

1

00:00:00,167 --> 00:00:02,750
(bright music)

2

00:00:07,973 --> 00:00:09,136
♪ Hey ♪

3

00:00:09,136 --> 00:00:09,969
(bright music)

4

00:00:09,969 --> 00:00:12,620
– Welcome back to "Conversations
at the Perimeter."

5

00:00:12,620 --> 00:00:16,070
Today, we're bringing you a
conversation with Lucien Hardy.

6

00:00:16,070 --> 00:00:19,110
Lucien is a theorist here
at the Perimeter Institute,

7

00:00:19,110 --> 00:00:22,510
and he works in quantum
foundations and quantum gravity.

8

00:00:22,510 --> 00:00:25,170
– And Lucien was actually one
of the very first researchers

9

00:00:25,170 --> 00:00:27,770
to come to Perimeter
Institute about 20 years ago,

10

00:00:27,770 --> 00:00:29,850
when the institute itself was really

11

00:00:29,850 --> 00:00:32,610
just a theoretical idea
from Mike Lazaridis,

12

00:00:32,610 --> 00:00:34,670

the founder and the
creator of the Blackberry.

13

00:00:34,670 --> 00:00:36,670

So I loved hearing Lucien tell stories

14

00:00:36,670 --> 00:00:38,260

about some of the early days working

15

00:00:38,260 --> 00:00:40,340

with the other original researchers here,

16

00:00:40,340 --> 00:00:42,310

like Lee Smolin and Rob Myers,

17

00:00:42,310 --> 00:00:43,940

who's now the director here at Perimeter.

18

00:00:43,940 --> 00:00:46,140

- I also really liked the
part of the conversation

19

00:00:46,140 --> 00:00:48,640

where he told us that his
perspectives on physics

20

00:00:48,640 --> 00:00:51,180

and specifically the operational approach

21

00:00:51,180 --> 00:00:53,490

that he uses to study quantum theory was

22

00:00:53,490 --> 00:00:55,510

significantly influenced by the time

23

00:00:55,510 --> 00:00:57,530

that he spent in an experimental lab.

24

00:00:57,530 --> 00:00:59,180

He actually says that every theorist

25

00:00:59,180 --> 00:01:00,946

should have to spend time in a lab.

26

00:01:00,946 --> 00:01:02,300

(Colin laughs)

- And Lucien is also,

27

00:01:02,300 --> 00:01:05,220

I'm pretty sure, the only person
that I've ever interviewed

28

00:01:05,220 --> 00:01:07,410

who has a paradox named after him.

29

00:01:07,410 --> 00:01:09,730

Hardy's paradox is this thought experiment

30

00:01:09,730 --> 00:01:11,900

that he devised in the early 1990s,

31

00:01:11,900 --> 00:01:14,120

and he tells us about
in this conversation.

32

00:01:14,120 --> 00:01:16,310

He also told us that Hardy's paradox

33

00:01:16,310 --> 00:01:18,840

paradoxically may not
actually be a paradox.

34

00:01:18,840 --> 00:01:21,710

So try to get ready to
wrap your mind around that,

35

00:01:21,710 --> 00:01:24,117
and let's step inside the Perimeter.

36

00:01:24,117 --> 00:01:27,380
(light music)

37

00:01:27,380 --> 00:01:30,100
Lucien, thank you so much
for joining us here today.

38

00:01:30,100 --> 00:01:31,310
- It's my pleasure.

39

00:01:31,310 --> 00:01:33,370
- You've been with Perimeter Institute,

40

00:01:33,370 --> 00:01:34,900
I looked, for 20 years.

41

00:01:34,900 --> 00:01:37,350
It's 2002, and we're coming up on-

42

00:01:37,350 --> 00:01:39,280
- Yeah, yeah-
- Your 20-year anniversary-

43

00:01:39,280 --> 00:01:40,113
- Almost 20 years.

44

00:01:40,113 --> 00:01:41,520
- Can you tell us what does somebody do

45

00:01:41,520 --> 00:01:44,390
as a theoretical physicist
at Perimeter for 20 years?

46

00:01:44,390 --> 00:01:46,013

- Well, I mean, lots of things.

47

00:01:46,013 --> 00:01:47,010

(Lauren laughs)

(Colin laughs)

48

00:01:47,010 --> 00:01:48,560

I guess one of the
great things about being

49

00:01:48,560 --> 00:01:50,683

in an environment like
this is it influences you,

50

00:01:50,683 --> 00:01:52,610

and you change your research direction.

51

00:01:52,610 --> 00:01:57,140

So when I came here, I had some
interest in quantum gravity,

52

00:01:57,140 --> 00:01:59,130

but that's now increasingly the main thing

53

00:01:59,130 --> 00:02:01,350

I'm interested in, 'cause
of people around it

54

00:02:01,350 --> 00:02:02,630

are thinking about this, too.

55

00:02:02,630 --> 00:02:05,230

So there's never a shortage
of people to talk to,

56

00:02:05,230 --> 00:02:08,580

and ideas to think about,
and so, yeah, I'm busy.

57

00:02:08,580 --> 00:02:10,490
I have lots of things to work on.

58
00:02:10,490 --> 00:02:12,520
- You mentioned that right
now you're really focused

59
00:02:12,520 --> 00:02:13,770
on quantum gravity.

60
00:02:13,770 --> 00:02:15,830
Can you tell us what that is?

61
00:02:15,830 --> 00:02:17,140
- So I'd like to say that the,

62
00:02:17,140 --> 00:02:19,250
like there's a problem
with quantum gravity,

63
00:02:19,250 --> 00:02:20,860
and this is that we have two

64
00:02:20,860 --> 00:02:23,890
less fundamental physical
theories, so general relativity,

65
00:02:23,890 --> 00:02:26,841
Einstein's theory of
gravity on the one hand

66
00:02:26,841 --> 00:02:29,210
developed in 1915, 1916,

67
00:02:29,210 --> 00:02:31,357
and then we have quantum
theory on the other hand

68
00:02:31,357 --> 00:02:34,260

developed by a whole bunch of
people, including Einstein,

69

00:02:34,260 --> 00:02:36,440
so Heisenberg, Schrodinger, many others,

70

00:02:36,440 --> 00:02:38,550
developed in the mid-1920s.

71

00:02:38,550 --> 00:02:41,500
And those two theories are both
very successful predictively

72

00:02:41,500 --> 00:02:43,860
where they apply, but
they don't fit together.

73

00:02:43,860 --> 00:02:45,110
They don't fit together mathematically.

74

00:02:45,110 --> 00:02:46,940
They don't fit together conceptually.

75

00:02:46,940 --> 00:02:48,280
Really, it seems there ought to be

76

00:02:48,280 --> 00:02:49,830
a kind of unity in nature.

77

00:02:49,830 --> 00:02:51,110
We should really only have one theory

78

00:02:51,110 --> 00:02:52,060
that describes all of nature.

79

00:02:52,060 --> 00:02:54,410
So if we have two different
theories describing

80

00:02:54,410 --> 00:02:55,340
different parts of nature,

81

00:02:55,340 --> 00:02:57,420
that isn't a satisfactory situation.

82

00:02:57,420 --> 00:03:00,850
So the problem of quantum
gravity is to find a new theory,

83

00:03:00,850 --> 00:03:03,890
and probably a deeper,
more fundamental theory,

84

00:03:03,890 --> 00:03:07,720
which approximates to general relativity

85

00:03:07,720 --> 00:03:09,420
on the one hand in situations

86

00:03:09,420 --> 00:03:11,710
where that theory has been
experimentally confirmed,

87

00:03:11,710 --> 00:03:14,490
and approximates to quantum
theory on the other hand

88

00:03:14,490 --> 00:03:15,760
in situations where that theory

89

00:03:15,760 --> 00:03:17,550
has been experimentally confirmed.

90

00:03:17,550 --> 00:03:21,300
- When I was preparing some
notes for this conversation,

91

00:03:21,300 --> 00:03:23,930
I wrote down only one sentence
that had a big box around it

92
00:03:23,930 --> 00:03:25,157
in big block letters, and it said,

93
00:03:25,157 --> 00:03:26,960
"The problem with quantum gravity,"

94
00:03:26,960 --> 00:03:30,450
because it seems like
that's a very big problem.

95
00:03:30,450 --> 00:03:33,410
Why is it so difficult to
reconcile quantum mechanics

96
00:03:33,410 --> 00:03:34,980
with general relativity?

97
00:03:34,980 --> 00:03:36,210
- Yeah, I don't know.
(group laughs)

98
00:03:36,210 --> 00:03:38,240
I mean, if I knew the
answer to that question,

99
00:03:38,240 --> 00:03:39,580
I would have done it already.

100
00:03:39,580 --> 00:03:41,100
You know, it's 100 years or so now

101
00:03:41,100 --> 00:03:44,193
since the problem has been around.

102
00:03:44,193 --> 00:03:46,210

- I'm not placing all the
blame on you personally

103

00:03:46,210 --> 00:03:48,366
for not having done it-
- I have not done it so far.

104

00:03:48,366 --> 00:03:49,890
(Lauren and Colin laugh)
Yeah, I don't know.

105

00:03:49,890 --> 00:03:51,560
What I think is happening is that I think

106

00:03:51,560 --> 00:03:52,840
we're just not asking the right questions.

107

00:03:52,840 --> 00:03:55,498
We're not thinking in the right way.

108

00:03:55,498 --> 00:03:57,300
You know, if you look at,

109

00:03:57,300 --> 00:03:59,550
you know, historically
at other situations,

110

00:03:59,550 --> 00:04:02,480
like after Newton developed
his theory of gravity,

111

00:04:02,480 --> 00:04:04,540
his theory, universal theory of gravity,

112

00:04:04,540 --> 00:04:05,490
he wrote down this equation,

113

00:04:05,490 --> 00:04:08,249
he didn't like it, because of

it had instantaneous action,

114

00:04:08,249 --> 00:04:09,960

a distance, like I mentioned,

115

00:04:09,960 --> 00:04:12,720

and no substance mediating that force.

116

00:04:12,720 --> 00:04:14,120

And so, he did the natural thing.

117

00:04:14,120 --> 00:04:16,460

He tried to invent a sort of mechanism

118

00:04:16,460 --> 00:04:18,140

by which gravity could act like that,

119

00:04:18,140 --> 00:04:20,830

so two masses that are far apart
could influence each other,

120

00:04:20,830 --> 00:04:21,663

and not just him.

121

00:04:21,663 --> 00:04:23,720

Other people also tried to think of,

122

00:04:23,720 --> 00:04:25,680

they were called, you know,
mechanical aether models,

123

00:04:25,680 --> 00:04:27,920

so mechanical models that
you could use to explain

124

00:04:27,920 --> 00:04:29,500

how gravity worked.

125

00:04:29,500 --> 00:04:31,180
These models were, you know, amazing.

126
00:04:31,180 --> 00:04:32,230
They were quite detailed,

127
00:04:32,230 --> 00:04:34,430
and you know, people spent a
lot of time doing calculations,

128
00:04:34,430 --> 00:04:36,770
and sometimes successfully reproducing

129
00:04:36,770 --> 00:04:38,057
Newton's equation of gravity.

130
00:04:38,057 --> 00:04:41,420
You know, for example,
Newton himself had this idea

131
00:04:41,420 --> 00:04:44,220
that the force that caused
planets to be attracted

132
00:04:44,220 --> 00:04:46,780
to one another was the same as the force

133
00:04:46,780 --> 00:04:48,270
that causes aeroplanes to fly.

134
00:04:48,270 --> 00:04:51,420
So in some sense, he anticipated
the work of Bernoulli,

135
00:04:51,420 --> 00:04:53,880
which came, you know,
about 50 years later.

136
00:04:53,880 --> 00:04:56,020

You have an aeroplane wing.

137

00:04:56,020 --> 00:04:58,620

Then the speed at which
the air particles go

138

00:04:58,620 --> 00:05:00,070

underneath the wing is faster

139

00:05:00,070 --> 00:05:01,690

than at which they go over the wing,

140

00:05:01,690 --> 00:05:05,000

and if the speed is reduced,
if the particles go faster,

141

00:05:05,000 --> 00:05:06,910

then they don't hit the wing as often,

142

00:05:06,910 --> 00:05:09,460

so there's a lower pressure.

143

00:05:09,460 --> 00:05:11,350

And so, that puts a force on the wing,

144

00:05:11,350 --> 00:05:12,580

and makes the plane go up.

145

00:05:12,580 --> 00:05:14,900

And Newton had this idea,
you know, already back then,

146

00:05:14,900 --> 00:05:16,760

and he thought he could
come up with some mechanism

147

00:05:16,760 --> 00:05:18,200

which explained gravity.

148

00:05:18,200 --> 00:05:20,570

Rene Descartes had this
idea about vortices,

149

00:05:20,570 --> 00:05:21,980

very detailed models.

150

00:05:21,980 --> 00:05:23,600

There were many, you know,
interesting characters,

151

00:05:23,600 --> 00:05:25,330

and that seems to be a lot
of what people were doing

152

00:05:25,330 --> 00:05:27,040

were trying to come up
with mechanical models

153

00:05:27,040 --> 00:05:28,130

to explain gravity.

154

00:05:28,130 --> 00:05:30,400

And then even later with electromagnetism,

155

00:05:30,400 --> 00:05:34,060

when Maxwell, Maxwell
himself actually used

156

00:05:34,060 --> 00:05:36,050

a mechanical model to explain,

157

00:05:36,050 --> 00:05:38,590

to derive his equations
of electromagnetism,

158

00:05:38,590 --> 00:05:40,610

people were just trying to explain things

159
00:05:40,610 --> 00:05:42,400
in terms of the concepts they understood,

160
00:05:42,400 --> 00:05:44,316
in terms of the concepts
they were familiar with,

161
00:05:44,316 --> 00:05:46,950
and everyone was familiar
with stuff, you know,

162
00:05:46,950 --> 00:05:47,960
stuff pushing on stuff.

163
00:05:47,960 --> 00:05:51,280
That was a, that's a familiar concept.

164
00:05:51,280 --> 00:05:52,860
And so, and I think
that's where we are now.

165
00:05:52,860 --> 00:05:55,590
We're bringing to bear on the
problem of quantum gravity

166
00:05:55,590 --> 00:05:57,930
the ideas that we understand,

167
00:05:57,930 --> 00:05:59,540
and it's probably just not sufficient.

168
00:05:59,540 --> 00:06:02,210
We probably have to find a
way to think beyond that,

169
00:06:02,210 --> 00:06:03,650
or to somehow get out of ourselves,

170

00:06:03,650 --> 00:06:07,050
and look at the problem from
a different point of view.

171
00:06:07,050 --> 00:06:08,920
It turns out to be very difficult.

172
00:06:08,920 --> 00:06:11,450
- I think it's really a unique challenge

173
00:06:11,450 --> 00:06:12,310
in this field, right?

174
00:06:12,310 --> 00:06:15,300
Because you really, from
what you're describing,

175
00:06:15,300 --> 00:06:19,040
you really need to find a way
to think in a different way,

176
00:06:19,040 --> 00:06:20,920
and not rely too much on something

177
00:06:20,920 --> 00:06:22,080
that you already understand,

178
00:06:22,080 --> 00:06:24,290
whereas in other fields of research,

179
00:06:24,290 --> 00:06:25,660
we would be trying to build on things

180
00:06:25,660 --> 00:06:27,850
that we already understand,
or look at consequences

181
00:06:27,850 --> 00:06:29,220
of things that we already understand,

182

00:06:29,220 --> 00:06:32,010

and whereas you have to
probably keep reminding yourself

183

00:06:32,010 --> 00:06:33,490

don't think too much about those things

184

00:06:33,490 --> 00:06:36,580

that you already understand,
try to think in a new way.

185

00:06:36,580 --> 00:06:39,850

So how do you train yourself to be

186

00:06:39,850 --> 00:06:41,300

in a kind of state of mind

187

00:06:41,300 --> 00:06:44,620

where that new way of
thinking is possible?

188

00:06:44,620 --> 00:06:46,890

- You could imagine developing
a systematic approach

189

00:06:46,890 --> 00:06:47,820

to that sort of thing.

190

00:06:47,820 --> 00:06:48,920

You could perhaps follow

191

00:06:48,920 --> 00:06:50,730

sort of lateral thinking techniques,

192

00:06:50,730 --> 00:06:52,560

or some sort of meditative approach.

193

00:06:52,560 --> 00:06:54,000
I don't do that especially.

194
00:06:54,000 --> 00:06:56,060
I think I just, you know, sort
of throw myself in every day

195
00:06:56,060 --> 00:06:57,253
and try to think of new ideas.

196
00:06:57,253 --> 00:06:59,040
I don't have a good
answer to that question,

197
00:06:59,040 --> 00:07:01,310
but I think it's a question
that people should think about.

198
00:07:01,310 --> 00:07:03,850
What are the methodological tools

199
00:07:03,850 --> 00:07:06,320
you should bring to bear on physics?

200
00:07:06,320 --> 00:07:07,660
I've even asked philosophers.

201
00:07:07,660 --> 00:07:10,900
You know, philosophers spend a lot of time

202
00:07:10,900 --> 00:07:13,750
looking at physics, and
often speak about the work

203
00:07:13,750 --> 00:07:15,200
after it's been done.

204
00:07:15,200 --> 00:07:18,460
But philosophers could position

themselves in such a way

205

00:07:18,460 --> 00:07:21,180
as to attempt to provide
working physicists

206

00:07:21,180 --> 00:07:23,420
with methodological tools.

207

00:07:23,420 --> 00:07:24,830
You know, how do you go about,

208

00:07:24,830 --> 00:07:26,420
well, in this case, for example,

209

00:07:26,420 --> 00:07:27,863
finding a deeper, more fundamental theory

210

00:07:27,863 --> 00:07:29,540
when you have two less
fundamental theories?

211

00:07:29,540 --> 00:07:32,420
That seems like a fantastic
philosophical question.

212

00:07:32,420 --> 00:07:34,640
You know, even if you don't
actually construct the theory,

213

00:07:34,640 --> 00:07:37,150
just what are the
methodological approaches

214

00:07:37,150 --> 00:07:38,640
to solving that kind of problem?

215

00:07:38,640 --> 00:07:40,630
But philosophers haven't

really worked on that

216

00:07:40,630 --> 00:07:41,990

as far as I'm aware.

217

00:07:41,990 --> 00:07:43,560

So yeah, it's a fantastic question.

218

00:07:43,560 --> 00:07:44,980

I don't know the answer to it,

219

00:07:44,980 --> 00:07:46,412

but I think we should think about it.

220

00:07:46,412 --> 00:07:47,350

- That's great, yeah.

221

00:07:47,350 --> 00:07:49,140

As a follow-up to that, I'm just curious

222

00:07:49,140 --> 00:07:52,870

if there was a satisfying
solution of quantum gravity

223

00:07:52,870 --> 00:07:54,900

that was proposed in the near future,

224

00:07:54,900 --> 00:07:56,060

either by you, or someone else,

225

00:07:56,060 --> 00:07:58,860

so that you needed to go
think about some research

226

00:07:58,860 --> 00:08:00,980

in another field, would you want to look

227

00:08:00,980 --> 00:08:03,790

at the consequences of this
solution of quantum gravity,

228

00:08:03,790 --> 00:08:06,520
or would you wanna find
a new area of physics

229

00:08:06,520 --> 00:08:08,900
where you need to find another
more fundamental theory?

230

00:08:08,900 --> 00:08:11,030
Because that's kind of
the way of thinking.

231

00:08:11,030 --> 00:08:12,920
- Oh, right, so that's
a good question, too.

232

00:08:12,920 --> 00:08:16,880
If you look at, contrast
Newton and Einstein,

233

00:08:16,880 --> 00:08:18,480
the two people I keep confusing,

234

00:08:19,360 --> 00:08:22,120
Newton spent a lot of time,
you know, doing calculations,

235

00:08:22,120 --> 00:08:25,480
and being very careful
about what, you know,

236

00:08:25,480 --> 00:08:28,240
what is theory really
predicted, theory of gravity,

237

00:08:28,240 --> 00:08:30,470
and Einstein has been

criticized for not doing

238

00:08:30,470 --> 00:08:32,580
enough of that in the case
of general relativity,

239

00:08:32,580 --> 00:08:34,610
and there was kind of a
lull in general relativity,

240

00:08:34,610 --> 00:08:37,460
and then some years later,
people took up the cause again,

241

00:08:37,460 --> 00:08:40,240
and did all these amazing calculations.

242

00:08:40,240 --> 00:08:42,010
So I hope in that particular case,

243

00:08:42,010 --> 00:08:43,137
I would be more following along

244

00:08:43,137 --> 00:08:45,330
this sort of Newton type approach.

245

00:08:45,330 --> 00:08:47,678
It's difficult to anticipate-

246

00:08:47,678 --> 00:08:48,511
- Of course.
- In advance.

247

00:08:48,511 --> 00:08:49,344
- Yeah.

248

00:08:49,344 --> 00:08:51,460
- The challenge that you're working on,

249

00:08:51,460 --> 00:08:54,010

it seems like there's a
parallel to 100 years ago,

250

00:08:54,010 --> 00:08:57,270

and how are you trying
to build a model of,

251

00:08:57,270 --> 00:09:00,170

or a version of quantum
gravity that overcomes

252

00:09:00,170 --> 00:09:01,540

some of these differences

253

00:09:01,540 --> 00:09:03,550

between quantum mechanics, relativity?

254

00:09:03,550 --> 00:09:06,710

- So you mentioned that
parallel with the problem

255

00:09:06,710 --> 00:09:08,670

100 years ago that was solved by Einstein

256

00:09:08,670 --> 00:09:12,000

when he combined Newton's
theory of gravity

257

00:09:12,000 --> 00:09:13,970

with his theory of a special relativity,

258

00:09:13,970 --> 00:09:15,970

which included Maxwell's equations.

259

00:09:15,970 --> 00:09:17,190

It's a sort of an example.

260

00:09:17,190 --> 00:09:19,120
So I take that parallel very seriously,

261
00:09:19,120 --> 00:09:21,500
and if you look at what Einstein did,

262
00:09:21,500 --> 00:09:24,560
how did Einstein go about
solving that problem?

263
00:09:24,560 --> 00:09:25,393
How did he go about coming up

264
00:09:25,393 --> 00:09:28,160
with the theory of general relativity?

265
00:09:28,160 --> 00:09:29,770
Well, he had to go
through a number of steps,

266
00:09:29,770 --> 00:09:32,010
but his starting point was

267
00:09:32,010 --> 00:09:33,990
what he called the happiest
thought of his life,

268
00:09:33,990 --> 00:09:36,750
which was when he came up with
the principle of equivalence,

269
00:09:36,750 --> 00:09:39,880
and the principle of
equivalence is really just this.

270
00:09:39,880 --> 00:09:43,300
If you imagine having a box,
and it could be an elevator,

271

00:09:43,300 --> 00:09:46,360
and you have, you know, a person
inside it and some objects,

272
00:09:46,360 --> 00:09:48,690
and that box could be falling,

273
00:09:48,690 --> 00:09:50,890
or it could be floating out in space,

274
00:09:50,890 --> 00:09:52,260
and imagine there's no windows.

275
00:09:52,260 --> 00:09:54,000
So the person inside has no idea

276
00:09:54,000 --> 00:09:56,210
of which of the two situations they're in.

277
00:09:56,210 --> 00:09:57,550
So I suppose they'd be screaming.

278
00:09:57,550 --> 00:10:02,550
But aside from that, in the
case where the box is falling,

279
00:10:02,770 --> 00:10:04,260
everything would be
falling at the same rate.

280
00:10:04,260 --> 00:10:06,310
And so, it would feel like
it was floating around.

281
00:10:06,310 --> 00:10:08,950
It would feel like they
were floating out in space.

282
00:10:08,950 --> 00:10:11,910

And so, Einstein said these
two situations are equivalent,

283

00:10:11,910 --> 00:10:13,870
and that was the starting point,

284

00:10:13,870 --> 00:10:15,240
and then that idea gets turned

285

00:10:15,240 --> 00:10:17,080
into some beautiful mathematics,

286

00:10:17,080 --> 00:10:19,400
and he ends up incorporating
geometric ideas

287

00:10:19,400 --> 00:10:20,850
that he learned from Minkowski,

288

00:10:20,850 --> 00:10:24,990
and also from his childhood
friend Marcel Grossmann.

289

00:10:24,990 --> 00:10:26,300
Grossmann was a mathematician,

290

00:10:26,300 --> 00:10:30,650
who knew about the sort of
field of differential geometry,

291

00:10:30,650 --> 00:10:33,110
which went back to the mid-1800s.

292

00:10:33,110 --> 00:10:34,030
So there was lots of steps.

293

00:10:34,030 --> 00:10:36,160
It took him from 1907,

294

00:10:36,160 --> 00:10:38,920
when he had this happiest
thought of his life

295

00:10:38,920 --> 00:10:42,590
about the elevator, until 1915,

296

00:10:42,590 --> 00:10:45,563
when he finally wrote down
the correct field equations.

297

00:10:45,563 --> 00:10:48,640
- And how did he know in 1907

298

00:10:48,640 --> 00:10:50,980
when he had this thought
that it was definitely

299

00:10:50,980 --> 00:10:54,020
an important ingredient in formulating GR?

300

00:10:54,020 --> 00:10:56,090
You know, it still took
him eight years to finish,

301

00:10:56,090 --> 00:10:57,560
so I'm just curious.

302

00:10:57,560 --> 00:10:59,167
- Yeah, it's a great question,

303

00:10:59,167 --> 00:11:01,540
and I'm not enough of
a historian of science

304

00:11:01,540 --> 00:11:04,647
to know exactly what his
thinking was around that.

305

00:11:04,647 --> 00:11:07,040

But you can see looking at the idea

306

00:11:07,040 --> 00:11:08,140

that it has lots of promise.

307

00:11:08,140 --> 00:11:11,600

Suddenly, previously we
thought of gravity as a force.

308

00:11:11,600 --> 00:11:16,140

So Newton's first law says
that a body will continue,

309

00:11:16,140 --> 00:11:17,100

you know, at a state of rest,

310

00:11:17,100 --> 00:11:20,670

or in a constant speed in a straight line

311

00:11:20,670 --> 00:11:23,280

until it in essence is acted
upon by an external force,

312

00:11:23,280 --> 00:11:25,670

and gravity was regarded
as an external force.

313

00:11:25,670 --> 00:11:28,630

So under gravity, a body
wouldn't go in a straight line.

314

00:11:28,630 --> 00:11:32,030

It would go along a
curve, and that was okay,

315

00:11:32,030 --> 00:11:34,490

because gravity was regarded
as an external force.

316

00:11:34,490 --> 00:11:36,330

And suddenly, Einstein saw a way

317

00:11:36,330 --> 00:11:39,690

to stop thinking of
gravity as a force at all,

318

00:11:39,690 --> 00:11:43,220

and think of it as, you know,
more to do with geometry.

319

00:11:43,220 --> 00:11:45,560

So a particle would actually be going

320

00:11:45,560 --> 00:11:47,030

sort of in a straight line

321

00:11:47,030 --> 00:11:48,470

once you're in this
falling frame of reference,

322

00:11:48,470 --> 00:11:49,540

I mean, for a while.

323

00:11:49,540 --> 00:11:53,150

The principle of equivalence
only applies in small boxes

324

00:11:53,150 --> 00:11:54,430

over small periods of time.

325

00:11:54,430 --> 00:11:55,420

He must have seen that,

326

00:11:55,420 --> 00:11:56,800

and realized he was onto something big.

327

00:11:56,800 --> 00:11:58,350
I can see that would have been the case.

328
00:11:58,350 --> 00:11:59,183
- Mmm-hmm.

329
00:12:00,218 --> 00:12:04,190
- In terms of your research
into quantum gravity,

330
00:12:04,190 --> 00:12:06,270
what is the sort of parallel challenge,

331
00:12:06,270 --> 00:12:09,330
or the parallel path you're
trying to take to make progress?

332
00:12:09,330 --> 00:12:10,930
- So Einstein, as I said, started

333
00:12:10,930 --> 00:12:12,670
with this equivalence principle.

334
00:12:12,670 --> 00:12:16,093
And so, the idea is that perhaps there is

335
00:12:16,093 --> 00:12:19,520
a quantum equivalence principle
that can play a similar role

336
00:12:19,520 --> 00:12:21,210
in constructing a theory
of quantum gravity

337
00:12:21,210 --> 00:12:23,460
that the equivalence principle played

338
00:12:23,460 --> 00:12:26,510
in constructing the theory

of general relativity.

339

00:12:26,510 --> 00:12:27,900

So I should try to explain

340

00:12:27,900 --> 00:12:29,350

the quantum equivalence principle,

341

00:12:29,350 --> 00:12:31,810

but to do that, I kind
of need to back up a bit.

342

00:12:31,810 --> 00:12:33,980

You're asking the question
of how do I combine

343

00:12:33,980 --> 00:12:36,270

general relativity and quantum theory,

344

00:12:36,270 --> 00:12:38,170

where you should look
at these two theories,

345

00:12:38,170 --> 00:12:40,130

and ask, you know, what
kind of theories are they?

346

00:12:40,130 --> 00:12:42,940

They each have conservative
and radical features.

347

00:12:42,940 --> 00:12:45,510

So general relativity is conservative

348

00:12:45,510 --> 00:12:46,900

in that it's deterministic.

349

00:12:46,900 --> 00:12:48,580

It's a classical theory.

350

00:12:48,580 --> 00:12:51,090

- By conservative, do you
just mean that it's similar

351

00:12:51,090 --> 00:12:53,130

to other theories that came before it?

352

00:12:53,130 --> 00:12:55,680

- Similar to, yes, theories
in the past, yeah, yeah, yeah.

353

00:12:55,680 --> 00:12:57,190

I think that's what I mean.

354

00:12:57,190 --> 00:12:59,600

Yeah, it's not surprising in some sense,

355

00:12:59,600 --> 00:13:01,660

and perhaps it's not surprising
because of that similarity.

356

00:13:01,660 --> 00:13:03,460

- Mmm-hmm.

- So it's conservative

357

00:13:03,460 --> 00:13:05,050

in that sense, that it's deterministic.

358

00:13:05,050 --> 00:13:08,660

But it's radical in that
the causal structure is

359

00:13:08,660 --> 00:13:11,710

dynamically influenced by
the distribution of matter.

360

00:13:11,710 --> 00:13:15,510

So the causal structure is the

pattern of before and after,

361

00:13:15,510 --> 00:13:17,010
things, how things are, things,

362

00:13:17,010 --> 00:13:18,300
events are before other events.

363

00:13:18,300 --> 00:13:19,133
It's this pattern of events

364

00:13:19,133 --> 00:13:21,210
that are before and after each other,

365

00:13:21,210 --> 00:13:22,650
and that pattern is influenced

366

00:13:22,650 --> 00:13:24,120
by the curvature of space-time.

367

00:13:24,120 --> 00:13:28,640
So if you, if matter affects
the curvature of space-time,

368

00:13:28,640 --> 00:13:30,530
then matter affects the causal structure.

369

00:13:30,530 --> 00:13:32,210
And so, that's radically different

370

00:13:32,210 --> 00:13:34,090
from Newtonian physics, for example,

371

00:13:34,090 --> 00:13:37,540
where time was regarded
as this absolute structure

372

00:13:37,540 --> 00:13:39,620

in the background.

373

00:13:39,620 --> 00:13:42,460
Time just evolved,
unaffected by anything else.

374

00:13:42,460 --> 00:13:44,870
So dynamical causal structure
is this radical element

375

00:13:44,870 --> 00:13:46,560
from general relativity.

376

00:13:46,560 --> 00:13:48,240
And now, if you look at quantum theory,

377

00:13:48,240 --> 00:13:51,423
well, it also has radical
and conservative elements.

378

00:13:52,433 --> 00:13:54,053
The conservative element is

379

00:13:54,053 --> 00:13:57,500
that the causal structure is fixed.

380

00:13:57,500 --> 00:13:59,310
Just like Newtonian causal
structure, it's fixed.

381

00:13:59,310 --> 00:14:00,143
It's in the background.

382

00:14:00,143 --> 00:14:01,930
It doesn't change.

383

00:14:01,930 --> 00:14:05,450
And the radical element
is it has this property,

384

00:14:05,450 --> 00:14:07,560
I would call it indefiniteness.

385

00:14:07,560 --> 00:14:10,420
So a particle, if it can
go along one of two paths,

386

00:14:10,420 --> 00:14:11,960
it actually goes along both paths at once.

387

00:14:11,960 --> 00:14:13,470
It doesn't go along a definite path.

388

00:14:13,470 --> 00:14:16,200
So it's indefinite as to
which path it goes along.

389

00:14:16,200 --> 00:14:17,870
But I call that indefiniteness.

390

00:14:17,870 --> 00:14:21,140
So if you take those two
radical properties together,

391

00:14:21,140 --> 00:14:23,670
and if you believe a theory of
quantum gravity has to follow

392

00:14:23,670 --> 00:14:25,980
the radical path in both cases,

393

00:14:25,980 --> 00:14:27,940
then you expect a theory
of quantum gravity

394

00:14:27,940 --> 00:14:30,220
to have indefinite causal structure.

395

00:14:30,220 --> 00:14:32,970

Causal structure will not
just be something that varies,

396

00:14:32,970 --> 00:14:35,340

that changes, but also there will be

397

00:14:35,340 --> 00:14:36,300

two different causal structures

398

00:14:36,300 --> 00:14:37,730

at the same time, in some sense.

399

00:14:37,730 --> 00:14:38,580

Same time is the wrong word,

400

00:14:38,580 --> 00:14:40,880

but two different causal
structures will both,

401

00:14:40,880 --> 00:14:42,350

would both be, would both hold.

402

00:14:42,350 --> 00:14:45,000

So that's, I think, the
sort of the central property

403

00:14:45,000 --> 00:14:47,360

we're likely to have in
theory of quantum gravity.

404

00:14:47,360 --> 00:14:50,270

And that's a really strange idea,

405

00:14:50,270 --> 00:14:52,310

the idea that if you have two events,

406

00:14:52,310 --> 00:14:53,143

you know, usually you'd think,

407

00:14:53,143 --> 00:14:55,370

"Well, one event is
before the other event."

408

00:14:55,370 --> 00:14:57,170

You know, event A is before event B.

409

00:14:57,170 --> 00:14:58,690

But here, you could have it being true

410

00:14:58,690 --> 00:15:00,840

that event A is before event B,

411

00:15:00,840 --> 00:15:03,080

and also event A is after event B.

412

00:15:03,080 --> 00:15:05,454

Both of those things would be
true, not just one of them.

413

00:15:05,454 --> 00:15:06,800

Yeah, so you'd have indefiniteness

414

00:15:06,800 --> 00:15:07,900

as to the causal structure.

415

00:15:07,900 --> 00:15:08,800

That is not something that we're used to,

416

00:15:08,800 --> 00:15:10,770

or it is not, that we're
not used to thinking

417

00:15:10,770 --> 00:15:12,830

about the world in those terms.

418

00:15:12,830 --> 00:15:14,900
So the question is how do
you make sense of that?

419
00:15:14,900 --> 00:15:16,090
How do you do physics still

420
00:15:16,090 --> 00:15:17,660
when you have something like that?

421
00:15:17,660 --> 00:15:21,760
And so, the idea is to
look at what Einstein did

422
00:15:21,760 --> 00:15:23,790
with the equivalence principle,

423
00:15:23,790 --> 00:15:28,100
and what he did was he said,
well, you may have behavior,

424
00:15:28,100 --> 00:15:29,940
which is, let's see, like non-inertial,

425
00:15:29,940 --> 00:15:33,280
so it looks like things
are moving in curved lines.

426
00:15:33,280 --> 00:15:35,720
It looks like things are
behaving in a weird way.

427
00:15:35,720 --> 00:15:38,520
But you can always transform
into a frame of reference

428
00:15:38,520 --> 00:15:40,970
where you just have objects
moving in straight lines,

429

00:15:40,970 --> 00:15:43,330
where Newton's laws apply,
where things are just moving

430

00:15:43,330 --> 00:15:45,520
in straight lines, and that's
called inertial behavior.

431

00:15:45,520 --> 00:15:48,590
So, and the way you do that
is just by looking at it

432

00:15:48,590 --> 00:15:50,610
in a frame of reference that's falling.

433

00:15:50,610 --> 00:15:52,060
At least for short while locally

434

00:15:52,060 --> 00:15:54,520
things will be moving in a straight line.

435

00:15:54,520 --> 00:15:57,210
So a different way of
understanding what Einstein did

436

00:15:57,210 --> 00:15:59,040
with the equivalence principle is to say

437

00:15:59,040 --> 00:16:02,140
the equivalence principle
says that there always exists

438

00:16:02,140 --> 00:16:04,700
a frame of reference with which,

439

00:16:04,700 --> 00:16:06,970
with respect to which
the behavior is inertial

440
00:16:06,970 --> 00:16:09,400
in a small vicinity around any point.

441
00:16:09,400 --> 00:16:11,360
The question is can we
take that principle forward

442
00:16:11,360 --> 00:16:12,940
to the problem of quantum gravity?

443
00:16:12,940 --> 00:16:17,920
And the idea is to draw an
analogy between inertial behavior

444
00:16:17,920 --> 00:16:20,400
and definite causal
structure on the one hand,

445
00:16:20,400 --> 00:16:25,060
and non-inertial behavior and
indefinite causal structure,

446
00:16:25,060 --> 00:16:26,420
'cause in general relativity,

447
00:16:26,420 --> 00:16:28,870
non-inertial behavior is
the sort of the weird thing

448
00:16:28,870 --> 00:16:30,370
that you're trying to tame by going

449
00:16:30,370 --> 00:16:31,620
to a falling frame of reference.

450
00:16:31,620 --> 00:16:34,390
In quantum gravity,
indefinite causal structure is

451

00:16:34,390 --> 00:16:36,490
the weird thing that
you're trying to tame.

452

00:16:36,490 --> 00:16:38,230
So that's the sort of background,

453

00:16:38,230 --> 00:16:40,630
and now, what would the principle say?

454

00:16:40,630 --> 00:16:43,110
Well, the principle would say can you find

455

00:16:43,110 --> 00:16:44,950
a sort of frame of reference,

456

00:16:44,950 --> 00:16:47,130
where you get rid of
indefinite causal structure,

457

00:16:47,130 --> 00:16:48,740
at least locally in a small region?

458

00:16:48,740 --> 00:16:49,620
Well, that's not quite enough.

459

00:16:49,620 --> 00:16:51,120
What you need to do is find

460

00:16:51,120 --> 00:16:52,920
what's called a quantum
frame of reference,

461

00:16:52,920 --> 00:16:55,840
and this is a subject that
was developed many years ago

462

00:16:55,840 --> 00:16:59,250

by Yakir Aharonov, and other people,

463

00:16:59,250 --> 00:17:00,530

quantum frames of reference.

464

00:17:00,530 --> 00:17:01,480

And it turns out you can do this.

465

00:17:01,480 --> 00:17:03,370

So what you can do is you could find

466

00:17:03,370 --> 00:17:05,370

a quantum frame of reference,

467

00:17:05,370 --> 00:17:07,660

a quantum coordinate system to measure

468

00:17:07,660 --> 00:17:09,180

that frame of reference,

469

00:17:09,180 --> 00:17:11,700

where locally in the
vicinity of a small point,

470

00:17:11,700 --> 00:17:14,130

you get rid of indefinite
causal structure.

471

00:17:14,130 --> 00:17:16,210

The causal structure becomes definite.

472

00:17:16,210 --> 00:17:18,290

- So you know that A causes B?

473

00:17:18,290 --> 00:17:20,190

- Yeah, you know that A causes B.

474

00:17:20,190 --> 00:17:21,740

Now, what you do when you impose that,

475

00:17:21,740 --> 00:17:23,220

you try to make it work in a small region,

476

00:17:23,220 --> 00:17:26,700

and then everywhere else it
goes haywire, but that's okay,

477

00:17:26,700 --> 00:17:28,640

'cause you can hope to use the tricks

478

00:17:28,640 --> 00:17:31,200

that Einstein used in general relativity.

479

00:17:31,200 --> 00:17:32,630

In his case, he knew he could

480

00:17:32,630 --> 00:17:34,320

locally make everything inertial,

481

00:17:34,320 --> 00:17:36,490

and if he did that, you know,
far, far away from there,

482

00:17:36,490 --> 00:17:38,270

it would kind of go haywire.

- Mmm-hmm.

483

00:17:38,270 --> 00:17:39,750

- Crazy, non-inertial
behavior, but that's okay,

484

00:17:39,750 --> 00:17:41,110

because he could write down some equations

485

00:17:41,110 --> 00:17:43,070

at that point that worked.

486

00:17:43,070 --> 00:17:45,160

And so, the hope is to be
able to do the same trick

487

00:17:45,160 --> 00:17:46,570

in quantum gravity.

488

00:17:46,570 --> 00:17:48,290

- Is it especially difficult

489

00:17:48,290 --> 00:17:51,960

because you're dealing
with these more radical,

490

00:17:51,960 --> 00:17:52,890

what's the other word?

491

00:17:52,890 --> 00:17:55,050

- Non-conservative?
- Non-conservative element?

492

00:17:55,050 --> 00:17:58,550

Is there more uncertainty,
or just probabilities,

493

00:17:58,550 --> 00:18:00,440

as opposed to certainties?

494

00:18:00,440 --> 00:18:01,637

- A different approach
would be to say, "Well, now,

495

00:18:01,637 --> 00:18:03,947

"I'm gonna take the more
conservative path in each case.

496

00:18:03,947 --> 00:18:06,367

"I'm gonna look for a theory
which is deterministic

497

00:18:06,367 --> 00:18:08,910

"and has fixed causal structure."

498

00:18:08,910 --> 00:18:10,593

It just seems unlikely to
me that that would work.

499

00:18:10,593 --> 00:18:12,520

I mean, it's not completely impossible.

500

00:18:12,520 --> 00:18:13,543

It may be you could find some theory

501

00:18:13,543 --> 00:18:15,530

that was in some sense more classical,

502

00:18:15,530 --> 00:18:17,810

more like older theories,
where that worked,

503

00:18:17,810 --> 00:18:19,210

and there are even ideas

504

00:18:19,210 --> 00:18:21,010

that I think fit into that category.

505

00:18:21,870 --> 00:18:24,040

It seems to me to be the wrong idea.

506

00:18:24,040 --> 00:18:25,750

One should embrace the radical elements,

507

00:18:25,750 --> 00:18:27,482

and see what, how to go forward.

508

00:18:27,482 --> 00:18:28,870

- And is that what's really unique

509

00:18:28,870 --> 00:18:31,480
about your approach to quantum gravity?

510

00:18:31,480 --> 00:18:35,700
Is that what sets your approach
apart from other approaches?

511

00:18:35,700 --> 00:18:37,750
- Definitely it's true that my approach is

512

00:18:37,750 --> 00:18:40,390
to put this indefinite causal structure

513

00:18:40,390 --> 00:18:41,530
front and central, I think.

514

00:18:41,530 --> 00:18:43,450
This is the central conceptual problem,

515

00:18:43,450 --> 00:18:44,820
and then we work out from that.

516

00:18:44,820 --> 00:18:47,260
Other approaches, in as
far as I understand them,

517

00:18:47,260 --> 00:18:49,395
are not doing that.

518

00:18:49,395 --> 00:18:51,080
But you know, everyone has
their own take on this.

519

00:18:51,080 --> 00:18:52,960
So I think what's important

520

00:18:52,960 --> 00:18:54,370

when it comes to solving problems

521

00:18:54,370 --> 00:18:55,900

like the problem of quantum gravity is

522

00:18:55,900 --> 00:18:58,410

that there are many different approaches.

523

00:18:58,410 --> 00:19:02,050

So pluralism is essential in physics,

524

00:19:02,050 --> 00:19:04,470

as it is in other walks of life.

525

00:19:04,470 --> 00:19:06,520

And so, I'm hoping to bring, you know,

526

00:19:06,520 --> 00:19:08,140

a different kind of approach.

527

00:19:08,140 --> 00:19:10,550

I mean, there are other
people now thinking

528

00:19:10,550 --> 00:19:14,340

about indefinite causal
structure and quantum gravity,

529

00:19:14,340 --> 00:19:18,210

so I'm hoping there's starting
to be a bit of a community.

530

00:19:18,210 --> 00:19:20,010

- Basically a 100-year-old problem

531

00:19:20,010 --> 00:19:23,880

more so in terms of
marrying these theories.

532
00:19:23,880 --> 00:19:25,910
Is that challenging for a researcher

533
00:19:25,910 --> 00:19:28,180
to be working on a problem
that has passed through

534
00:19:28,180 --> 00:19:30,980
other researchers' careers
without being solved?

535
00:19:30,980 --> 00:19:33,130
- Yeah-
- Do you foresee

536
00:19:33,130 --> 00:19:35,957
a day when you say, you,
or a colleague says,

537
00:19:35,957 --> 00:19:39,472
"Oh, yes, that's quantum
gravity, we've done it"?

538
00:19:39,472 --> 00:19:40,758
- I mean, I think we can do it.

539
00:19:40,758 --> 00:19:41,936
I mean, there are,

540
00:19:41,936 --> 00:19:43,703
I don't know the particular approach

541
00:19:43,703 --> 00:19:45,910
that I'm taking is the right one,

542
00:19:45,910 --> 00:19:49,500
and you know, it may well
not be the right one.

543

00:19:49,500 --> 00:19:53,400

There could be some young
physicist at the moment

544

00:19:53,400 --> 00:19:56,070

who has the right idea, or
somebody who's, you know,

545

00:19:56,070 --> 00:19:58,120

yet to even enter the field of physics.

546

00:19:58,120 --> 00:19:59,020

- Mmm-hmm.
- Typically,

547

00:19:59,020 --> 00:20:03,090

big breakthroughs are made
by young people in physics.

548

00:20:03,090 --> 00:20:08,090

And so, that's really where the hope lies.

549

00:20:08,290 --> 00:20:10,393

- And what would it mean if it were,

550

00:20:11,230 --> 00:20:12,930

maybe you haven't even thought about that,

551

00:20:12,930 --> 00:20:16,240

but if there, these big
questions had a solution,

552

00:20:16,240 --> 00:20:18,810

if the new theory, the
unifying theory, was found,

553

00:20:18,810 --> 00:20:20,910

what would that mean for physics?

554

00:20:20,910 --> 00:20:23,420

Would physics be, done
and we can all go home?

555

00:20:23,420 --> 00:20:24,262

- Yeah.

556

00:20:24,262 --> 00:20:25,538

(Lucien laughs)

(Colin laughs)

557

00:20:25,538 --> 00:20:26,690

I mean, again, it really depends

558

00:20:26,690 --> 00:20:28,900

on what the answer is, doesn't it?

559

00:20:28,900 --> 00:20:29,893

I don't know.

560

00:20:30,930 --> 00:20:32,240

You know, people were thinking

561

00:20:32,240 --> 00:20:35,760

about electricity and magnetism,

562

00:20:35,760 --> 00:20:37,280

and people started to become aware

563

00:20:37,280 --> 00:20:38,900

that there were these electric,

564

00:20:38,900 --> 00:20:41,040

started sending electricity through wires,

565

00:20:41,040 --> 00:20:43,640

and well, they had, you
know, magnets forever.

566

00:20:43,640 --> 00:20:46,680

And I don't know if people before,

567

00:20:46,680 --> 00:20:50,225

before the subject was
really completed by Maxwell,

568

00:20:50,225 --> 00:20:53,480

I don't know if people really
understood what it would mean,

569

00:20:53,480 --> 00:20:57,510

what it would mean to have
Maxwell's equations written out.

570

00:20:57,510 --> 00:20:58,343

Maxwell's equations have had

571

00:20:58,343 --> 00:21:00,110

a tremendous impact on humanity.

572

00:21:00,110 --> 00:21:02,430

So much of our technology
relies on understanding

573

00:21:02,430 --> 00:21:04,557

electricity and magnetism,
and conceptually, you know,

574

00:21:04,557 --> 00:21:07,310

I'm not sure if people
anticipated that this would lead

575

00:21:07,310 --> 00:21:09,910

to problems with relative motion.

576

00:21:09,910 --> 00:21:11,350

Problems come up when you get an answer,

577

00:21:11,350 --> 00:21:12,530
when you start to get a theory,

578

00:21:12,530 --> 00:21:15,510
and you can't really
anticipate that in advance.

579

00:21:15,510 --> 00:21:16,343
Who knows?

580

00:21:16,343 --> 00:21:18,350
When someone comes up with
a theory of quantum gravity,

581

00:21:18,350 --> 00:21:19,910
I think we'll be surprised by it.

582

00:21:19,910 --> 00:21:21,500
It'll be interesting,

583

00:21:21,500 --> 00:21:22,860
and I think it will lead to questions

584

00:21:22,860 --> 00:21:26,130
that we can't possibly
anticipate at at this stage.

585

00:21:26,130 --> 00:21:28,590
- I know that one thing
that's important in your work,

586

00:21:28,590 --> 00:21:31,980
if I understand correctly, is
that you have a set of axioms

587

00:21:31,980 --> 00:21:34,530
that you use as kind of
the center of your work,

588

00:21:34,530 --> 00:21:38,260
and can you talk about why
you use that kind of approach?

589

00:21:38,260 --> 00:21:40,220
- Yeah, so this is what happened.

590

00:21:40,220 --> 00:21:42,360
I mean, I should talk about my career.

591

00:21:42,360 --> 00:21:44,420
I started off in quantum foundations.

592

00:21:44,420 --> 00:21:49,020
I did my PhD in, from 1989 to 1992,

593

00:21:49,020 --> 00:21:50,940
a time that the field of
quantum foundations was

594

00:21:50,940 --> 00:21:54,018
very concerned with
interpretations of quantum theory,

595

00:21:54,018 --> 00:21:56,797
you know, how do you make
sense of quantum theory?

596

00:21:56,797 --> 00:21:58,950
And there was all these
different interpretations,

597

00:21:58,950 --> 00:22:01,470
like the many worlds interpretation,

598

00:22:01,470 --> 00:22:04,170
where every time there is a
quantum choice to be made,

599

00:22:04,170 --> 00:22:05,310
both things actually happen.

600

00:22:05,310 --> 00:22:07,370
The world splits into two copies

601

00:22:07,370 --> 00:22:11,150
with one thing happening
in each copy of the world.

602

00:22:11,150 --> 00:22:12,800
And by the world, I mean
the universe, everything,

603

00:22:12,800 --> 00:22:15,500
and there's the de Broglie-Bohm model,

604

00:22:15,500 --> 00:22:17,920
where the quantum wave function guides

605

00:22:17,920 --> 00:22:19,600
actual particles that exist,

606

00:22:19,600 --> 00:22:23,570
and those particles are guided
along a path by this wave,

607

00:22:23,570 --> 00:22:24,780
and many other interpretations.

608

00:22:24,780 --> 00:22:26,621
And so, that was what
people were thinking about,

609

00:22:26,621 --> 00:22:28,120
and that's what I was thinking about.

610

00:22:28,120 --> 00:22:31,050
I became a bit unsatisfied
with that way of thinking,

611
00:22:31,050 --> 00:22:34,960
because it didn't really seem
to lead to any new ideas.

612
00:22:34,960 --> 00:22:36,470
It didn't seem to lead to the possibility

613
00:22:36,470 --> 00:22:38,770
of real progress in fundamental physics.

614
00:22:38,770 --> 00:22:41,140
It was a lot like the aether theories,

615
00:22:41,140 --> 00:22:41,973
the mechanical aether theories.

616
00:22:41,973 --> 00:22:45,630
You know, people took Newton's
theory, or Maxwell's theories

617
00:22:45,630 --> 00:22:47,640
and tried to make sense
of those equations,

618
00:22:47,640 --> 00:22:50,680
and those ideas turned
out not to be useful,

619
00:22:50,680 --> 00:22:52,613
and my feeling increasingly was

620
00:22:52,613 --> 00:22:54,830
that this wasn't a useful
way of making progress

621

00:22:54,830 --> 00:22:57,010
in quantum foundations.

622
00:22:57,010 --> 00:23:01,150
And then I came under the
influence of Chris Fuchs,

623
00:23:01,150 --> 00:23:02,500
and he was asking this question.

624
00:23:02,500 --> 00:23:05,447
He was saying, "Well, can
you derive quantum theory?"

625
00:23:05,447 --> 00:23:08,550
"Can you derive quantum theory
from some more basic ideas?"

626
00:23:08,550 --> 00:23:09,773
He wasn't the first person
to ask that question,

627
00:23:09,773 --> 00:23:12,690
but it was the first time
I'd encountered the question.

628
00:23:12,690 --> 00:23:14,730
In his case in particular, he was working

629
00:23:14,730 --> 00:23:16,830
in this sort of new field
of quantum information,

630
00:23:16,830 --> 00:23:18,887
and he was saying, "Well, can you give

631
00:23:18,887 --> 00:23:20,537
"an information theoretic reason

632

00:23:20,537 --> 00:23:21,797
"for the axioms of quantum theory,

633
00:23:21,797 --> 00:23:24,670
"for the structure of
quantum theory as it was?"

634
00:23:24,670 --> 00:23:26,320
And so, I set about working on that.

635
00:23:26,320 --> 00:23:29,360
This was in 2000, 2001.

636
00:23:29,360 --> 00:23:30,970
And you know, eventually, I found a way

637
00:23:30,970 --> 00:23:32,150
to approach that problem.

638
00:23:32,150 --> 00:23:34,180
So the idea was to be very operational.

639
00:23:34,180 --> 00:23:36,110
What I mean by operational
is to just talk about

640
00:23:36,110 --> 00:23:39,655
what it is you do, the settings
of knob settings, and so on,

641
00:23:39,655 --> 00:23:40,488
and what it is you see,

642
00:23:40,488 --> 00:23:42,810
like detectors clicking, lights flashing.

643
00:23:42,810 --> 00:23:43,810
So he-
- Sorry to interrupt, though,

644

00:23:43,810 --> 00:23:47,250

but as a theorist, you are
proposing the theories,

645

00:23:47,250 --> 00:23:49,050

but you're not the one
actually turning the knobs,

646

00:23:49,050 --> 00:23:51,100

and watching the lights blink on and off?

647

00:23:51,100 --> 00:23:51,933

- Well, I mean, I,

648

00:23:51,933 --> 00:23:54,100

I mean, as an aside, I actually,

649

00:23:54,100 --> 00:23:56,620

I worked for two years in laboratories.

650

00:23:56,620 --> 00:23:59,290

So I worked for one year in the laboratory

651

00:23:59,290 --> 00:24:02,520

of Anton Zeilinger in
Innsbruck as it was then.

652

00:24:02,520 --> 00:24:03,780

I mean, I was a theorist,

653

00:24:03,780 --> 00:24:06,000

but I was allowed to
look at the experiments.

654

00:24:06,000 --> 00:24:07,254

- You're allowed to touch the lasers?

655

00:24:07,254 --> 00:24:08,275
- No, that was-
- Okay.

656
00:24:08,275 --> 00:24:09,108
- A step too far.
- Yeah.

657
00:24:09,108 --> 00:24:11,020
- I was allowed to be in the
same room as the experiments,

658
00:24:11,020 --> 00:24:15,150
and again with the same
restrictions I worked in Rome

659
00:24:15,150 --> 00:24:17,600
in the research group
of Francesco De Martini.

660
00:24:17,600 --> 00:24:18,840
- Mmm-hmm.
- So actually,

661
00:24:18,840 --> 00:24:20,620
he was more willing
for me to get involved,

662
00:24:20,620 --> 00:24:23,090
but by that point, I was too cautious.

663
00:24:23,090 --> 00:24:25,170
And that was really
interesting to actually see

664
00:24:25,170 --> 00:24:26,430
people doing experiments, you know,

665
00:24:26,430 --> 00:24:28,720
'cause it's a remarkable skill.

666

00:24:28,720 --> 00:24:30,680

People, experimentalists
have to solve problems

667

00:24:30,680 --> 00:24:32,360

that theorists can't even imagine.

668

00:24:32,360 --> 00:24:35,390

So for example, Rome, it's very hot,

669

00:24:35,390 --> 00:24:37,010

and the temperature goes up and down,

670

00:24:37,010 --> 00:24:38,900

and the air conditioning was broken.

671

00:24:38,900 --> 00:24:43,840

So you'd have these beam
splitters mounted on a metal base,

672

00:24:43,840 --> 00:24:45,820

but the metal would contract and expand,

673

00:24:45,820 --> 00:24:47,690

and that would mess the experiment up.

674

00:24:47,690 --> 00:24:49,240

They had to find a way
to solve that problem.

675

00:24:49,240 --> 00:24:50,840

They had to buy this metal called Invar

676

00:24:50,840 --> 00:24:54,300

that has a very low expansion coefficient,

677

00:24:54,300 --> 00:24:56,250

and then the experiment was stable.

678

00:24:56,250 --> 00:24:57,660

I find that fascinating, you know?

679

00:24:57,660 --> 00:25:00,060

The real stuff of experiments
is really interesting,

680

00:25:00,060 --> 00:25:02,500

and how do you get the
information from here to here,

681

00:25:02,500 --> 00:25:03,770

the electronics attaching to it?

682

00:25:03,770 --> 00:25:06,390

So I think every theorist
should be forced to work

683

00:25:06,390 --> 00:25:07,367

in another laboratory for a while.

684

00:25:07,367 --> 00:25:09,770

- You think that informed
your operational-

685

00:25:09,770 --> 00:25:10,603

- Absolutely, yeah-

- Approach?

686

00:25:10,603 --> 00:25:14,180

- So I think, so that was
probably in the back of my mind,

687

00:25:14,180 --> 00:25:16,230

and so, that's what pushed me towards

688

00:25:16,230 --> 00:25:17,910

this operational approach.

689

00:25:17,910 --> 00:25:19,090

So the operational approach is really

690

00:25:19,090 --> 00:25:20,070

just taking it seriously.

691

00:25:20,070 --> 00:25:21,290

Experimentalists have to do experiments.

692

00:25:21,290 --> 00:25:22,430

They have to go into the world,

693

00:25:22,430 --> 00:25:26,390

and put things in different
places, and set, you know,

694

00:25:26,390 --> 00:25:29,630

set knobs to different
positions, and read off the data.

695

00:25:29,630 --> 00:25:31,470

So I set up a framework like that,

696

00:25:31,470 --> 00:25:34,480

and then furthermore,
add in probabilities,

697

00:25:34,480 --> 00:25:36,680

because quantum theory is
all about probabilities.

698

00:25:36,680 --> 00:25:38,660

You know, in the end, quantum theory,

699

00:25:38,660 --> 00:25:42,250

in some sense, quantum theory
is a more natural descendant

700

00:25:42,250 --> 00:25:43,930
of classical probability theory

701

00:25:43,930 --> 00:25:45,800
than it is of Newton's theory.

702

00:25:45,800 --> 00:25:47,380
Quantum theory is a probabilistic theory.

703

00:25:47,380 --> 00:25:48,517
- Mmm-hmm.

704

00:25:48,517 --> 00:25:51,360
- And so, I set up this way to write down

705

00:25:51,360 --> 00:25:52,500
sort of just probabilistic theories

706

00:25:52,500 --> 00:25:53,660
that pertain to operational situations.

707

00:25:53,660 --> 00:25:55,360
So you have an operational situation.

708

00:25:55,360 --> 00:25:56,530
You have probabilities.

709

00:25:56,530 --> 00:25:58,320
You can write down a
mathematical framework

710

00:25:58,320 --> 00:26:00,200
that applies to that situation.

711

00:26:00,200 --> 00:26:01,033
- Mmm-hmm.

712

00:26:01,033 --> 00:26:02,790

- And then once you have
that mathematical framework,

713

00:26:02,790 --> 00:26:04,040

you can say, well, you know,

714

00:26:04,040 --> 00:26:06,890

maybe I can find some
principles, or postulates,

715

00:26:06,890 --> 00:26:10,340

or I call them axioms, that constrain you.

716

00:26:10,340 --> 00:26:11,520

And you know, so say, you know,

717

00:26:11,520 --> 00:26:13,950

initially you have all possible
probabilistic theories,

718

00:26:13,950 --> 00:26:16,040

but now you want to specialize

719

00:26:16,040 --> 00:26:18,130

to particular probabilistic theories.

720

00:26:18,130 --> 00:26:20,009

And so, the axioms I wrote down,

721

00:26:20,009 --> 00:26:20,842

I wrote down enough axioms

722

00:26:20,842 --> 00:26:22,670

that would get you to quantum theory,

723

00:26:22,670 --> 00:26:25,600

and that was work I did in 2001.

724

00:26:25,600 --> 00:26:27,400

So that was a very interesting exercise,

725

00:26:27,400 --> 00:26:29,800

and I felt like that kind of work helped to make progress.

726

00:26:29,800 --> 00:26:32,600

I felt like I was understanding quantum theory in a new way

727

00:26:32,600 --> 00:26:34,350

that I hadn't previously understood it.

728

00:26:34,350 --> 00:26:35,900

- You said you think all theorists should

729

00:26:35,900 --> 00:26:37,270

have to spend some time in the lab.

730

00:26:37,270 --> 00:26:39,900

Is that, is it a different part of the brain

731

00:26:39,900 --> 00:26:42,590

that activates to work in a experimental setting?

732

00:26:42,590 --> 00:26:43,423

- Absolutely, yeah.

733

00:26:43,423 --> 00:26:44,950

I mean, like I said, I've never actually

734

00:26:44,950 --> 00:26:47,030

sort of actually got my hands dirty, so to speak,

735
00:26:47,030 --> 00:26:48,570
and moved these things around,

736
00:26:48,570 --> 00:26:51,690
but really a laboratory looks nothing like

737
00:26:51,690 --> 00:26:53,710
a bunch of equations,
like these equations here.

738
00:26:53,710 --> 00:26:55,380
It's a completely different
world from a laboratory,

739
00:26:55,380 --> 00:26:57,750
and you don't really understand
physics until you understand

740
00:26:57,750 --> 00:27:00,480
that it is about the experimental world.

741
00:27:00,480 --> 00:27:02,530
It's about experiments in the end.

742
00:27:02,530 --> 00:27:04,650
- And would it be the same framework

743
00:27:04,650 --> 00:27:06,840
that you hope might give quantum gravity,

744
00:27:06,840 --> 00:27:09,000
but with a different set of axioms?

745
00:27:09,000 --> 00:27:12,830
- Yes, so what happens is
I did that work in 2001,

746
00:27:12,830 --> 00:27:14,350

just before I came to Perimeter Institute,

747

00:27:14,350 --> 00:27:15,250

and then I came here,

748

00:27:15,250 --> 00:27:16,977

and people were thinking
about quantum gravity.

749

00:27:16,977 --> 00:27:19,610

You know, there was string theorists,

750

00:27:19,610 --> 00:27:22,617

Rob Myers and Lee Smolin
working on loop quantum gravity.

751

00:27:22,617 --> 00:27:25,400

And so, quantum gravity
was very much in the air

752

00:27:25,400 --> 00:27:28,070

at Perimeter Institute
back then, as it is today.

753

00:27:28,070 --> 00:27:30,437

And I started thinking,
"Well, perhaps we can take

754

00:27:30,437 --> 00:27:32,327

"this kind of general
probabilistic technique

755

00:27:32,327 --> 00:27:33,647

"that I developed, and apply it

756

00:27:33,647 --> 00:27:35,280

"to the problem with quantum gravity."

757

00:27:35,280 --> 00:27:36,270

Otherwise, what is it good for?

758

00:27:36,270 --> 00:27:38,670

You know, it's a lot of fun to,

759

00:27:38,670 --> 00:27:39,640

it's called reconstruct quantum theory.

760

00:27:39,640 --> 00:27:41,450

So you start off with
some general framework,

761

00:27:41,450 --> 00:27:44,210

you write down some axioms,
and you get quantum theory.

762

00:27:44,210 --> 00:27:45,600

But we already knew
what quantum theory was,

763

00:27:45,600 --> 00:27:47,550

so it wasn't really pushing us forward.

764

00:27:47,550 --> 00:27:49,680

It was just providing a new
way of understanding things.

765

00:27:49,680 --> 00:27:52,440

What would be a real test
would be if we could start off

766

00:27:52,440 --> 00:27:54,380

with some general framework,
apply some axioms,

767

00:27:54,380 --> 00:27:56,090

and get quantum gravity,
a new physical theory.

768

00:27:56,090 --> 00:27:57,240
That would be a great test.

769
00:27:57,240 --> 00:27:59,690
So I started thinking about that.

770
00:27:59,690 --> 00:28:01,983
One of the problems was that
the operational framework

771
00:28:01,983 --> 00:28:04,230
I developed wasn't really hospitable

772
00:28:04,230 --> 00:28:06,490
to a theory of quantum gravity.

773
00:28:06,490 --> 00:28:07,800
I realized you'd have this property

774
00:28:07,800 --> 00:28:10,090
of indefinite causal
structure I mentioned earlier.

775
00:28:10,090 --> 00:28:11,970
The order of events would be indefinite,

776
00:28:11,970 --> 00:28:14,350
and well, the operational
framework had boxes

777
00:28:14,350 --> 00:28:15,940
with wires connecting them,

778
00:28:15,940 --> 00:28:17,930
and those wires were
the direction of time.

779
00:28:17,930 --> 00:28:20,270
So a wire, a particle would leave one box

780

00:28:20,270 --> 00:28:21,880
and go into another box,

781

00:28:21,880 --> 00:28:23,860
and that would be
happening forward in time.

782

00:28:23,860 --> 00:28:26,070
So it wasn't the right framework

783

00:28:26,070 --> 00:28:27,710
to treat the problem of quantum gravity.

784

00:28:27,710 --> 00:28:29,800
So I set about building a framework

785

00:28:29,800 --> 00:28:32,800
that would be hospitable to
quantum gravity, I hoped,

786

00:28:32,800 --> 00:28:35,290
and this was a frame, a
probabilistic framework

787

00:28:35,290 --> 00:28:38,920
that was capable of admitting
indefinite causal structure.

788

00:28:38,920 --> 00:28:41,760
I took a very general
operational approach.

789

00:28:41,760 --> 00:28:43,690
I tried to really sit back and ask,

790

00:28:43,690 --> 00:28:44,690
you know, what is an experiment?

791
00:28:44,690 --> 00:28:47,510
You know, what do we do in an experiment?

792
00:28:47,510 --> 00:28:50,019
How can we translate that
into a mathematical framework?

793
00:28:50,019 --> 00:28:51,810
You know, so in an experiment,

794
00:28:51,810 --> 00:28:54,610
what you do basically is you make choices.

795
00:28:54,610 --> 00:28:56,450
Like I said, you know,
you set knob settings,

796
00:28:56,450 --> 00:28:58,400
and you collect data.

797
00:28:58,400 --> 00:29:00,210
And so, I imagined a
mathematical framework

798
00:29:00,210 --> 00:29:03,130
that was capable of analyzing

799
00:29:03,130 --> 00:29:05,220
that sort of situation probabilistically,

800
00:29:05,220 --> 00:29:07,380
but very generally, without assuming

801
00:29:07,380 --> 00:29:08,770
any definite causal structure.

802
00:29:08,770 --> 00:29:10,697
So that was work I did in 2005,

803
00:29:10,697 --> 00:29:13,887
and I called it the causaloid framework,

804
00:29:13,887 --> 00:29:16,440
'cause the central mathematical
object in that framework

805
00:29:16,440 --> 00:29:18,540
was something I called the causaloid,

806
00:29:18,540 --> 00:29:20,870
and that's really driven all
my research since then is

807
00:29:20,870 --> 00:29:22,970
the attempt to formulate quantum gravity

808
00:29:22,970 --> 00:29:25,380
in this kind of more general
mathematical framework.

809
00:29:25,380 --> 00:29:26,500
You know, if you think about it,

810
00:29:26,500 --> 00:29:28,780
Einstein, when he was
developing general relativity,

811
00:29:28,780 --> 00:29:30,610
needed a mathematical
framework to do that in,

812
00:29:30,610 --> 00:29:34,120
and he was lucky that
Riemann 65 years earlier,

813
00:29:34,120 --> 00:29:36,740
or thereabouts, had developed

Riemannian geometry.

814

00:29:36,740 --> 00:29:39,340

This is a framework of curved spaces,

815

00:29:39,340 --> 00:29:40,520

and Einstein was able to take

816

00:29:40,520 --> 00:29:42,520

that mathematical framework directly,

817

00:29:42,520 --> 00:29:44,900

and use it for general relativity.

818

00:29:44,900 --> 00:29:46,360

And so, the question

was, well, maybe we need

819

00:29:46,360 --> 00:29:47,920

some similar sort of
mathematical framework,

820

00:29:47,920 --> 00:29:49,852

but for the problem of quantum gravity.

821

00:29:49,852 --> 00:29:50,848

So that was the idea.

822

00:29:50,848 --> 00:29:52,490

But that, you know, that was 2005,

823

00:29:52,490 --> 00:29:54,140

and I'm still working on it.

824

00:29:54,140 --> 00:29:56,180

So it's not clear to me

825

00:29:56,180 --> 00:29:57,490

that that's exactly the right framework,

826

00:29:57,490 --> 00:29:59,305

but at least it was an idea,

827

00:29:59,305 --> 00:30:01,070

and it's something that
came out of my earlier work

828

00:30:01,070 --> 00:30:03,750

on axioms for quantum
theory that you asked about.

829

00:30:03,750 --> 00:30:04,973

- Mmm-hmm.

- I jotted down

830

00:30:04,973 --> 00:30:06,620

some of the places that you've been.

831

00:30:06,620 --> 00:30:07,760

You've mentioned Ireland.

832

00:30:07,760 --> 00:30:10,640

You went to Tirol, Durham, and Rome,

833

00:30:10,640 --> 00:30:14,180

and Oxford, and then you came here.

834

00:30:14,180 --> 00:30:17,770

You mentioned to us how you
were convinced to come here.

835

00:30:17,770 --> 00:30:19,950

Can you just share that
briefly with (laughs)-

836

00:30:19,950 --> 00:30:21,090

- Yeah, I was in Oxford.

837

00:30:21,090 --> 00:30:22,300

I was happy in Oxford.

838

00:30:22,300 --> 00:30:24,320

I mean, I had a position that would've lasted for 10 years,

839

00:30:24,320 --> 00:30:25,760

and I was about halfway through that.

840

00:30:25,760 --> 00:30:27,330

I was very happy there, and I did seem,

841

00:30:27,330 --> 00:30:30,030

I just saw my life as continuing there.

842

00:30:30,030 --> 00:30:31,410

But then at a certain point,

843

00:30:31,410 --> 00:30:34,910

a sort of curious character visited called Howard Burton,

844

00:30:34,910 --> 00:30:36,680

and you know, I chatted with him for a little while.

845

00:30:36,680 --> 00:30:39,420

He said he was working on this project

846

00:30:39,420 --> 00:30:41,150

to set up a new institute, and then he went away,

847

00:30:41,150 --> 00:30:42,330

and I kind of forgot about it.

848

00:30:42,330 --> 00:30:45,900
About a year later I
was getting, you know,

849
00:30:45,900 --> 00:30:47,370
communications from him, emails,

850
00:30:47,370 --> 00:30:48,427
and he was trying to call me.

851
00:30:48,427 --> 00:30:51,092
- And this is just when Perimeter
Institute is starting at-

852
00:30:51,092 --> 00:30:52,610
- Yeah, so this was even before

853
00:30:52,610 --> 00:30:53,870
Perimeter Institute really existed,

854
00:30:53,870 --> 00:30:56,450
and he, I mean, I guess
formally it existed perhaps

855
00:30:56,450 --> 00:30:58,920
at that point, and he was, you know,

856
00:30:58,920 --> 00:31:01,460
he was starting to try and
recruit people, you know?

857
00:31:01,460 --> 00:31:02,710
So at that point, I don't know

858
00:31:02,710 --> 00:31:04,260
that he'd recruited anyone at that point.

859
00:31:04,260 --> 00:31:06,130
But then when he started to

communicate with me later,

860

00:31:06,130 --> 00:31:07,730

the place actually existed.

861

00:31:07,730 --> 00:31:09,060

There were people here.

862

00:31:09,060 --> 00:31:09,960

Lee Smolin was here,

863

00:31:09,960 --> 00:31:13,460

and Rob Myers were here
already, and other people.

864

00:31:13,460 --> 00:31:15,010

And he was calling,

865

00:31:15,010 --> 00:31:16,550

and of course, I never answer the phone,

866

00:31:16,550 --> 00:31:19,100

and he was sending emails,
and I never answer emails,

867

00:31:19,100 --> 00:31:21,710

and I was very busy at the
time with just life generally.

868

00:31:21,710 --> 00:31:25,270

And so, I ignored all
those communications.

869

00:31:25,270 --> 00:31:27,490

I mean, I meant to
respond, but I never did.

870

00:31:27,490 --> 00:31:30,637

And then Mike Mosca was visiting Oxford,

871
00:31:30,637 --> 00:31:33,947
and Mike Mosca had done his PhD in Oxford,

872
00:31:33,947 --> 00:31:36,120
so I knew I knew him very well.

873
00:31:36,120 --> 00:31:38,280
And then he had come over
here to, he's Canadian,

874
00:31:38,280 --> 00:31:41,300
he'd come to Waterloo,
and was very involved

875
00:31:41,300 --> 00:31:44,000
in setting up Perimeter Institute.

876
00:31:44,000 --> 00:31:46,910
So Mike Mosca was visiting
Oxford, and he came,

877
00:31:46,910 --> 00:31:49,630
and Howard sent a plane
ticket with Mike Mosca

878
00:31:49,630 --> 00:31:50,820
for me to travel to Canada.

879
00:31:50,820 --> 00:31:52,203
- A plane ticket with your name on it-

880
00:31:52,203 --> 00:31:54,090
- With my name on it, yeah, yeah.

881
00:31:54,090 --> 00:31:55,740
- That's bold-
- And so,

882

00:31:55,740 --> 00:31:57,760
so I guess I just agreed, I guess,

883

00:31:57,760 --> 00:32:00,270
at some point after he did, but I didn't-

884

00:32:00,270 --> 00:32:01,430
- And here we are, 20 minutes later.

885

00:32:01,430 --> 00:32:03,044
It wasn't a return ticket.

886

00:32:03,044 --> 00:32:03,972
(Lucien laughs)
(Lauren laughs)

887

00:32:03,972 --> 00:32:04,933
- Actually, it was a return.

888

00:32:04,933 --> 00:32:06,190
(Colin laughs)
(Lauren laughs)

889

00:32:06,190 --> 00:32:07,929
I remember being, you know, impressed,

890

00:32:07,929 --> 00:32:09,675
because, you know, I was,

891

00:32:09,675 --> 00:32:11,250
I remember being impressed
when I got to the airport

892

00:32:11,250 --> 00:32:12,370
and there was a limousine waiting

893

00:32:12,370 --> 00:32:14,090
to bring us to the institute.

894

00:32:14,090 --> 00:32:16,910

I'd never been in
limousine like that before.

895

00:32:16,910 --> 00:32:19,650

So you know, he brought
me here, and I met him,

896

00:32:19,650 --> 00:32:22,550

and I met Lee, and Rob,

897

00:32:22,550 --> 00:32:24,600

and I met Mike Lazaridis.

898

00:32:24,600 --> 00:32:27,020

I met Mike Lazaridis and David Johnston,

899

00:32:27,020 --> 00:32:29,975

and who subsequently became
the Governor General of Canada.

900

00:32:29,975 --> 00:32:33,620

At that point, he was the
head of the university.

901

00:32:33,620 --> 00:32:35,857

I met them in Ethel's Diner,

902

00:32:35,857 --> 00:32:37,370

(Lauren laughs)

903

00:32:37,370 --> 00:32:40,100

which was the location just on University-

904

00:32:40,100 --> 00:32:41,390

- Still there.

- Still, actually, no,

905

00:32:41,390 --> 00:32:42,453
it burned down,

906

00:32:42,453 --> 00:32:43,286
(Colin laughs)
(Lauren laughs)

907

00:32:43,286 --> 00:32:44,410
and then they built a new one.
- Yeah.

908

00:32:44,410 --> 00:32:47,130
- So the particular one
that we met in burned down.

909

00:32:47,130 --> 00:32:49,210
- That one was on University-
- Yeah, yeah-

910

00:32:49,210 --> 00:32:50,043
- That one, oh, I didn't know that.

911

00:32:50,043 --> 00:32:51,173
- Yeah it did.
- Okay.

912

00:32:51,173 --> 00:32:54,690
- So we met there, and I chatted,

913

00:32:54,690 --> 00:32:56,413
and you know, I realized that this was

914

00:32:56,413 --> 00:32:58,540
a really serious endeavor,

915

00:32:58,540 --> 00:33:00,571
and there was a lot of backing behind it.

916

00:33:00,571 --> 00:33:03,555
And so, I kind of, I caught the bug,

917
00:33:03,555 --> 00:33:05,947
and I agreed to come to Canada-

918
00:33:05,947 --> 00:33:07,333
- Did you agree on the spot?

919
00:33:07,333 --> 00:33:10,594
- So the way Howard did it back
then was he would, you know,

920
00:33:10,594 --> 00:33:12,020
he would bring people over,

921
00:33:12,020 --> 00:33:14,167
and then he would have them
visit lots of different people,

922
00:33:14,167 --> 00:33:15,860
and then he would take
them to a restaurant.

923
00:33:15,860 --> 00:33:17,480
It was just me and Howard,

924
00:33:17,480 --> 00:33:19,660
and he wrote a number on
a piece of, on a napkin,

925
00:33:19,660 --> 00:33:21,187
which was the salary
I was supposed to get,

926
00:33:21,187 --> 00:33:22,900
and he pushed it towards me.
- Oh, no-

927

00:33:22,900 --> 00:33:24,093
- Like a movie!
- Yeah!

928
00:33:24,093 --> 00:33:24,926
(group laughs)

929
00:33:24,926 --> 00:33:26,900
- Well, I think Mike had
done the same thing on Howard

930
00:33:26,900 --> 00:33:27,830
when he recruited Howard.

931
00:33:27,830 --> 00:33:29,000
So,
(Lauren laughs)

932
00:33:29,000 --> 00:33:30,710
and I didn't understand exactly

933
00:33:30,710 --> 00:33:31,710
what a Canadian dollar was worth,

934
00:33:31,710 --> 00:33:34,200
but it was, it seemed good,

935
00:33:34,200 --> 00:33:37,230
and so, I agreed at that point to come.

936
00:33:37,230 --> 00:33:39,330
- Going back even further, was this,

937
00:33:39,330 --> 00:33:40,960
were you a born physicist,
you were meant for this,

938
00:33:40,960 --> 00:33:42,870
and this was the path all along,

939

00:33:42,870 --> 00:33:45,350

or did you, did it take some time to find?

940

00:33:45,350 --> 00:33:46,340

Can you tell us a bit about

941

00:33:46,340 --> 00:33:48,600

when you first got interested in science?

942

00:33:48,600 --> 00:33:50,737

- I mean, of course, when

I was five years old,

943

00:33:50,737 --> 00:33:51,933

I wasn't reading physics textbooks.

944

00:33:51,933 --> 00:33:54,770

There were no physics textbooks around.

945

00:33:54,770 --> 00:33:56,540

More likely to be astrology textbooks

946

00:33:56,540 --> 00:33:58,973

than the physics textbooks

in my background.

947

00:33:59,840 --> 00:34:01,550

But I think I was always

interested in, you know,

948

00:34:01,550 --> 00:34:04,190

making things, hammering

together pieces of wood.

949

00:34:04,190 --> 00:34:06,060

At a certain point, we moved to a house,

950

00:34:06,060 --> 00:34:08,430
and across the back from the house,

951
00:34:08,430 --> 00:34:10,230
there was an electrical repair shop.

952
00:34:10,230 --> 00:34:14,220
This shop had, you know,
televisions, broken televisions.

953
00:34:14,220 --> 00:34:16,247
You know, the guy, when
he couldn't fix something,

954
00:34:16,247 --> 00:34:17,280
he threw it out the back.

955
00:34:17,280 --> 00:34:20,350
So there were broken televisions,
and broken record players,

956
00:34:20,350 --> 00:34:22,215
and broken radios, all sorts of things,

957
00:34:22,215 --> 00:34:23,730
and I was allowed to just
go and take that stuff,

958
00:34:23,730 --> 00:34:25,180
and look at it.

959
00:34:25,180 --> 00:34:27,190
So you know, I would take the stuff apart.

960
00:34:27,190 --> 00:34:29,780
There were, in those days,
things had vacuum tubes,

961
00:34:29,780 --> 00:34:32,530

rather than integrated circuits,

962

00:34:32,530 --> 00:34:33,810
which made a very satisfying noise

963

00:34:33,810 --> 00:34:34,738
when you threw them down.

964

00:34:34,738 --> 00:34:36,290
(Colin and Lauren laugh)
Bang.

965

00:34:36,290 --> 00:34:38,920
And so, I would take those
things, and I would, you know,

966

00:34:38,920 --> 00:34:40,780
like combine two broken
record players to make

967

00:34:40,780 --> 00:34:42,410
one functioning record player.

968

00:34:42,410 --> 00:34:44,430
I can't claim that I really understood

969

00:34:44,430 --> 00:34:45,370
exactly what was happening,

970

00:34:45,370 --> 00:34:47,220
but I think it got me interested.

971

00:34:47,220 --> 00:34:49,590
And so, that was probably
one of the earliest times

972

00:34:49,590 --> 00:34:50,970
I started to think, "Well,
this is something I could do,"

973

00:34:50,970 --> 00:34:52,557
and my mom said, "Well, you know,

974

00:34:52,557 --> 00:34:53,507
"this is a job you could have.

975

00:34:53,507 --> 00:34:55,740
"You could fix electrical objects,"

976

00:34:55,740 --> 00:34:57,150
and that seemed to be exciting to me.

977

00:34:57,150 --> 00:35:00,080
- So then how did becoming a
theoretical physicist happen?

978

00:35:00,080 --> 00:35:01,730
- Well, and then at a certain point,

979

00:35:01,730 --> 00:35:03,950
they started teaching physics at school,

980

00:35:03,950 --> 00:35:05,827
and I was very interested in that,

981

00:35:05,827 --> 00:35:08,060
and I studied it really, really hard.

982

00:35:08,060 --> 00:35:09,510
And so, I think, I guess
at that point it becomes

983

00:35:09,510 --> 00:35:11,707
a fairly, fairly standard sort of path.

984

00:35:11,707 --> 00:35:14,500
And the school I went to

wasn't terribly academic,

985

00:35:14,500 --> 00:35:16,383
but the teachers were very good,

986

00:35:16,383 --> 00:35:18,400
and the physics teacher
was great, Mr. Barnforth,

987

00:35:18,400 --> 00:35:20,500
and he got me interested in physics.

988

00:35:20,500 --> 00:35:23,090
So I, of course, I passed all those exams,

989

00:35:23,090 --> 00:35:23,970
and got to university.

990

00:35:23,970 --> 00:35:26,060
But even before I got to university,

991

00:35:26,060 --> 00:35:28,920
there was a radio program on BBC Radio 3

992

00:35:28,920 --> 00:35:31,900
that was made by Paul
Davies, who's a physicist,

993

00:35:31,900 --> 00:35:35,100
but also a very good
popularizer of physics,

994

00:35:35,100 --> 00:35:37,740
and it was called "The Ghost in the Atom."

995

00:35:37,740 --> 00:35:40,450
My dad recorded it on a tape cassette.

996

00:35:40,450 --> 00:35:42,260
Had the radio playing, and
he put the tape recorder

997
00:35:42,260 --> 00:35:43,970
next to it, recorded it,

998
00:35:43,970 --> 00:35:45,850
and he gave that tape cassette to me.

999
00:35:45,850 --> 00:35:47,500
So I had this tape
cassette in my possession

1000
00:35:47,500 --> 00:35:49,680
for a number of years,
and I would listen to it

1001
00:35:49,680 --> 00:35:51,830
over and over again, and
there were lots of physicists,

1002
00:35:51,830 --> 00:35:53,430
some of which I got to know later,

1003
00:35:53,430 --> 00:35:55,890
but he had people like
John Bell, David Deutsch,

1004
00:35:55,890 --> 00:35:59,050
Alain Aspect, many other
very interesting physicists

1005
00:35:59,050 --> 00:36:01,670
who were thinking about the
foundations of quantum theory,

1006
00:36:01,670 --> 00:36:02,920
and they were speaking in a way

1007

00:36:02,920 --> 00:36:05,590

I'd never heard anyone
speak about physics before.

1008

00:36:05,590 --> 00:36:07,310

This is a very weird subject, you know?

1009

00:36:07,310 --> 00:36:08,810

How did you interpret quantum theory?

1010

00:36:08,810 --> 00:36:09,841

What does the wave function mean?

1011

00:36:09,841 --> 00:36:10,900

All these-
- Mmm-hmm.

1012

00:36:10,900 --> 00:36:13,560

- All these questions
were completely new to me,

1013

00:36:13,560 --> 00:36:16,450

and I think that was when I
got hooked on quantum theory-

1014

00:36:16,450 --> 00:36:17,427

- And then-
- Quantum foundations.

1015

00:36:17,427 --> 00:36:19,890

- "The Ghost in the
Atom," the radio series,

1016

00:36:19,890 --> 00:36:21,570

it was collected as a
book as well, I believe-

1017

00:36:21,570 --> 00:36:23,380

- That's right, yeah, you

can still buy that, I think.

1018

00:36:23,380 --> 00:36:26,850

- And then there was a book called "Elegance and Enigma"-

1019

00:36:26,850 --> 00:36:27,683

- Yup.

1020

00:36:27,683 --> 00:36:30,310

- "The Quantum Interviews," which in the introduction

1021

00:36:30,310 --> 00:36:32,460

it says this book is in some ways

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00:36:32,460 --> 00:36:35,290

sort of a spiritual successor to "The Ghost in the Atom,"

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00:36:35,290 --> 00:36:37,260

and you are throughout this book.

1024

00:36:37,260 --> 00:36:39,080

How did you go from being inspired

1025

00:36:39,080 --> 00:36:41,200

by "The Ghost in the Atom" to essentially contributing

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00:36:41,200 --> 00:36:43,080

to its sequel-

- To its successor, yeah.

1027

00:36:43,080 --> 00:36:44,030

So I hadn't thought of it like that.

1028

00:36:44,030 --> 00:36:46,830

Well, it was a great idea

that Max Schlosshauer had

1029

00:36:46,830 --> 00:36:50,320
to put that book together,
and he sort of interviewed,

1030

00:36:50,320 --> 00:36:53,340
or he didn't interview us,
you know, in an audio way.

1031

00:36:53,340 --> 00:36:55,530
He got us to write little pieces,

1032

00:36:55,530 --> 00:36:58,060
and answer to a bunch of questions he had.

1033

00:36:58,060 --> 00:37:00,260
I guess he was asking questions
to the kind of successors

1034

00:37:00,260 --> 00:37:02,940
of the figures that appeared
in "The Ghost in the Atom."

1035

00:37:02,940 --> 00:37:05,245
It's a long story, 'cause I,
(Lauren laughs)

1036

00:37:05,245 --> 00:37:06,455
I did a degree in physics.

1037

00:37:06,455 --> 00:37:07,640
You know, if you want
to become a physicist,

1038

00:37:07,640 --> 00:37:10,440
probably the best way to do
that is do a degree in physics,

1039

00:37:10,440 --> 00:37:14,210
and then I did a PhD
in quantum foundations.

1040
00:37:14,210 --> 00:37:16,900
I mean, even that in itself
was a difficult thing to do

1041
00:37:16,900 --> 00:37:19,260
because there were very few people doing

1042
00:37:19,260 --> 00:37:21,130
quantum foundations at the time.

1043
00:37:21,130 --> 00:37:23,700
It was regarded rather unfavorably.

1044
00:37:23,700 --> 00:37:27,020
It was not thought of as
being a sort of subject

1045
00:37:27,020 --> 00:37:28,750
you would do if you were serious.

1046
00:37:28,750 --> 00:37:31,090
But I was too interested
in it to care about that.

1047
00:37:31,090 --> 00:37:34,890
So I found somebody who was
willing to supervise a PhD,

1048
00:37:34,890 --> 00:37:37,330
which was my supervisor, Euan Squires.

1049
00:37:37,330 --> 00:37:39,480
I did a PhD in it, and just kept going.

1050
00:37:39,480 --> 00:37:42,150

You know, once you start
doing research in physics,

1051

00:37:42,150 --> 00:37:45,550

you just keep going, and
it's endlessly fascinating.

1052

00:37:45,550 --> 00:37:47,240

Quantum theory is endlessly fascinating.

1053

00:37:47,240 --> 00:37:48,510

It's constantly surprising.

1054

00:37:48,510 --> 00:37:49,570

You think you've understood everything

1055

00:37:49,570 --> 00:37:51,020

there is to understand
about quantum theory.

1056

00:37:51,020 --> 00:37:53,760

You work on it for 20 years, 30 years,

1057

00:37:53,760 --> 00:37:55,490

and then it surprises you yet again.

1058

00:37:55,490 --> 00:37:56,830

So it's easy to keep going.

1059

00:37:56,830 --> 00:37:59,880

It's a really, really interesting subject.

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00:37:59,880 --> 00:38:02,100

- Well, we have more questions,

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00:38:02,100 --> 00:38:03,550

and they're not even from us.

1062

00:38:03,550 --> 00:38:05,650
We collected some questions from students.

1063
00:38:05,650 --> 00:38:07,780
So Lauren, do you want to-

1064
00:38:07,780 --> 00:38:09,580
- Sure, yeah, we have some great questions

1065
00:38:09,580 --> 00:38:11,360
from some graduate students here.

1066
00:38:11,360 --> 00:38:14,890
So I think we're ready for the first one.

1067
00:38:14,890 --> 00:38:17,690
- Matt Duschenes, a PhD
student at Perimeter.

1068
00:38:17,690 --> 00:38:19,580
I'm wondering do you feel
axiomatic approaches allow

1069
00:38:19,580 --> 00:38:21,950
for easier collaboration
and mutual understanding,

1070
00:38:21,950 --> 00:38:25,130
as everyone is coming from
the same starting point?

1071
00:38:25,130 --> 00:38:27,060
- Let me think about that.

1072
00:38:28,083 --> 00:38:29,670
I think that's right.

1073
00:38:29,670 --> 00:38:31,780
What these axiomatic approaches do is

1074

00:38:31,780 --> 00:38:35,810

they force you to clarify
very basic concepts,

1075

00:38:35,810 --> 00:38:38,500

so that you can talk to people,

1076

00:38:38,500 --> 00:38:41,800

and you end up having to
clarify these concepts

1077

00:38:41,800 --> 00:38:46,213

outside the natural
habitat of quantum physics.

1078

00:38:46,213 --> 00:38:48,530

So an example would be, you know,

1079

00:38:48,530 --> 00:38:50,870

in quantum theory you have Hilbert spaces.

1080

00:38:50,870 --> 00:38:52,030

You don't need to know
what a Hilbert space is,

1081

00:38:52,030 --> 00:38:54,420

but it's an object that
has a dimension, N .

1082

00:38:54,420 --> 00:38:55,270

So N is an integer.

1083

00:38:55,270 --> 00:38:57,520

It can be one, two,
three, four, et cetera,

1084

00:38:57,520 --> 00:39:00,570

and that's just a number that

appears in quantum theory.

1085

00:39:00,570 --> 00:39:02,930

But if you want to understand

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00:39:02,930 --> 00:39:04,460

what that concept really means,

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00:39:04,460 --> 00:39:07,060

then you should think about

it in operational terms.

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00:39:07,060 --> 00:39:09,750

And what it really means

in operational terms is

1089

00:39:09,750 --> 00:39:12,620

what are the number of preparations

1090

00:39:12,620 --> 00:39:15,010

that you can prepare for your system

1091

00:39:15,010 --> 00:39:17,220

that can be perfectly distinguished?

1092

00:39:17,220 --> 00:39:19,190

So by thinking in operational terms,

1093

00:39:19,190 --> 00:39:21,600

you're forced to clarify concepts

1094

00:39:21,600 --> 00:39:22,960

that might have just been elements

1095

00:39:22,960 --> 00:39:24,130

of an obscure mathematical framework,

1096

00:39:24,130 --> 00:39:26,650

and I think that's true
not just for that example,

1097
00:39:26,650 --> 00:39:28,730
but there's many concepts like that.

1098
00:39:28,730 --> 00:39:32,210
They help people make progress
in physics, I think, yes.

1099
00:39:32,210 --> 00:39:34,100
- The next question is
from another student

1100
00:39:34,100 --> 00:39:35,200
here at Perimeter Institute.

1101
00:39:35,200 --> 00:39:38,320
It was sent in anonymously,
so I'm gonna read it.

1102
00:39:38,320 --> 00:39:39,387
The question is,

1103
00:39:39,387 --> 00:39:42,897
"You've famously axiomatized
quantum mechanics.

1104
00:39:42,897 --> 00:39:45,657
"Do you think that a part of
trouble with quantum mechanics

1105
00:39:45,657 --> 00:39:47,057
"is similar to the one we have

1106
00:39:47,057 --> 00:39:49,057
"in the foundations of mathematics,

1107
00:39:49,057 --> 00:39:51,267

"where we know that there
are a lot of true statements

1108

00:39:51,267 --> 00:39:53,717

"that are not provable from the axioms?"

1109

00:39:53,717 --> 00:39:55,257

"Similarly, in quantum mechanics,

1110

00:39:55,257 --> 00:39:57,287

"even though we have a set of axioms,

1111

00:39:57,287 --> 00:39:59,557

"there will always be
statements in quantum mechanics

1112

00:39:59,557 --> 00:40:02,087

"that are true, but we can't derive them,

1113

00:40:02,087 --> 00:40:04,757

"or understand them starting
from first principles

1114

00:40:04,757 --> 00:40:07,450

"of quantum mechanics, such as axioms."

1115

00:40:07,450 --> 00:40:09,790

- So people have thought
about this kind of question.

1116

00:40:09,790 --> 00:40:10,930

I'm not among them.

1117

00:40:10,930 --> 00:40:12,047

There's this very interesting work

1118

00:40:12,047 --> 00:40:16,050

the question alludes to on
the logic of mathematics,

1119

00:40:16,050 --> 00:40:18,380

and whether that work has
some corresponding element

1120

00:40:18,380 --> 00:40:21,740

in physics, and people have
definitely thought about that.

1121

00:40:21,740 --> 00:40:22,587

I think it's a difficult question,

1122

00:40:22,587 --> 00:40:24,780

and it makes my mind go blank every time

1123

00:40:24,780 --> 00:40:26,160

I try to think about it.

1124

00:40:26,160 --> 00:40:28,670

I don't know how to begin
to answer that question,

1125

00:40:28,670 --> 00:40:33,670

but perhaps somebody who
doesn't have my blind spots can.

1126

00:40:34,480 --> 00:40:37,619

I really have no good things to say about,

1127

00:40:37,619 --> 00:40:40,180

no good answers to provide to
what is a very good question.

1128

00:40:40,180 --> 00:40:42,760

- It maybe requires a new way
of thinking like you said-

1129

00:40:42,760 --> 00:40:45,243

- Yeah, I, maybe I'm too old now to think

1130

00:40:45,243 --> 00:40:46,760

(Lauren laughs)

like that, yeah-

1131

00:40:46,760 --> 00:40:48,407

- Great, we have one more question,

1132

00:40:48,407 --> 00:40:50,387

and it's from someone

that you know quite well.

1133

00:40:50,387 --> 00:40:52,670

- I'm Nitica Sakharwade,

1134

00:40:52,670 --> 00:40:56,260

a PhD student of Lucien's

at Perimeter Institute.

1135

00:40:56,260 --> 00:40:58,210

I'm graduating soon.

1136

00:40:58,210 --> 00:41:00,340

I had a question for Lucien about,

1137

00:41:00,340 --> 00:41:04,240

like a broad question about the

field of quantum foundations

1138

00:41:04,240 --> 00:41:08,620

as it has evolved the

last couple of decades.

1139

00:41:08,620 --> 00:41:12,250

So I was just wondering,

I was, since I have been,

1140

00:41:12,250 --> 00:41:14,900

I had been writing my thesis recently,

1141
00:41:14,900 --> 00:41:18,150
I was also going through your thesis,

1142
00:41:18,150 --> 00:41:22,550
and I was just wondering
what it was like, right,

1143
00:41:22,550 --> 00:41:26,690
talking about nonlocality of
a single photon at that time,

1144
00:41:26,690 --> 00:41:30,150
when quantum foundations wasn't recognized

1145
00:41:30,150 --> 00:41:33,030
as a field in itself quite,

1146
00:41:33,030 --> 00:41:36,653
and how you think it has evolved?

1147
00:41:36,653 --> 00:41:40,430
In the decades since, like there
definitely has been a boom,

1148
00:41:40,430 --> 00:41:42,450
and I was wondering,

1149
00:41:42,450 --> 00:41:45,130
so with the rise of quantum information,

1150
00:41:45,130 --> 00:41:48,620
and then now more recently
quantum computing,

1151
00:41:48,620 --> 00:41:50,510
quantum hardware, quantum software,

1152

00:41:50,510 --> 00:41:52,830
all of these things that are coming up,

1153
00:41:52,830 --> 00:41:56,070
I was wondering what
quantum foundations has

1154
00:41:56,070 --> 00:41:59,200
to offer to them, and what are the things

1155
00:41:59,200 --> 00:42:03,580
that quantum computing can bring?

1156
00:42:03,580 --> 00:42:07,630
What questions it can bring
back to quantum foundations?

1157
00:42:07,630 --> 00:42:09,190
- Good questions, Nitica.

1158
00:42:09,190 --> 00:42:10,023
So yeah, definitely,

1159
00:42:10,023 --> 00:42:12,330
it was a very different
situation back then.

1160
00:42:12,330 --> 00:42:14,200
You know, you didn't go
into quantum foundations

1161
00:42:14,200 --> 00:42:16,822
if you wanted a job, you know?

1162
00:42:16,822 --> 00:42:18,370
It was sort of, you know,

1163
00:42:18,370 --> 00:42:19,500
a temporary state of affairs

1164

00:42:19,500 --> 00:42:21,870

before you had to find
employment elsewhere,

1165

00:42:21,870 --> 00:42:22,920

at least that was the idea,

1166

00:42:22,920 --> 00:42:25,160

and nobody was taking it seriously.

1167

00:42:25,160 --> 00:42:27,050

It started to be taken more seriously,

1168

00:42:27,050 --> 00:42:28,600

I think, with experiments,

1169

00:42:28,600 --> 00:42:31,710

so experiments in quantum
optics in particular.

1170

00:42:31,710 --> 00:42:33,670

So already, even before I started,

1171

00:42:33,670 --> 00:42:36,730

Alain Aspect did this sort
of test of Bell's theorem,

1172

00:42:36,730 --> 00:42:38,250

and even earlier
experiments have been done

1173

00:42:38,250 --> 00:42:39,990

by John Clauser and Freedman.

1174

00:42:39,990 --> 00:42:42,770

But in the 1990s, these experiments became

1175

00:42:42,770 --> 00:42:44,510
more and more serious.

1176
00:42:44,510 --> 00:42:48,230
Leonard Mandel in Rochester,
not so far away from here,

1177
00:42:48,230 --> 00:42:50,870
did all these beautiful
quantum optical experiments.

1178
00:42:50,870 --> 00:42:53,050
You know, when people do experiments,

1179
00:42:53,050 --> 00:42:54,040
the rest of the physics world starts

1180
00:42:54,040 --> 00:42:55,130
to take you more seriously,

1181
00:42:55,130 --> 00:42:57,370
and these experimentalists
were hungry for ideas,

1182
00:42:57,370 --> 00:42:58,310
things that they could test.

1183
00:42:58,310 --> 00:43:00,550
So that was a very good
collaboration between

1184
00:43:00,550 --> 00:43:04,170
the field of quantum foundations
and experimentalists.

1185
00:43:04,170 --> 00:43:06,260
And then as quantum
information came along,

1186

00:43:06,260 --> 00:43:07,950
and also quantum computing,

1187
00:43:07,950 --> 00:43:11,060
in the early days, the
fields of quantum information

1188
00:43:11,060 --> 00:43:13,190
and quantum computing were really,

1189
00:43:13,190 --> 00:43:15,710
it was really just a joining of the fields

1190
00:43:15,710 --> 00:43:18,560
of quantum foundations
and computer science.

1191
00:43:18,560 --> 00:43:21,210
So if you went to conferences

1192
00:43:21,210 --> 00:43:23,800
in the subject of quantum information,

1193
00:43:23,800 --> 00:43:25,720
then half the participants would be

1194
00:43:25,720 --> 00:43:28,480
from a background in quantum
foundations, people I knew,

1195
00:43:28,480 --> 00:43:31,180
and half would be people
from computer science,

1196
00:43:31,180 --> 00:43:33,390
and it was just these two
subjects talking to each other,

1197
00:43:33,390 --> 00:43:35,140

trying to get a common language, you know,

1198

00:43:35,140 --> 00:43:37,490

like for example, Ben Schumacher,

1199

00:43:37,490 --> 00:43:40,160

who was the quantum foundations person,

1200

00:43:40,160 --> 00:43:42,400

came up with the term qubit, you know,

1201

00:43:42,400 --> 00:43:45,370

qubit sort of borrowing on the term bit,

1202

00:43:45,370 --> 00:43:47,720

which is basic in computer science,

1203

00:43:47,720 --> 00:43:48,553

bits at one, or zero.

1204

00:43:48,553 --> 00:43:51,477

Well, qubit is the
quantum version of that.

1205

00:43:51,477 --> 00:43:53,540

And then once you start
thinking in that way,

1206

00:43:53,540 --> 00:43:54,820

all sorts of questions come up

1207

00:43:54,820 --> 00:43:56,620

that weren't there previously,

1208

00:43:56,620 --> 00:43:58,550

and you know, I worked in the
field of quantum information

1209

00:43:58,550 --> 00:44:00,260
a little bit myself for a while.

1210
00:44:00,260 --> 00:44:03,230
I have papers on quantum
cryptography, for example.

1211
00:44:03,230 --> 00:44:05,600
So this is a very exciting
new way of thinking,

1212
00:44:05,600 --> 00:44:06,760
and people in quantum foundations were

1213
00:44:06,760 --> 00:44:09,800
in a really great position
to contribute to that,

1214
00:44:09,800 --> 00:44:12,010
to the development, and just even the idea

1215
00:44:12,010 --> 00:44:13,300
of what that field was.

1216
00:44:13,300 --> 00:44:15,030
And more than that, what was happening

1217
00:44:15,030 --> 00:44:17,400
in quantum information
and quantum computing was

1218
00:44:17,400 --> 00:44:21,250
that you were finding a way
to use quantum weirdness.

1219
00:44:21,250 --> 00:44:22,870
So previously, quantum weirdness was

1220
00:44:22,870 --> 00:44:24,250

sort of an embarrassment.

1221

00:44:24,250 --> 00:44:26,887

It was something that
people hoped would go away,

1222

00:44:26,887 --> 00:44:30,220

you know, trying to find an
interpretation to get rid of it.

1223

00:44:30,220 --> 00:44:33,420

Suddenly, now quantum
weirdness was a resource.

1224

00:44:33,420 --> 00:44:35,010

It was something that you could use.

1225

00:44:35,010 --> 00:44:38,420

This is a point that Charlie
Bennett makes frequently

1226

00:44:38,420 --> 00:44:40,170

that rather than people in
quantum foundations being,

1227

00:44:40,170 --> 00:44:42,626

well, an embarrassment to
physics, suddenly, we were useful.

1228

00:44:42,626 --> 00:44:44,010

We could contribute.

1229

00:44:44,010 --> 00:44:44,843

That was a great-
- 'Cause you knew

1230

00:44:44,843 --> 00:44:45,830

all about the weird stuff?

1231

00:44:45,830 --> 00:44:46,955
- We knew all about the weird stuff.

1232
00:44:46,955 --> 00:44:47,979
Yeah, that's right, yeah.
(Lauren laughs)

1233
00:44:47,979 --> 00:44:50,670
(Lucien laughs)
Just for that reason.

1234
00:44:50,670 --> 00:44:51,866
So, and it was a wonderful period,

1235
00:44:51,866 --> 00:44:53,620
and when it really wasn't.

1236
00:44:53,620 --> 00:44:56,730
It was just an idea that
came from, you know,

1237
00:44:56,730 --> 00:44:57,880
marrying these two fields together,

1238
00:44:57,880 --> 00:44:59,910
and it was a very, very
fruitful way of thinking,

1239
00:44:59,910 --> 00:45:01,837
and so much was possible, you know?

1240
00:45:01,837 --> 00:45:04,250
But in those days, you didn't
have to think very hard

1241
00:45:04,250 --> 00:45:07,290
to write a paper that was
relatively significant

1242

00:45:07,290 --> 00:45:08,300
in the field.

1243
00:45:08,300 --> 00:45:11,470
The field of quantum
information has since become

1244
00:45:11,470 --> 00:45:13,430
much more technical, and people will build

1245
00:45:13,430 --> 00:45:16,450
their whole career in the
field of quantum information,

1246
00:45:16,450 --> 00:45:19,280
you know, without having worked separately

1247
00:45:19,280 --> 00:45:22,010
in quantum foundations, or in quantum,

1248
00:45:22,010 --> 00:45:23,180
or in computer science.

1249
00:45:23,180 --> 00:45:24,910
- So the conferences nowadays are

1250
00:45:24,910 --> 00:45:28,050
all quantum computing experts
instead of computer scientists

1251
00:45:28,050 --> 00:45:30,340
and quantum foundations?

1252
00:45:30,340 --> 00:45:31,540
- I mean, that's the impression I have.

1253
00:45:31,540 --> 00:45:32,560
I mean, not all, but they-
- Right.

1254

00:45:32,560 --> 00:45:33,393

- That's definitely-

- Primarily-

1255

00:45:33,393 --> 00:45:35,810

- The predominant makeup

of those conferences,

1256

00:45:35,810 --> 00:45:37,010

I think, which is, you know, is great,

1257

00:45:37,010 --> 00:45:38,520

because there's a lot of

very technical questions,

1258

00:45:38,520 --> 00:45:41,170

but I think it's important

still to keep looking

1259

00:45:41,170 --> 00:45:43,390

to people in those two

more basic subjects,

1260

00:45:43,390 --> 00:45:45,023

because there's new ideas.

1261

00:45:45,910 --> 00:45:47,967

One question I think is really important,

1262

00:45:47,967 --> 00:45:49,280

and I still think this is something

1263

00:45:49,280 --> 00:45:52,050

that we need to understand is what is it

1264

00:45:52,050 --> 00:45:56,480

that gives quantum computers their power?

1265
00:45:56,480 --> 00:45:58,130
Why are quantum computers more powerful

1266
00:45:58,130 --> 00:46:00,230
than classical computers?

1267
00:46:00,230 --> 00:46:02,050
And this is a question I remember

1268
00:46:02,050 --> 00:46:04,460
when the field of quantum computing

1269
00:46:04,460 --> 00:46:06,100
first started to be worked on

1270
00:46:06,100 --> 00:46:09,570
that people in quantum foundations
were very interested in.

1271
00:46:09,570 --> 00:46:12,830
I went to conferences with
people in quantum foundations,

1272
00:46:12,830 --> 00:46:15,520
and philosophers who were very
interested in this question.

1273
00:46:15,520 --> 00:46:18,320
What is it that makes a
quantum computer so powerful?

1274
00:46:18,320 --> 00:46:19,550
And there's many possible answers.

1275
00:46:19,550 --> 00:46:23,630
You might say, well, it's
because of quantum parallelism.

1276

00:46:23,630 --> 00:46:25,577
You have, you know,
different, in quantum theory,

1277
00:46:25,577 --> 00:46:27,530
you can have different things
happening at the same time,

1278
00:46:27,530 --> 00:46:29,150
this indefiniteness I mentioned.

1279
00:46:29,150 --> 00:46:30,540
- Mmm-hmm.
- David Deutsch believed

1280
00:46:30,540 --> 00:46:33,750
that it was, that quantum
computing was proof

1281
00:46:33,750 --> 00:46:35,500
of the many worlds interpretation,

1282
00:46:35,500 --> 00:46:36,570
'cause in the many worlds interpretation,

1283
00:46:36,570 --> 00:46:38,730
you have all these different realities

1284
00:46:38,730 --> 00:46:40,200
being true simultaneously.

1285
00:46:40,200 --> 00:46:41,920
And other people thought,
well, maybe, you know,

1286
00:46:41,920 --> 00:46:43,690
maybe it's quantum nonlocality.

1287
00:46:43,690 --> 00:46:46,360

Maybe the fact that you have entanglement,

1288

00:46:46,360 --> 00:46:50,210
and entanglement enables a
kind of nonlocal influence

1289

00:46:50,210 --> 00:46:52,830
between different distant systems,

1290

00:46:52,830 --> 00:46:55,020
and maybe that's what
powers quantum computing,

1291

00:46:55,020 --> 00:46:57,710
and people have working
on this to some extent.

1292

00:46:57,710 --> 00:46:59,416
You know, recent work
showing that actually

1293

00:46:59,416 --> 00:47:01,550
the advantage of quantum computers,

1294

00:47:01,550 --> 00:47:03,820
it does relate back to Bell's theorem,

1295

00:47:03,820 --> 00:47:06,020
does relate back to this-

1296

00:47:06,020 --> 00:47:06,853
- Foundational?

1297

00:47:06,853 --> 00:47:09,070
- Yeah, that relate back
to these foundational ideas

1298

00:47:09,070 --> 00:47:11,400
of John Bell proving nonlocality.

1299

00:47:11,400 --> 00:47:13,240

Another thing that
people have shown is that

1300

00:47:13,240 --> 00:47:15,547

it relates to something called
quantum noncontextuality.

1301

00:47:15,547 --> 00:47:16,910

I'm not gonna explain what that is,

1302

00:47:16,910 --> 00:47:18,950

but it's a very, a basic
idea in quantum foundations,

1303

00:47:18,950 --> 00:47:22,048

and there seems to be a connection to,

1304

00:47:22,048 --> 00:47:22,980

it seems that you can prove

1305

00:47:22,980 --> 00:47:25,020

that quantum computing
is related to that, too.

1306

00:47:25,020 --> 00:47:29,870

So Joe Emerson at the at
University of Waterloo nearby

1307

00:47:29,870 --> 00:47:31,600

has worked on that, and there was a paper

1308

00:47:31,600 --> 00:47:34,100

on the archive today talking about that.

1309

00:47:34,100 --> 00:47:36,690

So people are thinking about that,

1310
00:47:36,690 --> 00:47:38,220
but I think there's still a lot more scope

1311
00:47:38,220 --> 00:47:40,510
for that kind of interaction
between quantum foundations

1312
00:47:40,510 --> 00:47:42,520
and quantum information.

1313
00:47:42,520 --> 00:47:43,380
- We're running out of time,

1314
00:47:43,380 --> 00:47:45,690
but I have to ask, 'cause I've
interviewed a lot of people,

1315
00:47:45,690 --> 00:47:47,010
but I've never interviewed anybody

1316
00:47:47,010 --> 00:47:48,790
with a paradox named after them.

1317
00:47:48,790 --> 00:47:50,570
What is Hardy's paradox,

1318
00:47:50,570 --> 00:47:52,330
and what's it like to have a paradox?

1319
00:47:52,330 --> 00:47:53,747
- My wife asked me this
question, you know,

1320
00:47:53,747 --> 00:47:54,660
"How can you have a paradox?"

1321
00:47:54,660 --> 00:47:55,493
And I said, "Well, you can't.

1322

00:47:55,493 --> 00:47:57,327

"There isn't really any
such thing as a paradox.

1323

00:47:57,327 --> 00:47:59,207

"So you can't really have a paradox

1324

00:47:59,207 --> 00:48:01,537

"in physics, or mathematics.

1325

00:48:01,537 --> 00:48:03,407

"It's always the case
of you're not thinking

1326

00:48:03,407 --> 00:48:04,297

"about the situation right.

1327

00:48:04,297 --> 00:48:07,560

"So it looks like a paradox,
but it's not really a paradox."

1328

00:48:07,560 --> 00:48:09,297

And she said, "Okay, so I'm gonna call,

1329

00:48:09,297 --> 00:48:10,387

"invent Hardy's paradox,

1330

00:48:10,387 --> 00:48:12,750

"which is that there's no
such thing as a paradox."

1331

00:48:12,750 --> 00:48:14,970

And in that case, the
Hardy is her, you know?

1332

00:48:14,970 --> 00:48:17,204

So she called that Hardy's first paradox.

1333

00:48:17,204 --> 00:48:19,488

- Right-

- Zivy Hardy's paradox.

1334

00:48:19,488 --> 00:48:22,180

And so, then my paradox

became Hardy's second paradox,

1335

00:48:22,180 --> 00:48:24,550

and my paradox, which has

to do with quantum theory-

1336

00:48:24,550 --> 00:48:26,880

- I had a feeling it would.

(group laughs)

1337

00:48:26,880 --> 00:48:27,920

- Yeah, it has to do with quantum theory.

1338

00:48:27,920 --> 00:48:32,440

So it goes back to work

I did during my PhD,

1339

00:48:32,440 --> 00:48:33,273

and it's really a situation

1340

00:48:33,273 --> 00:48:35,170

where you have quantum entanglement,

1341

00:48:35,170 --> 00:48:37,310

and you have two systems,

1342

00:48:37,310 --> 00:48:39,170

and you can make

measurements on each of them.

1343

00:48:39,170 --> 00:48:40,480

I don't want to explain all the details,

1344
00:48:40,480 --> 00:48:42,540
but one way of thinking of it,

1345
00:48:42,540 --> 00:48:43,740
it's not the way I
originally thought of it,

1346
00:48:43,740 --> 00:48:47,340
but other various people
did, is that you can see it

1347
00:48:47,340 --> 00:48:50,420
as a breakdown of logical transitivity.

1348
00:48:50,420 --> 00:48:54,810
So if you have A implies
B, that's a true statement,

1349
00:48:54,810 --> 00:48:59,220
and then if B implies C, and C implies D,

1350
00:48:59,220 --> 00:49:00,850
so if all those things are true,

1351
00:49:00,850 --> 00:49:03,120
then you would expect
from normal logic to have

1352
00:49:03,120 --> 00:49:05,310
that A implies D,

1353
00:49:05,310 --> 00:49:07,140
and there's a situation
where that's not the case.

1354
00:49:07,140 --> 00:49:09,900
So you can have A implies
B, B implies C, C implies D,

1355
00:49:09,900 --> 00:49:11,170
but A does not imply D.

1356
00:49:11,170 --> 00:49:12,510
- Sounds like a paradox.

1357
00:49:12,510 --> 00:49:13,740
- So it seems like a paradox.

1358
00:49:13,740 --> 00:49:15,500
Now, it's only an apparent paradox

1359
00:49:15,500 --> 00:49:18,150
because what's happening is as you go

1360
00:49:18,150 --> 00:49:20,070
from each of those
statements one to the next

1361
00:49:20,070 --> 00:49:21,690
you're changing other things,

1362
00:49:21,690 --> 00:49:23,257
not the things that the
statement is concerned with,

1363
00:49:23,257 --> 00:49:24,870
but other stuff is being changed,

1364
00:49:24,870 --> 00:49:27,120
and so, we can't actually
make those logical inferences.

1365
00:49:27,120 --> 00:49:27,953
It's only an apparent paradox.

1366
00:49:27,953 --> 00:49:29,940
I mean, I didn't call it a paradox myself,

1367
00:49:29,940 --> 00:49:33,200
but I was quite happy to have a paradox.

1368
00:49:33,200 --> 00:49:34,870
- Second paradox.
(Lauren laughs)

1369
00:49:34,870 --> 00:49:36,284
Yeah, your wife gets the first paradox-

1370
00:49:36,284 --> 00:49:37,660
- Yeah, the first paradox, yes, yeah.

1371
00:49:37,660 --> 00:49:39,450
- Well, I think we're out of time,

1372
00:49:39,450 --> 00:49:41,010
but thank you so much for joining us.

1373
00:49:41,010 --> 00:49:43,140
I'm sure we could ask a
thousand more questions,

1374
00:49:43,140 --> 00:49:43,973
but we won't.

1375
00:49:43,973 --> 00:49:45,686
Maybe another time?
- Yeah, well, thank you.

1376
00:49:45,686 --> 00:49:46,843
It's been a pleasure.

1377
00:49:46,843 --> 00:49:49,426
(upbeat music)

1378
00:49:50,760 --> 00:49:52,320

- Thanks so much for listening.

1379

00:49:52,320 --> 00:49:53,340

Be sure to subscribe,

1380

00:49:53,340 --> 00:49:55,800

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of our conversations.

1381

00:49:55,800 --> 00:49:58,090

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many brilliant scientists

1382

00:49:58,090 --> 00:50:01,000

whose research spans from

the quantum to the cosmos,

1383

00:50:01,000 --> 00:50:03,470

and we can't wait for you to hear more.

1384

00:50:03,470 --> 00:50:05,260

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1387

00:50:10,580 --> 00:50:12,410

so please help us spread the word,

1388

00:50:12,410 --> 00:50:14,847

and thanks for being part of the equation.

1389

00:50:14,847 --> 00:50:17,430

(upbeat music)

