



CHARGING CAPACITORS USING GRAPHENE FLUCTUATIONS

PAUL THIBADO



**SOCIETY
FOR
SCIENTIFIC
EXPLORATION**

1
00:00:16,470 --> 00:00:14,629
uh let's get on to our next talk

2
00:00:19,349 --> 00:00:16,480
and the next talk

3
00:00:20,710 --> 00:00:19,359
is going to be by uh professor paul

4
00:00:21,830 --> 00:00:20,720
thibodeau

5
00:00:24,470 --> 00:00:21,840
uh

6
00:00:25,830 --> 00:00:24,480
paul is a professor at the university of

7
00:00:28,470 --> 00:00:25,840
arkansas

8
00:00:30,630 --> 00:00:28,480
he got his bachelor's in science in

9
00:00:32,229 --> 00:00:30,640
physics and mathematics at san diego

10
00:00:34,549 --> 00:00:32,239
state

11
00:00:36,790 --> 00:00:34,559
and his phd at the university of

12
00:00:40,229 --> 00:00:36,800
pennsylvania

13
00:00:43,190 --> 00:00:40,239

he works on surface physics and

14

00:00:44,630 --> 00:00:43,200

using scanning tunneling microscope

15

00:00:47,270 --> 00:00:44,640

microscopy

16

00:00:49,830 --> 00:00:47,280

and in particular for the last 10 years

17

00:00:52,150 --> 00:00:49,840

or so he's been looking at freestanding

18

00:00:55,110 --> 00:00:52,160

graphene films

19

00:00:57,430 --> 00:00:55,120

if you are like me you've been aware of

20

00:00:59,670 --> 00:00:57,440

paul's recent work for the last few

21

00:01:02,709 --> 00:00:59,680

years and have really been scratching

22

00:01:05,750 --> 00:01:02,719

your head about it because he has some

23

00:01:09,190 --> 00:01:05,760

intriguing and fascinating results in

24

00:01:12,870 --> 00:01:09,200

terms of harvesting essentially

25

00:01:14,789 --> 00:01:12,880

brownian type motion in graphene

26

00:01:17,190 --> 00:01:14,799

and uh

27

00:01:19,990 --> 00:01:17,200

it's yeah

28

00:01:22,550 --> 00:01:20,000

it's very interesting and

29

00:01:24,789 --> 00:01:22,560

may really require some some basic

30

00:01:27,670 --> 00:01:24,799

rethinks of

31

00:01:30,149 --> 00:01:27,680

a lot of the uh

32

00:01:32,390 --> 00:01:30,159

thermal vibration concepts that we've

33

00:01:34,630 --> 00:01:32,400

had so paul

34

00:01:37,830 --> 00:01:34,640

please uh the

35

00:01:40,390 --> 00:01:37,840

talk title is charging capacitors using

36

00:01:41,990 --> 00:01:40,400

graphene fluctuations

37

00:01:43,910 --> 00:01:42,000

paul

38

00:01:45,190 --> 00:01:43,920

great yeah thank you for that you know

39

00:01:47,510 --> 00:01:45,200

um

40

00:01:50,069 --> 00:01:47,520

i guess my video has been stopped by

41

00:01:55,190 --> 00:01:50,079

somebody so you can't really see me but

42

00:01:58,950 --> 00:01:57,429

paul you can just start the your video

43

00:02:01,109 --> 00:01:58,960

yourself

44

00:02:03,510 --> 00:02:01,119

you know it won't let me i won't let you

45

00:02:05,270 --> 00:02:03,520

huh it says you cannot start your video

46

00:02:08,389 --> 00:02:05,280

because the host has stopped it but

47

00:02:09,910 --> 00:02:08,399

that's okay can you see my screen

48

00:02:10,869 --> 00:02:09,920

uh yes

49

00:02:13,750 --> 00:02:10,879

okay

50

00:02:15,510 --> 00:02:13,760

so my video's off but it's not um not my

51

00:02:16,710 --> 00:02:15,520

doing here sorry

52

00:02:17,910 --> 00:02:16,720

um

53

00:02:19,670 --> 00:02:17,920

all right

54

00:02:22,309 --> 00:02:19,680

great your the host has asked me so

55

00:02:24,550 --> 00:02:22,319

let's let's start it okay all right

56

00:02:25,830 --> 00:02:24,560

great thank you

57

00:02:28,309 --> 00:02:25,840

okay well thank you for that

58

00:02:29,750 --> 00:02:28,319

introduction garrett also um yeah well

59

00:02:31,430 --> 00:02:29,760

i'm paul thibodeau of the university so

60

00:02:32,470 --> 00:02:31,440

let me just get that out of the way and

61

00:02:36,710 --> 00:02:32,480

um

62

00:02:38,150 --> 00:02:36,720

garrett and charles

63

00:02:39,910 --> 00:02:38,160

for

64

00:02:41,910 --> 00:02:39,920
you know talking to me and being

65

00:02:43,990 --> 00:02:41,920
interested in my research um it's i've

66

00:02:45,589 --> 00:02:44,000
had great conversations with them i'd

67

00:02:47,670 --> 00:02:45,599
also like to say that the talk that

68

00:02:50,309 --> 00:02:47,680
daniel gave was excellent that's the

69

00:02:52,550 --> 00:02:50,319
first i've heard his talks

70

00:02:54,790 --> 00:02:52,560
it was really well done

71

00:02:57,190 --> 00:02:54,800
i do want to clarify a little bit that

72

00:02:59,589 --> 00:02:57,200
my research is not about

73

00:03:01,990 --> 00:02:59,599
searching for violations the second law

74

00:03:03,270 --> 00:03:02,000
my research is about harvesting energy

75

00:03:05,030 --> 00:03:03,280
from the environment so i'm just going

76

00:03:06,869 --> 00:03:05,040

to kind of focus on that part of it but

77

00:03:08,550 --> 00:03:06,879

i do talk about the laws of physics of

78

00:03:11,430 --> 00:03:08,560

course

79

00:03:13,430 --> 00:03:11,440

and so let me just get started with that

80

00:03:15,990 --> 00:03:13,440

start a little timer here too my talk

81

00:03:17,670 --> 00:03:16,000

will probably take 35 minutes so it'll

82

00:03:19,110 --> 00:03:17,680

be plenty of time for questions if there

83

00:03:20,309 --> 00:03:19,120

are any

84

00:03:23,030 --> 00:03:20,319

i'm going to talk about charging

85

00:03:25,270 --> 00:03:23,040

capacitors using graphene fluctuations

86

00:03:27,430 --> 00:03:25,280

this is the circuit

87

00:03:28,550 --> 00:03:27,440

that i'm going to use

88

00:03:31,830 --> 00:03:28,560

we've actually been studying this

89

00:03:33,430 --> 00:03:31,840

circuit for about five years now

90

00:03:35,350 --> 00:03:33,440

i'm going to show you that this circuit

91

00:03:37,750 --> 00:03:35,360

can steal energy from the thermal

92

00:03:40,550 --> 00:03:37,760

surroundings

93

00:03:43,110 --> 00:03:40,560

these results actually were really just

94

00:03:45,110 --> 00:03:43,120

discovered and presented here first it

95

00:03:46,789 --> 00:03:45,120

was kind of good timing that i got

96

00:03:50,149 --> 00:03:46,799

contacted by

97

00:03:51,830 --> 00:03:50,159

daniel charles and garrett

98

00:03:54,010 --> 00:03:51,840

in the first part i'm going to talk

99

00:03:55,190 --> 00:03:54,020

about the deterministic

100

00:03:57,270 --> 00:03:55,200

[Music]

101

00:03:58,949 --> 00:03:57,280

properties or solutions if you like of

102

00:04:00,710 --> 00:03:58,959

this circuit

103

00:04:03,429 --> 00:04:00,720

and then the second part i'll talk about

104

00:04:06,149 --> 00:04:03,439

the stitch stochastic part

105

00:04:07,030 --> 00:04:06,159

see if this is alright

106

00:04:09,429 --> 00:04:07,040

okay

107

00:04:12,309 --> 00:04:09,439

so in the deterministic part

108

00:04:14,630 --> 00:04:12,319

it's this thing up here

109

00:04:15,750 --> 00:04:14,640

let me get

110

00:04:17,189 --> 00:04:15,760

um

111

00:04:19,430 --> 00:04:17,199

so the deterministic part all right

112

00:04:21,830 --> 00:04:19,440

graphene it's only one atom thick

113

00:04:23,830 --> 00:04:21,840

therefore it's extremely flexible a

114

00:04:26,230 --> 00:04:23,840

measure of that flexibility is called

115

00:04:28,550 --> 00:04:26,240

the flexural rigidity it's given by D

116

00:04:31,670 --> 00:04:28,560

here's the formula for it the important

117

00:04:32,950 --> 00:04:31,680

part is it has this parameter h to the

118

00:04:36,310 --> 00:04:32,960

third power

119

00:04:38,710 --> 00:04:36,320

where h is the thickness of the plate

120

00:04:40,230 --> 00:04:38,720

so graphene membrane is only about one

121

00:04:41,189 --> 00:04:40,240

nanometer thick

122

00:04:42,629 --> 00:04:41,199

whereas

123

00:04:46,710 --> 00:04:42,639

you could probably make a silicon

124

00:04:48,710 --> 00:04:46,720

nitride cantilever at best 10 nanometers

125

00:04:50,310 --> 00:04:48,720

that'd be the thinnest

126
00:04:52,310 --> 00:04:50,320
so right here

127
00:04:54,390 --> 00:04:52,320
that would tell you that the graphene is

128
00:04:57,430 --> 00:04:54,400
going to be a thousand times more

129
00:04:58,950 --> 00:04:57,440
flexible than this cantilever

130
00:05:01,110 --> 00:04:58,960
what that translates into if you think

131
00:05:03,670 --> 00:05:01,120
it kind of like hooks law or whatever if

132
00:05:05,990 --> 00:05:03,680
if a one nano newton force moves the

133
00:05:07,189 --> 00:05:06,000
silicon nitride cantilever a certain

134
00:05:09,350 --> 00:05:07,199
distance

135
00:05:10,870 --> 00:05:09,360
then a piconewton force

136
00:05:12,710 --> 00:05:10,880
a thousand times smaller could move the

137
00:05:15,350 --> 00:05:12,720
graphene the same distance

138
00:05:17,909 --> 00:05:15,360

so it's very flexible and easy to move

139

00:05:21,029 --> 00:05:17,919

when graphene moves how does that result

140

00:05:25,110 --> 00:05:22,870

i like to turn people to this paper

141

00:05:27,270 --> 00:05:25,120

inside of the physics teacher

142

00:05:29,510 --> 00:05:27,280

it basically talks about variable

143

00:05:31,110 --> 00:05:29,520

capacitors

144

00:05:33,590 --> 00:05:31,120

if you look at the definition the

145

00:05:34,710 --> 00:05:33,600

capacitance is how much charge it can

146

00:05:36,790 --> 00:05:34,720

store

147

00:05:37,590 --> 00:05:36,800

divided by the voltage you've applied to

148

00:05:43,510 --> 00:05:37,600

it

149

00:05:45,909 --> 00:05:43,520

change in charge

150

00:05:49,029 --> 00:05:45,919

here's a nice illustration of a parallel

151
00:05:52,230 --> 00:05:49,039
plate capacitor connected to a battery

152
00:05:54,710 --> 00:05:52,240
and it has four units of charge on it if

153
00:05:56,629 --> 00:05:54,720
we applied a force to this plate and

154
00:05:58,950 --> 00:05:56,639
pulled it to the right

155
00:06:01,029 --> 00:05:58,960
the capacitance would go down so the

156
00:06:02,469 --> 00:06:01,039
charge has to go down

157
00:06:05,029 --> 00:06:02,479
so what will happen is let's say these

158
00:06:06,870 --> 00:06:05,039
two charges will flow

159
00:06:08,629 --> 00:06:06,880
counterclockwise

160
00:06:10,390 --> 00:06:08,639
they'll go backwards through the battery

161
00:06:12,390 --> 00:06:10,400
and recharge it if it's rechargeable

162
00:06:14,790 --> 00:06:12,400
battery and then come around here to

163
00:06:16,390 --> 00:06:14,800

cancel these charges and the force that

164

00:06:18,070 --> 00:06:16,400

pulled that plate apart that's what's

165

00:06:19,749 --> 00:06:18,080

doing the work here

166

00:06:21,430 --> 00:06:19,759

so that's basically the fundamental

167

00:06:23,830 --> 00:06:21,440

operation of our

168

00:06:25,510 --> 00:06:23,840

uh circuit as well so as the distance

169

00:06:26,950 --> 00:06:25,520

between the graphene and the electrode

170

00:06:29,189 --> 00:06:26,960

changes because the graphene's so

171

00:06:31,270 --> 00:06:29,199

flexible it's moving all the time under

172

00:06:33,029 --> 00:06:31,280

the slightest influence

173

00:06:35,110 --> 00:06:33,039

the capacitance will increase and

174

00:06:38,469 --> 00:06:35,120

decrease and then the charge on the

175

00:06:40,550 --> 00:06:38,479

graphene will also increase and decrease

176
00:06:42,070 --> 00:06:40,560
when current flows in this circuit

177
00:06:44,230 --> 00:06:42,080
clockwise

178
00:06:47,749 --> 00:06:44,240
it'll go through diode 1 and charge

179
00:06:50,390 --> 00:06:47,759
capacitor c1 to complete the circuit

180
00:06:53,189 --> 00:06:50,400
when it flows counterclockwise

181
00:06:54,950 --> 00:06:53,199
it'll charge c2 going through d2 and go

182
00:06:56,950 --> 00:06:54,960
back to complete the circuit so that's

183
00:07:00,870 --> 00:06:56,960
basically how the energy harvesting work

184
00:07:03,110 --> 00:07:00,880
take an ac signal and charge these two

185
00:07:04,870 --> 00:07:03,120
we had an illustration we made of this a

186
00:07:06,790 --> 00:07:04,880
while back see if i can get it to go

187
00:07:09,110 --> 00:07:06,800
here we go

188
00:07:11,350 --> 00:07:09,120

um this is the idea so basically there's

189

00:07:12,309 --> 00:07:11,360

the graphing fluctuating nice slow

190

00:07:15,589 --> 00:07:12,319

motion

191

00:07:17,110 --> 00:07:15,599

as the capacitance increases the charge

192

00:07:19,990 --> 00:07:17,120

increase there it took power from the

193

00:07:22,469 --> 00:07:20,000

battery but now the

194

00:07:24,230 --> 00:07:22,479

battery got recharged and we also made

195

00:07:26,790 --> 00:07:24,240

it go through that storage capacity this

196

00:07:28,830 --> 00:07:26,800

is like that c_2 over here

197

00:07:31,990 --> 00:07:28,840

and as the graphene keeps moving it'll

198

00:07:33,990 --> 00:07:32,000

keep forcing charge onto the capacitor

199

00:07:36,070 --> 00:07:34,000

and off the capacitor

200

00:07:37,990 --> 00:07:36,080

we use these diodes to

201
00:07:39,830 --> 00:07:38,000
redirect the current

202
00:07:41,589 --> 00:07:39,840
so it can charge charge up the storage

203
00:07:45,909 --> 00:07:41,599
passion then we can use that

204
00:07:50,710 --> 00:07:48,390
all right what about the efficiency

205
00:07:53,189 --> 00:07:50,720
so we actually built this circuit uh

206
00:07:55,350 --> 00:07:53,199
here's a variable on a macroscopic scale

207
00:07:57,110 --> 00:07:55,360
so here is a

208
00:07:59,510 --> 00:07:57,120
variable capacitor you can vary the

209
00:08:01,510 --> 00:07:59,520
capacitance by turning this rod here

210
00:08:03,189 --> 00:08:01,520
here all these plates are overlapping

211
00:08:06,070 --> 00:08:03,199
one another to give the maximum

212
00:08:08,070 --> 00:08:06,080
capacitance in this picture they're

213
00:08:10,309 --> 00:08:08,080

not overlapping at all and it gives you

214

00:08:12,869 --> 00:08:10,319

the minimum capacitance

215

00:08:15,189 --> 00:08:12,879

this plot here shows the capacitance as

216

00:08:18,469 --> 00:08:15,199

a function of rotation it starts off at

217

00:08:20,550 --> 00:08:18,479

about one nanofarad drops to point one

218

00:08:22,629 --> 00:08:20,560

moves in a nice linear line actually and

219

00:08:24,790 --> 00:08:22,639

goes back to one again as you continue

220

00:08:27,430 --> 00:08:24,800

to rotate it through a full rotation

221

00:08:29,670 --> 00:08:27,440

this is a really high grade military

222

00:08:31,110 --> 00:08:29,680

variable capacitor

223

00:08:33,829 --> 00:08:31,120

that we did with this experience that

224

00:08:35,350 --> 00:08:33,839

has this nice precise capability we

225

00:08:37,829 --> 00:08:35,360

hooked it up to this circuit that's the

226

00:08:39,350 --> 00:08:37,839

same circuit we used transistors wired

227

00:08:41,670 --> 00:08:39,360

as diodes here they were a little bit

228

00:08:42,550 --> 00:08:41,680

better for this application

229

00:08:43,909 --> 00:08:42,560

and so

230

00:08:46,150 --> 00:08:43,919

what happens is that when the current

231

00:08:47,030 --> 00:08:46,160

goes clockwise it'll charge capacitor

232

00:08:48,470 --> 00:08:47,040

one

233

00:08:50,470 --> 00:08:48,480

and when the current goes

234

00:08:51,829 --> 00:08:50,480

counterclockwise it goes backwards

235

00:08:54,230 --> 00:08:51,839

through the battery

236

00:08:55,990 --> 00:08:54,240

and charges capacitor 2.

237

00:08:57,910 --> 00:08:56,000

here we're showing the voltage on

238

00:08:59,750 --> 00:08:57,920

capacitor 2 as a function of the number

239

00:09:01,269 --> 00:08:59,760

rotation so you can see that it's

240

00:09:03,750 --> 00:09:01,279

charging it up

241

00:09:06,790 --> 00:09:03,760

we can also measure the current flowing

242

00:09:09,030 --> 00:09:06,800

into capacitor 2 in time it has kind of

243

00:09:11,190 --> 00:09:09,040

a spiky nature it's pretty small it's

244

00:09:14,230 --> 00:09:11,200

only 10 nano amps

245

00:09:15,590 --> 00:09:14,240

um but it's wider here as the time goes

246

00:09:17,110 --> 00:09:15,600

on or the rotation's gone it gets

247

00:09:19,030 --> 00:09:17,120

narrower so the current is dropping as

248

00:09:20,790 --> 00:09:19,040

the capacitor is charging up

249

00:09:23,430 --> 00:09:20,800

the interesting thing that we found was

250

00:09:25,910 --> 00:09:23,440

the circuit has fifty percent efficiency

251
00:09:27,829 --> 00:09:25,920
when operated at the maximum power point

252
00:09:28,710 --> 00:09:27,839
so even though the current was small

253
00:09:30,470 --> 00:09:28,720
here

254
00:09:32,389 --> 00:09:30,480
and people thought okay well it'll work

255
00:09:34,389 --> 00:09:32,399
but the efficiency will be terrible

256
00:09:36,230 --> 00:09:34,399
turns actually the efficiency is

257
00:09:37,829 --> 00:09:36,240
excellent fifty 50 efficiency is very

258
00:09:41,430 --> 00:09:37,839
good

259
00:09:43,269 --> 00:09:41,440
here's a little video of it running

260
00:09:44,870 --> 00:09:43,279
so here's the variable capacitor being

261
00:09:46,710 --> 00:09:44,880
turned by a motor so it's nice and

262
00:09:48,790 --> 00:09:46,720
smooth and continuous

263
00:09:50,870 --> 00:09:48,800

this volt meter back here is measuring

264

00:09:52,389 --> 00:09:50,880

the voltage on capacitor 2 you can see

265

00:09:54,230 --> 00:09:52,399

it's increasing in the negative

266

00:10:00,070 --> 00:09:54,240

direction and here's a little breadboard

267

00:10:03,350 --> 00:10:02,389

and in fact we've been pushing this

268

00:10:05,190 --> 00:10:03,360

forward

269

00:10:06,150 --> 00:10:05,200

as hard as we can and we've actually

270

00:10:08,949 --> 00:10:06,160

made

271

00:10:11,350 --> 00:10:08,959

a first integrated circuit or a chip

272

00:10:13,350 --> 00:10:11,360

in 2021

273

00:10:15,750 --> 00:10:13,360

this is a five millimeter by five

274

00:10:17,750 --> 00:10:15,760

millimeter chip we had it made at taiwan

275

00:10:19,670 --> 00:10:17,760

semiconductor

276

00:10:21,110 --> 00:10:19,680

inside the chip are this is the diode

277

00:10:22,870 --> 00:10:21,120

circuitry

278

00:10:24,310 --> 00:10:22,880

and it connects to these bonding pads

279

00:10:26,230 --> 00:10:24,320

around the outside so there's a bunch of

280

00:10:29,030 --> 00:10:26,240

bonding pads here

281

00:10:32,470 --> 00:10:29,040

there's a big section here in the middle

282

00:10:34,389 --> 00:10:32,480

which is um basically we left blank

283

00:10:36,949 --> 00:10:34,399

and when the chips came back we did post

284

00:10:38,150 --> 00:10:36,959

processing we built an array of these

285

00:10:39,670 --> 00:10:38,160

graphene

286

00:10:41,910 --> 00:10:39,680

electrode

287

00:10:43,829 --> 00:10:41,920

systems on this chip

288

00:10:45,990 --> 00:10:43,839

and then connected those

289

00:10:47,509 --> 00:10:46,000

uh things to the bonding pads or the

290

00:10:49,430 --> 00:10:47,519

circuitry below

291

00:10:51,030 --> 00:10:49,440

you can see the graphene here this is

292

00:10:52,310 --> 00:10:51,040

graphene is covering the whole upper

293

00:10:54,150 --> 00:10:52,320

half of the chip

294

00:10:55,110 --> 00:10:54,160

touching the bonding pads naturally

295

00:10:56,870 --> 00:10:55,120

there

296

00:11:00,870 --> 00:10:56,880

the lower edge of the graphene can see

297

00:11:04,230 --> 00:11:00,880

right here so we're pushing this forward

298

00:11:08,470 --> 00:11:06,230

all right so so that's what i'm going to

299

00:11:10,230 --> 00:11:08,480

call the deterministic part

300

00:11:12,389 --> 00:11:10,240

let me ask this question so when the

301
00:11:14,389 --> 00:11:12,399
graphene shakes some really questionable

302
00:11:16,470 --> 00:11:14,399
points i'll get to the question below so

303
00:11:17,990 --> 00:11:16,480
when graphene shakes

304
00:11:20,389 --> 00:11:18,000
current flows

305
00:11:22,870 --> 00:11:20,399
and the diodes charge c_1 c_2 so hopefully

306
00:11:24,470 --> 00:11:22,880
i convinced you of that

307
00:11:26,870 --> 00:11:24,480
but here's the question

308
00:11:29,910 --> 00:11:26,880
will c_1 and c_2 will the capacitors

309
00:11:31,910 --> 00:11:29,920
charge if the only force acting

310
00:11:33,190 --> 00:11:31,920
is the thermal force

311
00:11:37,110 --> 00:11:33,200
and it's everything's at the same

312
00:11:41,030 --> 00:11:39,190
well what's motivating this we had some

313
00:11:42,870 --> 00:11:41,040

early success

314

00:11:44,550 --> 00:11:42,880

we were able to show that the brownian

315

00:11:47,910 --> 00:11:44,560

motion that's that thermal motion of

316

00:11:50,150 --> 00:11:47,920

graphene could power a circuit

317

00:11:52,389 --> 00:11:50,160

we did this using our scanning tunneling

318

00:11:54,069 --> 00:11:52,399

microscope chamber this is a tem grid

319

00:11:55,750 --> 00:11:54,079

with graphene overlay you can see the

320

00:11:57,590 --> 00:11:55,760

graphene film here

321

00:11:59,829 --> 00:11:57,600

this is pretty much the same circuit

322

00:12:03,030 --> 00:11:59,839

except we have ammeters here measuring

323

00:12:05,670 --> 00:12:03,040

the current in these two channels

324

00:12:07,110 --> 00:12:05,680

and so we could do that we did power a

325

00:12:09,110 --> 00:12:07,120

circuit

326

00:12:12,470 --> 00:12:09,120

and we determined that the power density

327

00:12:14,389 --> 00:12:12,480

was one pico watt per micron squared

328

00:12:16,790 --> 00:12:14,399

if you convert the units on that that's

329

00:12:19,190 --> 00:12:16,800

one watt per meter squared

330

00:12:22,069 --> 00:12:19,200

there was a really nice study done in

331

00:12:24,389 --> 00:12:22,079

2018 on draw your attention to

332

00:12:26,629 --> 00:12:24,399

that studied wind farms all around the

333

00:12:29,430 --> 00:12:26,639

world there's thousands of them and they

334

00:12:31,910 --> 00:12:29,440

found out the wind farms produce 0.5

335

00:12:33,750 --> 00:12:31,920

watts per meter squared so actually

336

00:12:35,829 --> 00:12:33,760

we're on the par with

337

00:12:38,389 --> 00:12:35,839

wind power here

338

00:12:40,150 --> 00:12:38,399

solar farms all over the world

339

00:12:42,629 --> 00:12:40,160

were also studied they only produce

340

00:12:44,069 --> 00:12:42,639

about five watts per meter squared

341

00:12:45,990 --> 00:12:44,079

so it's a

342

00:12:47,750 --> 00:12:46,000

viable it's worth pursuing i guess is

343

00:12:49,110 --> 00:12:47,760

what we would say

344

00:12:51,670 --> 00:12:49,120

this paper

345

00:12:53,750 --> 00:12:51,680

obtained a lot of attention

346

00:12:55,990 --> 00:12:53,760

one way you can see measure that is

347

00:12:59,110 --> 00:12:56,000

through this old metric score if it got

348

00:13:01,269 --> 00:12:59,120

a 286 well it's up to 286

349

00:13:01,990 --> 00:13:01,279

most of my papers get a zero or a one in

350

00:13:03,910 --> 00:13:02,000

this

351
00:13:05,829 --> 00:13:03,920
metric score

352
00:13:07,829 --> 00:13:05,839
honestly they get a higher alt metric

353
00:13:10,629 --> 00:13:07,839
score there were other papers in that

354
00:13:12,150 --> 00:13:10,639
year if you found a vaccine for covid

355
00:13:14,550 --> 00:13:12,160
and published that you got a higher

356
00:13:17,110 --> 00:13:14,560
altmetric score or if you found water on

357
00:13:18,629 --> 00:13:17,120
the moon so this is a big score

358
00:13:20,870 --> 00:13:18,639
and actually i got

359
00:13:22,949 --> 00:13:20,880
close to a thousand emails

360
00:13:23,750 --> 00:13:22,959
i'd say most were fan mail but there's a

361
00:13:25,110 --> 00:13:23,760
few

362
00:13:25,990 --> 00:13:25,120
haters out there

363
00:13:27,269 --> 00:13:26,000

um

364

00:13:28,949 --> 00:13:27,279

usually the questions were about the

365

00:13:32,629 --> 00:13:28,959

second law so i think that's partly why

366

00:13:36,150 --> 00:13:33,750

all right

367

00:13:38,150 --> 00:13:36,160

so let's move to part two the stochastic

368

00:13:40,069 --> 00:13:38,160

part so to do that we're going to talk

369

00:13:41,670 --> 00:13:40,079

about brownian motion and the ido

370

00:13:43,910 --> 00:13:41,680

launchment equation

371

00:13:46,470 --> 00:13:43,920

this is basically newton's second law

372

00:13:48,389 --> 00:13:46,480

but with a stochastic driving force so

373

00:13:50,629 --> 00:13:48,399

i've written that here

374

00:13:52,150 --> 00:13:50,639

this is m a

375

00:13:54,710 --> 00:13:52,160

the forces that are acting there's a

376

00:13:56,790 --> 00:13:54,720

drag force that's involved in brownian

377

00:13:59,350 --> 00:13:56,800

motion that basically is trying to bring

378

00:14:01,430 --> 00:13:59,360

the brownian particle to a dead stop and

379

00:14:03,590 --> 00:14:01,440

it will bring it to a dead stop

380

00:14:07,350 --> 00:14:03,600

but then there's a thermal force

381

00:14:09,430 --> 00:14:07,360

that is also present and this thing

382

00:14:11,189 --> 00:14:09,440

transfers energy from the thermal

383

00:14:12,949 --> 00:14:11,199

environment to the brownian particle

384

00:14:14,389 --> 00:14:12,959

gives its energy to the particle and

385

00:14:16,790 --> 00:14:14,399

gets moving again let me show this

386

00:14:19,110 --> 00:14:16,800

little video so this is like our

387

00:14:21,829 --> 00:14:19,120

brownian particle this is in 3d but our

388

00:14:24,069 --> 00:14:21,839

our solutions will be in one dimension

389

00:14:25,910 --> 00:14:24,079

the drag force is taking the kinetic

390

00:14:27,269 --> 00:14:25,920

energy of the particle and giving it to

391

00:14:29,590 --> 00:14:27,279

the environment

392

00:14:31,189 --> 00:14:29,600

and then this force over here is taking

393

00:14:34,230 --> 00:14:31,199

the energy from the environment and

394

00:14:35,990 --> 00:14:34,240

giving it back to the particle

395

00:14:37,670 --> 00:14:36,000

this thermal force looks a lot like this

396

00:14:39,910 --> 00:14:37,680

it's basically kind of a noisy

397

00:14:41,990 --> 00:14:39,920

stochastic signal

398

00:14:45,750 --> 00:14:42,000

what we want to do is steal energy from

399

00:14:49,509 --> 00:14:48,069

notice the thermal force is zero if t

400

00:14:50,870 --> 00:14:49,519

equals zero the temperature is zero

401
00:14:52,470 --> 00:14:50,880
that's how we know it's the thermal

402
00:14:55,269 --> 00:14:52,480
force

403
00:14:57,590 --> 00:14:55,279
also notice that eta this parameter

404
00:14:59,750 --> 00:14:57,600
is in both places it's both here in the

405
00:15:01,750 --> 00:14:59,760
thermal force and in the drag force this

406
00:15:03,829 --> 00:15:01,760
ensures that we reach thermodynamic

407
00:15:07,189 --> 00:15:03,839
equilibrium this was a big breakthrough

408
00:15:09,670 --> 00:15:07,199
in the fluctuation dissipation theorem

409
00:15:12,310 --> 00:15:09,680
basically what it says is

410
00:15:13,750 --> 00:15:12,320
if the particle is giving energy to the

411
00:15:15,670 --> 00:15:13,760
environment

412
00:15:17,670 --> 00:15:15,680
and the energy is giving and sorry in

413
00:15:19,910 --> 00:15:17,680

the environment is giving energy to the

414

00:15:21,990 --> 00:15:19,920

particle if those two

415

00:15:24,310 --> 00:15:22,000

processes are equal to each other then

416

00:15:26,629 --> 00:15:24,320

we'll reach thermodynamic equilibrium

417

00:15:28,470 --> 00:15:26,639

and that's basically saying that the

418

00:15:30,389 --> 00:15:28,480

kinetic energy

419

00:15:33,269 --> 00:15:30,399

one-half mv^2 is equal to the

420

00:15:37,670 --> 00:15:33,279

thermal energy one-half $k_B T$ so we by

421

00:15:40,389 --> 00:15:38,790

graphene

422

00:15:42,870 --> 00:15:40,399

has a ripley structure this is an

423

00:15:44,870 --> 00:15:42,880

important property we think of graphing

424

00:15:46,550 --> 00:15:44,880

the surface of graphene like this except

425

00:15:48,790 --> 00:15:46,560

dynamic more like the surface of the

426

00:15:50,310 --> 00:15:48,800

ocean it has waves on it it has

427

00:15:52,550 --> 00:15:50,320

curvature

428

00:15:55,269 --> 00:15:52,560

we call these ripples the ripples can

429

00:15:57,110 --> 00:15:55,279

have a convex curvature or a concave

430

00:15:58,870 --> 00:15:57,120

curvature and they can invert their

431

00:16:02,069 --> 00:15:58,880

curvature as well so here's kind of an

432

00:16:03,590 --> 00:16:02,079

illustration of a ripple that is convex

433

00:16:04,949 --> 00:16:03,600

and it could flip over and become

434

00:16:07,509 --> 00:16:04,959

concave

435

00:16:09,189 --> 00:16:07,519

we've done molecular dynamic simulations

436

00:16:11,670 --> 00:16:09,199

of graphing ripples and sure enough they

437

00:16:14,069 --> 00:16:11,680

do do that so here's a ripple

438

00:16:17,829 --> 00:16:14,079

having this random motion but

439

00:16:18,710 --> 00:16:17,839

at a positive value here and then

440

00:16:21,110 --> 00:16:18,720

at

441

00:16:23,110 --> 00:16:21,120

this point in time it

442

00:16:25,910 --> 00:16:23,120

flips its curvature from convex to

443

00:16:27,590 --> 00:16:25,920

concave and goes on a long excursion and

444

00:16:28,949 --> 00:16:27,600

now sits down here for a while and goes

445

00:16:30,550 --> 00:16:28,959

back again

446

00:16:32,550 --> 00:16:30,560

so that means it lives in what we call a

447

00:16:34,470 --> 00:16:32,560

double well potential can either be at

448

00:16:36,949 --> 00:16:34,480

this point five or minus point five

449

00:16:39,269 --> 00:16:36,959

instead of zero so the force from the

450

00:16:41,509 --> 00:16:39,279

ripple double well potential that needs

451

00:16:43,430 --> 00:16:41,519

to be added in so we add that in

452

00:16:46,150 --> 00:16:43,440

it what it what we found it does is it

453

00:16:48,230 --> 00:16:46,160

lowers the frequency of the

454

00:16:50,230 --> 00:16:48,240

energy which is helpful for energy

455

00:16:53,350 --> 00:16:50,240

harvesting we still have this there's

456

00:16:54,470 --> 00:16:53,360

still thermodynamic equilibrium

457

00:16:56,310 --> 00:16:54,480

all right

458

00:16:58,790 --> 00:16:56,320

we're going to hook it up to a circuit

459

00:17:02,870 --> 00:16:58,800

it turns out electrons in a circuit also

460

00:17:04,710 --> 00:17:02,880

have are basically have brownian motion

461

00:17:06,949 --> 00:17:04,720

so there's an edo launchment equation

462

00:17:08,870 --> 00:17:06,959

for this as well let's start over here

463

00:17:10,230 --> 00:17:08,880

here's a circuit with a capacitor and a

464

00:17:12,150 --> 00:17:10,240

resistor i'll tell you this can't

465

00:17:14,470 --> 00:17:12,160

harvest energy

466

00:17:16,390 --> 00:17:14,480

i'll show that it can't

467

00:17:18,390 --> 00:17:16,400

what we start off with is kirchhoff's

468

00:17:21,429 --> 00:17:18,400

loop law it says that the voltage on

469

00:17:23,029 --> 00:17:21,439

this capacitor is q over c but it's also

470

00:17:24,630 --> 00:17:23,039

i times r

471

00:17:26,069 --> 00:17:24,640

instead of using the resistance we're

472

00:17:28,710 --> 00:17:26,079

going to use the conductance it's just

473

00:17:30,870 --> 00:17:28,720

one over the resistance so i equals the

474

00:17:34,390 --> 00:17:30,880

conductance times the voltage

475

00:17:36,630 --> 00:17:34,400

we put that here so i is dq/dt

476

00:17:39,270 --> 00:17:36,640

it's the conductance times the voltage

477

00:17:41,669 --> 00:17:39,280

and then we add the thermal current this

478

00:17:43,990 --> 00:17:41,679

time so here the resistance is trying to

479

00:17:45,029 --> 00:17:44,000

bring the electron to a dead stop and it

480

00:17:46,789 --> 00:17:45,039

will

481

00:17:48,870 --> 00:17:46,799

then the thermal

482

00:17:51,909 --> 00:17:48,880

current comes in gives it a kick and

483

00:17:53,750 --> 00:17:51,919

starts it moving again

484

00:17:56,310 --> 00:17:53,760

the thermal current is zero if the

485

00:17:58,310 --> 00:17:56,320

temperature is zero

486

00:18:00,390 --> 00:17:58,320

notice μ is in both places again so

487

00:18:02,710 --> 00:18:00,400

this is going to ensure that we satisfy

488

00:18:05,510 --> 00:18:02,720

the fluctuation dissipation theorem and

489

00:18:07,190 --> 00:18:05,520

that we're in thermodynamic equilibrium

490

00:18:08,789 --> 00:18:07,200

what that tells us here though is that

491

00:18:15,110 --> 00:18:08,799

the

492

00:18:17,669 --> 00:18:15,120

one half c

493

00:18:19,590 --> 00:18:17,679

voltage squared u squared if we

494

00:18:21,590 --> 00:18:19,600

rearrange that it says u squared the

495

00:18:24,150 --> 00:18:21,600

variance of u we say

496

00:18:26,630 --> 00:18:24,160

is $k_B T$ divided by c so notice the

497

00:18:27,750 --> 00:18:26,640

smaller c is the larger the voltage

498

00:18:29,510 --> 00:18:27,760

becomes

499

00:18:31,909 --> 00:18:29,520

so i plotted that here so even though

500

00:18:33,909 --> 00:18:31,919

the even though the mean voltage or the

501

00:18:36,310 --> 00:18:33,919

average voltage is zero

502

00:18:38,630 --> 00:18:36,320

the fluctuations

503

00:18:40,870 --> 00:18:38,640

or the standard deviation of the voltage

504

00:18:41,990 --> 00:18:40,880

increases dramatically as c becomes

505

00:18:46,150 --> 00:18:42,000

smaller and we're going to take

506

00:18:49,590 --> 00:18:47,669

all right let's replace the wrist

507

00:18:50,950 --> 00:18:49,600

resistor with a diode that we can't do

508

00:18:52,230 --> 00:18:50,960

anything with the resistor we need a

509

00:18:56,070 --> 00:18:52,240

diode

510

00:19:00,070 --> 00:18:56,080

tell you this circuit will not harvest

511

00:19:02,549 --> 00:19:00,080

energy either i can prove that i will

512

00:19:05,270 --> 00:19:02,559

the diode is special in the sense it has

513

00:19:07,350 --> 00:19:05,280

a non-linear conductance so it has a μ

514

00:19:09,270 --> 00:19:07,360

prime basically the r_a there's a rate of

515

00:19:10,549 --> 00:19:09,280

change in the diode conductance with

516

00:19:11,750 --> 00:19:10,559

voltage

517

00:19:14,470 --> 00:19:11,760

that's

518

00:19:16,230 --> 00:19:14,480

an added effect with a resistor this

519

00:19:17,669 --> 00:19:16,240

would be equal to zero but in a diode

520

00:19:20,070 --> 00:19:17,679

it's not zero

521

00:19:22,470 --> 00:19:20,080

well look what happens to the i_{to}

522

00:19:24,789 --> 00:19:22,480

longevin equation we get this extra term

523

00:19:26,390 --> 00:19:24,799

stuck in here this is called the thermal

524

00:19:29,830 --> 00:19:26,400

drift current

525

00:19:32,230 --> 00:19:29,840

zero see that

526

00:19:34,549 --> 00:19:32,240

it's also zero if μ prime goes to zero

527

00:19:37,590 --> 00:19:34,559

so if we were if this diode turns into a

528

00:19:39,590 --> 00:19:37,600

resistor it's gone

529

00:19:41,110 --> 00:19:39,600

but here's something okay why is this

530

00:19:43,590 --> 00:19:41,120

term here

531

00:19:44,310 --> 00:19:43,600

okay look over here so μ is over here

532

00:19:46,150 --> 00:19:44,320

to

533

00:19:49,190 --> 00:19:46,160

maintain the fluctuation dissipation

534

00:19:51,750 --> 00:19:49,200

theorem but now μ keeps changing

535

00:19:53,190 --> 00:19:51,760

in time it's actually also a stochastic

536

00:19:55,510 --> 00:19:53,200

variable now

537

00:19:58,070 --> 00:19:55,520

so this is very complicated took a long

538

00:20:00,390 --> 00:19:58,080

time to figure out

539

00:20:02,870 --> 00:20:00,400

what's happening is we have a noisy term

540

00:20:04,549 --> 00:20:02,880

mu times that thermal force which we

541

00:20:07,430 --> 00:20:04,559

know is noisy that gives us

542

00:20:09,510 --> 00:20:07,440

multiplicative noise that's extra noise

543

00:20:12,230 --> 00:20:09,520

it's complicated

544

00:20:14,470 --> 00:20:12,240

now you can you have to correct for that

545

00:20:16,870 --> 00:20:14,480

to maintain the fluctuation dissipation

546

00:20:19,110 --> 00:20:16,880

theorem it's a non-linear effect and

547

00:20:21,430 --> 00:20:19,120

that's what gives us this term

548

00:20:23,909 --> 00:20:21,440

so this drift current is ensure is

549

00:20:26,149 --> 00:20:23,919

basically ensuring that there's no net

550

00:20:27,990 --> 00:20:26,159

occurring a current flowing at any

551
00:20:32,710 --> 00:20:28,000
temperature basically we achieve

552
00:20:36,230 --> 00:20:34,310
it's because of this multiplicative

553
00:20:38,710 --> 00:20:36,240
noise we've got to correct for this here

554
00:20:41,669 --> 00:20:38,720
it's an exact correction

555
00:20:43,990 --> 00:20:41,679
but here we find a hint that we might be

556
00:20:46,149 --> 00:20:44,000
successful in energy harvesting so if we

557
00:20:48,149 --> 00:20:46,159
look at the steady state that is if d if

558
00:20:50,549 --> 00:20:48,159
 i goes to zero if the current stops

559
00:20:52,149 --> 00:20:50,559
flowing that's the steady state solution

560
00:20:53,270 --> 00:20:52,159
up here

561
00:20:55,350 --> 00:20:53,280
this term

562
00:20:57,110 --> 00:20:55,360
this voltage

563
00:21:00,149 --> 00:20:57,120

can't be zero it needs to equal this

564

00:21:03,270 --> 00:21:00,159

term so we have a voltage

565

00:21:05,750 --> 00:21:03,280

that must be present in the diode

566

00:21:07,590 --> 00:21:05,760

at some temperature t

567

00:21:09,110 --> 00:21:07,600

so that voltage is non-zero that's

568

00:21:13,510 --> 00:21:09,120

giving us a hint that we're going to

569

00:21:17,669 --> 00:21:14,870

all right let me just chat about the

570

00:21:19,830 --> 00:21:17,679

diodes real quick we do need diodes they

571

00:21:23,110 --> 00:21:19,840

have to be real diodes that that means

572

00:21:25,270 --> 00:21:23,120

they have to be leaky diodes

573

00:21:28,710 --> 00:21:25,280

for convenience we parameterize the

574

00:21:30,070 --> 00:21:28,720

diodes with um a sigmoid function which

575

00:21:31,830 --> 00:21:30,080

is what this is so this is the

576
00:21:33,430 --> 00:21:31,840
conductance

577
00:21:35,510 --> 00:21:33,440
the only parameter here which is

578
00:21:38,950 --> 00:21:35,520
convenient is u_0

579
00:21:41,590 --> 00:21:38,960
if u_0 is set equal to 0 it's called a

580
00:21:44,630 --> 00:21:41,600
perfect diode it'll have no conductance

581
00:21:46,710 --> 00:21:44,640
in reverse bias and it'll be a perfect

582
00:21:48,070 --> 00:21:46,720
have perfect unity conductance and

583
00:21:50,870 --> 00:21:48,080
forward bias

584
00:21:53,430 --> 00:21:50,880
so it's controlling the leakiness

585
00:21:55,110 --> 00:21:53,440
if we let u_0 become really large

586
00:21:58,070 --> 00:21:55,120
then the conductance flattens out in

587
00:22:00,310 --> 00:21:58,080
fact it turns into a resistor

588
00:22:01,750 --> 00:22:00,320

here's some iv characteristics you can

589

00:22:03,430 --> 00:22:01,760

see that they're leaking they're

590

00:22:05,350 --> 00:22:03,440

non-ideal

591

00:22:07,029 --> 00:22:05,360

i mentioned that μ the rate of change

592

00:22:10,230 --> 00:22:07,039

in μ is important so i'm just plotting

593

00:22:13,350 --> 00:22:10,240

that here as u_0 gets smaller this

594

00:22:18,470 --> 00:22:13,360

derivative gets larger and larger

595

00:22:22,710 --> 00:22:20,390

all right so here's the full system

596

00:22:24,390 --> 00:22:22,720

sorry i have a lot of math here

597

00:22:26,390 --> 00:22:24,400

the ito longevity equations with

598

00:22:27,990 --> 00:22:26,400

kirchhoff's laws so let's write down

599

00:22:29,909 --> 00:22:28,000

kirchhoff's loop laws i'll just point

600

00:22:31,830 --> 00:22:29,919

them out to you basically there's two

601
00:22:34,390 --> 00:22:31,840
loops in this circuit there's a diode

602
00:22:36,310 --> 00:22:34,400
one c one to the capacitor

603
00:22:38,549 --> 00:22:36,320
there's the kirchhoff's there's the

604
00:22:40,470 --> 00:22:38,559
diode voltage right here it's going to

605
00:22:44,230 --> 00:22:40,480
be this voltage plus this voltage we're

606
00:22:46,230 --> 00:22:44,240
going to let v equal zero from that one

607
00:22:48,390 --> 00:22:46,240
and then the other loop is going through

608
00:22:50,070 --> 00:22:48,400
the second diode the second capacitor

609
00:22:51,830 --> 00:22:50,080
and then the graphene okay so those are

610
00:22:53,750 --> 00:22:51,840
the two loops

611
00:22:55,990 --> 00:22:53,760
we also have a kirchhoff's junction law

612
00:22:58,470 --> 00:22:56,000
so any current that's coming from the

613
00:23:00,630 --> 00:22:58,480

graphene hits this junction

614

00:23:02,470 --> 00:23:00,640

and gets split so there's an i_1 goes

615

00:23:04,789 --> 00:23:02,480

this way and i_2 goes this way and they

616

00:23:06,710 --> 00:23:04,799

have to add up to i

617

00:23:08,710 --> 00:23:06,720

if we set all the initial charges on

618

00:23:11,190 --> 00:23:08,720

these three capacitors to zero we can

619

00:23:13,110 --> 00:23:11,200

rewrite this junction law is just q is

620

00:23:14,710 --> 00:23:13,120

q_1 plus q_2

621

00:23:16,470 --> 00:23:14,720

what i want to point out here just to

622

00:23:18,630 --> 00:23:16,480

give you a little force for the little

623

00:23:21,750 --> 00:23:18,640

foreshadowing

624

00:23:25,110 --> 00:23:21,760

there this is an algebraic constraint

625

00:23:27,590 --> 00:23:25,120

it's just conservation laws imposed on

626

00:23:30,310 --> 00:23:27,600

our stochastic equations these will have

627

00:23:32,149 --> 00:23:30,320

profound consequences we'll see

628

00:23:34,149 --> 00:23:32,159

so here's our three

629

00:23:36,070 --> 00:23:34,159

differential equation or this is the

630

00:23:38,149 --> 00:23:36,080

brownian motion for the graphene i added

631

00:23:39,990 --> 00:23:38,159

one more term since the graphene's near

632

00:23:41,990 --> 00:23:40,000

the electrode and it can have charge on

633

00:23:44,789 --> 00:23:42,000

it there's a coulomb interaction

634

00:23:46,630 --> 00:23:44,799

this q is stochastic and we square it so

635

00:23:49,590 --> 00:23:46,640

there's more multiplicative noise here

636

00:23:51,830 --> 00:23:49,600

it's very complicated

637

00:23:53,510 --> 00:23:51,840

there's the two differential equations

638

00:23:55,430 --> 00:23:53,520

for the current

639

00:23:57,510 --> 00:23:55,440

i is one and two here those are the same

640

00:24:00,470 --> 00:23:57,520

as i wrote down before so in the end we

641

00:24:01,669 --> 00:24:00,480

have three couple stochastic non-linear

642

00:24:03,830 --> 00:24:01,679

stiff

643

00:24:05,990 --> 00:24:03,840

differential equations they have to be

644

00:24:08,390 --> 00:24:06,000

solved numerically give a little shout

645

00:24:10,630 --> 00:24:08,400

out to uh mathematic here for the

646

00:24:13,750 --> 00:24:10,640

earlier talk this week i recommend using

647

00:24:15,590 --> 00:24:13,760

mathematica to solve these

648

00:24:18,549 --> 00:24:15,600

look we're going to look for solutions

649

00:24:20,230 --> 00:24:18,559

very far from equilibrium you have to do

650

00:24:22,230 --> 00:24:20,240

it numerically

651
00:24:25,909 --> 00:24:22,240
there's actually a very large parameter

652
00:24:28,310 --> 00:24:25,919
space here it took us 1.5 years now to

653
00:24:30,630 --> 00:24:28,320
study this parameter space we just

654
00:24:32,549 --> 00:24:30,640
wrapped this up we've been using a

655
00:24:35,269 --> 00:24:32,559
supercomputer

656
00:24:37,830 --> 00:24:35,279
we have 10 billion time steps for each

657
00:24:40,470 --> 00:24:37,840
simulation and each one we do with 3 000

658
00:24:44,950 --> 00:24:40,480
realizations and a huge parameter space

659
00:24:49,909 --> 00:24:47,510
so here's our surprise discovery

660
00:24:53,110 --> 00:24:49,919
charge is added to capacitors 1 and

661
00:24:55,110 --> 00:24:53,120
capacitor 2 and energy is harvested

662
00:24:57,350 --> 00:24:55,120
here's a plot showing the charge on all

663
00:24:59,110 --> 00:24:57,360

three capacitors in time

664

00:25:00,950 --> 00:24:59,120

let's start with the blue one the blue

665

00:25:03,110 --> 00:25:00,960

one is the graphene

666

00:25:05,669 --> 00:25:03,120

the graphene doesn't build up any charge

667

00:25:07,430 --> 00:25:05,679

well mostly the voltage is set to zero

668

00:25:08,870 --> 00:25:07,440

so that's going to keep the charge here

669

00:25:10,070 --> 00:25:08,880

at zero

670

00:25:11,750 --> 00:25:10,080

and so it

671

00:25:13,510 --> 00:25:11,760

just fluctuates a little bit and stays

672

00:25:17,029 --> 00:25:13,520

zero the whole time but look at this

673

00:25:19,830 --> 00:25:17,039

green one the charge rises quite quickly

674

00:25:23,269 --> 00:25:19,840

and reaches a steady state close to 20.

675

00:25:25,590 --> 00:25:23,279

this is q2 so this is the charge on c2

676
00:25:27,510 --> 00:25:25,600
the red one is decreasing had building

677
00:25:29,510 --> 00:25:27,520
up a negative charge on it so it gets to

678
00:25:31,909 --> 00:25:29,520
about negative 20 and reaches a steady

679
00:25:34,549 --> 00:25:31,919
state that's c1

680
00:25:38,230 --> 00:25:34,559
notice that q1 and q2 are strongly

681
00:25:40,549 --> 00:25:38,240
anti-correlated anywhere q1 goes q2 has

682
00:25:42,789 --> 00:25:40,559
to do the opposite there's a strong

683
00:25:45,750 --> 00:25:42,799
anti-correlation here this is coming

684
00:25:47,990 --> 00:25:45,760
about because of kirchhoff's laws

685
00:25:50,149 --> 00:25:48,000
so how can this circuit harvest energy

686
00:25:52,390 --> 00:25:50,159
from the thermal environment

687
00:25:54,070 --> 00:25:52,400
there's three ingredients we believe are

688
00:25:56,549 --> 00:25:54,080

needed

689

00:25:58,470 --> 00:25:56,559

the graphene which is the very c of x

690

00:26:00,789 --> 00:25:58,480

capacitor we need it to be much much

691

00:26:03,029 --> 00:26:00,799

smaller than the storage capacitors this

692

00:26:05,190 --> 00:26:03,039

boosts the voltage to really high levels

693

00:26:08,390 --> 00:26:05,200

for the diodes

694

00:26:09,590 --> 00:26:08,400

the diodes generate multiplicative noise

695

00:26:12,070 --> 00:26:09,600

i pointed that out to you there's

696

00:26:14,230 --> 00:26:12,080

multiplicative noise in diodes that

697

00:26:15,909 --> 00:26:14,240

shifts the voltage the diode voltage

698

00:26:18,070 --> 00:26:15,919

away from zero so we can have a

699

00:26:20,470 --> 00:26:18,080

persistent voltage

700

00:26:21,269 --> 00:26:20,480

we also need this junction

701
00:26:23,430 --> 00:26:21,279
here

702
00:26:25,590 --> 00:26:23,440
the junction in fact the junction has to

703
00:26:26,950 --> 00:26:25,600
be followed by diodes wired in

704
00:26:28,710 --> 00:26:26,960
opposition

705
00:26:30,789 --> 00:26:28,720
we've run the simulations with the

706
00:26:32,950 --> 00:26:30,799
diodes oriented in the same direction

707
00:26:35,110 --> 00:26:32,960
you can't harvest energy then

708
00:26:38,549 --> 00:26:35,120
we've also cut off this loop if you

709
00:26:39,510 --> 00:26:38,559
force q_2 to go to zero then q_1 goes to

710
00:26:41,269 --> 00:26:39,520
0.

711
00:26:42,390 --> 00:26:41,279
you need these two loops you need the

712
00:26:44,230 --> 00:26:42,400
junction

713
00:26:45,269 --> 00:26:44,240

you can kind of see that here we have

714

00:26:48,470 --> 00:26:45,279

that q

715

00:26:51,590 --> 00:26:48,480

is equal to q_1 plus q_2 if we look at the

716

00:26:54,230 --> 00:26:51,600

time averages or ensemble averages

717

00:26:56,630 --> 00:26:54,240

we know q is zero so that says that q_1

718

00:26:58,710 --> 00:26:56,640

is negative of q_2

719

00:27:00,630 --> 00:26:58,720

if we square this thing let's kind of

720

00:27:03,590 --> 00:27:00,640

talk about the energy

721

00:27:06,950 --> 00:27:03,600

q_1 squared plus q_2 squared is going to

722

00:27:08,870 --> 00:27:06,960

be q squared minus $2q_1$ this is a

723

00:27:11,190 --> 00:27:08,880

correlation function here really between

724

00:27:13,269 --> 00:27:11,200

these stochastic variables

725

00:27:15,430 --> 00:27:13,279

we can see q_1 squared

726
00:27:17,909 --> 00:27:15,440
it's just negative 20 times negative 20.

727
00:27:19,590 --> 00:27:17,919
it's $400 q_2^2$ squared

728
00:27:21,190 --> 00:27:19,600
is also 400

729
00:27:23,590 --> 00:27:21,200
 q squared is zero

730
00:27:26,190 --> 00:27:23,600
and then minus two this is q_1 times it's

731
00:27:29,110 --> 00:27:26,200
20 times negative 20. so we the the

732
00:27:31,350 --> 00:27:29,120
anticorrelation of q_1 and q_2 is driving

733
00:27:34,470 --> 00:27:31,360
the energy harvesting it's responsible

734
00:27:37,830 --> 00:27:34,480
for it you can see that here

735
00:27:41,350 --> 00:27:37,840
let's look at the ensemble averages

736
00:27:47,269 --> 00:27:44,789
if you plot the capacitor charge

737
00:27:50,389 --> 00:27:47,279
as a function of capacitance the storage

738
00:27:53,510 --> 00:27:50,399

capacitors capacitance

739

00:27:55,510 --> 00:27:53,520

you we find that you'll store more

740

00:27:57,909 --> 00:27:55,520

charge if you have a bigger capacitor in

741

00:27:59,430 --> 00:27:57,919

fact it's linearly precisely linear in

742

00:28:01,110 --> 00:27:59,440

that what does that mean it means

743

00:28:03,350 --> 00:28:01,120

they're all being charged to the same

744

00:28:05,669 --> 00:28:03,360

voltage the same that's that diode

745

00:28:07,750 --> 00:28:05,679

voltage i pointed out there's some diode

746

00:28:09,510 --> 00:28:07,760

persistent diode voltage which be it's

747

00:28:11,830 --> 00:28:09,520

being held here

748

00:28:14,230 --> 00:28:11,840

now let's look at the diode parameter

749

00:28:15,909 --> 00:28:14,240

turns out you can maximize the charge

750

00:28:18,950 --> 00:28:15,919

stored on the capacitor if the diode

751

00:28:21,110 --> 00:28:18,960

parameter is about 0.15 and very

752

00:28:23,510 --> 00:28:21,120

interestingly if the diode parameter

753

00:28:26,149 --> 00:28:23,520

gets smaller and smaller we follow this

754

00:28:28,630 --> 00:28:26,159

all the way to zero it goes to zero it's

755

00:28:31,110 --> 00:28:28,640

exactly zero if you have a perfect diode

756

00:28:33,029 --> 00:28:31,120

you can't harvest energy

757

00:28:35,029 --> 00:28:33,039

on the flip side if the diode primer

758

00:28:36,630 --> 00:28:35,039

gets larger and larger it also goes to

759

00:28:38,710 --> 00:28:36,640

zero that's because it turns into a

760

00:28:41,029 --> 00:28:38,720

resistor so you can't harvest energy

761

00:28:43,029 --> 00:28:41,039

with resistor

762

00:28:45,110 --> 00:28:43,039

if you look at the ensemble averages in

763

00:28:47,430 --> 00:28:45,120

the capacitor charge that earlier one

764

00:28:48,870 --> 00:28:47,440

was one realization so we do 3000

765

00:28:51,590 --> 00:28:48,880

realizations

766

00:28:54,310 --> 00:28:51,600

you get these nice smooth capacitor

767

00:28:57,750 --> 00:28:54,320

charge versus time curves in fact

768

00:29:00,950 --> 00:28:57,760

they're exactly rc charging circuits

769

00:29:03,669 --> 00:29:00,960

if you look at the time constant τ of

770

00:29:05,510 --> 00:29:03,679

the rc circuit which is r times c it's

771

00:29:07,750 --> 00:29:05,520

perfectly linear

772

00:29:09,909 --> 00:29:07,760

in capacitance

773

00:29:12,630 --> 00:29:09,919

so it's exactly like the rc charging

774

00:29:14,470 --> 00:29:12,640

which i showed you in the deterministic

775

00:29:16,549 --> 00:29:14,480

so then we can look at the charge the

776

00:29:19,029 --> 00:29:16,559

voltage the current and the power as a

777

00:29:21,029 --> 00:29:19,039

function of time so here's the capacitor

778

00:29:23,029 --> 00:29:21,039

charge charging up

779

00:29:24,549 --> 00:29:23,039

that allows us to determine the voltage

780

00:29:26,789 --> 00:29:24,559

on the capacitor

781

00:29:28,230 --> 00:29:26,799

it's rate it's continuously rising we

782

00:29:30,549 --> 00:29:28,240

can also get the current so see the

783

00:29:32,470 --> 00:29:30,559

current starts high and then decays

784

00:29:34,070 --> 00:29:32,480

exponentially in time

785

00:29:35,750 --> 00:29:34,080

if you take the current times the

786

00:29:37,510 --> 00:29:35,760

voltage you'll get the power look

787

00:29:39,190 --> 00:29:37,520

there's a peak power remember i

788

00:29:41,510 --> 00:29:39,200

mentioned the peak power this circuit

789

00:29:45,190 --> 00:29:41,520

has 50 efficiency there's the peak

790

00:29:50,870 --> 00:29:46,950

all right can we find can we really find

791

00:29:52,630 --> 00:29:50,880

the source of energy we can in fact

792

00:29:55,190 --> 00:29:52,640

using what's called stochastic

793

00:29:57,269 --> 00:29:55,200

thermodynamics this is an emergent field

794

00:29:59,590 --> 00:29:57,279

of physics honestly with low hanging

795

00:30:01,430 --> 00:29:59,600

fruit you know anything we look at never

796

00:30:04,549 --> 00:30:01,440

been seen before

797

00:30:05,830 --> 00:30:04,559

is revealing a lot of nice things so

798

00:30:09,190 --> 00:30:05,840

basically

799

00:30:10,789 --> 00:30:09,200

it allows us to look intimately at all

800

00:30:12,389 --> 00:30:10,799

the sources of

801
00:30:14,230 --> 00:30:12,399
energy

802
00:30:16,149 --> 00:30:14,240
heat and work

803
00:30:19,110 --> 00:30:16,159
so here's the graphene

804
00:30:22,230 --> 00:30:19,120
heat bath we can track the we can track

805
00:30:25,590 --> 00:30:22,240
what it's doing here's the graphing uh

806
00:30:28,470 --> 00:30:25,600
drag the resistance basically the losses

807
00:30:32,149 --> 00:30:28,480
there's the resistor dissipated power

808
00:30:33,750 --> 00:30:32,159
and there's the resistors heat valve

809
00:30:34,950 --> 00:30:33,760
so what we do is we write down the

810
00:30:36,950 --> 00:30:34,960
energy of the system that's

811
00:30:39,350 --> 00:30:36,960
straightforward we use the first law of

812
00:30:41,350 --> 00:30:39,360
thermodynamics says the energy is the

813
00:30:43,750 --> 00:30:41,360

heat plus the work and then we go ahead

814

00:30:45,029 --> 00:30:43,760

and we calculate the heat from the point

815

00:30:46,549 --> 00:30:45,039

of view of the graphene you have to pick

816

00:30:49,350 --> 00:30:46,559

some point of view

817

00:30:50,870 --> 00:30:49,360

the heat flux produced by friction

818

00:30:52,630 --> 00:30:50,880

is this for me and these are these two

819

00:30:54,230 --> 00:30:52,640

terms over here

820

00:30:56,630 --> 00:30:54,240

those in fact

821

00:30:57,509 --> 00:30:56,640

um during the energy harvesting phase

822

00:30:59,909 --> 00:30:57,519

we've

823

00:31:01,830 --> 00:30:59,919

calculated those precisely there's there

824

00:31:04,389 --> 00:31:01,840

this is zero there's no heat there's no

825

00:31:06,149 --> 00:31:04,399

heat flux produced by graphene

826

00:31:08,230 --> 00:31:06,159

it turns out the work so this term here

827

00:31:11,110 --> 00:31:08,240

is zero so all of the energy is coming

828

00:31:13,190 --> 00:31:11,120

from the work well the work done on the

829

00:31:14,950 --> 00:31:13,200

graphene by the circuit that's given by

830

00:31:16,470 --> 00:31:14,960

this a little bit complicated and you

831

00:31:18,950 --> 00:31:16,480

can't write it analytically but it's

832

00:31:20,389 --> 00:31:18,960

close to this term this $k_B T$ over rc

833

00:31:22,630 --> 00:31:20,399

that's the power

834

00:31:25,509 --> 00:31:22,640

of the thermal bath

835

00:31:27,350 --> 00:31:25,519

being put into the diode basically and

836

00:31:29,669 --> 00:31:27,360

this is the

837

00:31:31,509 --> 00:31:29,679

dissipated power by the diode well

838

00:31:33,430 --> 00:31:31,519

here's what happens during the energy

839

00:31:35,590 --> 00:31:33,440

harvesting phase while the capacitors

840

00:31:37,909 --> 00:31:35,600

are charging up this term

841

00:31:39,509 --> 00:31:37,919

the thermal power coming from the

842

00:31:42,149 --> 00:31:39,519

thermal bath

843

00:31:44,710 --> 00:31:42,159

is slightly bigger than the dissipated

844

00:31:47,110 --> 00:31:44,720

power of the diodes and that extra

845

00:31:50,310 --> 00:31:47,120

energy charges the capacitor so that's

846

00:31:52,710 --> 00:31:50,320

the source of power we can prove that

847

00:31:54,549 --> 00:31:52,720

here's a graph of that

848

00:31:57,190 --> 00:31:54,559

so the red line here

849

00:31:59,190 --> 00:31:57,200

these all start at zero but the red line

850

00:32:00,870 --> 00:31:59,200

is the energy of the system so this is

851
00:32:02,870 --> 00:32:00,880
the charging of the capacitors of course

852
00:32:04,710 --> 00:32:02,880
they're storing energy so their energy

853
00:32:07,669 --> 00:32:04,720
is changing in time

854
00:32:09,590 --> 00:32:07,679
the green one is the work plus the heat

855
00:32:11,110 --> 00:32:09,600
but we also separately check the heat

856
00:32:12,470 --> 00:32:11,120
it's actually zero so this is really

857
00:32:15,430 --> 00:32:12,480
just the work

858
00:32:17,269 --> 00:32:15,440
if you subtract these two

859
00:32:18,870 --> 00:32:17,279
they're basically always zero there's

860
00:32:20,230 --> 00:32:18,880
this is actually it's numerically

861
00:32:22,230 --> 00:32:20,240
challenging there's some slight

862
00:32:24,389 --> 00:32:22,240
numerical drift here that's happening in

863
00:32:26,710 --> 00:32:24,399

time which we've worked very hard to

864

00:32:29,669 --> 00:32:26,720

deal with but notice how this hairiness

865

00:32:32,149 --> 00:32:29,679

goes away this tells us the first law is

866

00:32:34,149 --> 00:32:32,159

rigorously obeyed at every time step

867

00:32:36,230 --> 00:32:34,159

this is what this is telling us so we

868

00:32:39,029 --> 00:32:36,240

are satisfying the law the first law of

869

00:32:41,669 --> 00:32:39,039

physics which is here

870

00:32:44,789 --> 00:32:41,679

so energy is increasing in time as the

871

00:32:47,110 --> 00:32:44,799

capacitors charge up so h is growing

872

00:32:49,509 --> 00:32:47,120

graphing does not provide an energy q is

873

00:32:51,509 --> 00:32:49,519

zero the power comes from the thermal

874

00:32:53,590 --> 00:32:51,519

bath of the diode so the work done is

875

00:32:55,909 --> 00:32:53,600

what's giving us the energy

876

00:32:57,990 --> 00:32:55,919

the graphene does provide the voltage

877

00:32:59,990 --> 00:32:58,000

though at these top rails so this is a

878

00:33:02,070 --> 00:33:00,000

very interesting thing

879

00:33:04,470 --> 00:33:02,080

why you need these two loops

880

00:33:07,269 --> 00:33:04,480

so current actually flows

881

00:33:09,029 --> 00:33:07,279

between the diodes basically forming a

882

00:33:11,430 --> 00:33:09,039

vortex here

883

00:33:14,070 --> 00:33:11,440

the circulating current is here charging

884

00:33:16,149 --> 00:33:14,080

one positive the other negative

885

00:33:18,070 --> 00:33:16,159

and all the power and the current is

886

00:33:20,310 --> 00:33:18,080

here even though the voltage is set by

887

00:33:22,710 --> 00:33:20,320

this guy over here along these top rails

888

00:33:24,470 --> 00:33:22,720

again v is zero here

889

00:33:25,669 --> 00:33:24,480

very interesting all right what about

890

00:33:28,310 --> 00:33:25,679

the entry

891

00:33:30,710 --> 00:33:28,320

the measure of disorder we can track the

892

00:33:32,470 --> 00:33:30,720

entropy during charging using the shin

893

00:33:34,070 --> 00:33:32,480

and entropy formula basically looks at

894

00:33:37,190 --> 00:33:34,080

the probability

895

00:33:38,710 --> 00:33:37,200

of having a certain charge in time

896

00:33:40,549 --> 00:33:38,720

all right so we have those three

897

00:33:42,230 --> 00:33:40,559

thousand realizations so everything's

898

00:33:43,269 --> 00:33:42,240

the same except the random numbers

899

00:33:45,269 --> 00:33:43,279

change

900

00:33:47,590 --> 00:33:45,279

we always start with q equals zero and

901
00:33:49,990 --> 00:33:47,600
then we track q_1 and q_2 in time just

902
00:33:51,909 --> 00:33:50,000
like the graph showed before

903
00:33:54,389 --> 00:33:51,919
and then we find the probability of

904
00:33:56,950 --> 00:33:54,399
having a specific set of charges q_1 and

905
00:33:57,909 --> 00:33:56,960
 q_2 at a specific time

906
00:33:59,830 --> 00:33:57,919
all right

907
00:34:01,590 --> 00:33:59,840
so here's the graph of the entropy it

908
00:34:03,990 --> 00:34:01,600
starts off at zero i'll explain that in

909
00:34:06,870 --> 00:34:04,000
a second but then jumps fairly quickly

910
00:34:08,790 --> 00:34:06,880
to around four there's a slight decay in

911
00:34:11,190 --> 00:34:08,800
the entropy here we should chat about

912
00:34:13,430 --> 00:34:11,200
that maybe daniel might check on that

913
00:34:16,310 --> 00:34:13,440

uh but anyhow there's an overall

914

00:34:18,629 --> 00:34:16,320

positive production entropy from zero to

915

00:34:20,230 --> 00:34:18,639

four entropy is produced here

916

00:34:22,950 --> 00:34:20,240

at t equals zero let's see what's going

917

00:34:25,669 --> 00:34:22,960

on there so the initial conditions are

918

00:34:27,750 --> 00:34:25,679

that uh there's everything set to zero

919

00:34:29,109 --> 00:34:27,760

so for every simulation they all have

920

00:34:31,270 --> 00:34:29,119

the same initial conditions whatever

921

00:34:33,990 --> 00:34:31,280

that doesn't matter so there's a hundred

922

00:34:36,470 --> 00:34:34,000

percent probability of having the same

923

00:34:38,790 --> 00:34:36,480

initial condition and the log here which

924

00:34:40,950 --> 00:34:38,800

comes in here the log of one is zero so

925

00:34:43,030 --> 00:34:40,960

the entropy starts off at zero and it's

926
00:34:44,230 --> 00:34:43,040
positive we have a positive production

927
00:34:47,109 --> 00:34:44,240
of entropy

928
00:34:49,109 --> 00:34:47,119
so we're happy with that

929
00:34:51,190 --> 00:34:49,119
all right let me just throw some i got a

930
00:34:53,030 --> 00:34:51,200
lot of email get lots of questions let

931
00:34:54,550 --> 00:34:53,040
me just guess some questions and throw

932
00:34:56,869 --> 00:34:54,560
out some answers here

933
00:34:59,589 --> 00:34:56,879
does our energy harvesting system

934
00:35:00,550 --> 00:34:59,599
violate the first law of thermodynamics

935
00:35:03,430 --> 00:35:00,560
no

936
00:35:04,470 --> 00:35:03,440
the energy is equal to the heat plus the

937
00:35:06,790 --> 00:35:04,480
work

938
00:35:09,750 --> 00:35:06,800

that's the first law actually we found

939

00:35:14,710 --> 00:35:09,760

the heat is zero so all the work

940

00:35:18,069 --> 00:35:16,790

where does the stored capacitor energy

941

00:35:19,430 --> 00:35:18,079

come from

942

00:35:21,750 --> 00:35:19,440

well it comes from the thermal

943

00:35:24,390 --> 00:35:21,760

surroundings it's coming from this kbt

944

00:35:26,150 --> 00:35:24,400

over r c so it's the thermal it's the

945

00:35:27,829 --> 00:35:26,160

environment the thermal environment

946

00:35:29,430 --> 00:35:27,839

stealing energy from that massive

947

00:35:31,030 --> 00:35:29,440

thermal environment that daniel talked

948

00:35:32,710 --> 00:35:31,040

about

949

00:35:34,950 --> 00:35:32,720

is work done at thermodynamic

950

00:35:37,589 --> 00:35:34,960

equilibrium no our system's not in

951
00:35:39,030 --> 00:35:37,599
thermodynamic the charges are always

952
00:35:41,030 --> 00:35:39,040
moving they're always adding and

953
00:35:43,430 --> 00:35:41,040
removing

954
00:35:45,990 --> 00:35:43,440
from the system it's actually very far

955
00:35:48,470 --> 00:35:46,000
from equilibrium

956
00:35:50,710 --> 00:35:48,480
is it is useful work done at a single

957
00:35:52,470 --> 00:35:50,720
temperature yes everything's at the same

958
00:35:53,430 --> 00:35:52,480
temperature we ensured that through

959
00:35:57,270 --> 00:35:53,440
those

960
00:35:58,710 --> 00:35:57,280
you

961
00:36:00,069 --> 00:35:58,720
does our system violate the second law

962
00:36:03,030 --> 00:36:00,079
of thermodynamics

963
00:36:05,190 --> 00:36:03,040

no our system starts from equilibrium

964

00:36:07,109 --> 00:36:05,200

sorry far from equilibrium

965

00:36:09,190 --> 00:36:07,119

and is driven to a steady state by

966

00:36:10,950 --> 00:36:09,200

unbalanced forces i'll give a good

967

00:36:12,950 --> 00:36:10,960

example of this in a second those

968

00:36:15,910 --> 00:36:12,960

unbalanced forces this is the diode

969

00:36:18,069 --> 00:36:15,920

voltage it turns out that extra term

970

00:36:19,030 --> 00:36:18,079

is driving it

971

00:36:21,349 --> 00:36:19,040

is

972

00:36:23,910 --> 00:36:21,359

entropy produced yes the capacitor

973

00:36:26,069 --> 00:36:23,920

entropy increases from zero to four

974

00:36:27,990 --> 00:36:26,079

are there any pedagogical examples of

975

00:36:29,349 --> 00:36:28,000

thermal work being done at a single

976
00:36:32,470 --> 00:36:29,359
temperature

977
00:36:34,230 --> 00:36:32,480
yes as a framework consider the ideal

978
00:36:37,109 --> 00:36:34,240
gas which daniel talked about this is

979
00:36:39,349 --> 00:36:37,119
very helpful for this talk

980
00:36:41,510 --> 00:36:39,359
so here let consider work and entropy

981
00:36:43,670 --> 00:36:41,520
during an isothermal expansion so

982
00:36:44,790 --> 00:36:43,680
imagine two masses sitting on this

983
00:36:47,430 --> 00:36:44,800
balloon

984
00:36:48,550 --> 00:36:47,440
we're going to remove the first mass

985
00:36:50,230 --> 00:36:48,560
and as the

986
00:36:52,310 --> 00:36:50,240
mass gets removed the balloon can kind

987
00:36:53,589 --> 00:36:52,320
of expand because the weight's been

988
00:36:55,190 --> 00:36:53,599

removed

989

00:36:56,150 --> 00:36:55,200

and we're going to analyze

990

00:36:58,470 --> 00:36:56,160

the

991

00:37:00,230 --> 00:36:58,480

work done on this second mass as it's

992

00:37:01,589 --> 00:37:00,240

raised up a height h

993

00:37:03,430 --> 00:37:01,599

we're going to have a heater here we'll

994

00:37:05,270 --> 00:37:03,440

see we need to have that so this is to

995

00:37:07,430 --> 00:37:05,280

keep the temperature fixed

996

00:37:09,829 --> 00:37:07,440

we have uh before and after pictures

997

00:37:12,310 --> 00:37:09,839

here let's apply the first law to the

998

00:37:14,550 --> 00:37:12,320

second mass here this one

999

00:37:16,470 --> 00:37:14,560

here's the first law the heat there's no

1000

00:37:18,950 --> 00:37:16,480

heat change in this mass

1001
00:37:21,589 --> 00:37:18,960
the energy change because it was raised

1002
00:37:24,150 --> 00:37:21,599
mgh and the work was done the normal

1003
00:37:26,790 --> 00:37:24,160
force of the balloon pushed it

1004
00:37:29,670 --> 00:37:26,800
for a distance h so work was done on the

1005
00:37:31,750 --> 00:37:29,680
mass and the energy increased from that

1006
00:37:34,150 --> 00:37:31,760
this is exactly what i was saying in our

1007
00:37:36,710 --> 00:37:34,160
situation so work was done

1008
00:37:38,950 --> 00:37:36,720
by the thermal environment on the

1009
00:37:40,790 --> 00:37:38,960
capacitors or on the circuit if you like

1010
00:37:42,550 --> 00:37:40,800
and it raised its energy and the heat

1011
00:37:43,829 --> 00:37:42,560
was there was no heat change this is the

1012
00:37:45,750 --> 00:37:43,839
same as ours

1013
00:37:47,589 --> 00:37:45,760

now let's analyze the gas this is the

1014

00:37:50,310 --> 00:37:47,599

thermal gas

1015

00:37:52,710 --> 00:37:50,320

so here we know for an ideal gas that

1016

00:37:55,109 --> 00:37:52,720

the work done in an isothermal process

1017

00:37:57,430 --> 00:37:55,119

is given by this formula now here the

1018

00:37:58,630 --> 00:37:57,440

work is done by the gas so the work's

1019

00:38:01,430 --> 00:37:58,640

negative

1020

00:38:03,349 --> 00:38:01,440

let's apply the first law to the gas

1021

00:38:05,430 --> 00:38:03,359

here is the first law there's no

1022

00:38:07,750 --> 00:38:05,440

internal energy to this gas so it's

1023

00:38:09,750 --> 00:38:07,760

ideal so we're going to let h be zero so

1024

00:38:11,670 --> 00:38:09,760

that means that Δq

1025

00:38:14,870 --> 00:38:11,680

is equal to minus

1026

00:38:17,910 --> 00:38:14,880

delta w or positive so that means heat

1027

00:38:19,910 --> 00:38:17,920

flows to the gas that's why we need the

1028

00:38:22,230 --> 00:38:19,920

heater so the heater heats the gas to

1029

00:38:24,069 --> 00:38:22,240

keep the temperature constant that heat

1030

00:38:26,550 --> 00:38:24,079

is positive because it's flowing into

1031

00:38:28,230 --> 00:38:26,560

the gas that means entropy is produced

1032

00:38:29,670 --> 00:38:28,240

and it's positive these are all kind of

1033

00:38:31,829 --> 00:38:29,680

these are basically

1034

00:38:34,390 --> 00:38:31,839

equal you know in some some ideal

1035

00:38:36,870 --> 00:38:34,400

circumstances

1036

00:38:38,310 --> 00:38:36,880

so yeah so that's uh for us uh this is

1037

00:38:42,069 --> 00:38:38,320

the thermal environment around the

1038

00:38:46,950 --> 00:38:44,150

all right so let me summarize

1039

00:38:48,950 --> 00:38:46,960

stochastic thermodynamics is yielding

1040

00:38:51,670 --> 00:38:48,960

quantitative insights far from

1041

00:38:54,550 --> 00:38:51,680

equilibrium

1042

00:38:56,550 --> 00:38:54,560

graphene this capacitor c of x we've

1043

00:38:58,390 --> 00:38:56,560

i've mentioned shifts the power to low

1044

00:39:00,790 --> 00:38:58,400

frequencies due to this double well this

1045

00:39:03,190 --> 00:39:00,800

has some technological value

1046

00:39:05,030 --> 00:39:03,200

the average capacitance of graphene

1047

00:39:06,550 --> 00:39:05,040

determines the voltage

1048

00:39:08,310 --> 00:39:06,560

that's kind of like the gain or the

1049

00:39:10,870 --> 00:39:08,320

bandwidth you can think of

1050

00:39:12,710 --> 00:39:10,880

if you think of the

1051

00:39:15,190 --> 00:39:12,720

impedance

1052

00:39:17,109 --> 00:39:15,200

of a circuit the imaginary part is the

1053

00:39:18,790 --> 00:39:17,119

capacitance so it can it can do

1054

00:39:20,069 --> 00:39:18,800

something like change the gain or the

1055

00:39:22,550 --> 00:39:20,079

bandwidth

1056

00:39:24,550 --> 00:39:22,560

but the current circulates between the

1057

00:39:27,349 --> 00:39:24,560

diodes that's the resistance that's the

1058

00:39:29,829 --> 00:39:27,359

real part and it's doing the work here

1059

00:39:31,829 --> 00:39:29,839

energy harvested increases in time and

1060

00:39:33,430 --> 00:39:31,839

then stops it reaches a steady state

1061

00:39:34,790 --> 00:39:33,440

it's not like some perpetual motion

1062

00:39:36,470 --> 00:39:34,800

machine it just

1063

00:39:38,390 --> 00:39:36,480

tries to it's trying to reach steady

1064

00:39:39,910 --> 00:39:38,400

state the capacitors would

1065

00:39:41,589 --> 00:39:39,920

normally in the room right now which

1066

00:39:43,510 --> 00:39:41,599

capacitors charge would be zero and

1067

00:39:45,910 --> 00:39:43,520

that's its steady state when you hook it

1068

00:39:47,109 --> 00:39:45,920

to the circuit it wants to be something

1069

00:39:49,430 --> 00:39:47,119

else

1070

00:39:51,510 --> 00:39:49,440

that's its steady state

1071

00:39:53,829 --> 00:39:51,520

the energy source is the diode's thermal

1072

00:39:54,710 --> 00:39:53,839

bath because the remember the heat was

1073

00:39:57,829 --> 00:39:54,720

zero

1074

00:39:59,349 --> 00:39:57,839

to four

1075

00:40:00,710 --> 00:39:59,359

estimates of our power density i

1076

00:40:03,349 --> 00:40:00,720

mentioned there before it's worth kind

1077

00:40:05,510 --> 00:40:03,359

of pursuing these things

1078

00:40:07,430 --> 00:40:05,520

and then let me just acknowledge pradeep

1079

00:40:09,109 --> 00:40:07,440

and saran been chatting with them for

1080

00:40:11,750 --> 00:40:09,119

years about this has been extremely

1081

00:40:14,630 --> 00:40:11,760

helpful also john new at uc berkeley and

1082

00:40:16,550 --> 00:40:14,640

louis vanilla carlos iii these guys are

1083

00:40:18,309 --> 00:40:16,560

world experts in stochastic

1084

00:40:19,910 --> 00:40:18,319

thermodynamics we couldn't move forward

1085

00:40:20,790 --> 00:40:19,920

without them

1086

00:40:23,510 --> 00:40:20,800

we are

1087

00:40:25,589 --> 00:40:23,520

summarizing this paper i hope to get it

1088

00:40:28,470 --> 00:40:25,599

on the archive before we submit it for

1089

00:40:31,109 --> 00:40:28,480

publication here in a few weeks and also

1090

00:40:33,829 --> 00:40:31,119

let me thank funding sources here

1091

00:40:34,950 --> 00:40:33,839

that i'm done thank you very much

1092

00:40:38,710 --> 00:40:34,960

thank you

1093

00:40:41,510 --> 00:40:38,720

uh what a fantastic presentation uh this

1094

00:40:44,790 --> 00:40:41,520

uh your work is so careful

1095

00:40:47,349 --> 00:40:44,800

and so fascinating um i'm sure they're

1096

00:40:49,829 --> 00:40:47,359

gonna be a lot of questions uh i'll

1097

00:40:51,030 --> 00:40:49,839

start off with a very quick one and that

1098

00:40:53,109 --> 00:40:51,040

is that you

1099

00:40:55,030 --> 00:40:53,119

have described your

1100

00:40:58,150 --> 00:40:55,040

uh

1101
00:41:01,270 --> 00:40:58,160
system as being far from equilibrium and

1102
00:41:03,670 --> 00:41:01,280
therefore not violating the second law

1103
00:41:07,270 --> 00:41:03,680
if you take your system

1104
00:41:09,670 --> 00:41:07,280
of the graphene and you just start it in

1105
00:41:11,990 --> 00:41:09,680
a thermal equilibrium

1106
00:41:14,309 --> 00:41:12,000
what nudges it to be far from

1107
00:41:17,589 --> 00:41:14,319
equilibrium if it isn't the system

1108
00:41:22,870 --> 00:41:18,630
yes

1109
00:41:27,670 --> 00:41:24,870
so for example here

1110
00:41:30,390 --> 00:41:27,680
uh once the charge has reached this

1111
00:41:34,309 --> 00:41:30,400
steady state value

1112
00:41:35,190 --> 00:41:34,319
so that is the steady state solution to

1113
00:41:39,829 --> 00:41:35,200

this

1114

00:41:42,390 --> 00:41:39,839

and

1115

00:41:45,750 --> 00:41:42,400

it's not that's not in thermodynamic

1116

00:41:47,349 --> 00:41:45,760

equilibrium but it is in a steady state

1117

00:41:49,190 --> 00:41:47,359

and if you start the system in the

1118

00:41:50,390 --> 00:41:49,200

steady state it stays in that steady

1119

00:41:52,390 --> 00:41:50,400

state

1120

00:41:54,390 --> 00:41:52,400

if you start with the capacitors with

1121

00:41:57,270 --> 00:41:54,400

more charges so you start with 100 units

1122

00:41:59,670 --> 00:41:57,280

of charge on the capacitor it will lose

1123

00:42:01,589 --> 00:41:59,680

charge until it gets down to 20. it's

1124

00:42:04,390 --> 00:42:01,599

trying to get to here

1125

00:42:07,270 --> 00:42:04,400

at this um 20 level and if you start it

1126

00:42:10,230 --> 00:42:07,280

with zero which is what we like to do

1127

00:42:11,349 --> 00:42:10,240

uh then it will rise to 20. so does that

1128

00:42:13,589 --> 00:42:11,359

answer the question that that's

1129

00:42:16,950 --> 00:42:13,599

basically what will happen yes so if you

1130

00:42:19,109 --> 00:42:16,960

start from zero from equilibrium it it

1131

00:42:22,470 --> 00:42:19,119

goes into this far from equilibrium

1132

00:42:24,470 --> 00:42:22,480

state spontaneously and if you bleed the

1133

00:42:27,030 --> 00:42:24,480

charge off say into a motor or a

1134

00:42:30,390 --> 00:42:27,040

resistor or something like that are you

1135

00:42:34,230 --> 00:42:30,400

will that happen continuously

1136

00:42:38,390 --> 00:42:34,240

yeah yeah so you could uh you know it's

1137

00:42:39,270 --> 00:42:38,400

ideal to run this type of circuit at the

1138

00:42:41,109 --> 00:42:39,280

uh

1139

00:42:43,270 --> 00:42:41,119

peak power

1140

00:42:44,790 --> 00:42:43,280

i think i have that here so here's where

1141

00:42:47,030 --> 00:42:44,800

you'd want to that'd be the operating

1142

00:42:48,710 --> 00:42:47,040

point for the circuit basically because

1143

00:42:51,109 --> 00:42:48,720

then you're drawing the most amount of

1144

00:42:53,510 --> 00:42:51,119

power from the thermal environment

1145

00:42:55,589 --> 00:42:53,520

right um and so what you would do is try

1146

00:42:59,030 --> 00:42:55,599

to hold it at that point

1147

00:43:01,349 --> 00:42:59,040

by removing current at the rate that the

1148

00:43:03,270 --> 00:43:01,359

current is coming in at so it's stuck

1149

00:43:04,390 --> 00:43:03,280

there basically and you get the most

1150

00:43:07,750 --> 00:43:04,400

efficient

1151
00:43:09,990 --> 00:43:07,760
machine at that point

1152
00:43:12,470 --> 00:43:10,000
okay uh i we will have to talk about the

1153
00:43:13,829 --> 00:43:12,480
implications

1154
00:43:14,710 --> 00:43:13,839
um

1155
00:43:16,870 --> 00:43:14,720
i think

1156
00:43:18,150 --> 00:43:16,880
schaefer is the next person shaffer has

1157
00:43:21,190 --> 00:43:18,160
the next question

1158
00:43:23,349 --> 00:43:21,200
yeah aiden schaefer um real simple

1159
00:43:25,270 --> 00:43:23,359
question on that

1160
00:43:28,870 --> 00:43:25,280
the chipset the larger chip that you

1161
00:43:33,589 --> 00:43:28,880
built was that uh an even or odd number

1162
00:43:37,589 --> 00:43:35,510
well you know we've done a whole bunch

1163
00:43:40,710 --> 00:43:37,599

of things we've made a bunch of chips

1164

00:43:42,309 --> 00:43:40,720

there it's expensive to make these shoes

1165

00:43:45,270 --> 00:43:42,319

okay

1166

00:43:47,430 --> 00:43:45,280

um we run lots of experiments on each

1167

00:43:49,589 --> 00:43:47,440

chip it turns out as well

1168

00:43:51,910 --> 00:43:49,599

so you'll find pretty much anything and

1169

00:43:54,710 --> 00:43:51,920

everything you can i i

1170

00:43:56,069 --> 00:43:54,720

i only we were only able to

1171

00:43:58,870 --> 00:43:56,079

prove

1172

00:44:01,190 --> 00:43:58,880

that if you if you have one loop here if

1173

00:44:03,670 --> 00:44:01,200

you just do a one like a half wave

1174

00:44:05,910 --> 00:44:03,680

rectifier it won't right in in the

1175

00:44:08,790 --> 00:44:05,920

thermal in the if you want to harvest

1176
00:44:10,710 --> 00:44:08,800
thermal energy it won't work it'll work

1177
00:44:12,470 --> 00:44:10,720
in the deterministic case i mean if

1178
00:44:13,270 --> 00:44:12,480
something's shaking the graphene it'll

1179
00:44:16,069 --> 00:44:13,280
work

1180
00:44:18,550 --> 00:44:16,079
but um if you want to harvest thermal

1181
00:44:23,230 --> 00:44:18,560
energy well then you need you need a

1182
00:44:23,240 --> 00:44:26,309
[Music]

1183
00:44:32,870 --> 00:44:29,990
a capacitor diode ladder filter

1184
00:44:35,270 --> 00:44:32,880
um and it only functions

1185
00:44:39,510 --> 00:44:35,280
all of the diodes are in one direction

1186
00:44:42,230 --> 00:44:39,520
but uh its job is to center a waveform

1187
00:44:45,430 --> 00:44:42,240
uh that's going through it so it's

1188
00:44:47,990 --> 00:44:45,440

this is just uh reminiscent of that but

1189

00:44:51,190 --> 00:44:48,000

you have the diodes in opposite pairs

1190

00:44:53,430 --> 00:44:51,200

for energy generation

1191

00:44:56,150 --> 00:44:53,440

right there's a there's a lot of circuit

1192

00:44:58,150 --> 00:44:56,160

topologies out there

1193

00:45:00,710 --> 00:44:58,160

and and we've played with a whole bunch

1194

00:45:02,950 --> 00:45:00,720

of them and uh you know some are like

1195

00:45:05,430 --> 00:45:02,960

like a cockroft walton generator

1196

00:45:07,109 --> 00:45:05,440

multiplier right so there's a lot of

1197

00:45:09,109 --> 00:45:07,119

really interesting

1198

00:45:12,390 --> 00:45:09,119

i kind of mentioned the low hanging

1199

00:45:13,990 --> 00:45:12,400

fruit here i mean each topology requires

1200

00:45:16,390 --> 00:45:14,000

that you go through

1201

00:45:18,470 --> 00:45:16,400

what we did in great detail

1202

00:45:20,150 --> 00:45:18,480

because they're it's hard to map from

1203

00:45:22,950 --> 00:45:20,160

one to the next

1204

00:45:26,950 --> 00:45:24,950

i think that's why double e such is its

1205

00:45:28,950 --> 00:45:26,960

own field because every topology you

1206

00:45:30,550 --> 00:45:28,960

gotta sit and take a look at it and see

1207

00:45:32,230 --> 00:45:30,560

what it's gonna do

1208

00:45:35,510 --> 00:45:32,240

okay thank you there's a lot of

1209

00:45:36,870 --> 00:45:35,520

opportunity here though yeah

1210

00:45:42,230 --> 00:45:36,880

thank you uh

1211

00:45:47,190 --> 00:45:44,710

paul thank you for just a marvelous talk

1212

00:45:50,710 --> 00:45:47,200

um really nicely explained and very

1213

00:45:51,910 --> 00:45:50,720

careful um i i'm still at a loss i mean

1214

00:45:53,589 --> 00:45:51,920

i i think i understand what you're

1215

00:45:54,710 --> 00:45:53,599

saying your system comes to a steady

1216

00:45:57,430 --> 00:45:54,720

state

1217

00:45:59,510 --> 00:45:57,440

and as it's posed

1218

00:46:01,510 --> 00:45:59,520

as far as you've gone i would agree that

1219

00:46:03,109 --> 00:46:01,520

the second law is not is not violated i

1220

00:46:05,829 --> 00:46:03,119

agree with you on that

1221

00:46:07,750 --> 00:46:05,839

however i i i don't feel you've really

1222

00:46:09,910 --> 00:46:07,760

addressed the question if if you're con

1223

00:46:12,309 --> 00:46:09,920

if you can constantly siphon off energy

1224

00:46:15,510 --> 00:46:12,319

from each of these capacitors

1225

00:46:17,510 --> 00:46:15,520

to do external work then thermodynamics

1226

00:46:19,750 --> 00:46:17,520

is pretty clear that if you're if if you

1227

00:46:21,910 --> 00:46:19,760

are turning thermal energy

1228

00:46:23,589 --> 00:46:21,920

into into the capacitive energy which

1229

00:46:25,030 --> 00:46:23,599

you're claiming and then you're using

1230

00:46:27,910 --> 00:46:25,040

that energy

1231

00:46:31,190 --> 00:46:27,920

to carry out external work and if your

1232

00:46:32,309 --> 00:46:31,200

capacitor continues to recharge

1233

00:46:33,750 --> 00:46:32,319

in my book that's a second law of

1234

00:46:35,589 --> 00:46:33,760

violation so

1235

00:46:37,349 --> 00:46:35,599

um i realize that you've circumscribed

1236

00:46:39,349 --> 00:46:37,359

your system carefully but could you

1237

00:46:40,829 --> 00:46:39,359

expand it please to a situation where

1238

00:46:43,109 --> 00:46:40,839

you're doing external

1239

00:46:45,670 --> 00:46:43,119

work let's say on something like what

1240

00:46:48,069 --> 00:46:45,680

garrett said a motor or

1241

00:46:50,470 --> 00:46:48,079

tv or whatever it happens to be if it's

1242

00:46:54,390 --> 00:46:50,480

doing external work does it still not

1243

00:46:56,950 --> 00:46:55,910

okay well this one took a year and a

1244

00:46:59,670 --> 00:46:56,960

half

1245

00:47:02,150 --> 00:46:59,680

and i always hate to speculate on like

1246

00:47:04,069 --> 00:47:02,160

maybe the next circuit we should study

1247

00:47:06,550 --> 00:47:04,079

or the next situation

1248

00:47:09,349 --> 00:47:06,560

uh but um

1249

00:47:14,950 --> 00:47:12,230

draw say something kind of related and i

1250

00:47:17,750 --> 00:47:14,960

think it i think it'll support my point

1251
00:47:18,870 --> 00:47:17,760
and give some clarity to your question

1252
00:47:21,430 --> 00:47:18,880
um

1253
00:47:23,190 --> 00:47:21,440
if in in you know we like to talk about

1254
00:47:25,270 --> 00:47:23,200
feynman's brownie and ratchet you know

1255
00:47:27,510 --> 00:47:25,280
he says if you stick a windmill in your

1256
00:47:29,270 --> 00:47:27,520
room and the air is not flowing at all

1257
00:47:32,150 --> 00:47:29,280
then it's not going to sit and turn the

1258
00:47:34,309 --> 00:47:32,160
windmill you know basically

1259
00:47:36,630 --> 00:47:34,319
so that's kind of a thermodynamic

1260
00:47:38,630 --> 00:47:36,640
equilibrium position that you're sitting

1261
00:47:42,069 --> 00:47:38,640
in but but

1262
00:47:44,710 --> 00:47:42,079
i i bet you don't disagree with this if

1263
00:47:46,470 --> 00:47:44,720

i take this mass off this balloon will

1264

00:47:48,309 --> 00:47:46,480

expand and raise it

1265

00:47:51,829 --> 00:47:48,319

so what we're really doing is we're

1266

00:47:54,549 --> 00:47:51,839

creating a system that has uh an

1267

00:47:55,670 --> 00:47:54,559

unbalanced set of forces that drives the

1268

00:47:57,670 --> 00:47:55,680

system

1269

00:47:59,589 --> 00:47:57,680

in one direction to balance out the

1270

00:48:02,150 --> 00:47:59,599

forces just maybe like water going off a

1271

00:48:04,870 --> 00:48:02,160

waterfall so there's unbalanced forces

1272

00:48:06,630 --> 00:48:04,880

in the system and they drive the system

1273

00:48:09,349 --> 00:48:06,640

in one direction nothing wrong with the

1274

00:48:11,349 --> 00:48:09,359

laws of physics or thermodynamics there

1275

00:48:14,549 --> 00:48:11,359

and that's exactly where this work comes

1276
00:48:16,470 --> 00:48:14,559
from is from those forces doing work and

1277
00:48:18,870 --> 00:48:16,480
entropy you know you kind of went

1278
00:48:20,790 --> 00:48:18,880
through this nice little argument here

1279
00:48:23,030 --> 00:48:20,800
you know you can you can connect all the

1280
00:48:26,069 --> 00:48:23,040
dots together in a night in an ideal

1281
00:48:27,589 --> 00:48:26,079
picture um i i honestly thought well

1282
00:48:28,470 --> 00:48:27,599
yeah i should let you answer but i kind

1283
00:48:29,750 --> 00:48:28,480
of was

1284
00:48:31,829 --> 00:48:29,760
thought you might be interested the

1285
00:48:33,990 --> 00:48:31,839
entropy does decay it's a it's a

1286
00:48:36,549 --> 00:48:34,000
well-controlled thing here does decrease

1287
00:48:38,470 --> 00:48:36,559
in time as the capacitors charge there's

1288
00:48:40,069 --> 00:48:38,480

some organization that's happening as

1289

00:48:41,910 --> 00:48:40,079

the capacitor starts a very interesting

1290

00:48:43,349 --> 00:48:41,920

thing but anyhow just try to throw that

1291

00:48:45,670 --> 00:48:43,359

out there yeah so i i kind of would

1292

00:48:47,910 --> 00:48:45,680

point you to this it's a non-equilibrium

1293

00:48:49,910 --> 00:48:47,920

there's unbalanced forces there's no

1294

00:48:52,470 --> 00:48:49,920

problem here with this with this thing

1295

00:48:54,309 --> 00:48:52,480

doing work the difference here is that

1296

00:48:56,150 --> 00:48:54,319

with the gas there's internal energy

1297

00:48:57,829 --> 00:48:56,160

that's then being converted into work

1298

00:48:59,430 --> 00:48:57,839

right and if you add the mass back and

1299

00:49:01,349 --> 00:48:59,440

you kind of revert to your initial

1300

00:49:02,790 --> 00:49:01,359

position there'll be no energy gain

1301
00:49:04,230 --> 00:49:02,800
because all that energy goes back in the

1302
00:49:05,990 --> 00:49:04,240
potential the gas

1303
00:49:07,750 --> 00:49:06,000
versus in our in your system it sounds

1304
00:49:09,670 --> 00:49:07,760
like you're able to

1305
00:49:11,750 --> 00:49:09,680
complete a cycle and have this energy

1306
00:49:14,710 --> 00:49:11,760
extracted so yeah

1307
00:49:15,670 --> 00:49:14,720
okay yeah no no thanks paul so so okay

1308
00:49:16,950 --> 00:49:15,680
so

1309
00:49:18,710 --> 00:49:16,960
let's

1310
00:49:23,910 --> 00:49:18,720
it's a little different than i think you

1311
00:49:23,920 --> 00:49:27,990
you muted yourself

1312
00:49:33,109 --> 00:49:30,790
i think you're muted

1313
00:49:35,430 --> 00:49:33,119

paul we can't hear you oh okay so sorry

1314

00:49:37,270 --> 00:49:35,440

i'm back now somehow muted muted me

1315

00:49:40,309 --> 00:49:37,280

sorry about that so okay

1316

00:49:42,870 --> 00:49:40,319

so um let's go back to this picture here

1317

00:49:45,829 --> 00:49:42,880

so if i take the second mass which i

1318

00:49:49,030 --> 00:49:45,839

slid off let's say i have to raise it to

1319

00:49:51,589 --> 00:49:49,040

h and set it back down on here and then

1320

00:49:54,150 --> 00:49:51,599

it will compress this back down

1321

00:49:56,630 --> 00:49:54,160

so i have to do some work on the mass

1322

00:49:59,030 --> 00:49:56,640

and then it'll compress the gas back and

1323

00:50:01,270 --> 00:49:59,040

i can now do work on the environment put

1324

00:50:02,470 --> 00:50:01,280

energy back into the environment from

1325

00:50:03,990 --> 00:50:02,480

myself

1326

00:50:06,230 --> 00:50:04,000

so how do i do that with mine well i

1327

00:50:09,270 --> 00:50:06,240

take the capacitors away from the

1328

00:50:11,190 --> 00:50:09,280

circuit i hook them up to resistors they

1329

00:50:13,190 --> 00:50:11,200

discharge through the resistor

1330

00:50:14,470 --> 00:50:13,200

dissipating energy back to the

1331

00:50:16,790 --> 00:50:14,480

environment

1332

00:50:20,710 --> 00:50:19,430

it's the same thing but i will give you

1333

00:50:25,190 --> 00:50:20,720

something

1334

00:50:28,230 --> 00:50:25,200

i can put my finger on it

1335

00:50:30,309 --> 00:50:28,240

i can take that empty capacitor hook it

1336

00:50:32,710 --> 00:50:30,319

back up to the circuit it will recharge

1337

00:50:35,030 --> 00:50:32,720

itself it's like i'm getting it for free

1338

00:50:37,430 --> 00:50:35,040

here i had to raise the mass to get it

1339

00:50:40,790 --> 00:50:37,440

back to the initial condition right yeah

1340

00:50:44,630 --> 00:50:40,800

so there's some element of freeness here

1341

00:50:49,670 --> 00:50:44,640

that's happening but it's really because

1342

00:50:52,470 --> 00:50:49,680

the the diodes have this voltage in them

1343

00:50:54,150 --> 00:50:52,480

and they're trying to their equilibrium

1344

00:50:55,829 --> 00:50:54,160

is different than the earth's

1345

00:50:58,390 --> 00:50:55,839

equilibrium

1346

00:51:00,069 --> 00:50:58,400

sure anyhow it's it's a it's a very

1347

00:51:03,190 --> 00:51:00,079

interesting system and i hope other

1348

00:51:06,150 --> 00:51:03,200

people will look at it too

1349

00:51:08,950 --> 00:51:06,160

there's so many questions i just to push

1350

00:51:10,710 --> 00:51:08,960

into what what paul was just saying so

1351

00:51:13,030 --> 00:51:10,720

both daniel and i are talking about

1352

00:51:16,390 --> 00:51:13,040

bleeding the energy off continuously as

1353

00:51:17,670 --> 00:51:16,400

opposed to switching back and forth

1354

00:51:18,549 --> 00:51:17,680

uh

1355

00:51:23,030 --> 00:51:18,559

can you

1356

00:51:27,410 --> 00:51:25,829

yes so um

1357

00:51:28,790 --> 00:51:27,420

so you're basically saying

1358

00:51:34,390 --> 00:51:28,800

[Music]

1359

00:51:38,870 --> 00:51:36,470

somehow hook up a circuit here with the

1360

00:51:41,829 --> 00:51:38,880

resistor

1361

00:51:44,150 --> 00:51:41,839

right here so it draws current

1362

00:51:48,150 --> 00:51:44,160

off this thing

1363

00:51:50,390 --> 00:51:48,160

but the rate of current is basically

1364

00:51:52,390 --> 00:51:50,400

such that it doesn't just pull it all

1365

00:51:53,270 --> 00:51:52,400

off you know it kind of does it at some

1366

00:51:55,990 --> 00:51:53,280

certain

1367

00:51:57,829 --> 00:51:56,000

right rate

1368

00:51:59,829 --> 00:51:57,839

so basically that's going to be taking

1369

00:52:01,750 --> 00:51:59,839

the energy of the capacitor again

1370

00:52:03,109 --> 00:52:01,760

putting it back into the thermal

1371

00:52:05,430 --> 00:52:03,119

environment

1372

00:52:07,750 --> 00:52:05,440

that that originally came from

1373

00:52:09,510 --> 00:52:07,760

you know you know to some extent

1374

00:52:11,910 --> 00:52:09,520

you know people don't didn't i don't

1375

00:52:13,510 --> 00:52:11,920

think really got this but

1376

00:52:16,150 --> 00:52:13,520

um

1377

00:52:18,470 --> 00:52:16,160

i like to think honestly this paper was

1378

00:52:21,270 --> 00:52:18,480

almost more significant here we're

1379

00:52:24,309 --> 00:52:21,280

powering the circuit directly

1380

00:52:26,309 --> 00:52:24,319

from the thermal environment

1381

00:52:28,549 --> 00:52:26,319

and it's doing work it can do work it

1382

00:52:30,790 --> 00:52:28,559

can power a circuit

1383

00:52:33,030 --> 00:52:30,800

that's really

1384

00:52:34,870 --> 00:52:33,040

to me was more significant but honestly

1385

00:52:37,430 --> 00:52:34,880

i got so much

1386

00:52:39,510 --> 00:52:37,440

mail about well you're not really doing

1387

00:52:41,829 --> 00:52:39,520

anything useful what if you charged a

1388

00:52:44,069 --> 00:52:41,839

capacitor and you stole energy from the

1389

00:52:46,630 --> 00:52:44,079

earth then you'd be doing something now

1390

00:52:49,109 --> 00:52:46,640

you're doing something real so actually

1391

00:52:50,630 --> 00:52:49,119

we did do that we did steal energy from

1392

00:52:51,990 --> 00:52:50,640

the environment we maybe we did

1393

00:52:53,670 --> 00:52:52,000

something real

1394

00:52:55,910 --> 00:52:53,680

but now you're gonna now you're kind of

1395

00:52:57,510 --> 00:52:55,920

wanting to go back to the earlier one

1396

00:53:00,230 --> 00:52:57,520

you realize in your question well what

1397

00:53:02,950 --> 00:53:00,240

if i just use it directly right that's

1398

00:53:04,790 --> 00:53:02,960

just an easier problem okay fascinating

1399

00:53:07,190 --> 00:53:04,800

thank you yeah

1400

00:53:08,549 --> 00:53:07,200

quick questions uh james lee and then

1401
00:53:10,630 --> 00:53:08,559
tom vallone

1402
00:53:16,309 --> 00:53:10,640
yeah

1403
00:53:19,030 --> 00:53:16,319
solid i'm so pretty to see

1404
00:53:21,589 --> 00:53:19,040
as daniel and also um

1405
00:53:23,910 --> 00:53:21,599
talk about it it's actually your process

1406
00:53:25,910 --> 00:53:23,920
actually built a very nice

1407
00:53:27,750 --> 00:53:25,920
type of b energy process we now

1408
00:53:29,910 --> 00:53:27,760
discovered in

1409
00:53:31,910 --> 00:53:29,920
my work actually in biology exists in

1410
00:53:32,950 --> 00:53:31,920
your body in my body in the whole world

1411
00:53:34,390 --> 00:53:32,960
actually

1412
00:53:36,950 --> 00:53:34,400
so um

1413
00:53:38,790 --> 00:53:36,960

yes your intuitive component as you said

1414

00:53:40,710 --> 00:53:38,800

uh you know follow the second law very

1415

00:53:43,510 --> 00:53:40,720

very well okay like your capacity

1416

00:53:46,630 --> 00:53:43,520

charging you know all that but your

1417

00:53:50,150 --> 00:53:46,640

overall process as any point yeah

1418

00:53:52,069 --> 00:53:50,160

you are now exchanging heat energy from

1419

00:53:54,549 --> 00:53:52,079

you know charging can become useful

1420

00:53:56,710 --> 00:53:54,559

energy right so you can do work

1421

00:53:59,829 --> 00:53:56,720

actually so you don't be afraid of um

1422

00:54:01,750 --> 00:53:59,839

you don't this in that case your energy

1423

00:54:04,230 --> 00:54:01,760

b process actually the second one does

1424

00:54:06,069 --> 00:54:04,240

not apply we'll talk more about it

1425

00:54:08,069 --> 00:54:06,079

so don't be afraid you know saying hey

1426

00:54:09,990 --> 00:54:08,079

you know this second knot does not pie

1427

00:54:11,589 --> 00:54:10,000

because you do see a phenomenon you say

1428

00:54:12,870 --> 00:54:11,599

getting something you know interesting

1429

00:54:14,390 --> 00:54:12,880

as you said

1430

00:54:16,069 --> 00:54:14,400

unusual right

1431

00:54:17,829 --> 00:54:16,079

yeah so that's my point

1432

00:54:20,069 --> 00:54:17,839

yeah i agree i think the second law

1433

00:54:22,630 --> 00:54:20,079

doesn't apply because they're unbalanced

1434

00:54:24,870 --> 00:54:22,640

forces we're driving the system

1435

00:54:27,349 --> 00:54:24,880

and like letting water go off a cliff of

1436

00:54:29,349 --> 00:54:27,359

course you can harvest energy from that

1437

00:54:31,030 --> 00:54:29,359

and it's just um it's just out of

1438

00:54:33,030 --> 00:54:31,040

equilibrium

1439

00:54:35,190 --> 00:54:33,040

yeah so daniel and i also talk about you

1440

00:54:37,270 --> 00:54:35,200

have a symmetrical process there when

1441

00:54:39,510 --> 00:54:37,280

it's symmetric going on

1442

00:54:41,990 --> 00:54:39,520

as at any point you are so the second

1443

00:54:44,470 --> 00:54:42,000

one be careful sometimes you can apply

1444

00:54:46,630 --> 00:54:44,480

sometimes you don't apply

1445

00:54:50,230 --> 00:54:46,640

so that's my point thank you wonderful

1446

00:54:50,240 --> 00:54:53,510

tom

1447

00:54:53,520 --> 00:54:59,910

uh you're muted

1448

00:55:03,670 --> 00:55:01,829

my tom i can't hear you

1449

00:55:06,309 --> 00:55:03,680

okay um

1450

00:55:08,870 --> 00:55:06,319

yeah how you doing i i'm the author of

1451
00:55:12,630 --> 00:55:08,880
the book on practical conversion zero

1452
00:55:15,430 --> 00:55:12,640
point energy um i haven't corresponded

1453
00:55:17,670 --> 00:55:15,440
with you yet but i've been a great fan

1454
00:55:19,430 --> 00:55:17,680
and i wanted to call your attention to

1455
00:55:21,670 --> 00:55:19,440
johnson noise

1456
00:55:26,950 --> 00:55:21,680
1927 fizzrev

1457
00:55:28,710 --> 00:55:26,960
um also kellen and welton uh in 1951 and

1458
00:55:31,030 --> 00:55:28,720
also estumian

1459
00:55:33,030 --> 00:55:31,040
those are references that might actually

1460
00:55:34,470 --> 00:55:33,040
start you in the direction of including

1461
00:55:36,870 --> 00:55:34,480
zero point energy

1462
00:55:40,390 --> 00:55:36,880
uh one half h nu

1463
00:55:43,750 --> 00:55:40,400

and it could be another factor that's

1464

00:55:46,230 --> 00:55:43,760

adding to the input energy especially if

1465

00:55:47,109 --> 00:55:46,240

the temperature changes and starts to go

1466

00:55:48,789 --> 00:55:47,119

down

1467

00:55:50,230 --> 00:55:48,799

that's the test for

1468

00:55:51,990 --> 00:55:50,240

whether zero point energy is a

1469

00:55:54,789 --> 00:55:52,000

contribution

1470

00:55:57,750 --> 00:55:54,799

coke or coach koch

1471

00:55:59,030 --> 00:55:57,760

did experiments at liquid nitrogen

1472

00:56:01,270 --> 00:55:59,040

temperatures did with helium

1473

00:56:03,750 --> 00:56:01,280

temperatures actually and still found

1474

00:56:05,510 --> 00:56:03,760

oscillations and and fluctuations that

1475

00:56:07,430 --> 00:56:05,520

are available so they're non-thermal

1476

00:56:09,109 --> 00:56:07,440

fluctuations that could be contributing

1477

00:56:10,710 --> 00:56:09,119

to the effect you're having

1478

00:56:13,829 --> 00:56:10,720

yeah thanks for that you know i'm a big

1479

00:56:17,270 --> 00:56:13,839

fan of johnson noise and nyquist uh

1480

00:56:19,510 --> 00:56:17,280

theory that i pointed out the imaginary

1481

00:56:21,670 --> 00:56:19,520

part and the real part here actually as

1482

00:56:23,750 --> 00:56:21,680

kind of a nod to them because that's

1483

00:56:25,829 --> 00:56:23,760

really what he originally proved was the

1484

00:56:28,309 --> 00:56:25,839

real part is the important part kind of

1485

00:56:30,309 --> 00:56:28,319

the power but you can control the gain

1486

00:56:31,829 --> 00:56:30,319

with the imaginary part so i kind of

1487

00:56:33,030 --> 00:56:31,839

that's an interesting

1488

00:56:36,950 --> 00:56:33,040

factor here

1489

00:56:40,230 --> 00:56:36,960

but yeah i never thought about the um

1490

00:56:41,990 --> 00:56:40,240

the zero point energy um here before so

1491

00:56:43,750 --> 00:56:42,000

that i'll i'll take a look at that too

1492

00:56:46,069 --> 00:56:43,760

that's a good question i'll send you the

1493

00:56:47,910 --> 00:56:46,079

books i've got and references and

1494

00:56:49,109 --> 00:56:47,920

hopefully help you along

1495

00:56:54,549 --> 00:56:49,119

thank you

1496

00:56:58,150 --> 00:56:54,559

call it there so that we can take a

1497

00:57:00,390 --> 00:56:58,160

one-minute break before the next talk

1498

00:57:02,390 --> 00:57:00,400

so thank you again for a fascinating

1499

00:57:03,670 --> 00:57:02,400

talk and i look forward to talking more

1500

00:57:05,670 --> 00:57:03,680

about this

1501

00:57:07,109 --> 00:57:05,680

uh in the panel discussion with you this