



1
00:00:00,833 --> 00:00:06,833
[music playing]

2
00:00:16,733 --> 00:00:22,633
- Welcome to the 2016 NASA
Ames Summer Series.

3
00:00:22,633 --> 00:00:26,733
When Robert C. Hook, in 1653,

4
00:00:26,733 --> 00:00:29,333
took a thin slice of cork

5
00:00:29,333 --> 00:00:31,900
and observed it
under a microscope,

6
00:00:31,900 --> 00:00:38,366
he discovered modular chambers
he termed "cells."

7
00:00:38,366 --> 00:00:41,400
Upon further studies,

8
00:00:41,400 --> 00:00:44,066
we found that living cells

9
00:00:44,066 --> 00:00:46,500
have the capability to react

10
00:00:46,500 --> 00:00:50,633
and adapt to the environment.

11
00:00:50,633 --> 00:00:54,966
Imagine a world
where vehicles start off

12
00:00:54,966 --> 00:00:56,766

with a particular form

13

00:00:56,766 --> 00:01:01,633
and have the capability
to morph, during travel,

14

00:01:01,633 --> 00:01:06,666
to the environment
that they experience.

15

00:01:06,666 --> 00:01:08,733
Today's seminar, entitled

16

00:01:08,733 --> 00:01:11,233
"Building Blocks
for Aerostructures,"

17

00:01:11,233 --> 00:01:16,666
will be given by
Dr. Kenny Cheung.

18

00:01:16,666 --> 00:01:18,833
Dr. Cheung received
a Bachelor of Arts

19

00:01:18,833 --> 00:01:21,466
from Cornell University,

20

00:01:21,466 --> 00:01:24,733
then came over to this side

21

00:01:24,733 --> 00:01:28,500
and received a Masters
in Computer Science--

22

00:01:28,500 --> 00:01:30,300
actually didn't.
Sorry, I apologize.

23

00:01:30,300 --> 00:01:32,666
Stayed at MIT.

24

00:01:32,666 --> 00:01:35,533
Did a Masters
in computer science at MIT,

25

00:01:35,533 --> 00:01:41,600
followed by a PhD
in applied physics.

26

00:01:41,600 --> 00:01:44,166
He joined Ames
and is currently

27

00:01:44,166 --> 00:01:45,666
a research scientist
with the Office

28

00:01:45,666 --> 00:01:47,466
of Chief Technologist,

29

00:01:47,466 --> 00:01:49,700
and he conducts research
on the application

30

00:01:49,700 --> 00:01:51,800
of building blocks,
base materials,

31

00:01:51,800 --> 00:01:57,633
and algorithms for aeronautical
and space systems.

32

00:01:57,633 --> 00:02:01,400
Please join me
in welcoming Dr. Cheung.

33

00:02:01,400 --> 00:02:05,766
[applause]

34

00:02:05,766 --> 00:02:12,200

- Thank you, and thank
you all for coming today.

35

00:02:12,200 --> 00:02:16,133

I'd like to begin
by acknowledging the various

36

00:02:16,133 --> 00:02:17,433

contributing organizations

37

00:02:17,433 --> 00:02:19,800

to the work that
you'll see in this talk.

38

00:02:19,800 --> 00:02:23,866

In particular,
the Aero Research Mission

39

00:02:23,866 --> 00:02:27,166

Directorate's Convergent
Aeronautics Solutions program,

40

00:02:27,166 --> 00:02:30,400

which is right now
our biggest sponsor,

41

00:02:30,400 --> 00:02:32,100

if you will,
under the Transformative

42

00:02:32,100 --> 00:02:34,233

Aeronautics Concepts program.

43

00:02:34,233 --> 00:02:37,300

That work extends from NASA

44

00:02:37,300 --> 00:02:40,800

Aeronautics Research Institute,
Team Seedling.

45

00:02:40,800 --> 00:02:42,766

That was very enabling.

46

00:02:42,766 --> 00:02:45,266

And we also have some work
that you'll see today

47

00:02:45,266 --> 00:02:48,266

that's been funded under
the Space Tech Mission

48

00:02:48,266 --> 00:02:51,466

Directorate's game-changing
development program.

49

00:02:51,466 --> 00:02:55,100

Also involved are--

50

00:02:55,100 --> 00:02:57,266

with in-kind support

51

00:02:57,266 --> 00:03:01,966

as well as just
collaborators, UCSC,

52

00:03:01,966 --> 00:03:04,000

the Massachusetts Institute
of Technology Center

53

00:03:04,000 --> 00:03:09,066

for Bits and Atoms,
and MOOG's base systems.

54

00:03:09,066 --> 00:03:15,366

I also want
to acknowledge the two

55

00:03:15,366 --> 00:03:17,700

most significant mentors
I've had here at Ames,

56

00:03:17,700 --> 00:03:20,200

in the short period of time
I've been here so far,

57

00:03:20,200 --> 00:03:23,066

which is Harry Partridge
and Sean Swei.

58

00:03:23,066 --> 00:03:28,033

And Sean Swei has also
spent time sitting in the lab

59

00:03:28,033 --> 00:03:30,766

as well as all the faces
that you see here,

60

00:03:30,766 --> 00:03:32,966

which are the minds

61

00:03:32,966 --> 00:03:34,600

and hands behind the work

62

00:03:34,600 --> 00:03:38,166

that you'll see
in this presentation.

63

00:03:38,166 --> 00:03:42,433

And being here at NASA
Ames Research Center

64

00:03:42,433 --> 00:03:45,133

has been really wonderful.

65

00:03:45,133 --> 00:03:48,733

You can see this is just some of

all of the people here

66

00:03:48,733 --> 00:03:50,600
who have been involved
in this work,

67

00:03:50,600 --> 00:03:52,833
and it hasn't been going
on that long here.

68

00:03:52,833 --> 00:03:55,200
So you get an idea
of the kind of support

69

00:03:55,200 --> 00:03:57,533
we have here at NASA Ames.

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00:03:57,533 --> 00:03:59,200
So, thank you all.

71

00:03:59,200 --> 00:04:03,000
So I'm here today to talk about

72

00:04:03,000 --> 00:04:05,433
building blocks
for aerostructures.

73

00:04:05,433 --> 00:04:08,866
And this comes from
an intersection

74

00:04:08,866 --> 00:04:12,333
of digital materials,
cellular solids,

75

00:04:12,333 --> 00:04:14,433
and fiber composites.

76

00:04:14,433 --> 00:04:16,700

And so what I aim to show
is that it's possible

77

00:04:16,700 --> 00:04:18,333
to make things lighter,

78

00:04:18,333 --> 00:04:19,666
in a way, stronger,

79

00:04:19,666 --> 00:04:22,533
as well as possibly
faster and cheaper

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00:04:22,533 --> 00:04:24,600
by assembling
composite materials

81

00:04:24,600 --> 00:04:26,900
from small,
discrete parts.

82

00:04:26,900 --> 00:04:29,533
Short-term applications
include infrastructure

83

00:04:29,533 --> 00:04:31,900
like buildings
and bridges,

84

00:04:31,900 --> 00:04:33,900
or vehicles like airplanes.

85

00:04:33,900 --> 00:04:36,266
In all cases,
the most significant benefit

86

00:04:36,266 --> 00:04:38,966
might be immaterial life cycles.

87

00:04:38,966 --> 00:04:42,800

So, the most obvious
short-term benefit

88

00:04:42,800 --> 00:04:44,633

comes from the reduced weight.
For example,

89

00:04:44,633 --> 00:04:46,700

less structural weight
in an aircraft

90

00:04:46,700 --> 00:04:49,400

means less required fuel.

91

00:04:49,400 --> 00:04:53,900

Oops. Sorry--which itself
means less weight,

92

00:04:53,900 --> 00:04:56,166

which means lower
structural requirements

93

00:04:56,166 --> 00:04:57,666

and even less
required fuel.

94

00:04:57,666 --> 00:05:00,500

So I'll say a bit about
each of these areas,

95

00:05:00,500 --> 00:05:02,100

and then explain how it
all fits together

96

00:05:02,100 --> 00:05:03,666

and show a couple of examples

97

00:05:03,666 --> 00:05:06,833

that we're pursuing

as applications.

98

00:05:06,833 --> 00:05:09,366

So what are digital materials?

99

00:05:09,366 --> 00:05:11,566

Digital materials

are made from a small

100

00:05:11,566 --> 00:05:13,700

and discrete set of parts,

101

00:05:13,700 --> 00:05:16,500

with discrete locations

and discrete connections.

102

00:05:16,500 --> 00:05:18,300

They form as low-cost

and reversible ways

103

00:05:18,300 --> 00:05:19,533

of making things,

104

00:05:19,533 --> 00:05:21,866

with low precision

assembly requirements.

105

00:05:21,866 --> 00:05:24,200

Think about the precision

of a 3-year-old,

106

00:05:24,200 --> 00:05:27,400

relative to the precision

of the assemblies

107

00:05:27,400 --> 00:05:31,500

that he or she can make

from, say, Lego bricks.

108

00:05:31,500 --> 00:05:33,933

So this is accomplished
with aero reduction,

109

00:05:33,933 --> 00:05:35,966

tolerance,
and correction mechanisms,

110

00:05:35,966 --> 00:05:37,800

which is just like
what we see in digital

111

00:05:37,800 --> 00:05:39,966

communication
and computation systems.

112

00:05:39,966 --> 00:05:42,166

So digital systems in general,

113

00:05:42,166 --> 00:05:44,466

as we understand them,
employ many--

114

00:05:44,466 --> 00:05:46,033

and as we've engineered them--

115

00:05:46,033 --> 00:05:48,600

employ many fungible units
to form assemblies

116

00:05:48,600 --> 00:05:51,033

with a wide range
of size and function.

117

00:05:51,033 --> 00:05:52,666

All from low
and finite sets of types

118

00:05:52,666 --> 00:05:54,333

of discrete building blocks.

119

00:05:54,333 --> 00:05:57,300

If the application
of this to materials sounds

120

00:05:57,300 --> 00:05:58,800

to you a bit like biology,

121

00:05:58,800 --> 00:06:03,533

and Jacob helped to
introduce this analogy,

122

00:06:03,533 --> 00:06:06,400

that's because it is indeed
similar to our basic models

123

00:06:06,400 --> 00:06:09,033

for how materials
are used in living organisms.

124

00:06:09,033 --> 00:06:10,266

So in biology,

125

00:06:10,266 --> 00:06:12,966

we see discrete assembly
resulting in structures

126

00:06:12,966 --> 00:06:15,766

with a wide range of size
and function in organisms

127

00:06:15,766 --> 00:06:17,200

as a whole,

128

00:06:17,200 --> 00:06:19,566

or specialized organs
and tissues,

129

00:06:19,566 --> 00:06:21,300

all from a low
and finite set of types

130
00:06:21,300 --> 00:06:22,866
of discrete building blocks.

131
00:06:22,866 --> 00:06:27,600
So the most, the simplest way

132
00:06:27,600 --> 00:06:29,800
you can look this
is amino acids

133
00:06:29,800 --> 00:06:31,633
as building blocks.

134
00:06:31,633 --> 00:06:33,033
And so the diversity of things

135
00:06:33,033 --> 00:06:35,666
that can be made with this
sort of combinatorial system,

136
00:06:35,666 --> 00:06:37,500
at various levels of hierarchy,

137
00:06:37,500 --> 00:06:38,800
is plainly evident

138
00:06:38,800 --> 00:06:40,933
and the small number
of required building blocks,

139
00:06:40,933 --> 00:06:43,033
along with system scalability,

140
00:06:43,033 --> 00:06:45,433
has allowed synthetic biologists

141
00:06:45,433 --> 00:06:46,666
to make new systems

142
00:06:46,666 --> 00:06:48,866
from the same
or similar material.

143
00:06:48,866 --> 00:06:51,466
It's amazing work with
incredible rates of progress,

144
00:06:51,466 --> 00:06:53,066
some of which
is going on here.

145
00:06:53,066 --> 00:06:58,166
For many of our current
manufacturing applications,

146
00:06:58,166 --> 00:07:00,333
however, we may be able
to take advantage

147
00:07:00,333 --> 00:07:02,900
of the ability to work
at a much larger scale,

148
00:07:02,900 --> 00:07:05,466
and with many fewer
building block types,

149
00:07:05,466 --> 00:07:09,500
or diversity of parameters
and objective functions.

150
00:07:09,500 --> 00:07:13,700
So short of setting out
to try and re-create life,

151

00:07:13,700 --> 00:07:16,533
which is being done

152
00:07:16,533 --> 00:07:20,700
in the synthetic
biology world right now,

153
00:07:20,700 --> 00:07:25,300
we're looking at modular systems
that, on the surface,

154
00:07:25,300 --> 00:07:26,800
appear not that different
from those

155
00:07:26,800 --> 00:07:30,100
that have been studied for ages,

156
00:07:30,100 --> 00:07:32,400
but historically,

157
00:07:32,400 --> 00:07:34,600
these kinds of physical systems
are often considered

158
00:07:34,600 --> 00:07:38,200
to be a mechanical compromise
relative to conventional

159
00:07:38,200 --> 00:07:39,966
manufacturing methods.

160
00:07:39,966 --> 00:07:41,233
So there's a couple things

161
00:07:41,233 --> 00:07:43,566
I want to point out
on this slide.

162

00:07:43,566 --> 00:07:45,133

The first is that,

163

00:07:45,133 --> 00:07:49,166

while it's sad that

the Lego house got torn down,

164

00:07:49,166 --> 00:07:51,033

it's not sad

that most of the parts

165

00:07:51,033 --> 00:07:53,033

got distributed

amongst many children

166

00:07:53,033 --> 00:07:56,266

and therefore maintained

most of their utility.

167

00:07:56,266 --> 00:07:59,766

It's harder to do that with

your typical demolition job.

168

00:07:59,766 --> 00:08:01,900

So can I have a show of hands

169

00:08:01,900 --> 00:08:05,666

for how many of you played

170

00:08:05,666 --> 00:08:08,866

with toy sets like that?

171

00:08:14,133 --> 00:08:16,133

And so can I now

have a show of hands

172

00:08:16,133 --> 00:08:17,900

for how many of you,

173

00:08:17,900 --> 00:08:21,166

given a set like
the one in the middle,

174

00:08:21,166 --> 00:08:23,166

would only use
the provided bricks

175

00:08:23,166 --> 00:08:27,233

to make the things shown
on the cover of the box?

176

00:08:27,233 --> 00:08:33,333

So in a way, that set,

177

00:08:33,333 --> 00:08:36,633

for a wind turbine set,
is very realistic

178

00:08:36,633 --> 00:08:38,000

because it comes with a truck

179

00:08:38,000 --> 00:08:40,033

that is almost
as big as the turbine.

180

00:08:40,033 --> 00:08:43,166

And today's terrestrial
wind turbines

181

00:08:43,166 --> 00:08:44,566

are indeed size-constrained by

182

00:08:44,566 --> 00:08:46,466

that truck,
which is, in turn,

183

00:08:46,466 --> 00:08:48,600

constrained by the geometry
of the roadway system.

184

00:08:48,600 --> 00:08:54,700

So we have wind turbines
that are set by the roadways.

185

00:08:54,700 --> 00:08:56,966

So, the funny thing
is that the Lego version

186

00:08:56,966 --> 00:08:58,933

doesn't actually need
the enormous truck.

187

00:08:58,933 --> 00:09:01,200

And you can bet
that there are some kids

188

00:09:01,200 --> 00:09:03,700

that have made some
curiously big wind turbines,

189

00:09:03,700 --> 00:09:05,933

together with mysteriously
small trucks,

190

00:09:05,933 --> 00:09:08,433

just like how the parts
are meant to be exchanged

191

00:09:08,433 --> 00:09:11,533

among the hundred or so
explicit designs

192

00:09:11,533 --> 00:09:14,200

in the reconfigurable
plane sets.

193

00:09:14,200 --> 00:09:16,200

Okay?
So, one of the things

194

00:09:16,200 --> 00:09:17,866

that make toys
like this work so well

195

00:09:17,866 --> 00:09:21,566

is that the parts fit
together into a regular lattice

196

00:09:21,566 --> 00:09:23,000

and when it comes to studying

197

00:09:23,000 --> 00:09:24,833

the mechanics of
lattice structures,

198

00:09:24,833 --> 00:09:27,000

we have the science
of cellular solids.

199

00:09:27,000 --> 00:09:29,033

And so this was forged
in the '80s

200

00:09:29,033 --> 00:09:31,400

by Lorna Gibson
and Michael Ashby,

201

00:09:31,400 --> 00:09:33,700

and it shows that we can treat
these kind of materials

202

00:09:33,700 --> 00:09:36,166

as continuous materials
with bulk properties.

203

00:09:36,166 --> 00:09:38,333

That really changes
how you can design

204

00:09:38,333 --> 00:09:40,900

with these kinds of materials.

205

00:09:40,900 --> 00:09:42,666

And so the result

has been the modern

206

00:09:42,666 --> 00:09:45,733

engineering use

of materials

207

00:09:45,733 --> 00:09:48,133

with useful characteristics

208

00:09:48,133 --> 00:09:51,000

like lower density,

greater elasticity,

209

00:09:51,000 --> 00:09:52,833

and better energy absorption

210

00:09:52,833 --> 00:09:54,400

than previously commonly used.

211

00:09:54,400 --> 00:09:57,366

So these include the foam

in bicycle helmets,

212

00:09:57,366 --> 00:09:58,666

optimize uses for wood,

213

00:09:58,666 --> 00:10:00,600

and ultralight materials

like aerogel.

214

00:10:00,600 --> 00:10:03,000

So the properties

of any cellular solid

215
00:10:03,000 --> 00:10:05,066
are defined by the properties
of the solid material

216
00:10:05,066 --> 00:10:06,433
that it's made from,

217
00:10:06,433 --> 00:10:10,300
and the geometric spatial
configuration of that material.

218
00:10:10,300 --> 00:10:13,033
So if we're going to assemble
a cellular solid

219
00:10:13,033 --> 00:10:15,100
from small parts,

220
00:10:15,100 --> 00:10:18,433
we could do whatever we wanted
with a spatial configuration.

221
00:10:18,433 --> 00:10:22,600
So, what should we aim for?

222
00:10:22,600 --> 00:10:24,066
To get an idea
of what we could try,

223
00:10:24,066 --> 00:10:26,033
we can look at
a material property chart

224
00:10:26,033 --> 00:10:27,933
like those pioneered
by Michael Ashby,

225
00:10:27,933 --> 00:10:30,366
and this shows

most of the broad categories

226

00:10:30,366 --> 00:10:32,866
of materials that we use
in engineering today.

227

00:10:32,866 --> 00:10:34,633
It has density
along the X-axis

228

00:10:34,633 --> 00:10:37,000
and modular stiffness
along the Y-axis.

229

00:10:37,000 --> 00:10:40,233
So metals and ceramics
are the densest and stiffest

230

00:10:40,233 --> 00:10:43,100
and foams are the least dense
and least stiff.

231

00:10:43,100 --> 00:10:45,100
If we were to make anything
out of these materials,

232

00:10:45,100 --> 00:10:46,633
it's simple to see
what the optimal

233

00:10:46,633 --> 00:10:48,066
performance could be

234

00:10:48,066 --> 00:10:50,033
by following
the proportional modulus

235

00:10:50,033 --> 00:10:51,833
to density lines
down the chart.

236

00:10:51,833 --> 00:10:53,200

So if you build something sparse

237

00:10:53,200 --> 00:10:55,466

that optimally uses

any of these materials

238

00:10:55,466 --> 00:10:58,166

that you see in the bubbles

239

00:10:58,166 --> 00:11:00,100

to support the loads,

240

00:11:00,100 --> 00:11:03,266

with behavior that's dominated

by stretching of the material,

241

00:11:03,266 --> 00:11:04,466

then the relative stiffness

242

00:11:04,466 --> 00:11:06,466

will stay proportional

to the relative density,

243

00:11:06,466 --> 00:11:09,600

so it's gonna follow

down along those lines.

244

00:11:09,600 --> 00:11:12,233

So this is sort of the absolute

best case design goal,

245

00:11:12,233 --> 00:11:14,433

the physical boundary,

if you will.

246

00:11:14,433 --> 00:11:15,966

So we therefore know

247

00:11:15,966 --> 00:11:17,933
that we should be able
to access the area

248

00:11:17,933 --> 00:11:19,400
in yellow on this chart,

249

00:11:19,400 --> 00:11:21,366
by properly making
a cellular solid

250

00:11:21,366 --> 00:11:24,700
out of a known
constituent solid material.

251

00:11:24,700 --> 00:11:25,966
In practice, however,

252

00:11:25,966 --> 00:11:27,266
we've only followed these lines

253

00:11:27,266 --> 00:11:29,666
down about in order of magnitude
and relative density.

254

00:11:29,666 --> 00:11:31,900
So we've had reasonable success

255

00:11:31,900 --> 00:11:33,133
getting down to around 1/10

256

00:11:33,133 --> 00:11:35,233
the volume of the materials

257

00:11:35,233 --> 00:11:38,233
that you see here--
most of them--

258

00:11:38,233 --> 00:11:40,866
before reaching
the limits of conventional

259

00:11:40,866 --> 00:11:42,266
manufacturing methods.

260

00:11:42,266 --> 00:11:46,366
So if the designs that are truly
volumetric periodic structures,

261

00:11:46,366 --> 00:11:49,000
a pioneer of lattice-based
metallic structures,

262

00:11:49,000 --> 00:11:51,600
Hayden Wiley, has said
that it is not trivial

263

00:11:51,600 --> 00:11:54,333
to ensure that the increased
cost of periodic cellular

264

00:11:54,333 --> 00:11:56,466
manufacturing processes
is compensated

265

00:11:56,466 --> 00:11:57,933
for by the reduction in weight.

266

00:11:57,933 --> 00:12:01,766
So whatever cost gains
you get in your application

267

00:12:01,766 --> 00:12:03,166
through the reduction
and weight.

268

00:12:03,166 --> 00:12:05,333

So this presumably refers
to the technologies

269

00:12:05,333 --> 00:12:06,733
like the cast aluminum structure

270

00:12:06,733 --> 00:12:08,033
that you see
on the lower right.

271

00:12:08,033 --> 00:12:10,633
So architecture
and civil engineering

272

00:12:10,633 --> 00:12:12,500
have employed space
frame truss structures

273

00:12:12,500 --> 00:12:15,966
for a very long time
in buildings and aircraft

274

00:12:15,966 --> 00:12:17,800
but have yet to implement
the principal

275

00:12:17,800 --> 00:12:19,533
in a way that takes
advantage of the ability

276

00:12:19,533 --> 00:12:23,133
to treat such structures
as a continuum material.

277

00:12:23,133 --> 00:12:25,466
In any case,
the appreciation for designs

278

00:12:25,466 --> 00:12:26,900
that have lots

of similar elements,

279

00:12:26,900 --> 00:12:28,633

sharing structural duties
is evident

280

00:12:28,633 --> 00:12:31,233

throughout our history
of high performing structures.

281

00:12:31,233 --> 00:12:32,666

You think of the Eiffel Tower

282

00:12:32,666 --> 00:12:34,933

or you could think
of the geodetic aircraft,

283

00:12:34,933 --> 00:12:38,666

the Vickers aircraft,
from the '30s.

284

00:12:38,666 --> 00:12:41,300

So we're still left
with the red area

285

00:12:41,300 --> 00:12:42,966

on this materials
property graph,

286

00:12:42,966 --> 00:12:44,233

which is physically possible,

287

00:12:44,233 --> 00:12:45,866

but for which we still have yet

288

00:12:45,866 --> 00:12:49,666

to show suitable
methods of fabrication.

289

00:12:49,666 --> 00:12:52,766

So we do have methods
of creating cellular materials

290

00:12:52,766 --> 00:12:54,966

with greater reductions
in mass density

291

00:12:54,966 --> 00:12:58,100

than those 1 to 10
that I just mentioned.

292

00:12:58,100 --> 00:12:59,633

So these, however,
have the property

293

00:12:59,633 --> 00:13:01,433

that instead of material
stretching,

294

00:13:01,433 --> 00:13:03,200

the phenomenon
that governs their behavior

295

00:13:03,200 --> 00:13:04,566

under load is bending.

296

00:13:04,566 --> 00:13:07,000

This results in the bulk

297

00:13:07,000 --> 00:13:10,166

following reduced
mechanical property laws,

298

00:13:10,166 --> 00:13:12,066

which is shown here.

299

00:13:12,066 --> 00:13:13,400

And many of these materials

300
00:13:13,400 --> 00:13:15,366
can be produced
very efficiently.

301
00:13:15,366 --> 00:13:16,600
For instance, by bubbling

302
00:13:16,600 --> 00:13:19,766
or mixing a liquid state
with air before hardening.

303
00:13:19,766 --> 00:13:21,300
It is these kinds
of the materials

304
00:13:21,300 --> 00:13:23,866
that have achieved
ultralight status

305
00:13:23,866 --> 00:13:26,433
at the extreme left-hand
side of this chart.

306
00:13:26,433 --> 00:13:28,466
But this still leaves
this entire

307
00:13:28,466 --> 00:13:29,966
red region of the chart behind,

308
00:13:29,966 --> 00:13:31,766
due to the effect
of the beam-bending

309
00:13:31,766 --> 00:13:33,566
dominated behavior

310
00:13:33,566 --> 00:13:35,433
and the order of magnitude

practical limit

311

00:13:35,433 --> 00:13:37,266
for the processes
that produce materials

312

00:13:37,266 --> 00:13:38,600
with proportional scaling.

313

00:13:38,600 --> 00:13:41,266
So it's this region of
material property space

314

00:13:41,266 --> 00:13:44,900
that we focused on
with some success.

315

00:13:44,900 --> 00:13:47,100
So it's interesting because
for many applications,

316

00:13:47,100 --> 00:13:49,400
it's not a strength
or stiffness that matters

317

00:13:49,400 --> 00:13:50,866
or weight that matters,

318

00:13:50,866 --> 00:13:53,333
it's strength
or stiffness per weight.

319

00:13:53,333 --> 00:13:55,400
So you can make something

320

00:13:55,400 --> 00:13:57,000
with the same stiffness
per weight,

321

00:13:57,000 --> 00:13:58,633
but at a lower weight.

322
00:13:58,633 --> 00:14:01,200
Then it costs less to do things
like move it around,

323
00:14:01,200 --> 00:14:03,866
keep it steady, heat it up
or cool it down.

324
00:14:03,866 --> 00:14:06,133
So one current
industry strategy

325
00:14:06,133 --> 00:14:09,133
for trying to get total systems
into this regime

326
00:14:09,133 --> 00:14:11,300
is with fiber composites,

327
00:14:11,300 --> 00:14:13,066
which is a technology
that's undergoing a bit

328
00:14:13,066 --> 00:14:15,366
of a Renaissance
in prototyping capabilities

329
00:14:15,366 --> 00:14:18,733
and extensibility of
manufacturing equipment.

330
00:14:18,733 --> 00:14:20,466
So, here we traditionally
have a process

331
00:14:20,466 --> 00:14:22,233
where the manufacturing

systems are larger

332

00:14:22,233 --> 00:14:24,300
and more complex
than the product,

333

00:14:24,300 --> 00:14:25,966
which can be a problem
when your product

334

00:14:25,966 --> 00:14:29,100
is as large and complex
as a passenger aircraft.

335

00:14:29,100 --> 00:14:32,300
So this diagram is from a guide
that does an admirable job

336

00:14:32,300 --> 00:14:35,466
of distilling the best practices
for composites material design

337

00:14:35,466 --> 00:14:37,266
analysis and manufacturing,

338

00:14:37,266 --> 00:14:38,666
as well as testing,

339

00:14:38,666 --> 00:14:44,733
into a concise,
693-page handbook.

340

00:14:44,733 --> 00:14:48,800
Commercial aircraft are used
as examples in this guide

341

00:14:48,800 --> 00:14:50,966
and new composite aircraft
architecture can be partly

342

00:14:50,966 --> 00:14:53,033
considered as attempts
to reduce the enormity

343

00:14:53,033 --> 00:14:56,400
of this pyramid of design
analysis and testing.

344

00:14:56,400 --> 00:14:59,233
For example,
we now have the cockpit

345

00:14:59,233 --> 00:15:00,933
and forward fuselage

346

00:15:00,933 --> 00:15:05,433
down behind the ninth
passenger window.

347

00:15:05,433 --> 00:15:07,700
All the way from
basically in the nose

348

00:15:07,700 --> 00:15:11,333
to behind the ninth
passenger window,

349

00:15:11,333 --> 00:15:14,233
as a single piece
manufactured as a single,

350

00:15:14,233 --> 00:15:16,200
monolithic
carbon fiber winding.

351

00:15:16,200 --> 00:15:17,800
So this one part
is about 1/6

352

00:15:17,800 --> 00:15:19,466
the size of the entire plane,

353

00:15:19,466 --> 00:15:21,533
and needs a tool or framework

354

00:15:21,533 --> 00:15:23,866
that's about 1/3 the size
of the entire plane,

355

00:15:23,866 --> 00:15:25,266
which needs to go
into an autoclave

356

00:15:25,266 --> 00:15:26,500
to cure the composite

357

00:15:26,500 --> 00:15:28,600
that's almost the size
of the plane,

358

00:15:28,600 --> 00:15:30,300
and then get processed
on a CNC mill

359

00:15:30,300 --> 00:15:33,066
that is also almost
the size of the plane.

360

00:15:33,066 --> 00:15:34,566
When it comes to
shipping the part

361

00:15:34,566 --> 00:15:36,133
to the final assembly plant,

362

00:15:36,133 --> 00:15:37,700
it has to go on a plane

363

00:15:37,700 --> 00:15:41,000

that's twice
the size of a plane.

364

00:15:41,000 --> 00:15:42,566

This plane was custom-designed

365

00:15:42,566 --> 00:15:45,433

and built as part of
the manufacturing process

366

00:15:45,433 --> 00:15:46,700

for another plane.

367

00:15:46,700 --> 00:15:49,300

So this isn't
particularly scalable.

368

00:15:49,300 --> 00:15:54,766

By the way, not only one
manufacturer has done this.

369

00:15:54,766 --> 00:15:57,933

This isn't the first time
in history this has been done.

370

00:15:57,933 --> 00:16:00,100

But it isn't
particularly scalable,

371

00:16:00,100 --> 00:16:02,566

though they've done an
admirable job up to this point.

372

00:16:02,566 --> 00:16:05,666

But it's largely in the name
of lighter weight.

373

00:16:05,666 --> 00:16:08,566

So what digital

composites propose

374

00:16:08,566 --> 00:16:11,533

is to assemble structures
from a lot of linked parts.

375

00:16:11,533 --> 00:16:13,666

The core concept is that

376

00:16:13,666 --> 00:16:16,600

if we can effectively couple
loops of fibers,

377

00:16:16,600 --> 00:16:18,900

then a chain of discrete
fiber composite parts

378

00:16:18,900 --> 00:16:21,400

can be close to the strength
of a monolithic part,

379

00:16:21,400 --> 00:16:23,233

and would have advantages
with manufacturing

380

00:16:23,233 --> 00:16:25,166

processes, serviceability,

381

00:16:25,166 --> 00:16:26,933

and reusability,

382

00:16:26,933 --> 00:16:29,233

in addition to the tunability
and extensibility

383

00:16:29,233 --> 00:16:32,833

that are general goals
of digital materials.

384

00:16:32,833 --> 00:16:34,433
And the tunability in particular

385
00:16:34,433 --> 00:16:38,800
is also a very specific
goal of composites.

386
00:16:38,800 --> 00:16:42,300
And so, at the sort of larger
scale than amino acids,

387
00:16:42,300 --> 00:16:44,433
of course, recent work has shown

388
00:16:44,433 --> 00:16:46,266
that a building block approach

389
00:16:46,266 --> 00:16:49,066
can be used to achieve
novel material properties

390
00:16:49,066 --> 00:16:50,566
and cellular materials

391
00:16:50,566 --> 00:16:52,566
with centimeter scale
lattice pitch.

392
00:16:52,566 --> 00:16:54,666
So these are essentially
three-dimensional,

393
00:16:54,666 --> 00:16:56,600
optimized fiber composites.

394
00:16:56,600 --> 00:17:01,866
You get the unidirectional
material performance scaling,

395

00:17:01,866 --> 00:17:05,633
but now in a quasi-isotropic
cellular solid.

396
00:17:05,633 --> 00:17:09,700
So we've shown better
specific modulus scaling

397
00:17:09,700 --> 00:17:11,933
than previously known
ultralight materials,

398
00:17:11,933 --> 00:17:14,300
and this is possible
because assembly allows us

399
00:17:14,300 --> 00:17:16,933
to produce geometries
that have not been achieved

400
00:17:16,933 --> 00:17:19,266
with conventional
ultralight processes.

401
00:17:19,266 --> 00:17:21,600
So, the strength of the material
performed similarly

402
00:17:21,600 --> 00:17:23,866
to the expectations of other
high-performance

403
00:17:23,866 --> 00:17:25,233
ultralight materials,

404
00:17:25,233 --> 00:17:28,033
and the stiffness
is much better.

405
00:17:28,033 --> 00:17:30,133

So despite how light it is,

406

00:17:30,133 --> 00:17:32,800

you don't need much
of this stuff to, for instance,

407

00:17:32,800 --> 00:17:35,300

support the weight of a person.

408

00:17:35,300 --> 00:17:37,600

And you'll see some
application slides

409

00:17:37,600 --> 00:17:38,900

that demonstrate that.

410

00:17:38,900 --> 00:17:40,866

But we're not that interested
in quasi-static

411

00:17:40,866 --> 00:17:42,966

applications here.

412

00:17:42,966 --> 00:17:44,666

There are many metrics
that we can use

413

00:17:44,666 --> 00:17:46,366

to compare the usefulness
of this material

414

00:17:46,366 --> 00:17:48,700

to what we use today
and a simple example

415

00:17:48,700 --> 00:17:50,066

is a beam performance index,

416

00:17:50,066 --> 00:17:52,800

first described by
Ashby and Cebon,

417

00:17:52,800 --> 00:17:55,066

which simply quantifies
beam-bending stiffness.

418

00:17:55,066 --> 00:17:58,433

So if we're given
description of a beam,

419

00:17:58,433 --> 00:18:00,800

a given cross-sectional
mass distribution,

420

00:18:00,800 --> 00:18:02,533

or a second moment
of inertia,

421

00:18:02,533 --> 00:18:04,533

this is governed by
the square root of the material

422

00:18:04,533 --> 00:18:07,266

modulus divided by the mass
density of the material.

423

00:18:07,266 --> 00:18:10,733

So, we can immediately
recognize that exceeding

424

00:18:10,733 --> 00:18:12,733

the quadratic relative density

425

00:18:12,733 --> 00:18:15,366

to relative modulus
of cellular solid scaling

426

00:18:15,366 --> 00:18:16,833

will have a very

positive effect

427

00:18:16,833 --> 00:18:18,166
on beam performance.

428

00:18:18,166 --> 00:18:20,533
So by reducing the weight

429

00:18:20,533 --> 00:18:25,433
for these very specific
performance metrics,

430

00:18:25,433 --> 00:18:27,733
we don't have to maintain
ideal performance,

431

00:18:27,733 --> 00:18:30,733
as long as we don't go below
the quadratic scaling

432

00:18:30,733 --> 00:18:33,266
to actually increase
the functional performance

433

00:18:33,266 --> 00:18:34,766
in an application.

434

00:18:34,766 --> 00:18:38,500
Even for one
as simple as a beam.

435

00:18:38,500 --> 00:18:42,633
So, here we see

436

00:18:42,633 --> 00:18:45,666
that we've achieved

437

00:18:45,666 --> 00:18:49,400
an experiment

of better performance

438

00:18:49,400 --> 00:18:51,500
than conventional
aerostructure materials.

439

00:18:51,500 --> 00:18:53,933
So this is based on
the linear elastic regime,

440

00:18:53,933 --> 00:18:56,466
which is generally considered
to be the useful bit.

441

00:18:56,466 --> 00:18:59,433
And when you exceed
the linear elastic regime,

442

00:18:59,433 --> 00:19:04,733
we do see a non-dissipative
super elastic mode.

443

00:19:04,733 --> 00:19:07,633
And so this--

444

00:19:07,633 --> 00:19:10,666
I won't go too much
into detail here,

445

00:19:10,666 --> 00:19:16,766
but what you see is

446

00:19:16,766 --> 00:19:18,466
there's this effective twisting,

447

00:19:18,466 --> 00:19:19,833
the free end node
is transferring

448

00:19:19,833 --> 00:19:22,666
a substantial bending moment
through these nodes,

449
00:19:22,666 --> 00:19:27,400
and you'll see from
the strut spacing

450
00:19:27,400 --> 00:19:31,000
and the buckling of the struts

451
00:19:31,000 --> 00:19:34,700
that you have this
coordinating twisting motion.

452
00:19:34,700 --> 00:19:36,166
And so throughout
a large structure,

453
00:19:36,166 --> 00:19:39,100
this appears to develop into
a coordinated buckling behavior

454
00:19:39,100 --> 00:19:40,900
that is something like
a three-dimensional

455
00:19:40,900 --> 00:19:42,600
folding or pleating.

456
00:19:42,600 --> 00:19:44,933
This is also readily apparent
in simulation work

457
00:19:44,933 --> 00:19:48,200
being done by Khan and Joseph.

458
00:19:48,200 --> 00:19:50,066
And the rotational displacements

459

00:19:50,066 --> 00:19:53,266

that develop for each node
are anti-symmetric

460

00:19:53,266 --> 00:19:56,000

relative to most
of its neighbors.

461

00:19:56,000 --> 00:19:58,000

A kind of unconstrained
coordinated twisting

462

00:19:58,000 --> 00:19:59,933

stress response
has been reported

463

00:19:59,933 --> 00:20:02,466

in two-dimensional surfaces,

464

00:20:02,466 --> 00:20:04,400

particularly some natural ones.

465

00:20:04,400 --> 00:20:06,233

And we're currently
working to describe this

466

00:20:06,233 --> 00:20:08,766

for such a partially
constrained condition

467

00:20:08,766 --> 00:20:10,566

in three-dimensional lattices.

468

00:20:10,566 --> 00:20:11,766

So what happens if we keep

469

00:20:11,766 --> 00:20:15,400

loading the material
past this point?

470

00:20:15,400 --> 00:20:17,433

A significant
perceived pain point

471

00:20:17,433 --> 00:20:18,966

with fiber composites

472

00:20:18,966 --> 00:20:21,566

is with failure modes
of typical engineered parts.

473

00:20:21,566 --> 00:20:23,733

A caricature of
the stress strain curve

474

00:20:23,733 --> 00:20:25,500

for a typical fiber
composite part

475

00:20:25,500 --> 00:20:27,900

is a straight
linear elastic line

476

00:20:27,900 --> 00:20:29,766

that abruptly ends in breakage.

477

00:20:29,766 --> 00:20:31,433

And what this means,
in a practical sense,

478

00:20:31,433 --> 00:20:33,566

is that breakages can be
accompanied by elastic

479

00:20:33,566 --> 00:20:36,500

unloading of a great deal
of stored energy.

480

00:20:36,500 --> 00:20:38,600

And this can be quite dangerous.

481

00:20:38,600 --> 00:20:40,333

So now we still have a great deal of work

482

00:20:40,333 --> 00:20:41,500

to do on this topic,

483

00:20:41,500 --> 00:20:43,866

of failure mechanisms for digital composites,

484

00:20:43,866 --> 00:20:45,533

but early tests suggest the possibility

485

00:20:45,533 --> 00:20:47,000

of being able to tune materials

486

00:20:47,000 --> 00:20:48,966

to behave in new ways.

487

00:20:48,966 --> 00:20:53,133

So this is an open frontier in materials science.

488

00:20:53,133 --> 00:20:55,233

So why does this work?

489

00:20:55,233 --> 00:20:57,166

So it's possible that we have mechanics at work

490

00:20:57,166 --> 00:20:59,966

that can be described as stretch-bend coupling.

491

00:20:59,966 --> 00:21:02,800

And this has been described,

492

00:21:02,800 --> 00:21:09,400

not so much in the bulk

material solids literature...

493

00:21:09,400 --> 00:21:13,566

but...

494

00:21:13,566 --> 00:21:15,100

once there's any tendency

495

00:21:15,100 --> 00:21:17,933

towards microstructural

bending under load,

496

00:21:17,933 --> 00:21:20,366

for the kinds of materials

497

00:21:20,366 --> 00:21:22,366

that have been considered

498

00:21:22,366 --> 00:21:24,166

in the class

of stochastic materials

499

00:21:24,166 --> 00:21:27,066

in the cellular solids

literature,

500

00:21:27,066 --> 00:21:29,900

it seems that the

geometries that result

501

00:21:29,900 --> 00:21:33,100

from the typical ways

of making engineered foams,

502

00:21:33,100 --> 00:21:36,033

stochastic engineered foams,
predispose the structure

503

00:21:36,033 --> 00:21:38,066

to fall into
a bending-dominated behavior.

504

00:21:38,066 --> 00:21:40,933

So we don't really see
this middle regime

505

00:21:40,933 --> 00:21:43,300

in most of engineered
cellular solids.

506

00:21:43,300 --> 00:21:46,900

There just doesn't appear to be
much observable middle ground.

507

00:21:46,900 --> 00:21:48,866

In contrast,
studies of biomaterials

508

00:21:48,866 --> 00:21:52,233

such as intracellular meshworks
of actin,

509

00:21:52,233 --> 00:21:54,366

microtubules
and extracellular matrices

510

00:21:54,366 --> 00:21:57,166

of fibrin and collagen have
shown mechanical performance

511

00:21:57,166 --> 00:22:00,166

that exceeds predictions based
on framework rigidity theory.

512

00:22:00,166 --> 00:22:02,166

So these are the same theories

513

00:22:02,166 --> 00:22:06,033

that underpin
the cellular solids work.

514

00:22:06,033 --> 00:22:08,433

And they use these
rigidity criteria as bases

515

00:22:08,433 --> 00:22:10,700

for estimating the balance
of degrees of freedom

516

00:22:10,700 --> 00:22:12,133

and constraints
in a structure.

517

00:22:12,133 --> 00:22:14,133

So recent work suggests

518

00:22:14,133 --> 00:22:15,700

that departing from
these principles

519

00:22:15,700 --> 00:22:17,566

by assuming that significant
bending moments

520

00:22:17,566 --> 00:22:20,000

can be transmitted through
the nodes in the structure,

521

00:22:20,000 --> 00:22:25,233

can result in effective
models of these biomaterials.

522

00:22:25,233 --> 00:22:26,966

So we think,

523

00:22:26,966 --> 00:22:29,033

while many support
this model

524

00:22:29,033 --> 00:22:30,700

for its simplicity
with an understanding

525

00:22:30,700 --> 00:22:32,733

of the relative magnitude
of the forces concerned

526

00:22:32,733 --> 00:22:38,633

when you're talking
about biomaterials,

527

00:22:38,633 --> 00:22:41,766

and if in principle
this kind of framework exists,

528

00:22:41,766 --> 00:22:44,233

then we should be able to create
one with a macroscale

529

00:22:44,233 --> 00:22:46,833

and it looks like we have.

530

00:22:46,833 --> 00:22:48,866

The level of description
that's being used

531

00:22:48,866 --> 00:22:52,700

for the biomaterials
actually suits

532

00:22:52,700 --> 00:22:55,800

what we're doing

perhaps even better.

533

00:22:55,800 --> 00:22:57,500

So if we apply
a simple adjustment

534

00:22:57,500 --> 00:22:59,300

to the dimensional
scaling arguments

535

00:22:59,300 --> 00:23:01,933

that so efficiently describe
classical cellular solids,

536

00:23:01,933 --> 00:23:03,400

we produce a scaling rule

537

00:23:03,400 --> 00:23:05,000

for stretch-bend coupled
lattices

538

00:23:05,000 --> 00:23:06,600

that's very close
to the behavior

539

00:23:06,600 --> 00:23:10,633

that we actually see.

540

00:23:10,633 --> 00:23:14,233

And so we have these
different lattice types

541

00:23:14,233 --> 00:23:16,966

that we've essentially
been playing with,

542

00:23:16,966 --> 00:23:20,766

with building blocks
that we produce.

543

00:23:20,766 --> 00:23:26,666

We snapped them together,
initially by hand.

544

00:23:26,666 --> 00:23:29,266

And we have these different
types of geometries

545

00:23:29,266 --> 00:23:30,533

that we're working with.

546

00:23:30,533 --> 00:23:32,033

There's nothing
magical about any one

547

00:23:32,033 --> 00:23:33,600

of these particular geometries,

548

00:23:33,600 --> 00:23:35,033

there's just ones
that work and ones

549

00:23:35,033 --> 00:23:37,600

that we can get
to work together.

550

00:23:37,600 --> 00:23:39,466

And so, we can ask the question
of what happens

551

00:23:39,466 --> 00:23:42,800

if we start mixing them?

552

00:23:42,800 --> 00:23:44,866

And so, to illustrate

553

00:23:44,866 --> 00:23:47,966

the sort of exponential fan-out
and variability

554

00:23:47,966 --> 00:23:49,500

that you can get by doing this,

555

00:23:49,500 --> 00:23:50,966

this is an example

of designer

556

00:23:50,966 --> 00:23:52,833

material properties

from this approach.

557

00:23:52,833 --> 00:23:55,333

So each of these

towers are built

558

00:23:55,333 --> 00:23:57,466

with the same set of components

559

00:23:57,466 --> 00:23:59,266

but compress or buckle

in different ways,

560

00:23:59,266 --> 00:24:00,900

under identical

boundary conditions,

561

00:24:00,900 --> 00:24:02,533

all as a result of differences

562

00:24:02,533 --> 00:24:06,266

in the ordering or spatial

arrangement of the parts.

563

00:24:06,266 --> 00:24:12,300

So this becomes

a jumping-off point for us,

564

00:24:12,300 --> 00:24:17,200

as an example of bringing it
down to an application

565

00:24:17,200 --> 00:24:18,966
that utilizes the variability

566

00:24:18,966 --> 00:24:20,600
that you get
as you mix these parts.

567

00:24:20,600 --> 00:24:22,266
So the key thing
to understand here

568

00:24:22,266 --> 00:24:24,500
is that there's
this global variability

569

00:24:24,500 --> 00:24:26,000
that we can produce by

570

00:24:26,000 --> 00:24:28,866
mixing a very small set
of different types of parts,

571

00:24:28,866 --> 00:24:30,400
as long as we have
a lot of them.

572

00:24:30,400 --> 00:24:32,133
And so it's exponential,
the behaviors

573

00:24:32,133 --> 00:24:35,033
that we get are exponential

574

00:24:35,033 --> 00:24:36,233
with a number of parts

575

00:24:36,233 --> 00:24:39,133
that compose our system.

576

00:24:39,133 --> 00:24:45,433
So the first example is wings.

577

00:24:45,433 --> 00:24:53,933
If I can get this to play.

578

00:24:53,933 --> 00:24:56,433
So this shows,

579

00:24:56,433 --> 00:25:00,533
with the same models
of the large lattices

580

00:25:00,533 --> 00:25:03,533
that I just showed,

581

00:25:03,533 --> 00:25:05,300
what kinds of deformations
can be produced

582

00:25:05,300 --> 00:25:07,433
by simple actuators

583

00:25:07,433 --> 00:25:11,700
with just specified
arrangement of stiffer

584

00:25:11,700 --> 00:25:14,433
and less stiff parts
in a structure.

585

00:25:20,600 --> 00:25:22,333
And so we did some
initial testing

586

00:25:22,333 --> 00:25:23,900

of different kinds
of shapes

587

00:25:23,900 --> 00:25:27,066

going between
different kinds of shapes,

588

00:25:27,066 --> 00:25:29,333

and seeing if in principle,

589

00:25:29,333 --> 00:25:30,933

they could hold up
for instance,

590

00:25:30,933 --> 00:25:33,533

in a wind tunnel.

591

00:25:33,533 --> 00:25:35,333

And the results
look promising enough

592

00:25:35,333 --> 00:25:39,400

that we went forward
with the NARI

593

00:25:39,400 --> 00:25:43,833

Team Seedling project,

594

00:25:43,833 --> 00:25:48,933

which basically takes
the pyramid of tests

595

00:25:48,933 --> 00:25:52,233

and takes out the middle.

596

00:25:52,233 --> 00:25:55,800

So the top
of the pyramid of tests

597

00:25:55,800 --> 00:25:57,566
are the small coupon tests,

598
00:25:57,566 --> 00:26:00,866
and our parts look like
those small coupons.

599
00:26:00,866 --> 00:26:03,833
And so we can go very quickly,

600
00:26:03,833 --> 00:26:07,266
as far as the entire
process from design

601
00:26:07,266 --> 00:26:09,000
and manufacturing,

602
00:26:09,000 --> 00:26:11,033
from those small coupon tests,

603
00:26:11,033 --> 00:26:14,066
to a complete structure

604
00:26:14,066 --> 00:26:19,666
with apparently
complex behavior.

605
00:26:19,666 --> 00:26:22,733
And so this shows
the process...

606
00:26:32,633 --> 00:26:38,366
Including some testing
of our skin structure.

607
00:26:42,300 --> 00:26:45,933
That was on campus, by the way.

608
00:26:45,933 --> 00:26:47,200

And so we can go through--

609

00:26:47,200 --> 00:26:50,166
and the skins are
also discrete units.

610

00:26:50,166 --> 00:26:53,433
And so this obeys the same
sort of property

611

00:26:53,433 --> 00:26:56,500
of what we can do, in terms
of the design and testing,

612

00:26:56,500 --> 00:26:58,666
and very quickly
get to the wind tunnel

613

00:26:58,666 --> 00:27:00,133
model that you see here.

614

00:27:00,133 --> 00:27:02,933
And in fact, we had two.

615

00:27:02,933 --> 00:27:06,800
And we have the parts
for another one.

616

00:27:06,800 --> 00:27:10,933
And so you see the bench
testing that we've done

617

00:27:10,933 --> 00:27:12,733
to validate

618

00:27:12,733 --> 00:27:17,400
the behavior and the stiffness
of the structure.

619

00:27:17,400 --> 00:27:20,933
And we've been able to bring

620
00:27:20,933 --> 00:27:25,533
the modeling down
in the same way.

621
00:27:25,533 --> 00:27:29,466
So, here we're looking
at vibrational modes,

622
00:27:29,466 --> 00:27:30,766
using a modeling strategy

623
00:27:30,766 --> 00:27:34,200
that actually obeys
the same kind of principles

624
00:27:34,200 --> 00:27:37,233
as our fabrication strategy.

625
00:27:37,233 --> 00:27:38,633
And so what I mean by this is

626
00:27:38,633 --> 00:27:43,400
that a traditional
finite element model

627
00:27:43,400 --> 00:27:44,900
will break down the geometry

628
00:27:44,900 --> 00:27:47,166
into a number
of finite elements

629
00:27:47,166 --> 00:27:49,133
that compose your mesh.

630
00:27:49,133 --> 00:27:51,566

And what we've been able to show

631

00:27:51,566 --> 00:27:56,100
is that we can have a number
of different mesh element

632

00:27:56,100 --> 00:28:00,200
types that equals the number
of different parts of we have.

633

00:28:00,200 --> 00:28:02,600
And we can model
and exhaustively test

634

00:28:02,600 --> 00:28:05,900
to tune the model
of those individual parts,

635

00:28:05,900 --> 00:28:09,100
and then each one of those
is a single simplex

636

00:28:09,100 --> 00:28:11,400
in the mesh for our simulation.

637

00:28:11,400 --> 00:28:15,033
And that allows us to do things,

638

00:28:15,033 --> 00:28:18,433
in terms of the simulation
and design,

639

00:28:18,433 --> 00:28:21,666
essentially in real-time
and with computational loads

640

00:28:21,666 --> 00:28:27,566
that vastly undercut
traditional processes.

641
00:28:27,566 --> 00:28:31,466
And so all this work
in the wind tunnel tests

642
00:28:31,466 --> 00:28:33,366
that you just saw videos of

643
00:28:33,366 --> 00:28:36,066
led up to a direct comparison

644
00:28:36,066 --> 00:28:38,900
between the white
3-D printed model

645
00:28:38,900 --> 00:28:40,333
you see on the bottom.

646
00:28:40,333 --> 00:28:42,400
It's not a biplane.

647
00:28:42,400 --> 00:28:44,266
They're just stacked
on top of each other.

648
00:28:44,266 --> 00:28:47,633
And the twist model
on top.

649
00:28:47,633 --> 00:28:51,166
And you can see
on the bottom model

650
00:28:51,166 --> 00:28:53,766
that we have
conventional ailerons

651
00:28:53,766 --> 00:28:56,400
that are replaceable
on the bottom model.

652

00:28:56,400 --> 00:28:58,600

The bottom model, by the way,
was 3-D printed

653

00:28:58,600 --> 00:29:04,766

by Gary Wainwright at Langley.

654

00:29:04,766 --> 00:29:06,900

And so we were able to do
a direct comparison

655

00:29:06,900 --> 00:29:10,966

between these two

656

00:29:10,966 --> 00:29:12,233

and show the viability

657

00:29:12,233 --> 00:29:15,100

of the digital
composite structure.

658

00:29:15,100 --> 00:29:20,033

So as opposed to a traditional
wind tunnel model

659

00:29:20,033 --> 00:29:24,500

that is often built
extremely stiff,

660

00:29:24,500 --> 00:29:29,800

sometimes out of
a solid block of metal,

661

00:29:29,800 --> 00:29:34,433

we were able to use
a structure that,

662

00:29:34,433 --> 00:29:37,066

in this case,
weighs 100 grams on each side.

663
00:29:43,733 --> 00:29:47,466
And we had some fun
with the wind tunnel tests.

664
00:29:47,466 --> 00:29:53,166
Here, we're driving it
with a forced oscillation

665
00:29:53,166 --> 00:29:57,400
and also driving
the wings

666
00:29:57,400 --> 00:29:59,566
to actually counter the motion

667
00:29:59,566 --> 00:30:03,300
of the forced oscillation
of the wind tunnel rig.

668
00:30:03,300 --> 00:30:06,300
So this is the team,

669
00:30:06,300 --> 00:30:08,700
including the flight
dynamics group at Langley,

670
00:30:08,700 --> 00:30:13,033
that was wonderful
to work with.

671
00:30:13,033 --> 00:30:16,966
And so we moved forward
with 100 grams per wing,

672
00:30:16,966 --> 00:30:19,800
and surviving to full pressure
of the wind tunnel

673

00:30:19,800 --> 00:30:21,633
that we used,

674

00:30:21,633 --> 00:30:25,733
we thought, "Why not fly it?"

675

00:30:25,733 --> 00:30:33,266
And so we took the same
wings and flew them.

676

00:30:37,366 --> 00:30:41,733
There was sound, but you can
imagine the sound that it makes.

677

00:30:41,733 --> 00:30:43,066
Vroom!

678

00:30:49,566 --> 00:30:55,133
And that's a barrel roll,

679

00:30:55,133 --> 00:30:58,233
thanks to a very skilled pilot.

680

00:31:07,033 --> 00:31:10,333
And so what we're going forward
with for this project,

681

00:31:10,333 --> 00:31:12,600
which is the Mission Adaptive
Digital Composite

682

00:31:12,600 --> 00:31:14,200
Aerostructures
Technologies project,

683

00:31:14,200 --> 00:31:17,033
or MADCAT for short,

684
00:31:17,033 --> 00:31:21,466
are what we're calling X
to the N planes.

685
00:31:21,466 --> 00:31:23,900
And so you can see that,

686
00:31:23,900 --> 00:31:26,366
if we have the set of
building blocks,

687
00:31:26,366 --> 00:31:28,933
that we can show
can be rapidly integrated

688
00:31:28,933 --> 00:31:31,533
into a flying aircraft,

689
00:31:31,533 --> 00:31:34,833
and we can take that
same set of building blocks

690
00:31:34,833 --> 00:31:37,100
and just by snapping them apart

691
00:31:37,100 --> 00:31:38,666
and snapping them
back together again

692
00:31:38,666 --> 00:31:44,066
in a different configuration,

693
00:31:44,066 --> 00:31:46,200
meet very rapidly,

694
00:31:46,200 --> 00:31:49,300
through design and analysis,

695

00:31:49,300 --> 00:31:52,933

all of the goals
of aircraft design

696

00:31:52,933 --> 00:31:55,766

analysis and manufacturing.

697

00:31:55,766 --> 00:31:58,566

That means that
we can very quickly

698

00:31:58,566 --> 00:32:01,200

get into the air
lots of different,

699

00:32:01,200 --> 00:32:04,633

maybe novel, maybe theorized
in the literature,

700

00:32:04,633 --> 00:32:09,300

but difficult to fabricate
aircraft types including,

701

00:32:09,300 --> 00:32:12,833

in particular,
the morphing aircraft types.

702

00:32:12,833 --> 00:32:15,166

Because what we've
been able to show

703

00:32:15,166 --> 00:32:18,766

is the ability to change

704

00:32:18,766 --> 00:32:20,966

where a stiffer part
and a less stiff part

705

00:32:20,966 --> 00:32:22,600

is throughout the structure,

706

00:32:22,600 --> 00:32:24,800
in order to define
global deformation modes

707

00:32:24,800 --> 00:32:27,000
with very simple actuation.

708

00:32:27,000 --> 00:32:34,233
There are only two servos
on the twist wing

709

00:32:34,233 --> 00:32:35,733
that I just showed.

710

00:32:35,733 --> 00:32:38,766
And we think we can keep

711

00:32:38,766 --> 00:32:40,800
the number of actuators
extremely low

712

00:32:40,800 --> 00:32:44,633
for essentially arbitrarily
complex deformation modes,

713

00:32:44,633 --> 00:32:46,733
where the number
of states relates

714

00:32:46,733 --> 00:32:48,333
to the number of actuators,

715

00:32:48,333 --> 00:32:53,433
not the complexity
of the deformation mode.

716

00:32:53,433 --> 00:32:55,433
And the manufacturing techniques

717

00:32:55,433 --> 00:32:57,166

that we look to employ
with these methods

718

00:32:57,166 --> 00:32:58,566

and that we're going
forward with,

719

00:32:58,566 --> 00:33:01,533

are ones that suit
mass manufacturing.

720

00:33:01,533 --> 00:33:04,700

Which means that
the cost of all

721

00:33:04,700 --> 00:33:07,933

of the components
can come very close

722

00:33:07,933 --> 00:33:11,900

to the theoretical energy cost
of those components.

723

00:33:16,833 --> 00:33:18,600

And the long-term vision,

724

00:33:18,600 --> 00:33:22,633

if you have a material ecosystem

725

00:33:22,633 --> 00:33:25,900

that works this way,

726

00:33:25,900 --> 00:33:28,933

is the ability to take
that fundamental energy

727

00:33:28,933 --> 00:33:33,833

cost and amortize it over many different applications,

728

00:33:33,833 --> 00:33:37,500

because the actual cost of assembling these things

729

00:33:37,500 --> 00:33:41,166

by snapping them together is extremely, extremely low.

730

00:33:41,166 --> 00:33:42,833

And so you can start to envision

731

00:33:42,833 --> 00:33:49,166

completely new ways of managing material.

732

00:33:49,166 --> 00:33:56,166

So this brings us to this question of--

733

00:33:56,166 --> 00:33:59,933

I've brought this to this question of price-performance.

734

00:33:59,933 --> 00:34:01,466

And so to put this in perspective,

735

00:34:01,466 --> 00:34:03,666

we can briefly look at how this proposal relates

736

00:34:03,666 --> 00:34:07,066

to aerostructures fabrication as we know it.

737

00:34:07,066 --> 00:34:09,800

And so the closest example

738

00:34:09,800 --> 00:34:12,400
of an aerostructure built
with the principle

739

00:34:12,400 --> 00:34:13,833
of distributing
load requirements

740

00:34:13,833 --> 00:34:15,500
over many smaller parts
is probably

741

00:34:15,500 --> 00:34:17,433
the Vickers geodetic aircraft.

742

00:34:17,433 --> 00:34:19,166
So one of them is a plane

743

00:34:19,166 --> 00:34:22,100
that still holds the record
for distance flown nonstop

744

00:34:22,100 --> 00:34:23,633
by a single engine aircraft.

745

00:34:23,633 --> 00:34:26,133
Over 7,000 miles.

746

00:34:26,133 --> 00:34:29,500
So we can assume that this was
not a heavy aircraft, obviously.

747

00:34:29,500 --> 00:34:32,533
So it also had
the reputation of it

748

00:34:32,533 --> 00:34:34,733

being extraordinarily
damage tolerant,

749

00:34:34,733 --> 00:34:37,400

and the unusual robustness
came at a perceived

750

00:34:37,400 --> 00:34:40,133

cost of manufacturer ability.

751

00:34:40,133 --> 00:34:42,000

And the factory countered
this perception

752

00:34:42,000 --> 00:34:43,600

was a much-publicized exercise

753

00:34:43,600 --> 00:34:45,500

where they built
an entire aircraft from start

754

00:34:45,500 --> 00:34:47,366

to finish in 24 hours,

755

00:34:47,366 --> 00:34:51,033

actually taking off
after that much time.

756

00:34:51,033 --> 00:34:52,733

There's not a lot
of information out there

757

00:34:52,733 --> 00:34:54,800

on how many parts
are in those aircraft.

758

00:34:54,800 --> 00:34:57,066

But the time of production
is similar to today's

759

00:34:57,066 --> 00:34:58,666

commercial production
capability

760

00:34:58,666 --> 00:35:03,533

for, say, a Boeing 737.

761

00:35:03,533 --> 00:35:05,633

So the current 737 fuselage

762

00:35:05,633 --> 00:35:08,066

is comprised of a couple
hundred of thousand parts,

763

00:35:08,066 --> 00:35:11,300

an additional couple hundred
of thousand fasteners, rivets,

764

00:35:11,300 --> 00:35:13,466

are used to attach
these parts to each other.

765

00:35:13,466 --> 00:35:16,133

With the factory system
of about 700 people,

766

00:35:16,133 --> 00:35:19,166

about 1 fuselage
per day is completed.

767

00:35:19,166 --> 00:35:21,533

And therefore, we can estimate
that on average,

768

00:35:21,533 --> 00:35:24,066

7,000 parts are added
to the assembly per hour,

769

00:35:24,066 --> 00:35:25,933

or 10 per person, per hour,

770

00:35:25,933 --> 00:35:27,166

or about 2 per second.

771

00:35:27,166 --> 00:35:28,800

And estimating

the total structural

772

00:35:28,800 --> 00:35:31,100

volume of the fuselage

as a cylinder,

773

00:35:31,100 --> 00:35:35,000

4 meters in diameter,

40 meters long,

774

00:35:35,000 --> 00:35:36,333

25 centimeters thick,

775

00:35:36,333 --> 00:35:41,000

gives us about

120 cubic meters.

776

00:35:41,000 --> 00:35:43,966

And this would require

about 900,000 parts,

777

00:35:43,966 --> 00:35:45,766

if we simply use

the cuboct truss

778

00:35:45,766 --> 00:35:48,500

digital composite

design presented earlier.

779

00:35:48,500 --> 00:35:50,733

So I know that trained students

780

00:35:50,733 --> 00:35:53,733

can place one of the
cuboct truss parts

781

00:35:53,733 --> 00:35:56,566

every 5 minutes or faster.

782

00:35:56,566 --> 00:35:57,900

So with the same workforce,

783

00:35:57,900 --> 00:36:00,233

the job would get done
in about five days.

784

00:36:00,233 --> 00:36:01,533

So we're not even
talking about

785

00:36:01,533 --> 00:36:03,600

a necessarily great
increase in parts

786

00:36:03,600 --> 00:36:05,166

to realize some
of the advantages

787

00:36:05,166 --> 00:36:06,833

of digital construction.

788

00:36:06,833 --> 00:36:10,466

And the difference here
is that for an entire plane,

789

00:36:10,466 --> 00:36:12,433

we would now have a few million
of the same part,

790

00:36:12,433 --> 00:36:15,133

instead of around
a million of custom parts,

791

00:36:15,133 --> 00:36:18,600
with around a million
of the same rivet.

792

00:36:18,600 --> 00:36:21,200
So the life cycle implications
are not trivial,

793

00:36:21,200 --> 00:36:23,266
from design through fabrication,

794

00:36:23,266 --> 00:36:25,166
to repair and reuse.

795

00:36:25,166 --> 00:36:28,766
It's easy to see
the potential advantages.

796

00:36:28,766 --> 00:36:33,866
So this points out
that your typical

797

00:36:33,866 --> 00:36:37,566
toy building block
price per kilogram

798

00:36:37,566 --> 00:36:42,200
comes very close
to what you would expect

799

00:36:42,200 --> 00:36:44,966
for the cost
to produce the raw material

800

00:36:44,966 --> 00:36:49,600
that it's composed of.

801

00:36:49,600 --> 00:36:54,566

The next vertical line over
are the materials

802
00:36:54,566 --> 00:37:01,033
that we're currently
using for our experiments.

803
00:37:01,033 --> 00:37:04,533
And we can expect
to come reasonably close

804
00:37:04,533 --> 00:37:08,666
to that cost,
at scale,

805
00:37:08,666 --> 00:37:13,733
for producing
arbitrarily large structures

806
00:37:13,733 --> 00:37:15,466
per kilogram.

807
00:37:15,466 --> 00:37:17,833
And so that's compared
against things

808
00:37:17,833 --> 00:37:20,133
like tennis rackets
and bicycles,

809
00:37:20,133 --> 00:37:22,100
consumer drones,

810
00:37:22,100 --> 00:37:25,533
which, I'm not sure why
they're that expensive except

811
00:37:25,533 --> 00:37:30,200
that maybe that's what you
all will pay for them.

812

00:37:30,200 --> 00:37:36,500

And then we have the newest
composite aircraft

813

00:37:36,500 --> 00:37:39,066

and your phones,

814

00:37:39,066 --> 00:37:42,300

which actually cost
more per unit kilogram.

815

00:37:42,300 --> 00:37:46,400

But, at least looks less
than an orbital launch,

816

00:37:46,400 --> 00:37:49,133

except when you consider

817

00:37:49,133 --> 00:37:55,166

what SpaceX seems
to be able to do,

818

00:37:55,166 --> 00:37:59,266

which is actually just
under what your phone costs

819

00:37:59,266 --> 00:38:02,866

per kilogram.

820

00:38:02,866 --> 00:38:04,800

And so we can look

821

00:38:04,800 --> 00:38:09,933

at what this means
for space applications,

822

00:38:09,933 --> 00:38:16,233

where this cannot only change

how you get to space,

823

00:38:16,233 --> 00:38:19,433

but what you do
once you get there.

824

00:38:19,433 --> 00:38:22,833

And so, what does it mean
to be building things in space

825

00:38:22,833 --> 00:38:24,400

and what does it do for you?

826

00:38:24,400 --> 00:38:27,733

And so the launch environment,
many of you know,

827

00:38:27,733 --> 00:38:29,866

almost always presents
the largest

828

00:38:29,866 --> 00:38:34,033

and governing structural
requirement for a spacecraft.

829

00:38:34,033 --> 00:38:35,800

And so using dimensional
scaling arguments

830

00:38:35,800 --> 00:38:37,800

in the difference between
the launch environment

831

00:38:37,800 --> 00:38:40,533

and, say,
space station deployment,

832

00:38:40,533 --> 00:38:42,966

for an assembled cube set,

833

00:38:42,966 --> 00:38:45,466

you could see a factor
of 10 difference

834

00:38:45,466 --> 00:38:48,300

in the low frequency
accelerations,

835

00:38:48,300 --> 00:38:51,933

which can theoretically result
in about a factor of 3 reduction

836

00:38:51,933 --> 00:38:54,366

in the required structural mass.

837

00:38:54,366 --> 00:38:55,766

And so this is even
more pronounced

838

00:38:55,766 --> 00:38:58,466

when you're considering
launch vibration,

839

00:38:58,466 --> 00:39:01,066

given the typical strategy
for avoiding vibration-induced

840

00:39:01,066 --> 00:39:03,400

damage by keeping natural

841

00:39:03,400 --> 00:39:05,166

resonance frequencies higher

842

00:39:05,166 --> 00:39:07,833

than the significant driving
frequencies during launch.

843

00:39:07,833 --> 00:39:09,700

And so for these

same cube sets,

844

00:39:09,700 --> 00:39:12,400

this could theoretically mean
a hundredfold or more decrease

845

00:39:12,400 --> 00:39:13,866

in the required
structural mass,

846

00:39:13,866 --> 00:39:17,633

depending on what
you need to carry.

847

00:39:17,633 --> 00:39:20,666

So that's a pretty big deal.

848

00:39:20,666 --> 00:39:26,300

And the state-of-the-art energy

849

00:39:26,300 --> 00:39:30,100

to low Earth orbit
right now,

850

00:39:30,100 --> 00:39:34,366

and that is based on
the Falcon 9.

851

00:39:34,366 --> 00:39:37,000

The gap between that
and what we know

852

00:39:37,000 --> 00:39:38,666

is the minimum
theoretical energy

853

00:39:38,666 --> 00:39:40,100

if you were, say,

854

00:39:40,100 --> 00:39:43,400
reusing all of
your launch mass--

855
00:39:43,400 --> 00:39:47,300
not including the fuel--

856
00:39:47,300 --> 00:39:48,866
is quite large,

857
00:39:48,866 --> 00:39:54,433
and actually spans the space

858
00:39:54,433 --> 00:39:58,600
of the production energy
per unit kilogram

859
00:39:58,600 --> 00:40:01,466
of a lot of the materials
that we use in space,

860
00:40:01,466 --> 00:40:04,700
or in engineered
materials in general.

861
00:40:04,700 --> 00:40:08,066
Which means as we
come down this chart

862
00:40:08,066 --> 00:40:09,566
with the right-hand line,

863
00:40:09,566 --> 00:40:11,833
it starts become
much more sensible

864
00:40:11,833 --> 00:40:15,866
to be not only building

865

00:40:15,866 --> 00:40:17,633
and doing manufacturing

866
00:40:17,633 --> 00:40:19,700
in space in general,

867
00:40:19,700 --> 00:40:22,433
but to be looking
for the materials

868
00:40:22,433 --> 00:40:26,166
to do so as well.

869
00:40:26,166 --> 00:40:30,066
Complete raw
manufacturing in space.

870
00:40:30,066 --> 00:40:33,066
And so this is something

871
00:40:33,066 --> 00:40:37,366
that's a lot of progress
has been made on,

872
00:40:37,366 --> 00:40:39,000
since the '80s,

873
00:40:39,000 --> 00:40:41,233
and we can leverage
the progress--

874
00:40:41,233 --> 00:40:46,700
the amazing progress
done by NASA,

875
00:40:46,700 --> 00:40:50,466
to look forward
to what this means

876

00:40:50,466 --> 00:40:53,833
when we know that we can now
create these bulk materials

877
00:40:53,833 --> 00:40:57,266
and cellular solids
out of composite materials.

878
00:40:57,266 --> 00:41:01,766
And now using potentially
a much smaller

879
00:41:01,766 --> 00:41:03,266
building block,

880
00:41:03,266 --> 00:41:05,366
and taking advantage
of all of the advances

881
00:41:05,366 --> 00:41:09,866
in robotics since then.

882
00:41:09,866 --> 00:41:12,000
And so here is
the building block

883
00:41:12,000 --> 00:41:13,466
as what you see on the left,

884
00:41:13,466 --> 00:41:15,833
which itself is composed
of building blocks,

885
00:41:15,833 --> 00:41:18,633
smaller building blocks.

886
00:41:18,633 --> 00:41:21,500
And they're injection
molded fiber composites,

887

00:41:21,500 --> 00:41:25,866

and the tubes are
pultruded carbon fiber.

888

00:41:25,866 --> 00:41:29,333

And these can be assembled
into these structures,

889

00:41:29,333 --> 00:41:32,100

which we can evaluate
on a load testing machine

890

00:41:32,100 --> 00:41:35,700

or by standing on them.

891

00:41:35,700 --> 00:41:39,633

And so, the bridge that you see
below weighs 18 kilograms.

892

00:41:39,633 --> 00:41:43,933

And we fit it into
two backpacks.

893

00:41:43,933 --> 00:41:48,500

And assembled it in a day.

894

00:41:48,500 --> 00:41:53,533

And then we disassembled it
and made into a boat.

895

00:41:53,533 --> 00:41:59,600

And disassembled it again
and made it into a structure.

896

00:41:59,600 --> 00:42:03,466

And so, some proof
that it's not that heavy.

897

00:42:03,466 --> 00:42:13,400

And this is the structure,

898

00:42:13,400 --> 00:42:19,000
the small habitat structure
that we built.

899

00:42:19,000 --> 00:42:23,133
And so the fungibility
of this unit, these units,

900

00:42:23,133 --> 00:42:27,233
actually extends beyond
mechanical systems.

901

00:42:27,233 --> 00:42:31,533
And so we've also been exploring

902

00:42:31,533 --> 00:42:36,233
what it means to combine
the electrical systems,

903

00:42:36,233 --> 00:42:39,066
the power systems,

904

00:42:39,066 --> 00:42:41,700
and the communication systems,

905

00:42:41,700 --> 00:42:43,166
whatever protocols for actually

906

00:42:43,166 --> 00:42:48,633
running a mission
on board a spacecraft.

907

00:42:48,633 --> 00:42:51,933
This is largely
Daniel and Greenfield's work.

908

00:42:51,933 --> 00:42:58,066

Sitting in front here.
Swell.

909
00:42:58,066 --> 00:43:01,533
This has a name
for the larger project,

910
00:43:01,533 --> 00:43:05,500
which is OuroburoSat.

911
00:43:05,500 --> 00:43:09,900
And Daniel would be happy
to discuss that name with you.

912
00:43:09,900 --> 00:43:13,733
And the OuroburoSat board

913
00:43:13,733 --> 00:43:15,266
is one of these white boards.

914
00:43:15,266 --> 00:43:18,166
And each one
can carry a payload,

915
00:43:18,166 --> 00:43:22,033
and what you see here

916
00:43:22,033 --> 00:43:24,266
includes a coms payload
on the one on the right

917
00:43:24,266 --> 00:43:25,900
and actually
an experimental payload

918
00:43:25,900 --> 00:43:28,166
on the one on the left.

919
00:43:28,166 --> 00:43:31,666

And so these boards can
all communicate with each other,

920
00:43:31,666 --> 00:43:35,233
not only share information,
but share power.

921
00:43:35,233 --> 00:43:38,166
And so they can
each handle power production

922
00:43:38,166 --> 00:43:41,500
with solar panels
and power storage.

923
00:43:41,500 --> 00:43:46,033
And they're reconfigurable
into different layouts.

924
00:43:46,033 --> 00:43:48,833
So we were lucky enough

925
00:43:48,833 --> 00:43:52,366
to be able to work with
Marcus Murbach

926
00:43:52,366 --> 00:43:55,300
to get a flight.

927
00:43:55,300 --> 00:43:59,400
And the space that we were
given was the shape of this,

928
00:43:59,400 --> 00:44:01,200
instead of the shape of this.

929
00:44:01,200 --> 00:44:04,866
So we just reconfigured it

930

00:44:04,866 --> 00:44:11,000
and flew that
on board a sounding rocket.

931
00:44:13,266 --> 00:44:15,000
So there's obviously
no underestimating

932
00:44:15,000 --> 00:44:18,466
what things you can learn

933
00:44:18,466 --> 00:44:20,500
from an actual
flight experiment.

934
00:44:20,500 --> 00:44:23,033
And so going forward with that,

935
00:44:23,033 --> 00:44:27,500
this version shows the inner
connectivity extending out,

936
00:44:27,500 --> 00:44:30,300
not just to a cube,
but in three dimensions

937
00:44:30,300 --> 00:44:33,700
to fill a volume.

938
00:44:33,700 --> 00:44:37,033
And so where
do we go from here?

939
00:44:37,033 --> 00:44:43,200
And so this is the direction
that we're trying to head in.

940
00:44:43,200 --> 00:44:51,733
And what we think is that this
is critical to getting here.

941
00:44:51,733 --> 00:44:55,000
So these are much
larger structures

942
00:44:55,000 --> 00:44:57,766
than anything we've built
in space,

943
00:44:57,766 --> 00:45:00,500
in fact, they're many orders
of magnitude,

944
00:45:00,500 --> 00:45:02,966
more mass,

945
00:45:02,966 --> 00:45:09,100
than everything we've put
in space combined.

946
00:45:09,100 --> 00:45:11,000
But there's no
physical principle

947
00:45:11,000 --> 00:45:13,966
saying that these
aren't possible.

948
00:45:13,966 --> 00:45:15,466
It's just that
our current methods

949
00:45:15,466 --> 00:45:21,133
for producing space hardware
don't suit.

950
00:45:21,133 --> 00:45:24,900
And so what does it mean
to have something,

951
00:45:24,900 --> 00:45:28,966
to have a system that
doesn't require your factory

952
00:45:28,966 --> 00:45:31,833
to be larger than the thing
you're making?

953
00:45:31,833 --> 00:45:34,433
And so we think
that we may be able

954
00:45:34,433 --> 00:45:39,233
to make progress
in this direction.

955
00:45:39,233 --> 00:45:42,666
And if this seems far-fetched,

956
00:45:42,666 --> 00:45:46,100
I like the example
of "The Brick Moon,"

957
00:45:46,100 --> 00:45:49,066
which is a short story
by Edward Everett Hale,

958
00:45:49,066 --> 00:45:51,500
published in 1869,

959
00:45:57,333 --> 00:46:02,033
which is said to be
the first historical proposal

960
00:46:02,033 --> 00:46:04,333
for a satellite.

961
00:46:04,333 --> 00:46:08,966
And the story goes that

it was an accident

962

00:46:08,966 --> 00:46:12,233

that people were still
on the brick moon

963

00:46:12,233 --> 00:46:14,066

before it got sent up,

964

00:46:14,066 --> 00:46:15,900

and they started
a colony up there.

965

00:46:15,900 --> 00:46:19,633

And this was completely
fanciful in 1869.

966

00:46:19,633 --> 00:46:25,166

That wasn't that long ago.

967

00:46:25,166 --> 00:46:31,066

So I want to leave
plenty of time for questions.

968

00:46:31,066 --> 00:46:35,133

So I'm going
to leave it at that.

969

00:46:35,133 --> 00:46:37,333

And open it up to questions.

970

00:46:37,333 --> 00:46:40,333

[applause]

971

00:46:45,833 --> 00:46:47,900

- If you have a question,
please raise your hand

972

00:46:47,900 --> 00:46:49,500

and wait for the microphone

973

00:46:49,500 --> 00:46:51,533

and ask a single question
at a time.

974

00:46:51,533 --> 00:46:52,533

Thanks.

975

00:47:02,566 --> 00:47:06,866

- Okay, so, imagine
you're on a space mission

976

00:47:06,866 --> 00:47:10,466

and you need to have the ability

977

00:47:10,466 --> 00:47:12,533

to make repairs
and do maintenance.

978

00:47:12,533 --> 00:47:16,300

And so there's the philosophy--

979

00:47:16,300 --> 00:47:21,700

or an approach of carrying
a lot of the modular parts,

980

00:47:21,700 --> 00:47:25,433

which are nearly all identical
like you describe,

981

00:47:25,433 --> 00:47:27,200

or you could be
even more fundamental

982

00:47:27,200 --> 00:47:29,966

and carry the completely
raw materials

983

00:47:29,966 --> 00:47:32,700
and 3-D print parts
as you need them.

984
00:47:32,700 --> 00:47:34,566
And so have you
given some thought

985
00:47:34,566 --> 00:47:36,133
about how you allocate
those resources

986
00:47:36,133 --> 00:47:40,966
in those directions?

987
00:47:40,966 --> 00:47:45,766
- It's a very good question.

988
00:47:45,766 --> 00:47:48,366
And in particular
because we are doing

989
00:47:48,366 --> 00:47:51,866
so much work on 3-D printing,

990
00:47:51,866 --> 00:48:01,166
NASA as a whole and it's
state-of-the-art in general.

991
00:48:01,166 --> 00:48:02,700
I think there's some question

992
00:48:02,700 --> 00:48:04,566
as to how you define
3-D printing

993
00:48:04,566 --> 00:48:07,866
and what counts is that additive
manufacturing.

994

00:48:07,866 --> 00:48:10,300

In a way, what I'm proposing
was snapping together--

995

00:48:10,300 --> 00:48:12,333

what we're proposing
was snapping together

996

00:48:12,333 --> 00:48:16,500

building blocks here,
is additive manufacturing.

997

00:48:16,500 --> 00:48:19,833

So in that sense,
it's one in the same.

998

00:48:19,833 --> 00:48:24,000

In terms of what we think
of as 3-D printing,

999

00:48:24,000 --> 00:48:26,666

in terms of
the 3-D printing devices

1000

00:48:26,666 --> 00:48:32,500

that we see for instance,
in the Space Shop.

1001

00:48:32,500 --> 00:48:36,500

One thing you can look at
is the energy cost.

1002

00:48:36,500 --> 00:48:39,133

And so, it becomes a question of

1003

00:48:39,133 --> 00:48:44,433

what your energy sources are.

1004

00:48:44,433 --> 00:48:48,300

By and large, when you
look at the total energy cost

1005
00:48:48,300 --> 00:48:52,600
to arrive
at a piece of hardware,

1006
00:48:52,600 --> 00:48:55,466
it appears that the majority
of that is worked up

1007
00:48:55,466 --> 00:48:58,566
in the raw materials production.

1008
00:48:58,566 --> 00:49:01,900
And a large proportion

1009
00:49:01,900 --> 00:49:05,666
of that you can arrive

1010
00:49:05,666 --> 00:49:08,800
at or estimate
just by,

1011
00:49:08,800 --> 00:49:10,200
for instance,

1012
00:49:10,200 --> 00:49:13,800
needing to overcome
latent heating fusion.

1013
00:49:13,800 --> 00:49:21,833
So needing to liquefy
any given material.

1014
00:49:21,833 --> 00:49:26,500
And since that dominates
the production cost,

1015

00:49:26,500 --> 00:49:32,233
processes that have
to re-liquefy the material

1016
00:49:32,233 --> 00:49:35,566
are sort of gonna
double your base

1017
00:49:35,566 --> 00:49:36,866
material production cost,

1018
00:49:36,866 --> 00:49:38,966
or significantly
add to it.

1019
00:49:38,966 --> 00:49:43,566
And so, the versatility
is undeniable

1020
00:49:43,566 --> 00:49:46,733
and it's moving towards--

1021
00:49:46,733 --> 00:49:50,966
of what we now think
of as conventional 3-D printing,

1022
00:49:50,966 --> 00:49:55,633
it's moving towards
being able to produce

1023
00:49:55,633 --> 00:49:59,000
well-characterized parts.

1024
00:49:59,000 --> 00:50:01,200
But as it is, in a situation

1025
00:50:01,200 --> 00:50:08,500
where you have
a very strict energy limit,

1026

00:50:08,500 --> 00:50:11,800

it can be difficult to justify
some of the processes

1027

00:50:11,800 --> 00:50:15,666

that are currently
used for 3-D printing.

1028

00:50:15,666 --> 00:50:18,500

And so, some of this comes down

1029

00:50:18,500 --> 00:50:20,666

to a question of whether

1030

00:50:20,666 --> 00:50:23,100

or not you can
even tell the difference.

1031

00:50:23,100 --> 00:50:27,766

And so this is a question
of pixelating a picture,

1032

00:50:27,766 --> 00:50:29,366

whether or not a digital picture

1033

00:50:29,366 --> 00:50:31,966

is sufficient versus

1034

00:50:31,966 --> 00:50:34,200

what you would term
an analog picture.

1035

00:50:34,200 --> 00:50:37,000

But some point, when you get
down to the molecules,

1036

00:50:37,000 --> 00:50:38,800

your color molecules
in the picture,

1037

00:50:38,800 --> 00:50:43,200
you could argue that you have
a digital picture anyway.

1038

00:50:43,200 --> 00:50:46,000
And so the only
fundamental difference

1039

00:50:46,000 --> 00:50:49,700
is your conventionally-
considered digital picture

1040

00:50:49,700 --> 00:50:54,200
has the pixels
on a regular lattice.

1041

00:50:54,200 --> 00:51:00,700
And so what we've found
with digital photography

1042

00:51:00,700 --> 00:51:05,133
and digital images that there
are all of these advantages.

1043

00:51:05,133 --> 00:51:08,033
You can do compression,

1044

00:51:08,033 --> 00:51:13,466
you can operate over
the actual functional image

1045

00:51:13,466 --> 00:51:15,166
in terms of the shapes
that are on the image,

1046

00:51:15,166 --> 00:51:18,366
with algorithms,
extremely efficiently.

1047

00:51:19,766 --> 00:51:24,933

And we think that
the same thing applies

1048

00:51:24,933 --> 00:51:27,266

to three-dimensional systems.

1049

00:51:27,266 --> 00:51:30,033

Where if you're defining
three-dimensional systems

1050

00:51:30,033 --> 00:51:31,833

in terms of voxels,

1051

00:51:31,833 --> 00:51:34,633

for given applications
there's a minimum resolution

1052

00:51:34,633 --> 00:51:37,833

that you need,
just like with pictures.

1053

00:51:37,833 --> 00:51:39,200

And as long as you meet that,

1054

00:51:39,200 --> 00:51:41,900

then there could be
all of these advantages

1055

00:51:41,900 --> 00:51:45,700

to being able
to address things

1056

00:51:45,700 --> 00:51:48,900

in terms of the discrete states.

1057

00:51:48,900 --> 00:51:52,200

And so I think there
are these advantages

1058

00:51:52,200 --> 00:51:53,500

in terms of scope,

1059

00:51:53,500 --> 00:51:56,400

of the kinds of things

you can do,

1060

00:51:56,400 --> 00:51:58,400

if your systems

are built in this

1061

00:51:58,400 --> 00:52:02,533

fundamentally

reconfigurable way versus

1062

00:52:02,533 --> 00:52:07,066

what's right now

considered as 3-D printing,

1063

00:52:07,066 --> 00:52:10,200

which sort of compresses a lot

1064

00:52:10,200 --> 00:52:12,966

of the industrial infrastructure

1065

00:52:12,966 --> 00:52:14,933

producing hardware

1066

00:52:14,933 --> 00:52:19,566

as we know it

into a small box.

1067

00:52:19,566 --> 00:52:21,200

Which is amazing.

1068

00:52:21,200 --> 00:52:23,333

And really useful.

1069

00:52:23,333 --> 00:52:30,066

But the extensibility
of the digital approach

1070

00:52:30,066 --> 00:52:35,000

I think is very promising
and interesting.

1071

00:52:35,000 --> 00:52:36,500

Thanks.

1072

00:52:36,500 --> 00:52:37,700

Yes.

1073

00:52:43,000 --> 00:52:45,366

- For the snap together
structures that you've shown,

1074

00:52:45,366 --> 00:52:48,166

would it be reasonable
to eventually have automated

1075

00:52:48,166 --> 00:52:51,500

assembly and reassembly?

1076

00:52:51,500 --> 00:52:53,400

- That's an easy one.

1077

00:52:53,400 --> 00:52:56,233

Yes.

1078

00:52:56,233 --> 00:52:58,366

And that's what
we're working on right now,

1079

00:52:58,366 --> 00:53:04,400

that's a major focus of our work
in the lab right now.

1080

00:53:04,400 --> 00:53:08,766

And we're talking about robots
that are actually quite simple.

1081

00:53:08,766 --> 00:53:11,933

You don't need many,
many degrees of freedom,

1082

00:53:11,933 --> 00:53:17,366

but you could have many robots.

1083

00:53:17,366 --> 00:53:19,700

- Hi, for the structures
you were showing,

1084

00:53:19,700 --> 00:53:21,233

that were composite materials,

1085

00:53:21,233 --> 00:53:24,900

they weren't separated
in discrete layers

1086

00:53:24,900 --> 00:53:27,300

but more combined
in a marble structure.

1087

00:53:27,300 --> 00:53:29,366

I was wondering
how is that determined

1088

00:53:29,366 --> 00:53:31,400

if you were measuring
the force loads

1089

00:53:31,400 --> 00:53:34,566

or just have a random algorithm

1090

00:53:34,566 --> 00:53:38,500

that determines

how that is made?

1091

00:53:38,500 --> 00:53:41,833

- So, the one where I showed

1092

00:53:41,833 --> 00:53:45,466

the blue low

connectivity structure

1093

00:53:45,466 --> 00:53:50,366

and the red denser structure

1094

00:53:50,366 --> 00:53:54,300

and then the sort of marbled

one, that one was random.

1095

00:53:54,300 --> 00:53:56,800

But it's a very good question

1096

00:53:56,800 --> 00:53:58,566

and it points to the direction

1097

00:53:58,566 --> 00:54:04,566

that we're headed

in at that point,

1098

00:54:04,566 --> 00:54:08,933

which is to look at how

to optimize the distribution.

1099

00:54:08,933 --> 00:54:12,100

And Holly, I'm not sure

she's here right now,

1100

00:54:12,100 --> 00:54:17,000

Holly Jackson has done some work

on exactly that question.

1101

00:54:17,000 --> 00:54:21,500

Of not only the question
between the red

1102
00:54:21,500 --> 00:54:23,566
and the blue ones was sort of,

1103
00:54:23,566 --> 00:54:25,866
if you have a stiffer one
and a less stiff one.

1104
00:54:25,866 --> 00:54:28,400
And the most basic version
of that question is,

1105
00:54:28,400 --> 00:54:31,966
do you have a part
or not in that location?

1106
00:54:31,966 --> 00:54:34,666
And so, it re-addresses

1107
00:54:34,666 --> 00:54:38,400
the topological
optimization problem

1108
00:54:38,400 --> 00:54:42,166
within the scope
of the finite element

1109
00:54:42,166 --> 00:54:44,333
tools in a way

1110
00:54:44,333 --> 00:54:46,200
that takes advantage
of our ability

1111
00:54:46,200 --> 00:54:49,066
to modularize the finite
element process as well.

1112

00:54:49,066 --> 00:54:50,933

So we can look at some
of these incredibly

1113

00:54:50,933 --> 00:54:57,166

computational-intensive
topological optimization methods

1114

00:54:57,166 --> 00:55:01,700

and apply them to something
that would have been also

1115

00:55:01,700 --> 00:55:04,333

an incredibly
computationally-intensive

1116

00:55:04,333 --> 00:55:07,533

finite element analysis problem.

1117

00:55:07,533 --> 00:55:10,666

But we can cut most of
the computational intensiveness

1118

00:55:10,666 --> 00:55:12,433

out of the finite element
analysis problem

1119

00:55:12,433 --> 00:55:16,066

and just focus on
the optimization problem.

1120

00:55:16,066 --> 00:55:21,266

And so that's the crux
of the approach

1121

00:55:21,266 --> 00:55:24,000

to the X to the N planes,
in fact.

1122

00:55:24,000 --> 00:55:25,466

Because what we'd like
to be able to do

1123

00:55:25,466 --> 00:55:28,433

is define the overall
boundary shape

1124

00:55:28,433 --> 00:55:31,166

and the deformation modes

1125

00:55:31,166 --> 00:55:32,433

and then really optimize

1126

00:55:32,433 --> 00:55:34,066

how the parts
are placed within that,

1127

00:55:34,066 --> 00:55:39,666

in order to meet that objective.

1128

00:55:39,666 --> 00:55:42,466

- So, please join me
in thanking