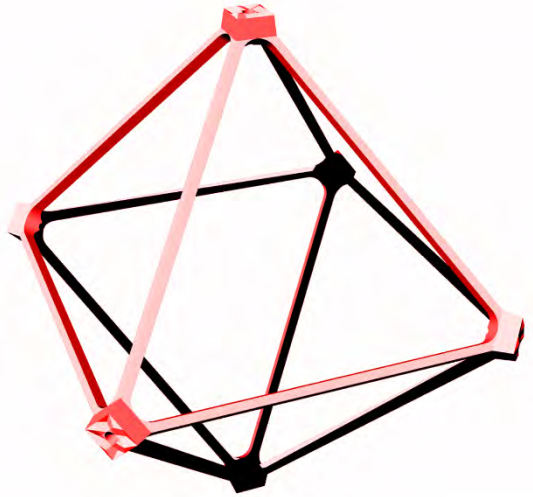
“Ultra-light and Scalable Composite Lattice Materials”

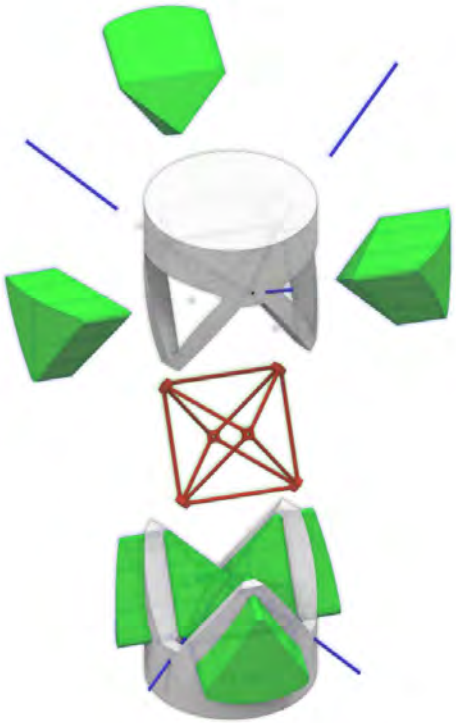


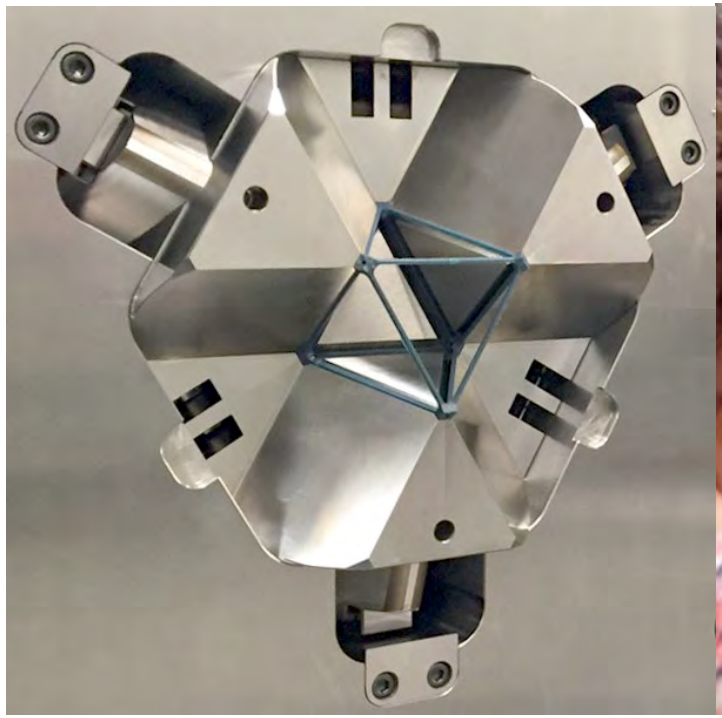


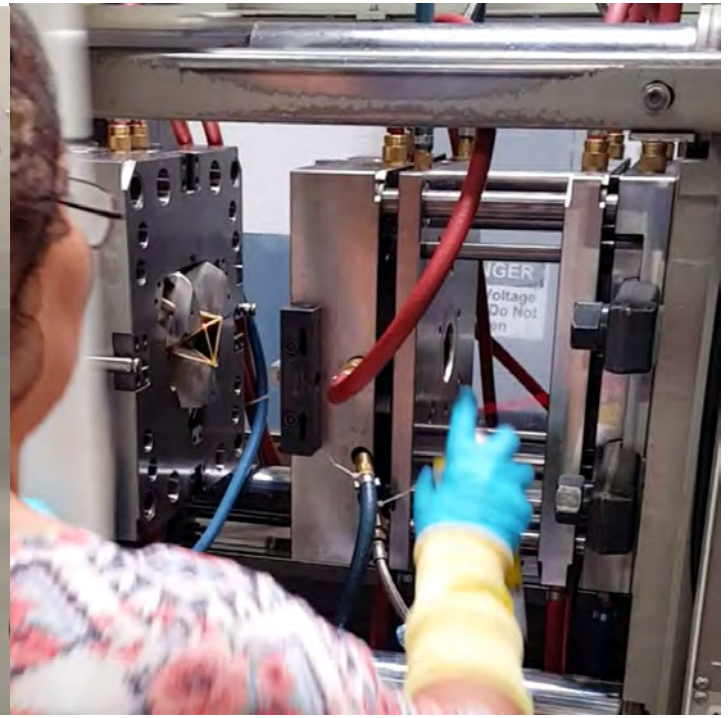
C.E. Gregg, J. H. Kim, K. C. Cheung. “Ultra-light scalable composite lattice materials.” *Advanced Engineering Materials.* 2018.

Unit Cell Manufacturing: Injection Molding





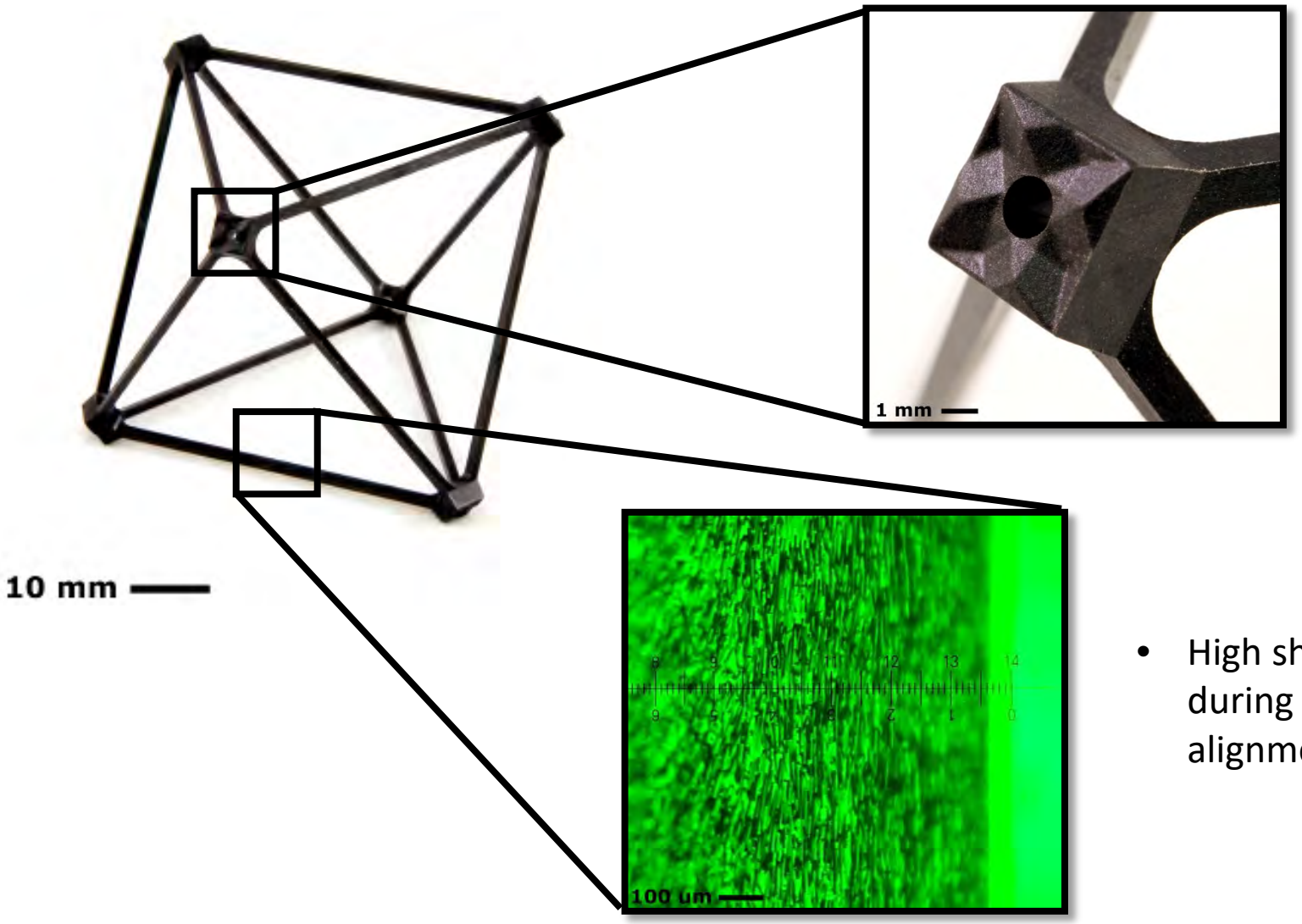




17 seconds/ part • highly repeatable • multi-material

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

Resulting Unit Cell or “Voxel”

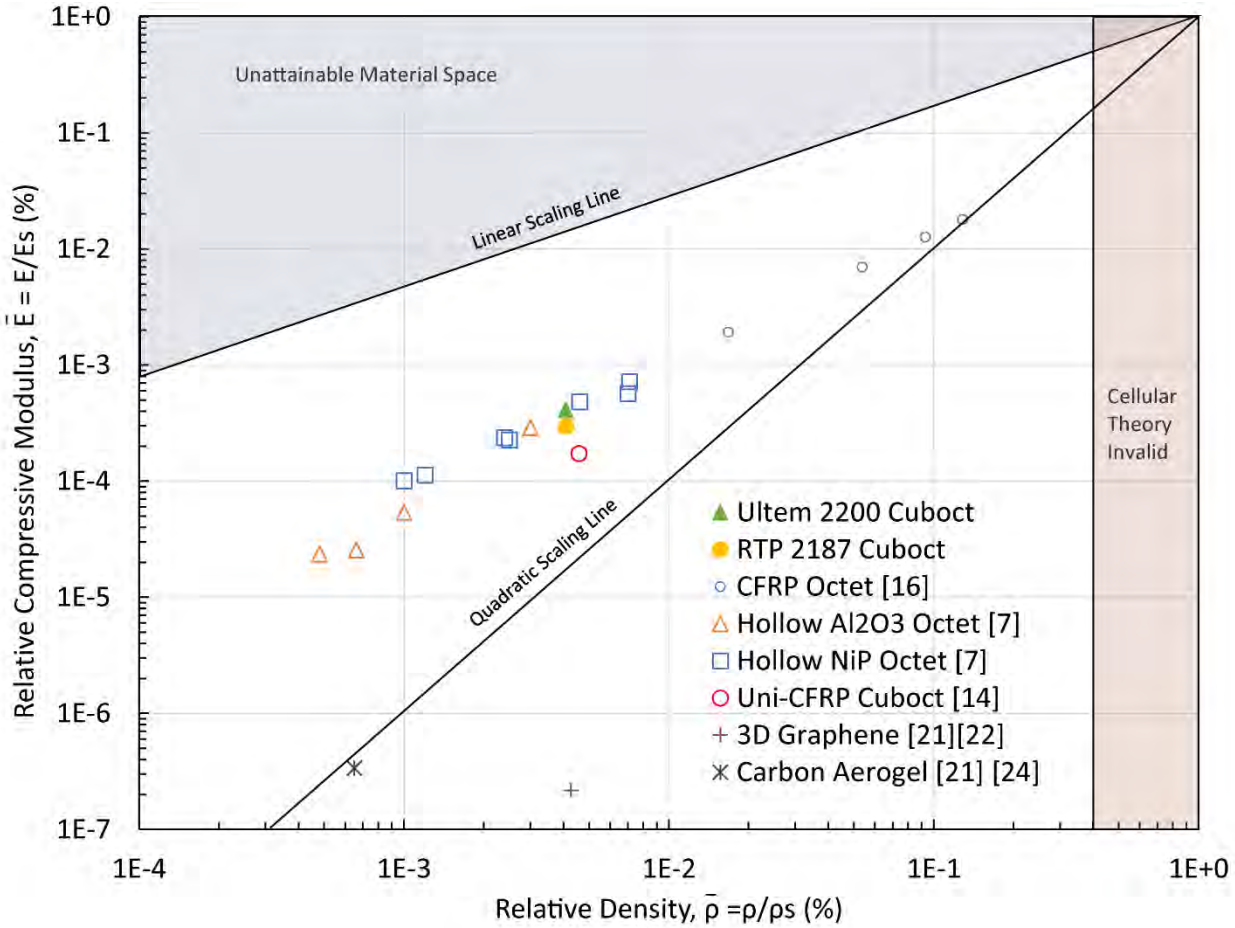


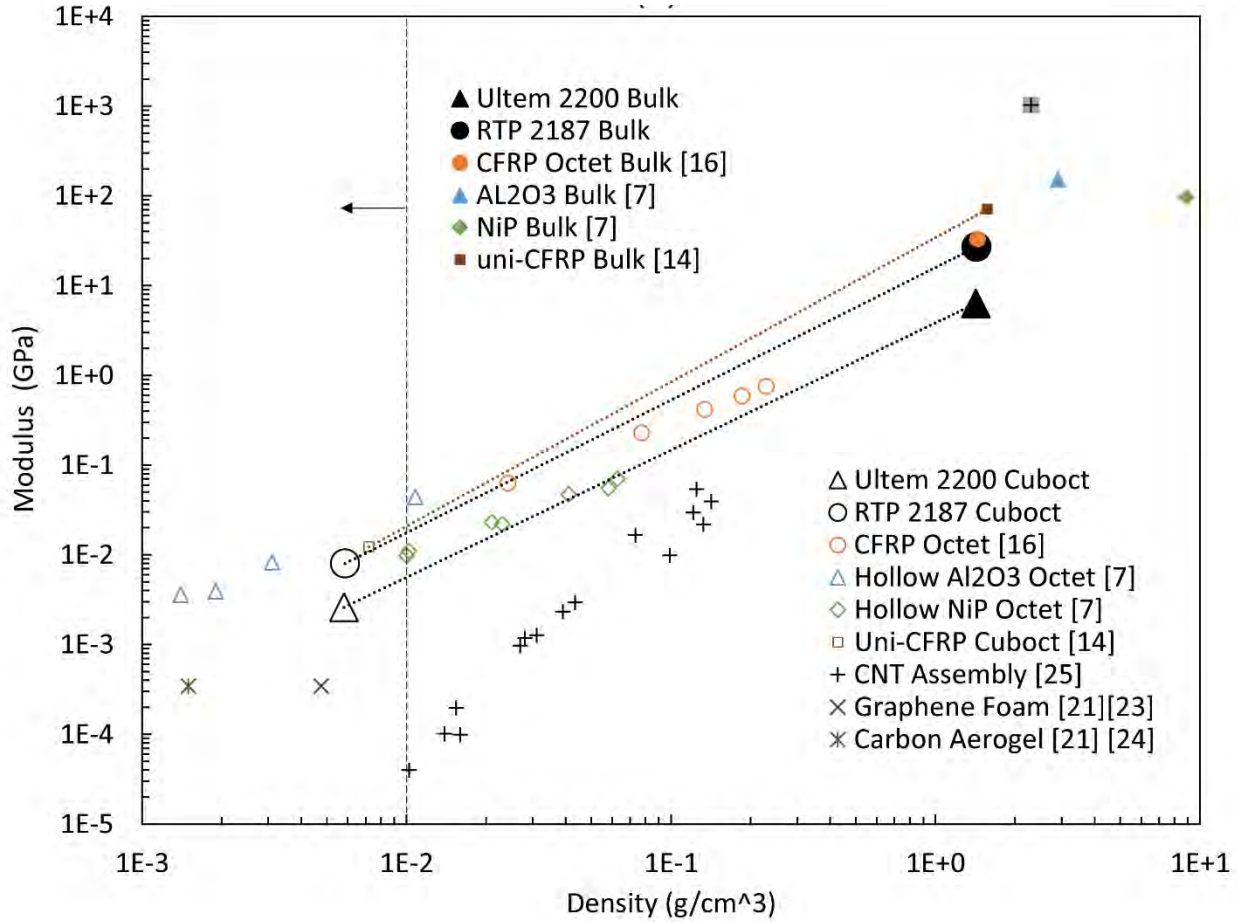
- Hirth joint ensures alignment during assembly
- Through-hole for pre-loaded bolted connection

- High sheer in thin features during molding produces fiber alignment

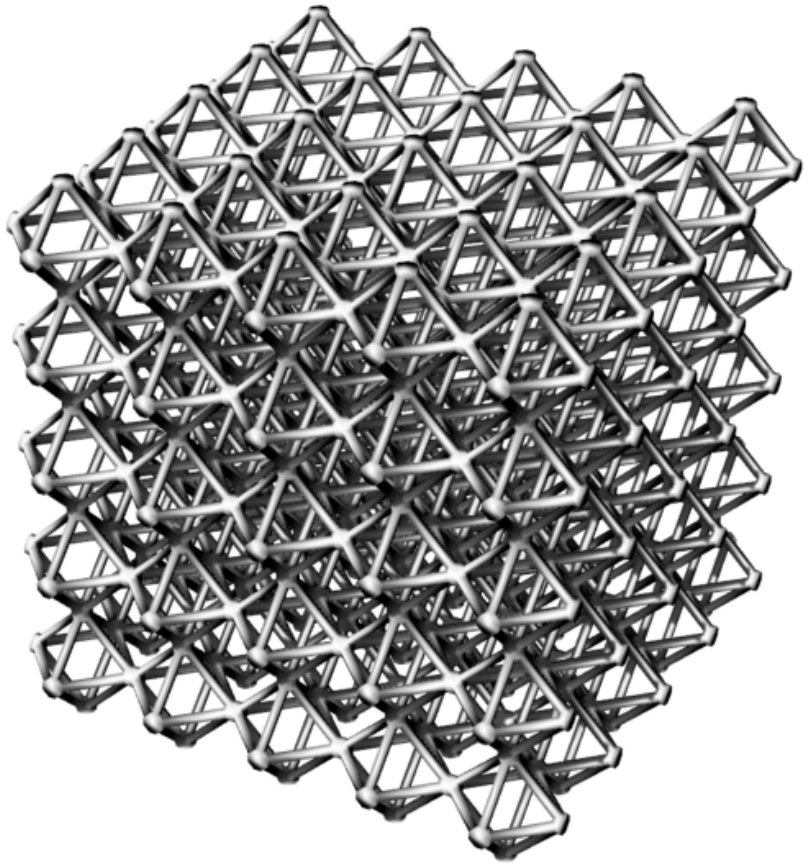
C.E. Gregg, J. H. Kim, K. C. Cheung. “Ultra-light scalable composite lattice materials.” *Advanced Engineering Materials.* 2018.

Comparison to SOA





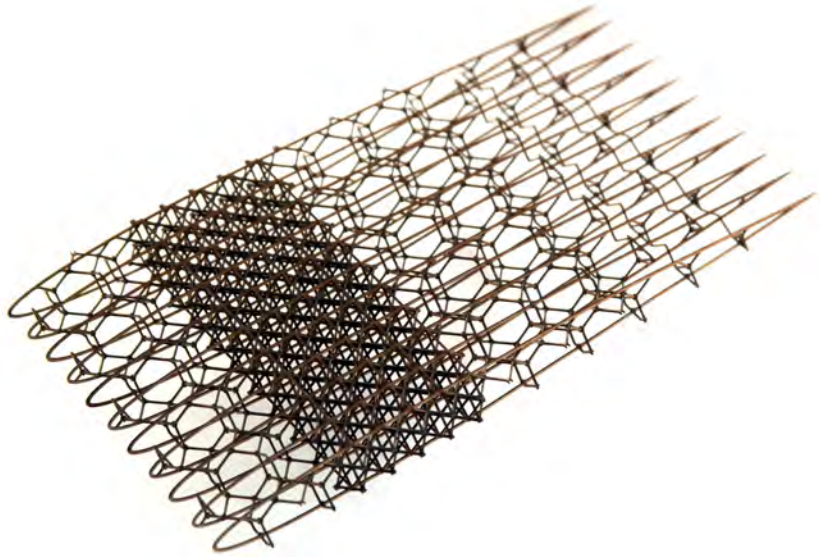
C.E. Gregg, J. H. Kim, K. C. Cheung. "Ultra-light scalable composite lattice materials." *Advanced Engineering Materials.* 2018.

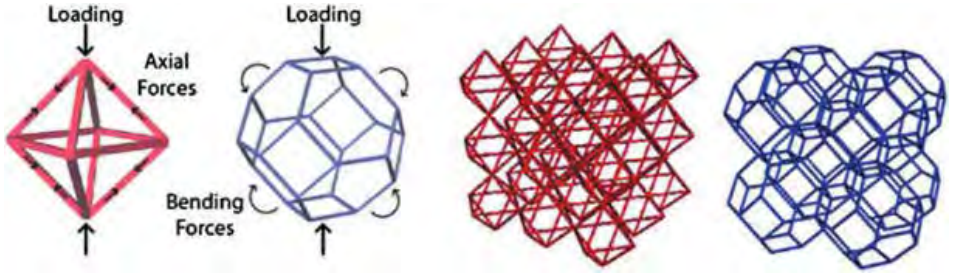


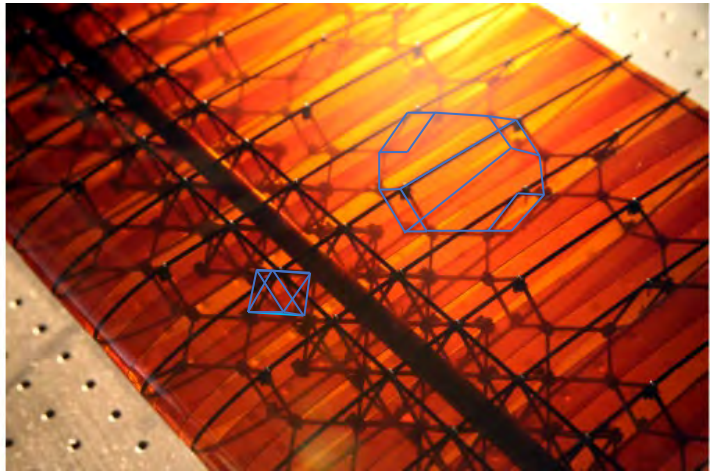
Small set of building block types → Large range of functionality

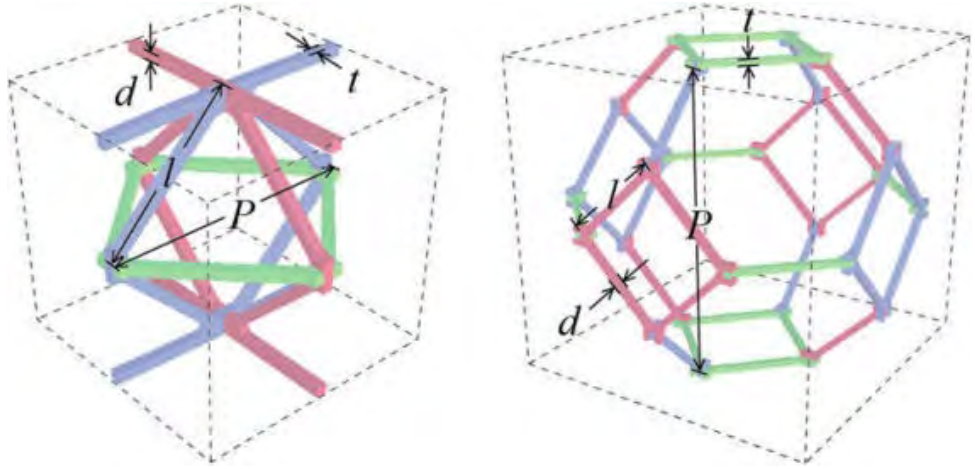
Image Credit: C. Gregg

Goal: Create a wing structure that actively morphs and passively deforms under aeroelastic load for more efficient flight

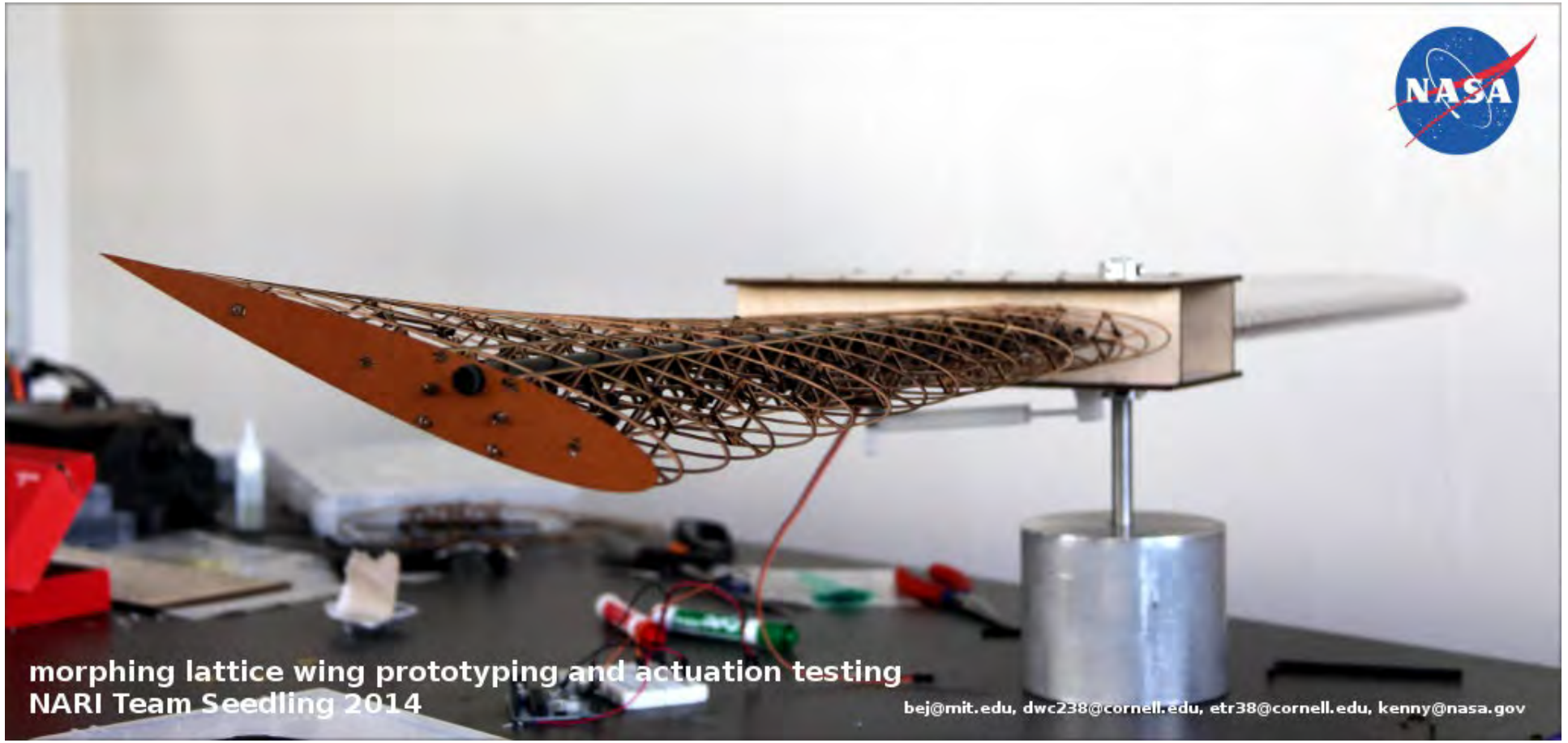




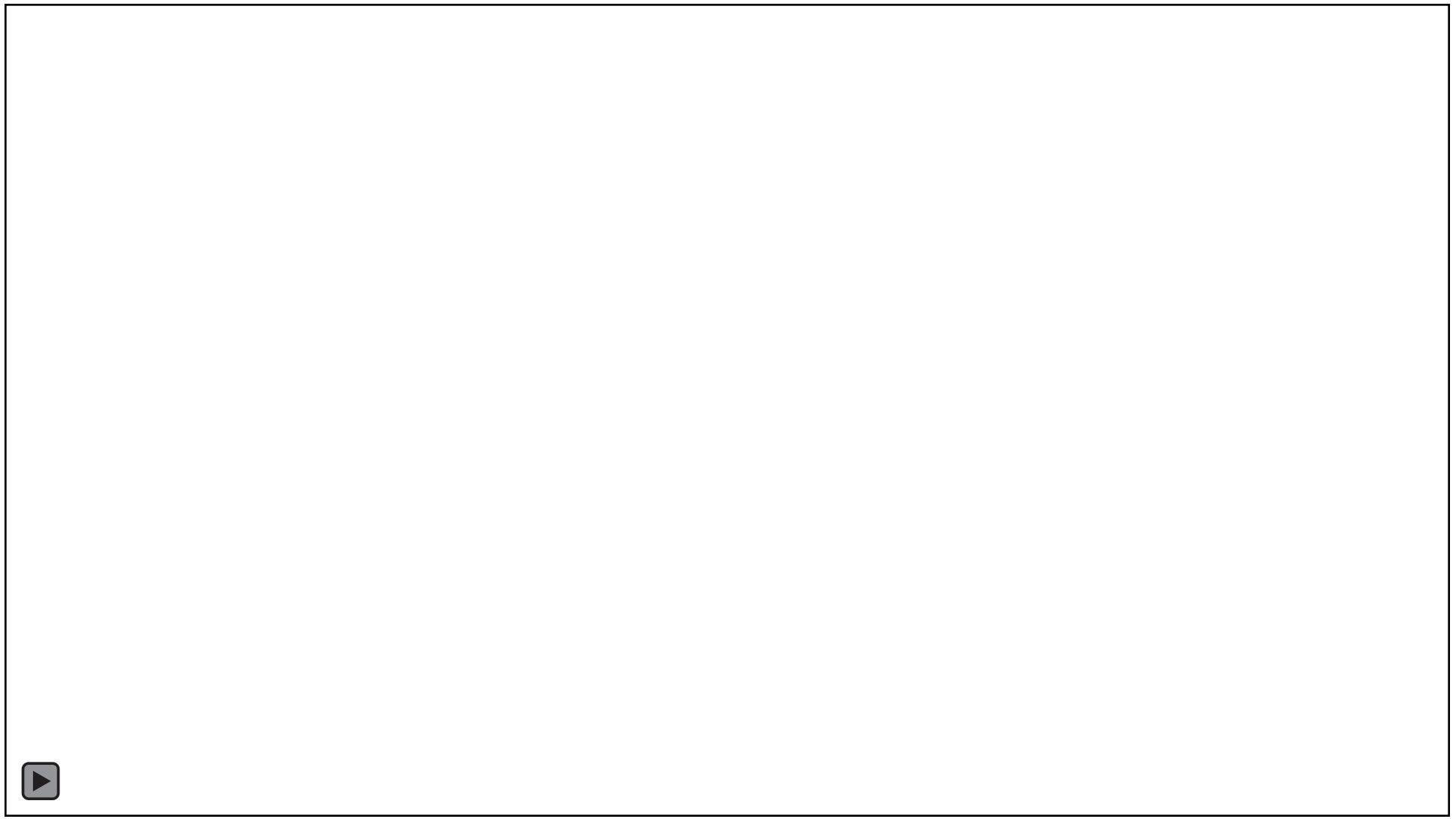




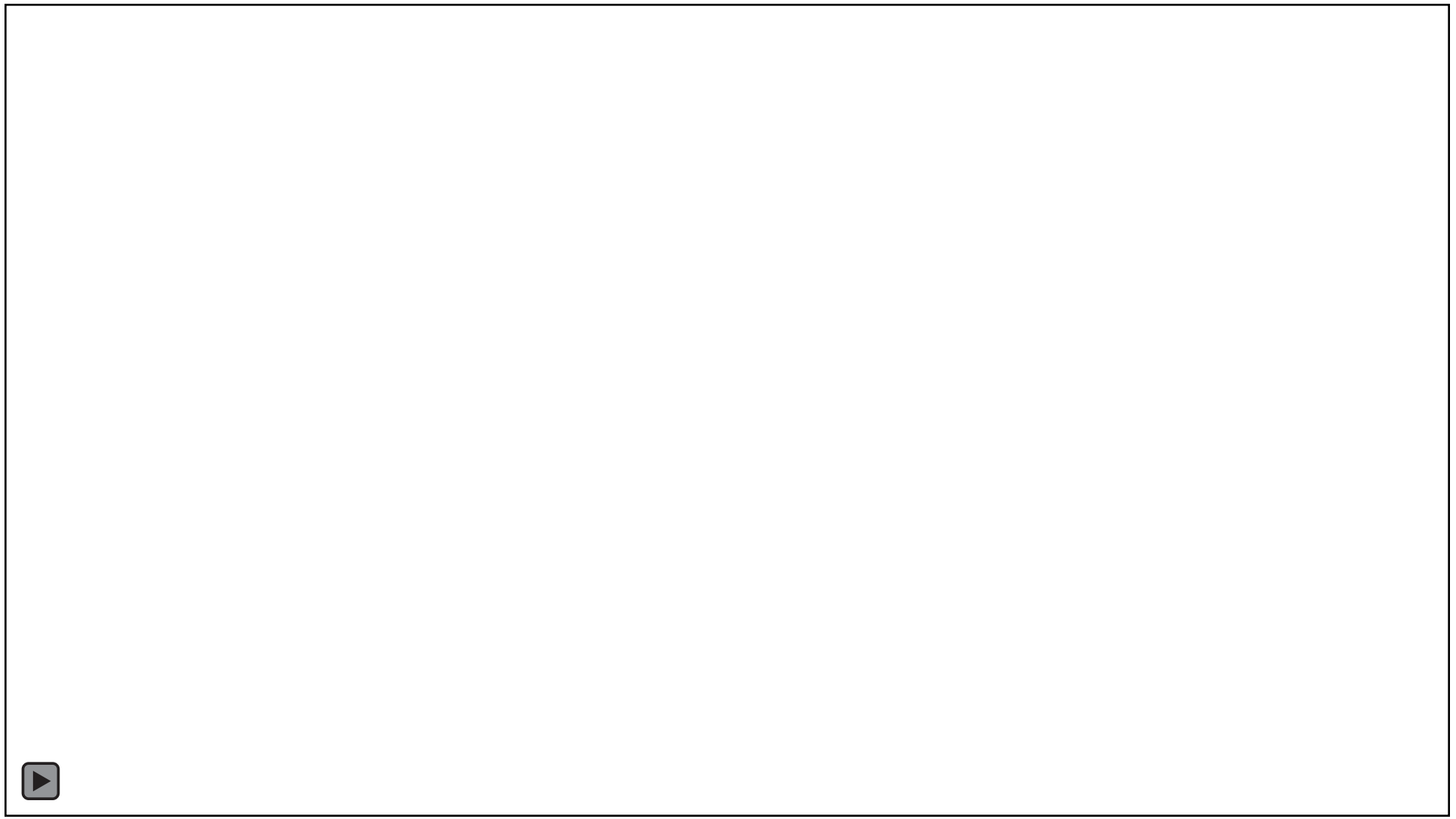
Jenett Benjamin, Calisch Sam, Cellucci Daniel, Cramer Nick, Gershenfeld Neil, Swei Sean, and Cheung Kenneth C.. Soft Robotics. March 2017, 4(1): 33-48. https://doi.org/10.1089/soro.2016.0032



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

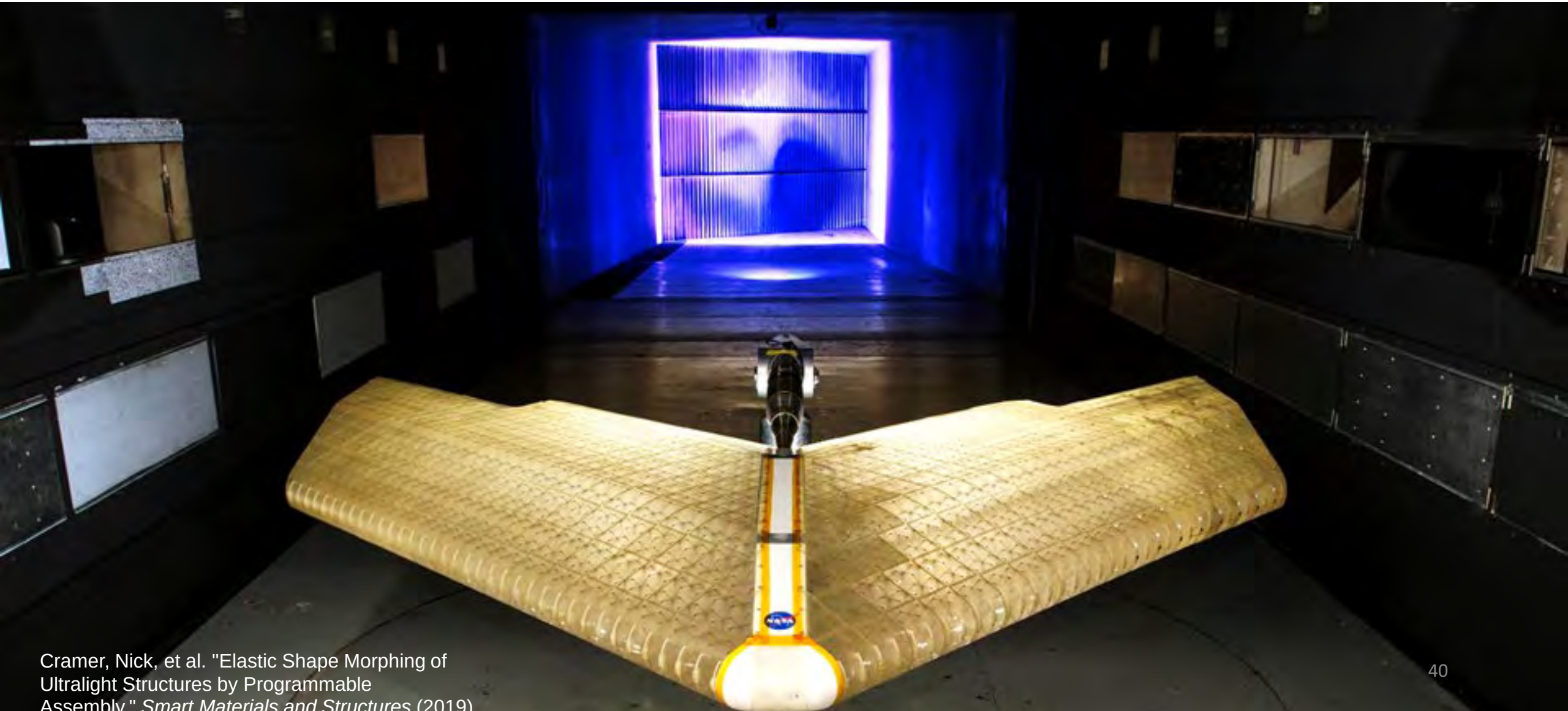


Jenett Benjamin, Calisch Sam, Cellucci Daniel, Cramer Nick, Gershenfeld Neil, Swei Sean, and Cheung Kenneth C.. Soft Robotics. March 2017, 4(1): 33-48. https://doi.org/10.1089/soro.2016.0032



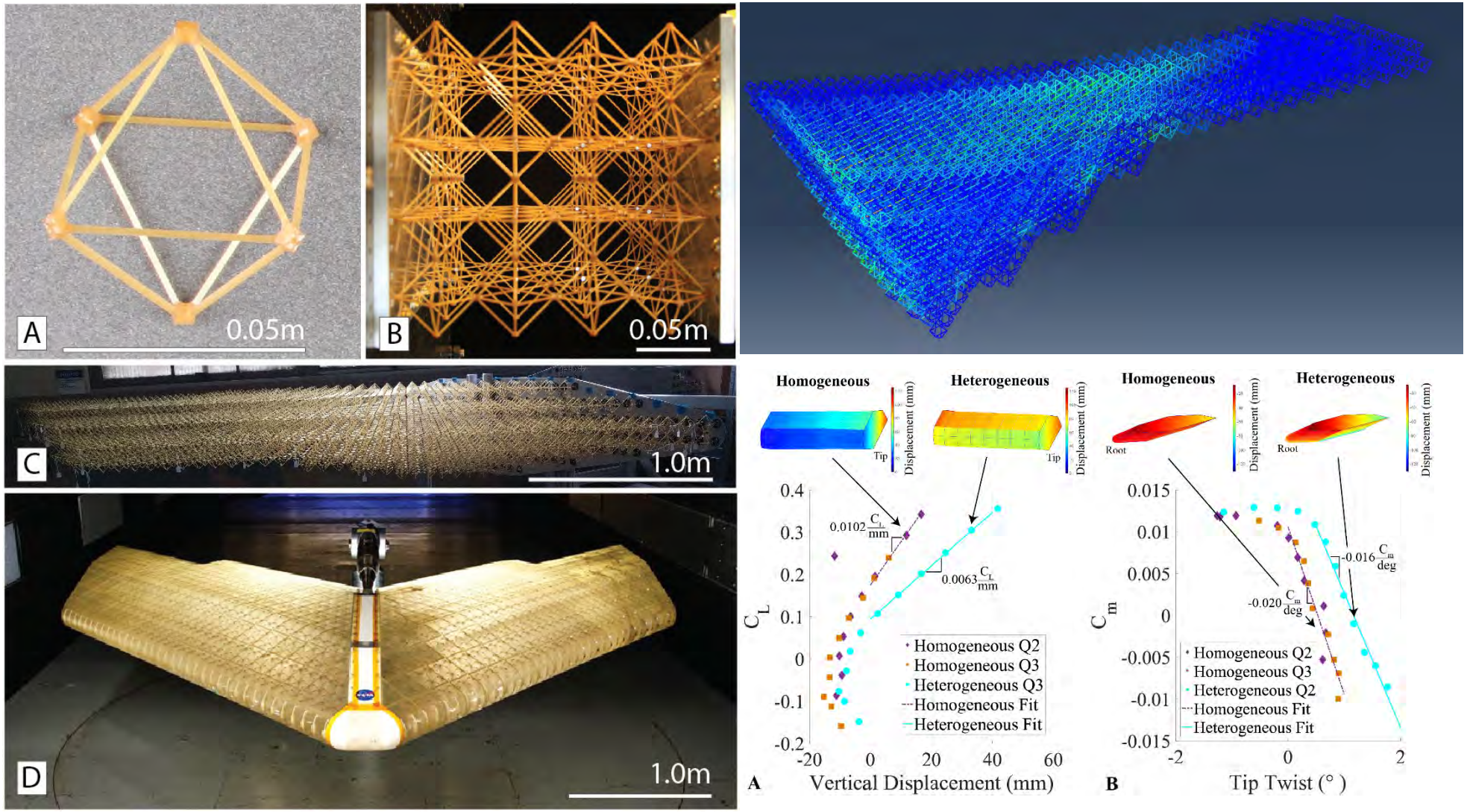
Jenett Benjamin, Calisch Sam, Cellucci Daniel, Cramer Nick, Gershenfeld Neil, Swei Sean, and Cheung Kenneth C.. Soft Robotics. March 2017, 4(1): 33-48. https://doi.org/10.1089/soro.2016.0032

MADCAT (Mission Adaptive Digital Composite Aerostructures Technologies) **Morphing Wing**



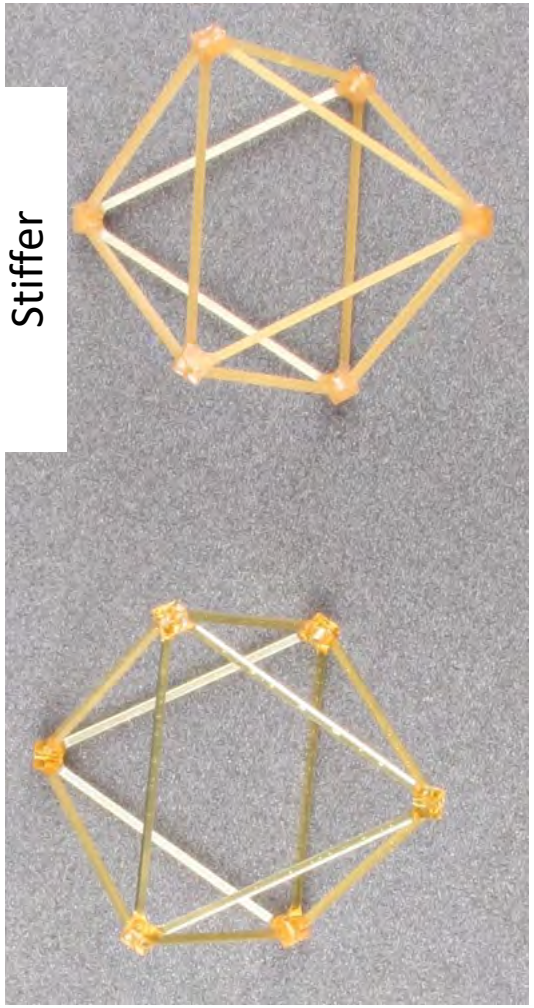
Cramer, Nick, et al. "Elastic Shape Morphing of Ultralight Structures by Programmable Assembly." *Smart Materials and Structures* (2019)

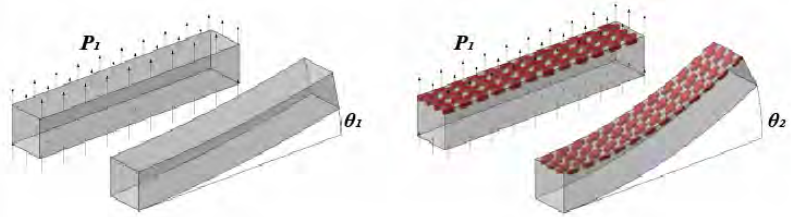
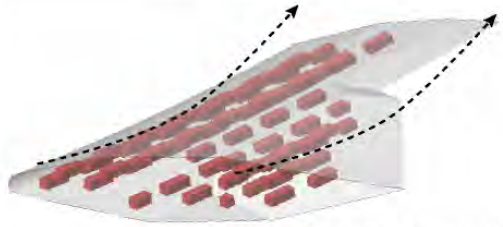
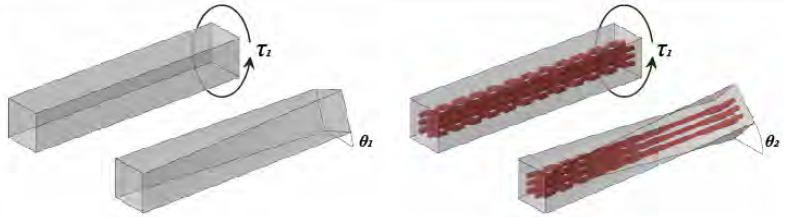
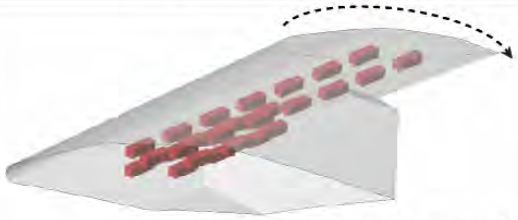
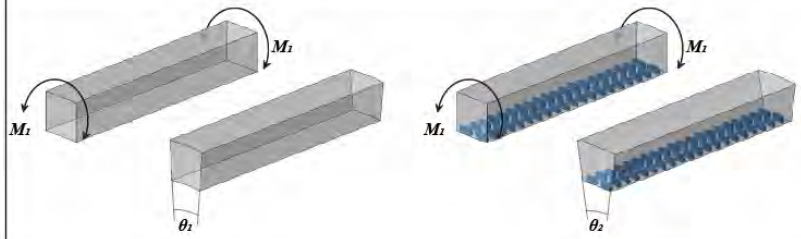
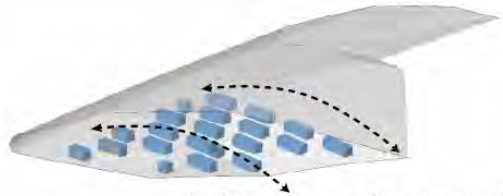
Programmable Soft Materials



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

Tunability through component placement



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).

Discrete Mechanical Metamaterials

Reconfigurable

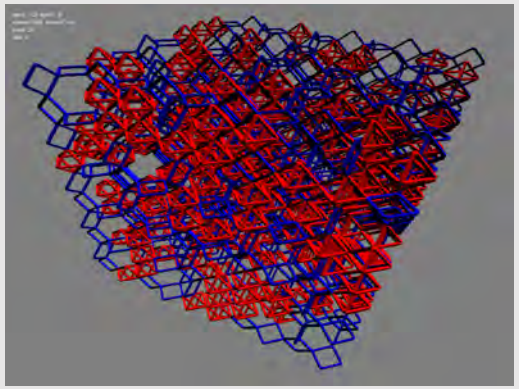


Jenett et al. “Meso-scale digital materials: Modular, Reconfigurable Lattice Structures.” ASME 2016 MSEC, Blacksburg, VA, 2016.

Scalable + Tunable

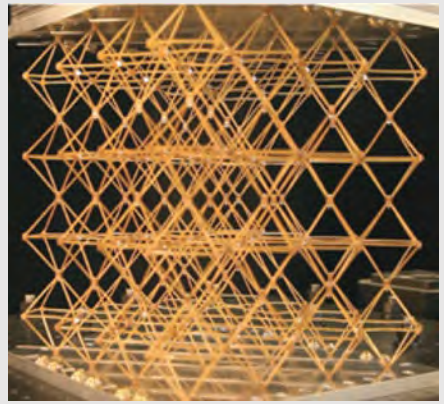


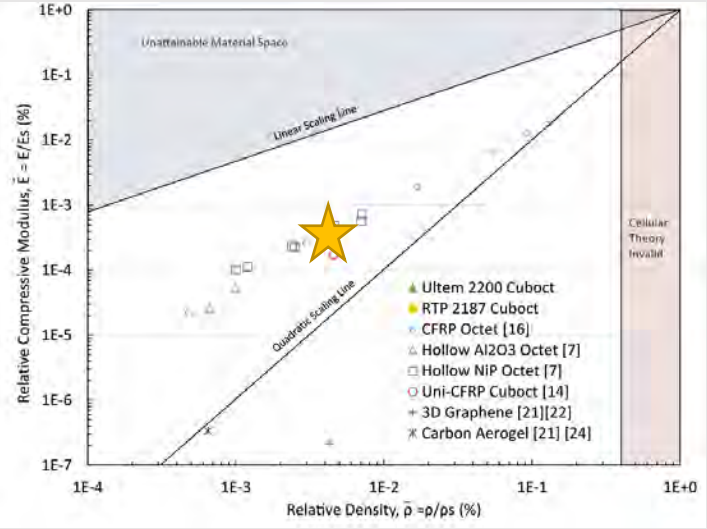
Cramer et. al. “Elastic shape morphing of ultralight structures by programmable assembly.” *Smart Materials and Structures,* 2019



Jenett et al. “Digital Morphing Wing: Active Wing Shaping Concept Using Composite Lattice-Based Cellular Structures.” *Soft Robotics,* 2016.

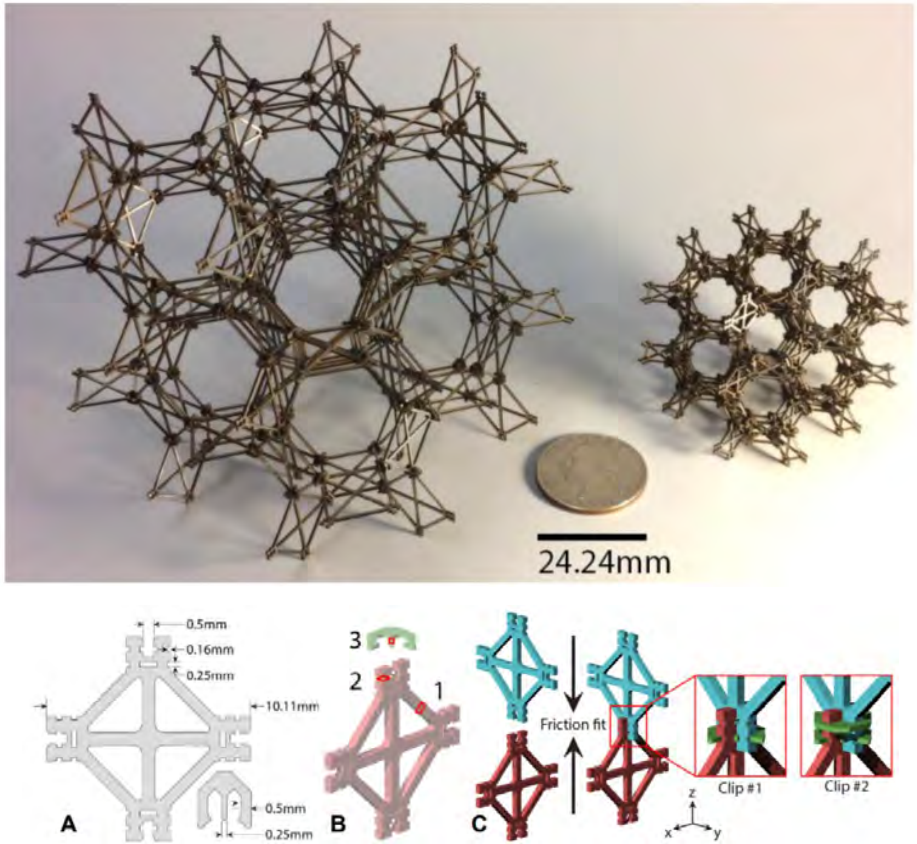
Ultra-light + Repairable



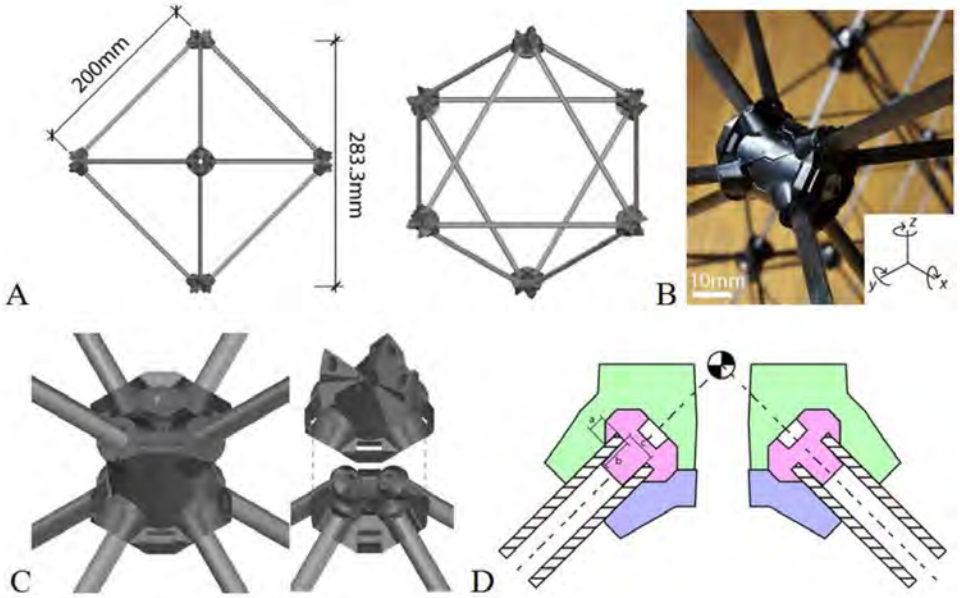


Gregg et al. “Ultra-light and Scalable Composite Lattice Materials.” *Advanced Engineering Materials,* 2018.

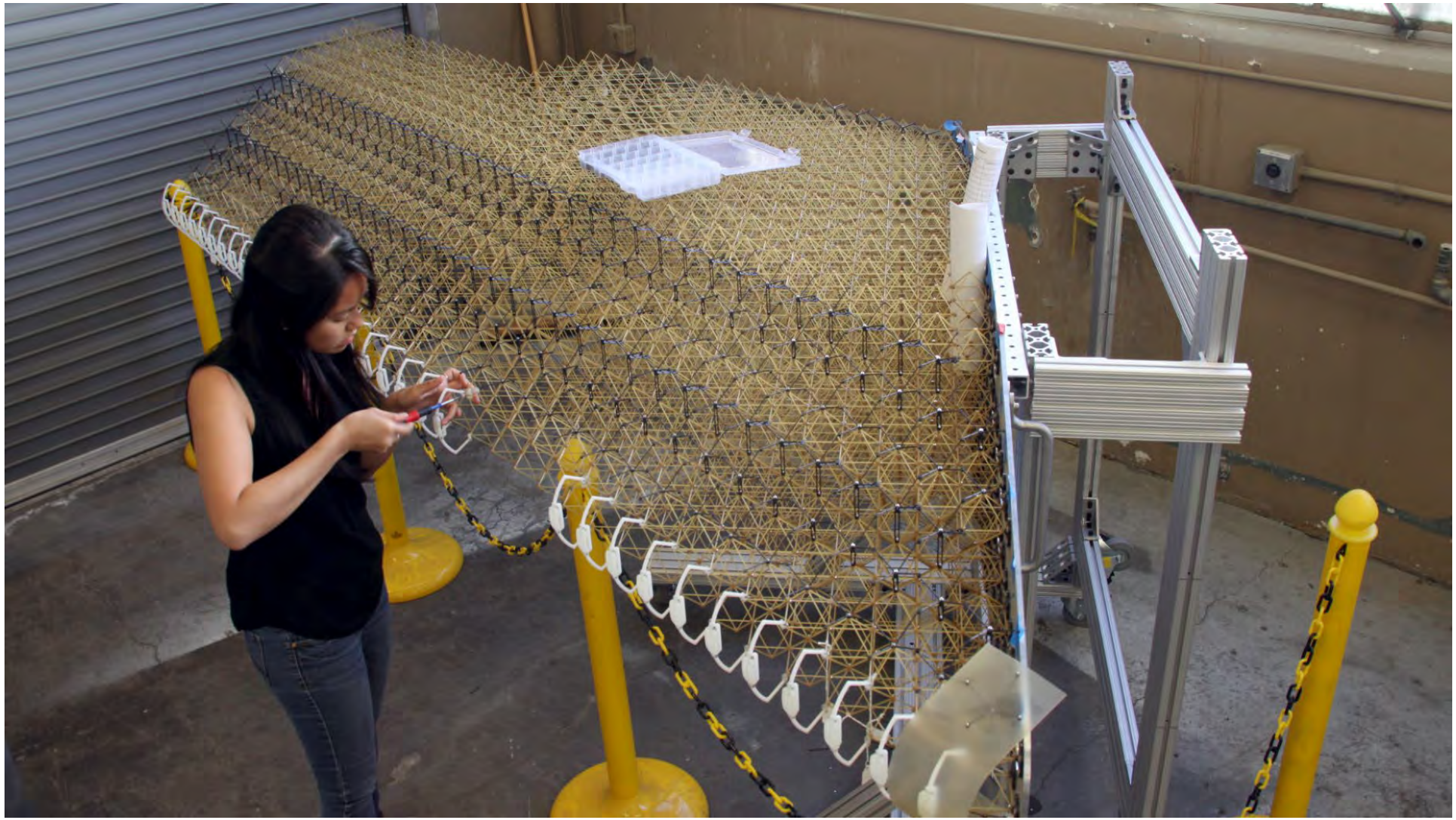
Many Materials. Many Sizes. Many Geometries.



Jenett, B., et al. "Building Block-Based Assembly of Scalable Metallic Lattices." ASME 2018 MSEC, 2018.

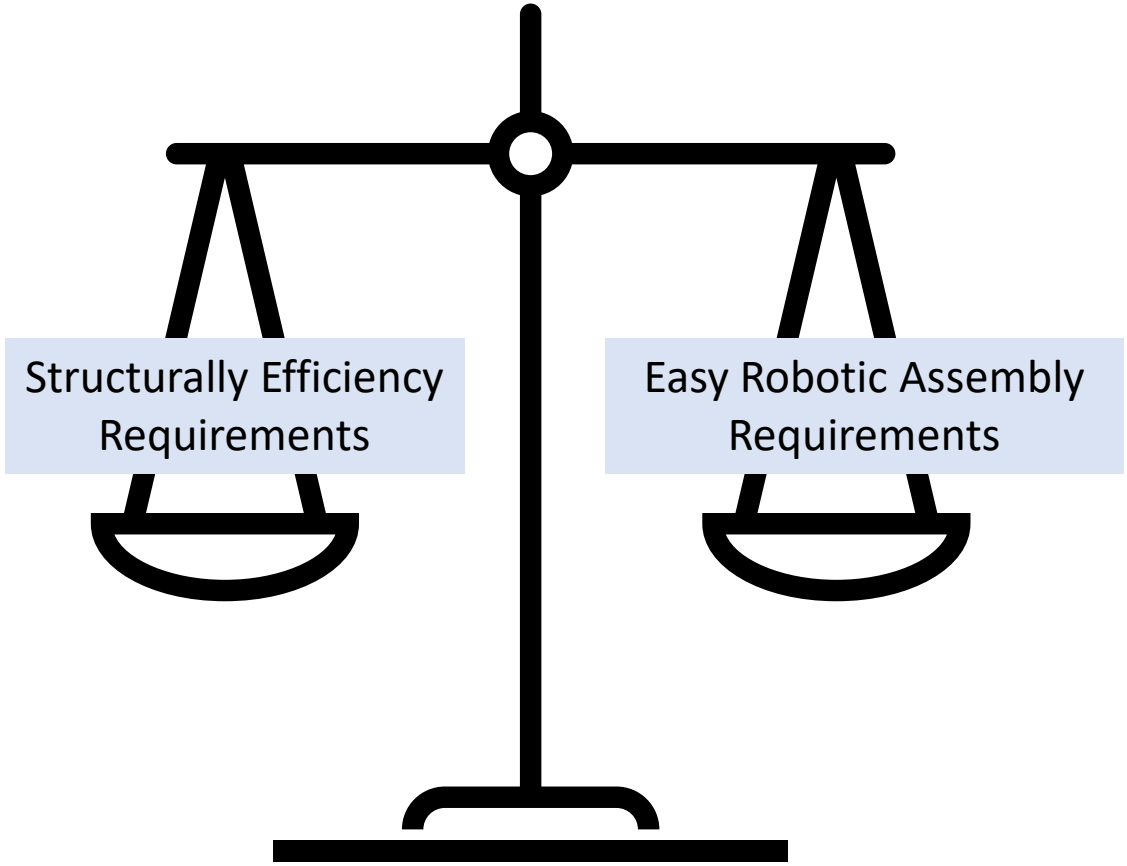


Jenett, B., et al. "Meso-scale Digital Materials: Modular, Reconfigurable Lattice-Based Structures." ASME 2018 MSEC, 2018.

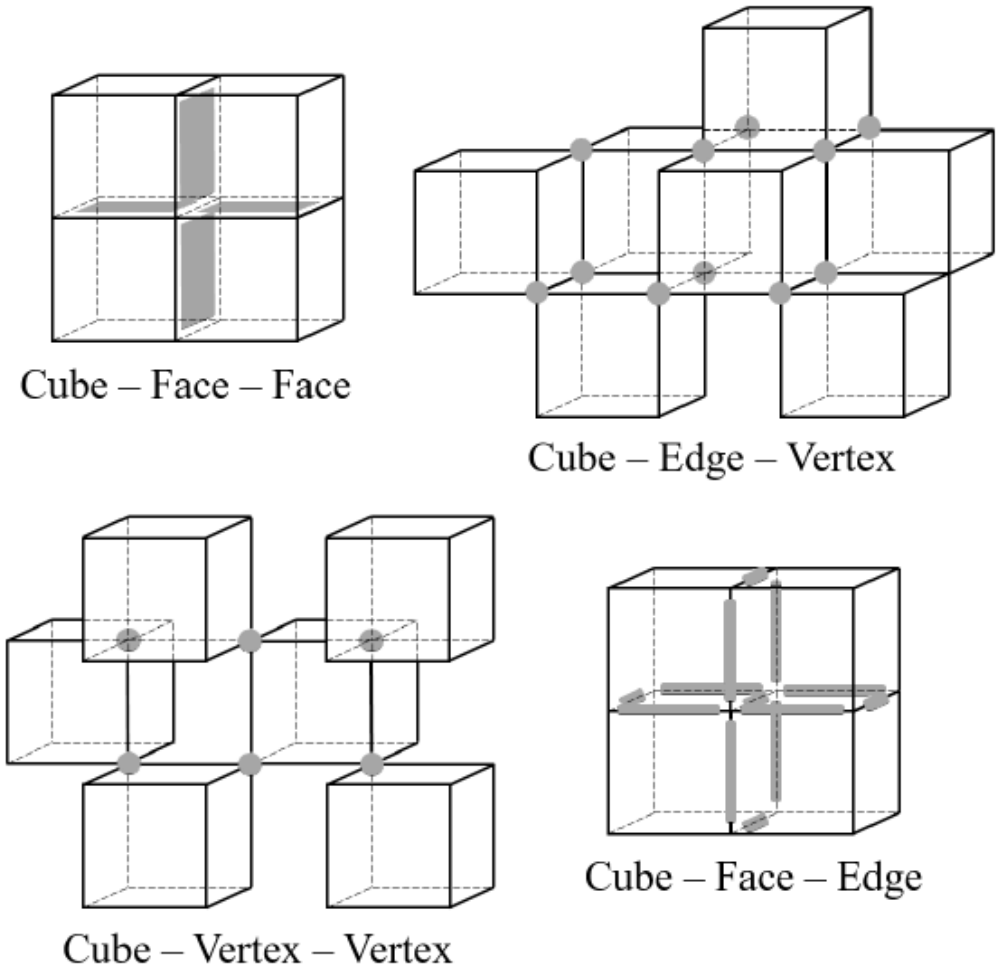


Cramer, Nick, et al. "Elastic Shape Morphing of Ultralight Structures by Programmable Assembly." *Smart Materials and Structures* (2019).

What should building blocks for robotic assembly look like for demanding NASA structural applications?

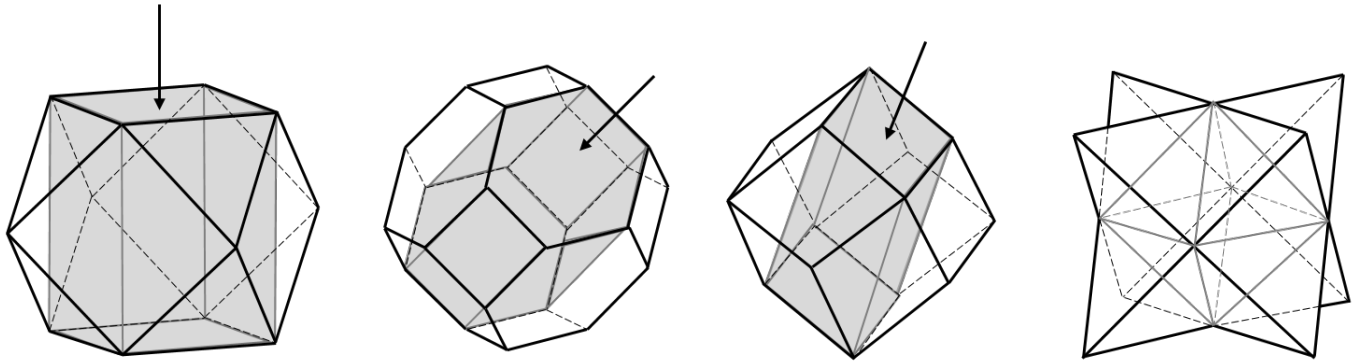


- Geometry (edge connectivity)
- Attachment Locations
- Attachment Types (node/node, face/face, edge/edge)
- Tiling
- …



Ochalek et al. “Geometry Systems for Lattice-Based Reconfigurable Space Structures.” IEEE Aeroconference, Big Sky, Montana, 2019.

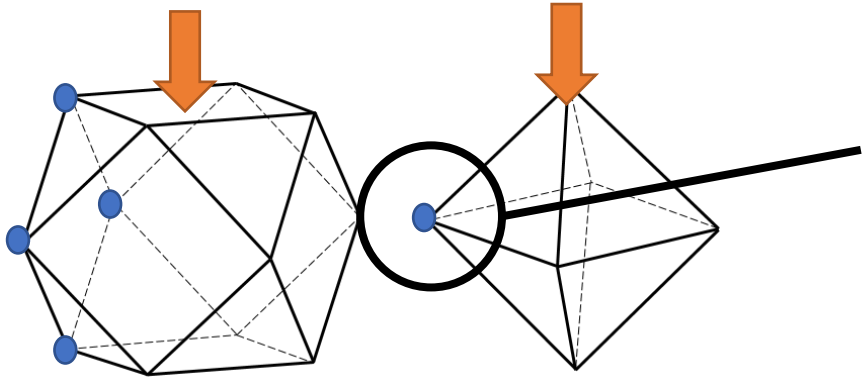
- Access to fasteners + internal clearance for robots



- Stability for traversing robots

Attachment to adjacent unit cell

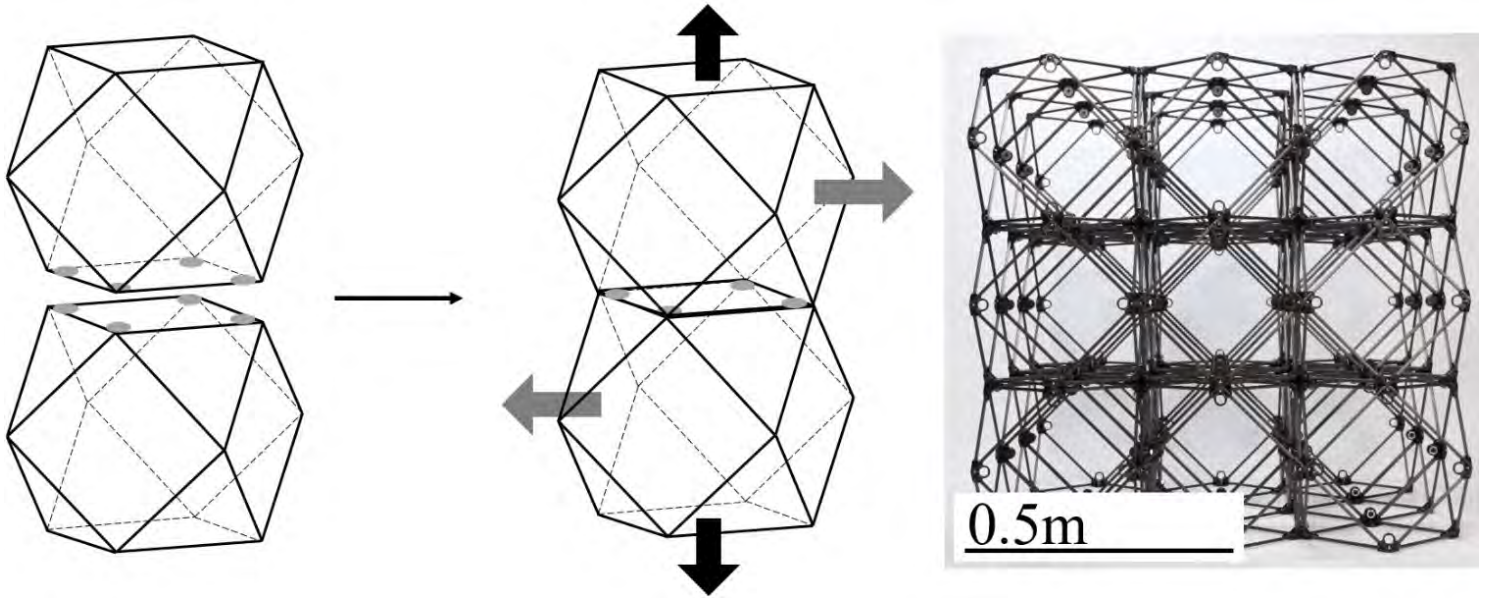
Robot locomotion loading



One attachment per adjacency leads to poor intermediate single unit support

Ochalek et al. “Geometry Systems for Lattice-Based Reconfigurable Space Structures.” IEEE Aeroconference, Big Sky, Montana, 2019.

Cuboctahedron unit cell and resulting lattice has high robotic clearance, favorable specific stiffness and strength scaling, acceptably scalable connection requirements

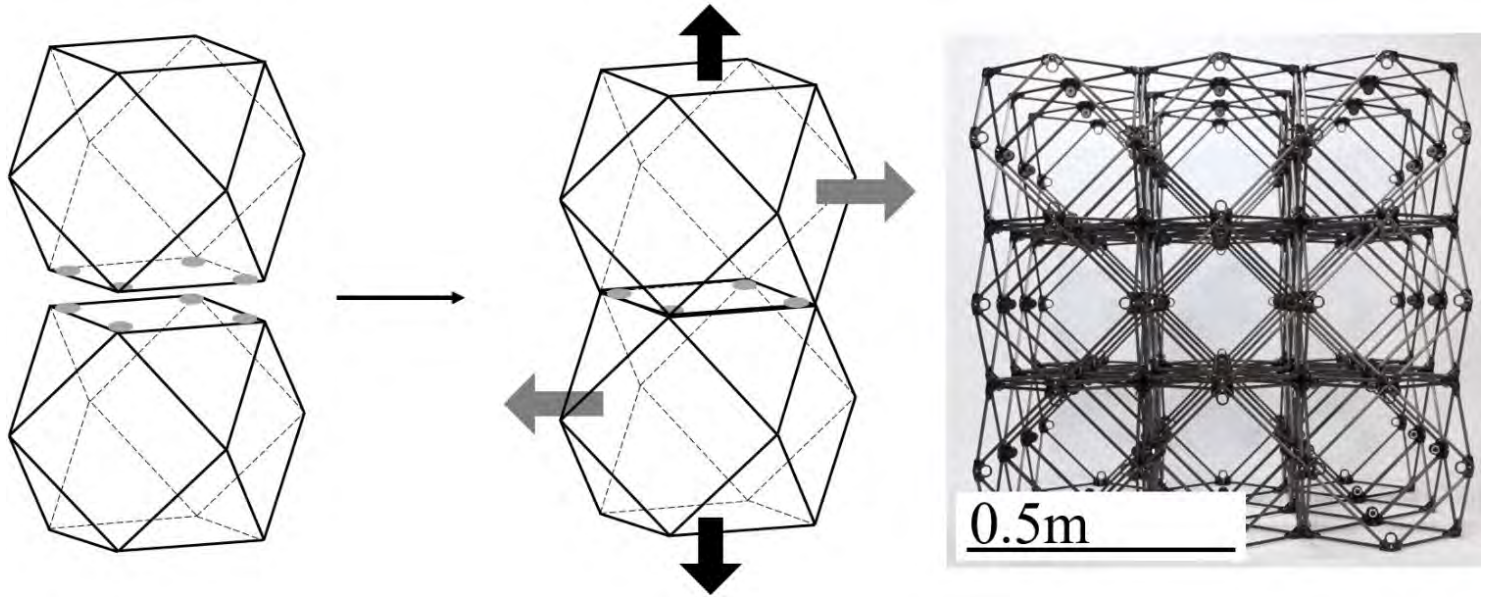


Result: Ochalek et al. “Geometry Systems for Lattice-Based Reconfigurable Space Structures.” IEEE Aeroconference, Big Sky, Montana, 2019.
Figure: Formoso, O., et al. “Androgynous Fasteners for Robotic Structural Assembly.” IEEE Aeroconference, Big Sky, Montana, 2020.

Fastener Systems for Digital Lattices: Optimize for Robotic Actuation

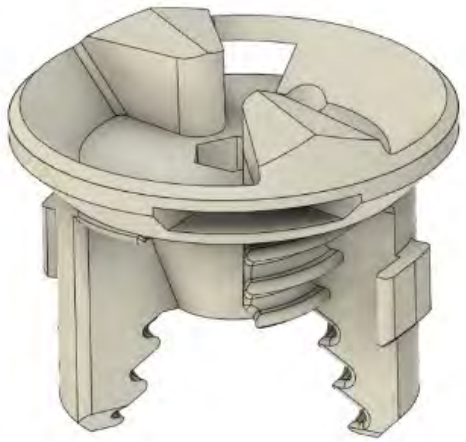
- Cuboctahedron building block geometry connects face to face, with attachments at four locations

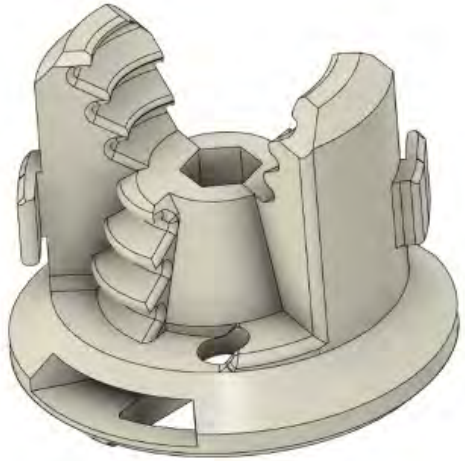
- Fastener requirements:
  - Strength (strut dominated lattice failure)
  - High robotic misalignment tolerance
  - Androgynous
  - High tensile strength/ activation energy ratio



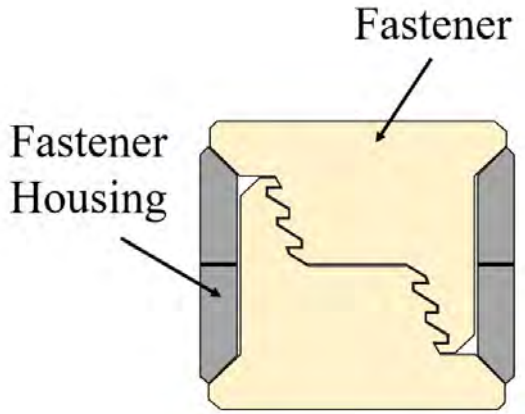
Formoso, O., et al. “Androgynous Fasteners for Robotic Structural Assembly.” IEEE Aeroconference, Big Sky, Montana, 2020.

- Androgynous fastener features interlocking teeth that form mating threads when twisted together
  - Actuated by pressing together and then applying quarter turn
- Fastener is captive in building block to reduce robotic material handling requirements
- Design is **injection moldable for high-throughput manufacturing**





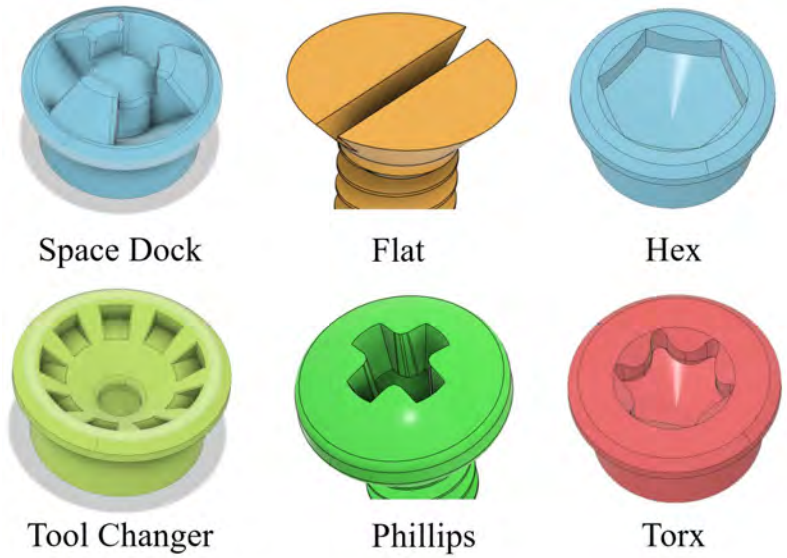




Formoso, O., et al. “Androgynous Fasteners for Robotic Structural Assembly.” IEEE Aeroconference, Big Sky, Montana, 2020.

Fastener Systems for Digital Lattices: Optimize for Robotic Actuation

Head was optimized for high translational, rotational, entry angle misalignment of the robotic tool



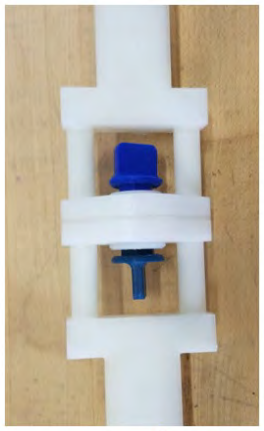
Multiple thread designs were tested to optimize tensile strength

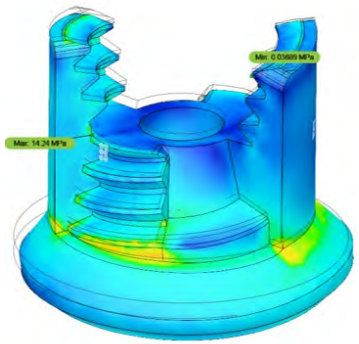


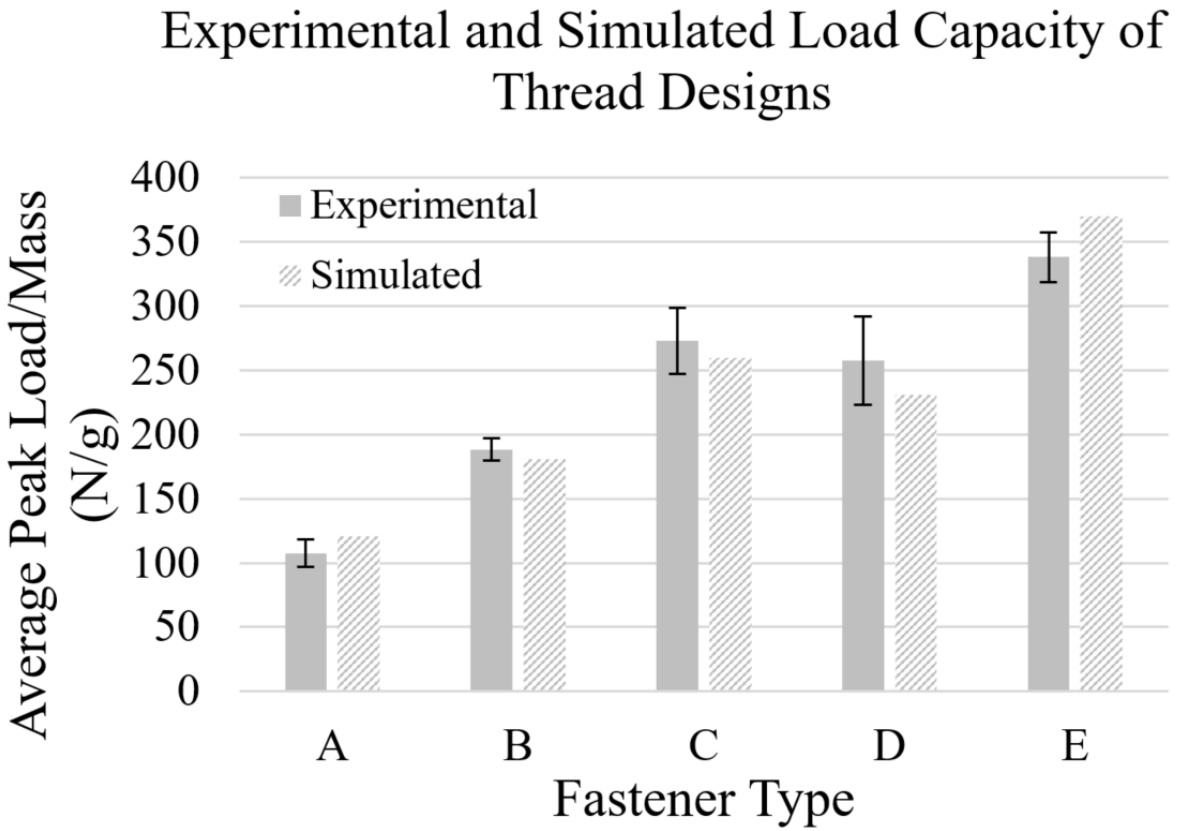
Formoso, O., et al. “Androgynous Fasteners for Robotic Structural Assembly.” IEEE Aeroconference, Big Sky, Montana, 2020.

Fastener Design: Experimental Results



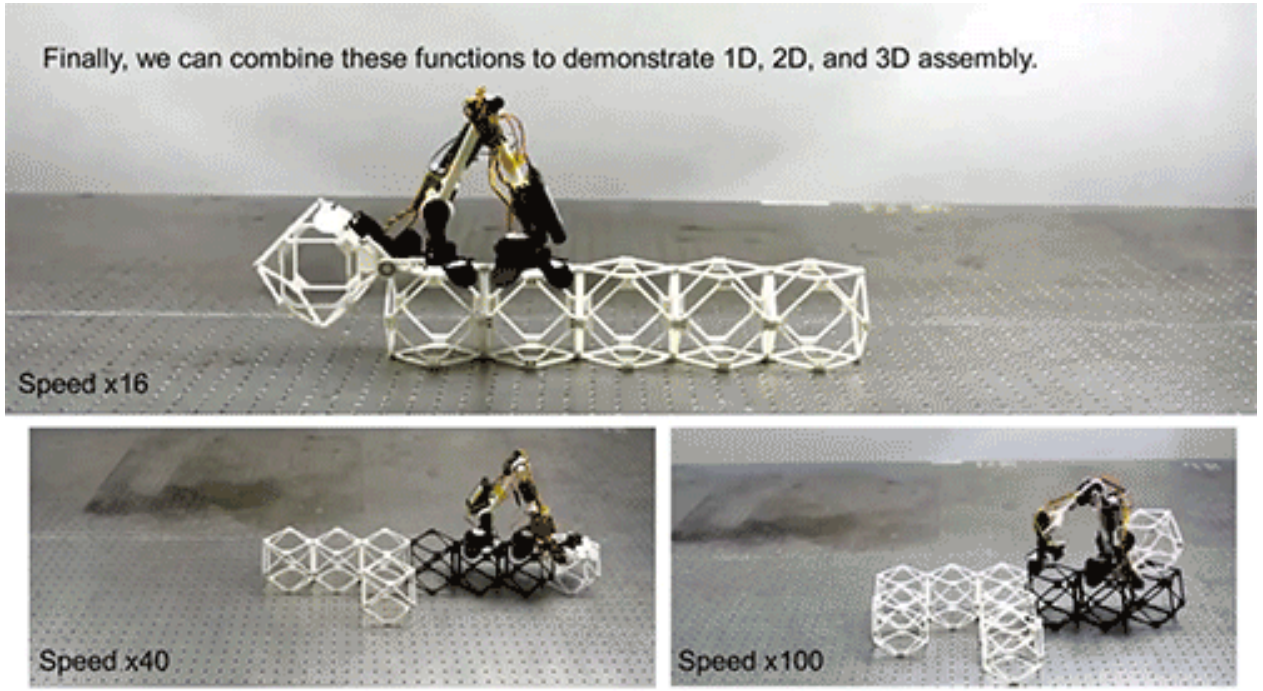




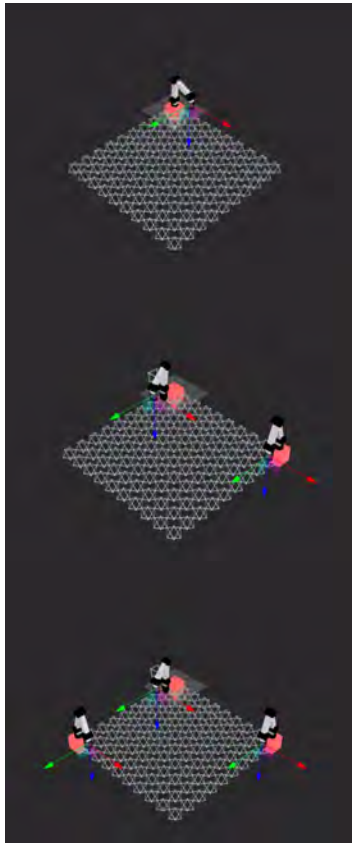


Formoso, O., et al. “Androgynous Fasteners for Robotic Structural Assembly.” IEEE Aeroconference, Big Sky, Montana, 2020.

Next Up: System Integration with Fully Structural Lattice Building Blocks + Relative Robots and Algorithms



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



Current Team: Damiana Catanoso, Kenneth Cheung, Olivia Formoso, Christine Gregg, Taiwo Olatunde, Inwon Park, Elizabeth Taylor, Greenfield Trinh







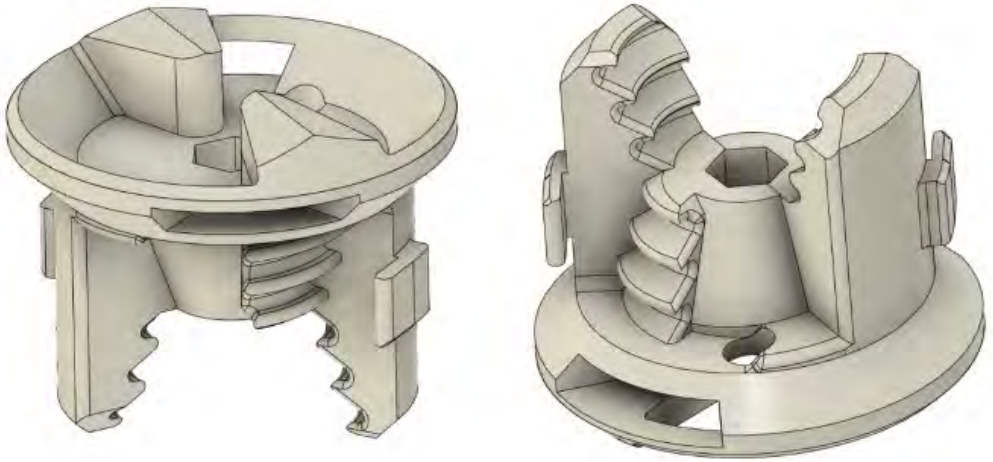
Previous Team: 20+ Contributors!



Questions?

christine.e.gregg@nasa.gov

Students + Faculty: Want to get involved with NASA?
https://intern.nasa.gov/



Fastener Parameter	Value
Thread Angle	30°
Number of Threads	3
Pitch	1.9 mm
Taper	70°
External Diameter	15.9 mm
Number of Teeth	2
Alignment Features	45°
Radial Fit	3.0 mm
Rotational Fit	50.4°
Draft angle	90°
Performance Metric	**Value**
Transverse Tolerance	3.0 mm
Rotational Tolerance	50.4°
Driver Azimuth Angle Tolerance	16.3°

Formoso, O., et al. “Androgynous Fasteners for Robotic Structural Assembly.” IEEE Aeroconference, Big Sky, Montana, 2020.

design exploration

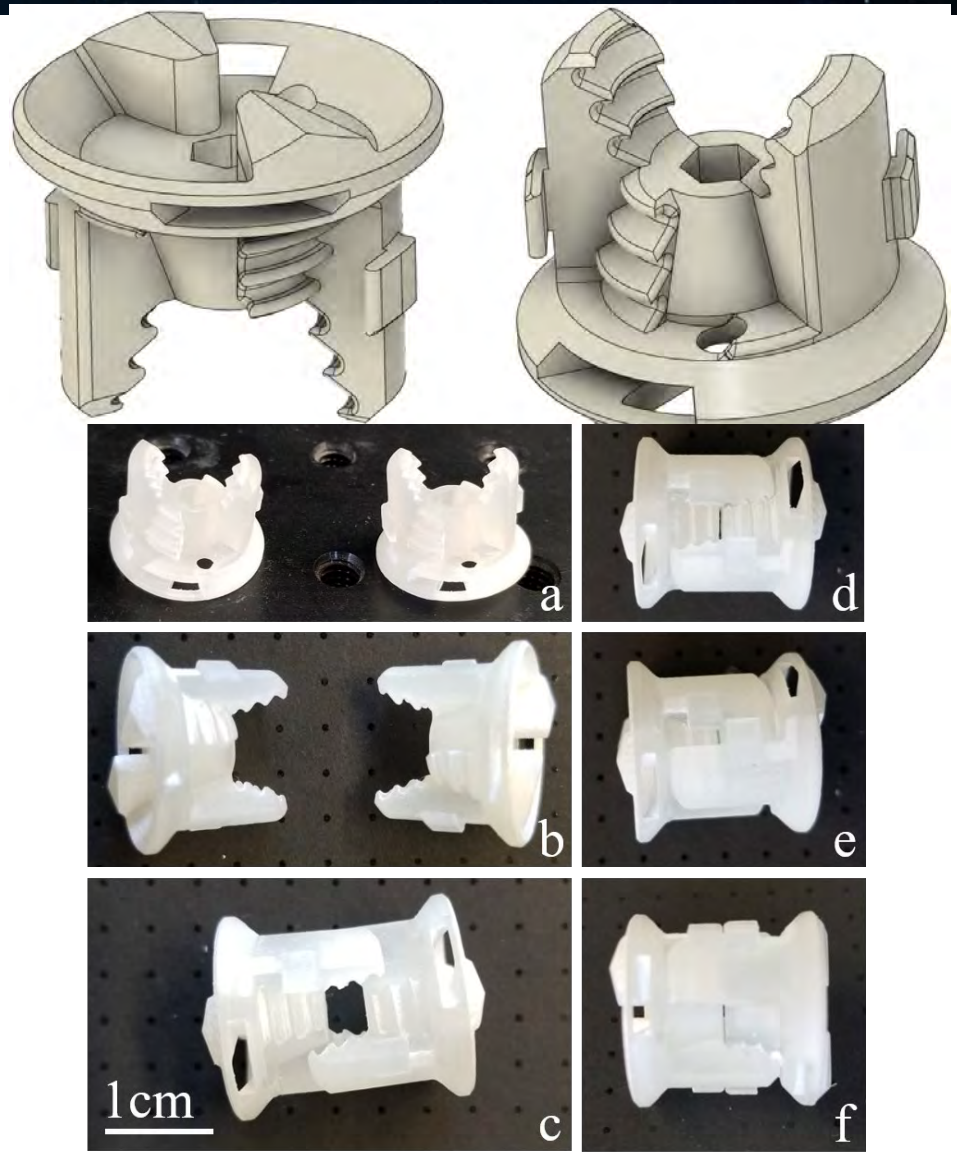
Design	Thread Angle	No. of Threads	Pitch, mm	Taper	Max Load$_{avg}$ per Mass, N/g	Max Load$_{sim}$ per Mass, N/g
A	0°	2	0.25	0°	107.4	121.1
B	0°	4	0.25	0°	188.3	181.1
C	60°	6	1.90	70°	272.9	259.4
D	60°	6	1.90	40°	257.4	231.2
E	30°	6	1.90	70°	338.3	369.7

Head Type	Transverse (x-dir), mm	Transverse (y-dir), mm	Rotational	Drive Angle
Phillips	1.0	1.0	2.5°	15°
Flat	1.0	7.6	3.5°	10°
Square	0.9	0.9	45°	20°
Hex	1.0	1.0	30°	20°
Torx	1.4	1.4	30°	20°
Space Dock	1.5	1.5	10°	2°
Tool Changer	6.0	6.0	3°	4°

Formoso, O., et al. “Androgynous Fasteners for Robotic Structural Assembly.” IEEE Aeroconference, Big Sky, Montana, 2020.

final design

Fastener Parameter	Value
Thread Angle	30°
Number of Threads	3
Pitch	1.9 mm
Taper	70°
External Diameter	15.9 mm
Number of Teeth	2
Alignment Features	45°
Radial Fit	3.0 mm
Rotational Fit	50.4°
Draft angle	90°
Performance Metric	**Value**
Transverse Tolerance	3.0 mm
Rotational Tolerance	50.4°
Driver Azimuth Angle Tolerance	16.3°



Formoso, O., et al. “Androgynous Fasteners for Robotic Structural Assembly.” IEEE Aeroconference, Big Sky, Montana, 2020.