Interviewee: Vipul Periwal
Place: National Institutes of Health

By: David Zierler
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ZIERLER: This is David Zierler, oral historian for the American Institute of Physics. It is March 16, 2020. It's my great pleasure to be here with Dr. Vipul Periwal of the NIH. Dr. Periwal, can you please tell us your job title and your affiliation here at NIH.

PERIWAL: I'm a senior investigator at the Laboratory of Biological Modeling. My group is called the Computational Medicine Section, and basically I apply methods from — not directly from physics, but methods from physical intuition to try to find predictive models of biological phenomena.

ZIERLER: Okay. So, we're going to start right at the beginning. Tell us about your childhood, where you grew up, your family.

PERIWAL: I grew up in India. My father was an entrepreneur.

ZIERLER: Where in India did you grow up?

PERIWAL: In Delhi. I was born in Delhi, and I lived in Delhi until I was 18, and went to the same high school from kindergarten through 11th grade. And then in 11th grade, I left school a year early to go to college. But I knew I wanted to do physics. And good students in India do not do physics.

ZIERLER: Really?

PERIWAL: Absolutely not.

ZIERLER: Well, let's go back a second. You said your father was an entrepreneur. What was his business?

PERIWAL: I come from a long line of completely non-intellectual people. There are people whose parents were intellectuals, or they had some intellectual bent somewhere. I don't come from such a background. My father was a businessman.

ZIERLER: What was his business?

PERIWAL: My father started — well, his family's business — the one that my grandfather started — was a bunch of different interests in rural India, like milling rice, and ice factories, which, believe it or not, was a big deal in India at that time. There was not —

ZIERLER: No refrigeration.

PERIWAL: No refrigeration. And things like that. So, my father grew up in pretty affluent circumstances.

ZIERLER: In Delhi.

PERIWAL: No, in Bihar, which is a very remote — I shouldn't say "very remote." It is fairly remote from big cities — part of India. So, my father was actually a freedom fighter against the British.

ZIERLER: Really?

PERIWAL: And this was all non-violent, because this was all under Mahatma ____ Gandhi, and the whole idea was non-violence, and so on. So, my father was very much into this.

ZIERLER: Would he have described himself as an anticolonialist?

PERIWAL: No. He just wanted — he was just inspired by Gandhi: the idea of being self-sufficient, that Indians should have their own…

ZIERLER: National destiny?

PERIWAL: …independence back. And so, when India finally became independent — my father was pretty young at this time. He was probably in his mid-20s. So, he felt that he wanted to go beyond the sort of industries that my grandfather was in. He wanted to contribute to making India self-reliant in things like electricity, and so on.

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At that time, India had a British heritage of massive amounts of bureaucracy and planning, and the first prime minister of India was Jawaharlal Nehru, who was educated in England and fell under the sway of the Fabians in — I forget whether it was at Oxford, or Cambridge, or whatever. Anyhow, he had the socialist — the prime minister had this socialist idea, and so everything had sort of planning involved, central planning. And this does not work out well. So, my father managed to get a license, you had to get a license before you could start any industries, and these licenses were apportioned according to different geographical locations, and so on. So, my father proceeded to get a license to start an electrical cable manufacturing company, in the southernmost tip of India. Now, Bihar is in the north of India. My father did not speak the local language at all. But in his patriotic fervor, so to say, off he decided to go and start factories — start a factory for making electrical cables.

ZIERLER: Did he have any background in electrical engineering?

PERIWAL: No. He had no background in engineering. In fact, my father didn't even graduate from college. He had two years of college, and then my grandfather needed him in the family business. So, he left college, and he proceeded to work with my grandfather. And then he got involved in this independence movement, and so on.

ZIERLER: Was it a northern Indian perspective to look at the south and see that this was an area ripe for development as part of a united India project?

PERIWAL: Honestly, I have no idea. It's just that — it wasn't that the south was underdeveloped or anything. In fact, where my father's license was located, that state, Kerala, has the highest literacy of any state in India. And it's a very highly educated work force, even to this day, by Indian standards — by any standards. I joke sometimes with people. They say, "Which part of India are you from?" So, I say, "I'm from the north of India." And all the smart people you meet, they're from the east of India, from Bengal, or from the south of India. [laughs] That's where the educated people are.

ZIERLER: [laughs] Okay.

PERIWAL: The Bengalis are from east India. That's not the intellectual background that I have, period. Okay? So, that's an aside.

ZIERLER: And what about your mom? What was her background?

PERIWAL: My mom was married to my father when she was 14 years old, and she was — my father died a few years ago, but my mom is still one of the smartest people I know. She graduated from high school, because they did what's called a "double promotion," meaning she skipped grades twice. [laughs] That's how smart she was, relative to the other —

ZIERLER: She was married when she was still in high school, though?

PERIWAL: Just when she was about to graduate.

ZIERLER: Oh, because she skipped so fast.

PERIWAL: Because she skipped. And in the very traditional society that my parents belonged to, it's sort of —

ZIERLER: Traditional, in the Hindu sense, or a caste sense?

PERIWAL: Yeah, traditional in a Hindu sense. People had no choice. The families — it was like — even to this day in India, people talk about matrimonial alliances. Right? So, my mom's family was an entrepreneur's family. My father's family was an entrepreneur's family.

ZIERLER: Joined businesses.

PERIWAL: Well, not really. But the backgrounds were similar. Okay? And so, the parents decided these two should marry, and off they went.

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ZIERLER: Do you have siblings?

PERIWAL: I have siblings. I have an elder sister and a younger brother. So, that's the background of where my father lived, and what he did, and so on.

ZIERLER: So, where did you develop your interest in science? Clearly, outside of the home.

PERIWAL: [laughs] Oh, yeah. Absolutely. So —

ZIERLER: I mean, before you get to college, you're clearly interested in science as a boy.

PERIWAL: Yeah. So, my mom always — I don't know. Somehow, I got the sense she was very frustrated that she couldn't actually study beyond.

ZIERLER: Yeah. College was not available to her.

PERIWAL: No, it was not. She was married, and my parents didn't have children until quite a few years after they were married. Obviously, my mom was 14. But college was not an option. She had to — they lived at that time with my grandfather, his mother, my grandmother, and so on. So, it was a joint family, and everyone sort of split up the work, and so on, and so forth. So, there was no college. It was very strange, as in —

ZIERLER: Vicariously, maybe, living through you?

PERIWAL: Yeah, maybe. I don't know. But what she always emphasized was: people can take anything material away from you, but no one can take away what's in your head. Right? And so, she always emphasized education. In fact, my parents moved from this remote part of Bihar to Delhi, solely so that their children could get a better education. [laughs] And now, you have to understand. Think of India as a kind of triangle. And my parents grew up sort of on — think of an inverted triangle. My parents grew up sort of midway along the upper edge, to the right. My father's business that he was starting was on the extreme tip of the inverted triangle — the apex of the triangle, except upside down. And so, they moved to roughly the center. Right? So, this was a thousand kilometers away from where my father's work was. This was like 700 kilometers away from where my father grew up. So, they had to start up from scratch, pretty much, in Delhi.

ZIERLER: And you were born in Delhi?

PERIWAL: I was born in Delhi.

ZIERLER: Okay.

PERIWAL: And that's where I lived.

ZIERLER: Did your father make a good living?

PERIWAL: No.

ZIERLER: He did not.

PERIWAL: No! In fact, it was kind of — it was interesting. As I said, my grandfather was a self-made man, and he really started from zero, because he was an orphan. And he grew to be pretty prosperous, I'm told. He died when I was 3 or so, so I have the vaguest memories of him. But my father did not want to be in my grandfather's business.

ZIERLER: He wanted to set off on his own.

PERIWAL: He wanted to set off on his own. And this was very, very difficult. India's a very corrupt country. It hasn't changed. But it was corrupt from the get-go. So, you know, my father at some point had a very close friend who said to him, you know, "Why don't we immigrate?" And his friend immigrated to the U.K., and another friend immigrated to the U.S. And they both urged my father to come work with them, but my father could not leave my grandfather behind. And he felt this patriotic thing. He needed to stay.

ZIERLER: And taking your grandfather along with him was not an option.

PERIWAL: No, that was absolutely not an option.

ZIERLER: He was not going anywhere.

PERIWAL: No. I mean, my grandfather, as I said, was a — he'd worked all his life. He'd built this enterprise and what not.

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And you know, there was no reason for him to leave.

ZIERLER: So, you grew up watching your father struggle in business.

PERIWAL: Yeah. One thing that — I have no idea why, but I always felt that this whole corruption thing was really demeaning.

ZIERLER: To who?

PERIWAL: To my parents. And I just thought — I don't know why — from a very young age, I just thought that I don't want to do anything that involves people, if people are like this.

ZIERLER: So, you were getting it from two sides: from your mother, you were getting the importance of education, and from your father you were getting — negatively, I would assume — you wanted to go into a career where this kind of activity really was not front and center.

PERIWAL: No. I really — there was the corruption aspect. My father was always excited by the entrepreneurship part. Right? And he was willing to tolerate all the corruption, because it let him get on with his entrepreneurship. And I couldn't quite separate these things. I mean, I was a pretty okay student.

ZIERLER: Your school growing up: was it a public school, a private school? What are the options in Delhi?

PERIWAL: No, it was — there were public schools and private schools, and public schools were not very good. And private schools were of different types. There were private schools that were sort of nonsectarian, and then the school I went to was actually run by the Christian Brothers, who were missionaries from Ireland.

ZIERLER: Really?

PERIWAL: Yes. So, I went to a Catholic school. I'm not a Catholic. But some of the finest teachers I knew — I mean, not all the teachers were these Christian Brothers, but some of them were. And some of the finest teachers I knew were these Christian Brothers.

ZIERLER: Were there tensions in terms of your personal family traditions or beliefs, and what you were learning in school? Or these were separate worlds?

PERIWAL: No, not at all. My parents — what was funny was I was very close with my younger brother, and I still am. And so, I had complete freedom to pretty much read whatever I wanted. So, all I remember of my teenage years is just reading all sorts of stuff. Very little effort was needed in school. Not because school wasn't challenging. Well, it wasn't really — actually, to be honest, it was not challenging at all. Okay? But I mean, I was a good student. It didn't take much effort to do —

ZIERLER: You had extra bandwidth for other pursuits.

PERIWAL: Yeah. I spent most of my time in my teenage years on photography and painting.

ZIERLER: In science classes, with this being a Catholic institution…

PERIWAL: Oh, no, no.

ZIERLER: …were things like creationism and evolution —

PERIWAL: No, absolutely — there was no problem whatsoever.

ZIERLER: You were getting a proper scientific education.

PERIWAL: Oh, yeah. Absolutely. Yeah, no. Actually, the brothers taught either math or English, and I don't remember a single science class taught by one of the brothers.

ZIERLER: Oh, local Indians would teach those classes?

PERIWAL: Yeah. And they were actually of all different religious backgrounds. I had Catholic teachers, I had Protestant teachers, I had Hindu teachers, I had Muslim teachers.

ZIERLER: The classes were all taught in English?

PERIWAL: Yeah.

ZIERLER: There was Hindi mixed in?

PERIWAL: No.

ZIERLER: Exclusively English.

PERIWAL: I could read and write English before I ever learned a single character of Hindi.

ZIERLER: Is that right?

PERIWAL: Yeah.

ZIERLER: But at home, you're speaking to your parents in Hindi?

PERIWAL: So, it's kind of funny. At this stage, I don't remember what it was like when I was 5 years old, but at this stage, or at some point when I was getting older, I realized that my mom would ask me a question, and the response she would get

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would be in English. And she'd be speaking in Hindi. Right?

ZIERLER: That's classic. Yeah.

PERIWAL: I do speak pretty much perfect Hindi, and it's —

ZIERLER: And you probably taught your mom English that way.

PERIWAL: No, my mom knew English.

ZIERLER: Oh, she knew English already?

PERIWAL: She taught herself. And so, my mom would sometimes joke with me: "When you speak to me in Hindi, it's like you're translating from English. It's not exactly perfectly idiomatic Hindi."

ZIERLER: [laughs] Right.

PERIWAL: But school was not that challenging, and so I spent my time, you know, on painting and photography.

ZIERLER: And when you graduate, what are the options that are available to you? College is automatic? You're definitely going to college at this point? That's enough of an emphasis?

PERIWAL: Yeah. No, there was never a question that we were going to college.

ZIERLER: Affording college: was that an issue, or that was not an issue?

PERIWAL: No. As far as my mom was concerned, no matter how badly —

ZIERLER: They needed to save and scrape.

PERIWAL: Yeah, we were going to — our schooling was not going to be disturbed. And no matter how badly my father's business was doing…

ZIERLER: You'd make it work.

PERIWAL: …it was going to happen, and that was it. There were no —

ZIERLER: So, what is the college system like? Do you declare a major right away?

PERIWAL: [laughs] No. So, I left — there are these famous universities in India called the Indian Institutes of Technology. And at the time when I was growing up, there were five of these.

ZIERLER: Is it modeled against the British system?

PERIWAL: No. Actually, these Indian Institutes of Technology were each of them set up with some foreign country helping India get on its feet after independence. So, there was on in Kanpur, which was set up with U.S. assistance; one in Delhi, that was set up with, I think, British assistance; and Chennai was set up with, I think, German. And I forget — Mumbai had some other affiliation. So, there was an entrance exam to these institutes, and which major you could pick depended on your rank in these entrance exams. And there was a period when India was transitioning from 11 grades of schooling to 12, and these Indian Institutes of Technology had five-year degree programs.

ZIERLER: For a bachelor's.

PERIWAL: For a bachelor's degree. So, there was a period of transition for a couple of years when students in 11th grade, who were supposed to go on to 12th grade, could actually take the entrance exam, supposedly then a year earlier than they should have been taking it.

ZIERLER: You were part of this transition?

PERIWAL: Yeah, I was part of this transition.

ZIERLER: And what year would this have been — 11th grade?

PERIWAL: This was in 1978. That's when I took the exam. Or, 1979. I know I entered — I did pretty well on this exam, so I had my choice of whatever major I wanted.

ZIERLER: Among any of the institutes?

PERIWAL: At any of the institutes. I did pretty well [laughs] on that exam. So, I could decide where I wanted to go and what I wanted to do. So, my parents were pretty happy about this. And then I wanted to do physics. Now, you have to understand that at that time, it used to be a couple hundred thousand, or 100,000, something like that, students take this exam. And 2,000 are going to get into the universities, these institutes. And the people who go into physics, or any of the natural sciences, would be the people who get ranks in the low, like 1,900, etcetera.

ZIERLER: Bottom of the top.

PERIWAL: Bottom of the top. And all the people who can will do electrical engineering. Computer science was a new-fangled thing. Okay?

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And so as far as — everyone my parents consulted was concerned. You know, it would be a tragedy if I went and did physics. And I could see this perspective, okay, because I did pretty well on this exam, and I knew people who were going to go do physics, and so on.

ZIERLER: Now, the exam was technical? It wasn't literature, English. It was all —

PERIWAL: No, it had English.

ZIERLER: Oh, it did.

PERIWAL: English, math, chemistry, physics. Those were the four subjects.

ZIERLER: Now, you were interested in physics, or by dint of how well you did on the exam and where you landed in those 2,000 —

PERIWAL: No. No, I was — [laughs]

ZIERLER: That sort of put you in the physics path.

PERIWAL: No. [laughs] School was easy. Right? The only subject that challenged me at all was physics.

ZIERLER: I see.

PERIWAL: So, it's like, what do you find hard? Is that what you want to do? Well, frankly, that's always what's attracted me.

ZIERLER: So, if you could think back to when you were 15 or 16, what was it about physics that was challenging to you?

PERIWAL: Probably my teachers were — the physics teachers are usually terrible. So, I would just read. Besides all the fiction I devoured, I'd read physics textbooks that I'd check out from the British Council library and other places, wherever I could get it.

ZIERLER: What kinds of things — like, were you reading Isaac Asimov, that kind of stuff? Like, popular books in physics?

PERIWAL: I read a lot of science fiction. But I'm talking about real physics textbooks. I would read Halliday and Resnick. That was a standard physics textbook for beginning college, whatever. So, I managed to get my hands on this, and then some time while preparing for this entrance exam, if I remember correctly, I worked through pretty much every single problem in this [laughs] two-volume set. It was just — I liked this.

ZIERLER: Your math skills were pretty strong?

PERIWAL: Yeah. The only thing is, I have trouble proving anything, so that's not — and it's not — it doesn't come naturally to me to think in terms of proof. I think I can produce a proof if I need to. It's more gut, so it just doesn't work. [laughs] So, I opted to do electrical engineering, and I didn't want to stay at home, and the best electrical engineering was at Kanpur, which is an overnight train ride away from home, whereas the Indian Institute of Technology in Delhi was literally a 15-minute walk from where I lived.

ZIERLER: But this was your opportunity to get out.

PERIWAL: Yeah, I didn't want to have — I definitely did not want to be able to walk home at any point. This is independence.

ZIERLER: This was an opportunity.

PERIWAL: Yeah. I wanted to be out. So, that's where I went for a year, and in the meantime, I was really depressed about this. Like, okay. I'm going to do electrical engineering. Yeah, I know there'll be smart kids there. But I want to do physics.

ZIERLER: I see. So, you really wanted to do physics, but you felt like you were forced into electrical engineering.

PERIWAL: Because I wanted also stimulating companions. Right?

ZIERLER: Yeah, because those are the best students, those in electrical engineering.

PERIWAL: Right. And so, that's what I went to do. So, I started looking around, and nobody at that time — now, there are tons of Indian students at U.S. colleges. At that time, I didn't know a single person who went abroad for an undergraduate education.

ZIERLER: And not just to the United States. You mean anywhere.

PERIWAL: Anywhere. Lots of people went for higher education, graduate students and so on. But I didn't know. [laughs] So, I had no idea — how does one even do this? There was no web. Right?

ZIERLER: You started to ask this question because you wanted to study abroad. Was that the idea?

PERIWAL: No, I wanted to study physics. [laughs]

ZIERLER: Aha. You wanted to study physics, but you wanted your classmates to be of a higher caliber.

PERIWAL: Right.

ZIERLER: And you realized that in order to square that circle, you would need to study abroad.

PERIWAL: I needed to go somewhere else.

ZIERLER: Interesting.

PERIWAL: Right? Hey. So, at that time, my father used to subscribe to *TIME* and *Newsweek* and so on.

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And there was an article on Caltech. And I had my hands on the Feynman lectures at that time. Right?

ZIERLER: Yeah.

PERIWAL: And I was like, "Wait a minute. How about I apply to Caltech?"

ZIERLER: What was your access point to the Feynman lectures? Were they reprinted in __India?__ —

PERIWAL: They were in the library.

ZIERLER: In journals.

PERIWAL: No, no. I mean, the books. The Feynman lecture books.

ZIERLER: Right. Okay.

PERIWAL: And this was at IIT. The IIT, as I said, was set up — the IIT Kanpur where I was, was set up with U.S. collaboration. So, they had all sorts of American textbooks. Right? Feynman lectures.

ZIERLER: What was so exciting to you about the Feynman lectures?

PERIWAL: Oh.

ZIERLER: This is opening a whole new world to you at this point, probably.

PERIWAL: Yeah, I mean —

ZIERLER: So, tell me. What was it?

PERIWAL: All this stuff that I was struggling with, trying to piece together because I had terrible teachers — you know, I read this, and it's like: oh, it's this simple. And it just changed my life, really. Just opening Volume 1 and — I forget. I think it starts with energy conservation, or something like that. I think Volume 1, at the very beginning. And he's talking about blocks, and you observe — and I was like, okay. This is good.

ZIERLER: This is your guy.

PERIWAL: Yeah. So, then I thought: okay, I've got to fly. I've got to go to this place.

ZIERLER: To Caltech.

PERIWAL: Yeah.

ZIERLER: Just to work with Feynman.

PERIWAL: Yeah.

ZIERLER: Now, in retrospect, was this naïve of you to think that a 19-year-old from India would have direct — because your goal was to work with Feynman, not just to be at the institution where he was.

PERIWAL: Yeah, yeah.

ZIERLER: Was this naïve of you to think that you would have direct interaction? [laughs]

PERIWAL: You think? But I did have some interaction with Feynman.

ZIERLER: You did. So, you applied.

PERIWAL: I applied. So, I thought: okay, this is a little ridiculous to think that I could — you know, I can be sure that I'm going to get into Caltech.

ZIERLER: Yeah. You applied what — was there a program that you applied — like, an international exchange program?

PERIWAL: No, no.

ZIERLER: You just applied.

PERIWAL: I just applied. Yeah. I wrote letters to Caltech, Princeton, Yale, a few others. Right? I got the application materials. It was not possible at that time to do foreign exchange restrictions for me to even submit application fees. Right? Now, there's all this application stuff saying if you can't afford it you don't have to pay— but I'm an international student. There was no such thing. So, my parents persuaded a friend of theirs who lived in Germany to send the application fee, for applying, to these universities. And I applied.

ZIERLER: Did you have any professors locally who were helping you?

PERIWAL: No.

ZIERLER: Was anybody writing you a letter of recommendation?

PERIWAL: So, a couple of my high-school teachers wrote me letters, and yeah. That was — my high-school teachers. I got two or three of them.

ZIERLER: Did you have any family in the United States?

PERIWAL: Not at all.

ZIERLER: Nothing.

PERIWAL: No. So, my parents are getting very scared about this.

ZIERLER: This sounds a little like your father setting up an electrical factory in the south of India of — all the way around —

PERIWAL: I actually pointed this out to my father that, you know, my grandfather moved from wherever he was born to where he set up — you moved from there. So, I'm just continuing the family tradition, doing something completely different in a completely different location. And my father thought that was amusing.

ZIERLER: So, when did you start hearing back when you submitted these applications?

PERIWAL: So, I submitted these applications, and then this was like — I get a telegram. Telegrams were a thing — from MIT. No, wait. I forget whether it was Princeton or MIT which was the first acceptance. And I was like, "Wow, this is awesome!" [laughs] And then I'm thinking, "How in heck am I going to afford this?"

ZIERLER: [laughs] Step two.

PERIWAL: Or, not me, but how are my parents possibly going to afford anything like this? But I did get admitted into a whole bunch of places. So then, I looked up the physics

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ratings, and as far as I can tell, I really needed to think about either Princeton or Caltech.

ZIERLER: You weren't thinking in terms of a specific branch in physics, because —

PERIWAL: No. I just wanted to do physics. [laughs]

ZIERLER: Right. Because some departments — I mean, when you say "better physics departments," it really depends what branch of physics you're talking about.

PERIWAL: What did I know?

ZIERLER: You had no idea.

PERIWAL: I had no idea.

ZIERLER: Nothing.

PERIWAL: I knew nothing. So, this is just "ignorance is bliss." I didn't have a clue.

ZIERLER: So, the top of the top at this point. You saw it came down to Princeton versus Caltech.

PERIWAL: Yeah, with no rational reason. It turned out later that I did not actually judge incorrectly.

ZIERLER: You got into both?

PERIWAL: Oh, yeah. I got into quite a few places.

ZIERLER: Do you remember — did you get rejected from anywhere?

PERIWAL: Yeah, I did get rejected from Pomona College. I have no idea why I ever applied there.

ZIERLER: I bet they would be very proud to know. [laughs]

PERIWAL: I have no idea whatsoever why I applied, except that there was an article in either — again, there was *TIME* and *Newsweek* that talked about this bucolic place.

ZIERLER: Malibu. It's right on the ocean.

PERIWAL: I had no idea where Malibu was. So, yeah. Harvard and Pomona. I was admitted to MIT, Princeton, Yale, Caltech, the University__ of Chicago, Columbia.

ZIERLER: Stanford, Berkeley? _____

PERIWAL: No, I did not apply to Stanford or Berkeley. I'd never heard of Stanford. Seriously. You know, what do I know? I'm this kid, growing up in India. I have these magazines for information.

ZIERLER: [laughs] They didn't talk about Stanford.

PERIWAL: They didn't talk about Stanford. I wouldn't have gone there anyway, because Feynman wasn't there. So, I went to Caltech after a year of college in —

ZIERLER: How'd you work out the tuition?

PERIWAL: So, they gave — you know, these are all private universities. I had had the sense to apply only places which were private universities, because they actually have funds for international students. So, I showed up. Then there was a family contribution, and my parents did again manage to provide the — I think it was $2,000 a year that they had to come up with.

ZIERLER: Which was a significant sum of money.

PERIWAL: It was a very significant sum of money, but they did manage to do it. And so then I felt — I knew sort of what a burden it was. So, I actually did graduate from Caltech in three years.

ZIERLER: Least you could do, right, to help your parents?

PERIWAL: Sorry?

ZIERLER: It's the least you could do. You saved your parents $2,000.

PERIWAL: Actually, yeah. So, that's how it was.

ZIERLER: Now, you came into Caltech as a freshman, or you came in as a sophomore?

PERIWAL: Yeah, I came as a freshman. Well, because see, I left school a year early, and then I left this college after one year. So, I had — actually, I still don't have a high-school diploma. And I certainly didn't graduate from the college in India. So, there I was at Caltech. And it's probably a good idea for me to — I opted for Caltech over Princeton, because Princeton had all sorts of requirements, and Caltech, as far as I could tell, with the sort of minimal requirements, I could do whatever I wanted. So, much more flexible. I think Caltech has changed a fair bit.

ZIERLER: Right. Princeton is famously strict with their procedures, and the west in general is more freewheeling.

PERIWAL: Yeah. So, I just looked at it like all these — and I had the catalogs, right? The admissions thing, they sent these catalogs, and I looked at the courses, and I'm like a kid in a candy store. You know? "Wow, I want to take this, this, this, this, this." And I'm thinking, at Princeton, I could not fit this, this, this, this — [laughs] what I want to do.

ZIERLER: Now, when you got to Caltech, were your fellow students as good as you had hoped? Was it worth the trip, just based on the caliber of your fellow students?

PERIWAL: Yeah.

ZIERLER: It was.

PERIWAL: It was.

ZIERLER: And what about the professors? Same?

PERIWAL: Oh, yeah. I had a grand time at Caltech. I had a very, very good time at Caltech.

ZIERLER: And what's the course —

PERIWAL: I overloaded like crazy. I should never have done this. People should have stopped me.

ZIERLER: [laughs] Did you have any opportunity for lab work, or it was strictly courses for the three years?

PERIWAL: No. I actually wrote a terrible senior thesis in physics, and I wrote a senior thesis in mathematics that was actually pretty good.

[40:00]

So, I did do research.

ZIERLER: So, you had a dual major in mathematics?

PERIWAL: Yes, I got a dual major in physics and math. And I had to actually petition — and this was one of the great things about Caltech at the time — was that it was this small place. It's still a small place. But you could go talk to anyone, petition anything, and you know —

ZIERLER: They'll just say "yes."

PERIWAL: Some committee would look over it, and they wouldn't just say "yes," but they would consider, and if you looked like you could handle it, they would.

ZIERLER: So, at what point in your undergraduate education did you start gravitating toward a particular branch of physics? When did you realize you were not into this, and you were into this?

PERIWAL: For some bizarre reason, I felt very strongly about theoretical physics. I have no idea why. I did okay in labs, but it didn't come intuitively to me. And I had friends to whom it did come intuitively. But theory, I could do, and probably because my math was okay.

ZIERLER: How does that fit in with your inclination that you don't like proofs in math?

PERIWAL: [laughs] So, I had some very, very fine teachers at Caltech. Michael Aschbacher taught me algebra and advanced algebra, and when I was applying to graduate school, I asked him if he would write me a letter. He was a very, very famous finite group theorist. I don't know if he's still alive. He probably still is. But he's one of the people who was responsible for completing the classification of all the finite simple groups. And he was a very, very clear teacher, but I remember asking him if he could

write me a letter, and he asked me, "What graduate school are you applying to? Physics, or math?" So, I said, "Physics." He said, "In that case, I'll write you a letter." [laughs] And then, my undergraduate advisor — so, I liked both subjects a lot. So, I thought: hey, I should try to do something in the middle. So, my undergraduate advisor was a guy called Barry Simon. And Barry had just arrived at Caltech.

ZIERLER: Where did he come from?

PERIWAL: Princeton. He was — I don't know why he moved to Caltech, but I think it might have been because at that time, the president of Caltech was Murph Goldberger. And Barry was Marvin Goldberger's godson, or something. And so, I think Goldberger enticed him to come to Caltech. And the Caltech math department was a pretty sleepy place. It had some very innovative people, like one of the pioneers in what's called nonstandard analysis. But compared to the physics department, which had at that time Feynman, Gell-Mann —

ZIERLER: It was a super-star faculty.

PERIWAL: There was like, no comparison, really. So, Barry was very, very active by the standards of the math department. I knew that I had absolutely amazing teachers in the Caltech math department. They were awesome. I learned so much from them. So, I got Barry Simon as my undergraduate advisor, so I thought I'd do mathematical physics, because — you know, combine them. Except the kind of mathematical physics that Barry Simon did — I don't know if you know this, but Barry Simon did a lot of constructive quantum field theory. He then did a huge amount of work on the behavior of Schrödinger equations in what's called "almost periodic potentials." Where, you know, if it's a periodic potential, you get a certain kind of spectrum of wave-functions, but if you have an almost periodic potential, there's a very beautiful mathematical theory of what kind of wave functions you get, and what's the spectrum of these Schrödinger operators for these almost periodic potentials, and so on.

[45:00]

And he was my advisor for my mathematics senior thesis, and I solved the problem he set me, and I got a little prize and what not. But it just didn't excite me.

ZIERLER: Why not? It was too dry?

PERIWAL: I didn't understand this at the time. Like, why not?

ZIERLER: Viscerally, it just didn't excite you.

PERIWAL: Yeah. It just didn't excite me. I mean, Barry Simon was so kind to me. Two years as his advisee, you know — he suggested when I was — so, at the end of my sophomore year — I remember at the end of my — sometime in the middle of my sophomore year, I did some adding up, and I made an appointment to go see him. And I said, "You know what? I could graduate with a math degree at the end of this year." And he said, "And what would you do?" I said, "Go to graduate school." And he said, "No."

ZIERLER: [laughs] As in, "You're not graduating now only to go to graduate school for math."

PERIWAL: Yeah, no. "Let's see. Next year, you're taking mostly graduate courses. So, let's see."

ZIERLER: In terms of what? What did he see in you where he wanted to prevent that from happening?

PERIWAL: I have no idea. As I said, he was extraordinarily kind to me, and he's not a person who's known for his kindness. This, I found out later.

ZIERLER: Now, culturally, are you like the only international student in the department? Are you sort of —

PERIWAL: [laughs] No.

ZIERLER: Are there students from all over the world?

PERIWAL: No. I'll tell you something. No, there weren't that many foreign students, actually, at Caltech. And I found out later that — you know, I talked to my fellow students, and they were like, "Wait, you came to Caltech over Princeton?" I had no idea that this was kind of a faux pas. [laughs] I was like, "Yeah, so what?" No, actually it turned out there were no other direct-from-India students at Caltech, other than one person, who was —

ZIERLER: You mean, not just in the physics department. You mean across the whole —

PERIWAL: At the whole — other than the person two years ahead of me, who — his name is Aneesh Manohar who actually, it turned out — he met me sometime in my freshman year, and he had had a very similar trajectory to mine. He spent a year at, I think, IIT Bombay, and then decided this was not for him. So, he came to Caltech, and he was also a physics major. [laughs]

ZIERLER: Oh, wow.

PERIWAL: There were, you know, Americans who were of Indian origin, but he was the only other *Indian* Indian at Caltech.

ZIERLER: Yeah. So maybe, Barry Simon was just — he took kindly to you because he knew you had no support system in the country. He just took you under his wing.

PERIWAL: No.

ZIERLER: No? That wasn't it?

PERIWAL: I never discussed anything about — you know? No.

ZIERLER: Well, you didn't have to discuss it. He clearly knew your background, where you came from.

PERIWAL: No.

ZIERLER: You don't think that had anything to do with it.

PERIWAL: I never had a conversation about that with him.

ZIERLER: So, he just liked you.

PERIWAL: I guess. Well, it's kind of funny. So, my sophomore year, I signed up to take his course, which was called "Rigorous Statistical Mechanics." And he started off in his first lecture with saying that "I'm just coming from Princeton, and I don't see why graduate students need grades." And that was actually

something that perked my ears up. I see — graduate students at Princeton at that time had no grades. Actually, they had no course requirements, period.

ZIERLER: Yeah. They were either doing well, or they were not. It was two options.

PERIWAL: Yeah. The only thing at Princeton, in graduate school at that time, was that you passed the qualifying exams and then you did research. You were not required to take any courses. If you took any courses, they were not graded. So, it was entirely a self-starter kind of place. So, that's a little step further. Anyhow, so I went to the first lecture, and Barry Simon was saying, you know, "Graduate students are not being graded." And then he says, "For the one undergraduate in this class, they will be pass/fail." So, I went up to him after, and I said, "No, I want a grade."

[50:00]

And he said, "Why do you want a grade?" I said, "Because it'll motivate me to work harder."

ZIERLER: Sure. Sure.

PERIWAL: So, he said, "Okay."

ZIERLER: It's more precise feedback.

PERIWAL: Yeah. So, he said, "Okay. In that case, your grade will be decided by an oral exam at the end of it." So, I said, "Okay, that's fine." So, that's how I —

ZIERLER: What did you get? What was your grade?

PERIWAL: A+. [laughs]

ZIERLER: [laughs] Okay.

PERIWAL: Yeah, so at the end of the term, he set up an appointment. I go to his office. He stands me up at the blackboard, and he said, "So, outline the __Onsager__ solution of the Ising model," which was something he had covered. So, I proceed to go through the steps of the solution of the Ising model by Onsager. I was not too unnerved by the fact that at the beginning, he says, "When I was a sophomore, I was grilled in an oral exam. I've always wanted to do this to someone." [laughs] Holy shit, Batman! But anyhow, yeah.

ZIERLER: You nailed it.

PERIWAL: Yeah, I did. And so, he was kindly disposed towards me.

ZIERLER: Now, you said you did have contact with Prof. Feynman.

PERIWAL: I did. He used to teach this — not teach as much as he used to give these little storytelling sessions that were restricted to freshmen and sophomores.

ZIERLER: Storytelling?

PERIWAL: Oh, yeah. All those stories that you've seen in, you know, *Surely You're Joking, Mr. Feynman*, and so on. I heard them firsthand from Feynman.

ZIERLER: Oh, wow. Wow.

PERIWAL: Yeah.

ZIERLER: What a treat.

PERIWAL: Oh, it was, absolutely. So after —

ZIERLER: What was his style? Was he funny?

PERIWAL: Oh, he was ridiculously funny, and very matter-of-fact. He was a raconteur. Really, he knew how to tell a story. So, you know, he'd build it up, and there would be a punchline, and then we'd laugh, and then he'd go on to another, knit it together with the next story, and so on, and so forth. So, almost every one of the stories in there, I'd heard from him.

ZIERLER: Oh, wow. Did you ever share with him your story about just wanting to come to Caltech just from reading his —

PERIWAL: No, but I did talk to him once or twice. At the end of this, I asked him, "Could you say a little bit about the __renormalization__ group or something?" These are things that I was intrigued by at that time.

ZIERLER: What was intriguing about them to you?

PERIWAL: Because everyone was talking about this. You know, that there was this — I mean, I was a sophomore at the time, and I was really into group theory, and I could not — I tried looking — I mean, what do I know? I was a sophomore learning group theory. But I couldn't really understand: what was the "group" part of it? It's because it's not really a group; it's a semigroup. But you know, that I know now, but at that time —

ZIERLER: Sure.

PERIWAL: And he said, "No, that's a little too advanced" — you know, then he says, "What year are you, anyway?" [laughs] since these talks were restricted to freshmen and sophomores. So, I said, "I'm a sophomore." So, then he said, "Oh, yeah." [laughs] "I think I see what you have in mind, but no, I'm not going to talk about it."

ZIERLER: As if you would have saved that for a graduate seminar, his answer?

PERIWAL: Yes. So, my junior year, I signed up to take his quantum chromodynamics course, except that was the year that course was cancelled because he had stomach cancer. So, I never got the chance to take a course from Feynman.

ZIERLER: Now, your third year was essentially your junior year and your senior year.

PERIWAL: Right.

ZIERLER: And it was exclusively devoted to graduate seminars.

PERIWAL: Pretty much graduate classes, yeah.

ZIERLER: Okay.

PERIWAL: [laughs] And a music class, and a computer science class, because Caltech wasn't quite all that free. You couldn't just do whatever you wanted.

ZIERLER: There were core requirements.

PERIWAL: There were some requirements. So, I really — in my junior year, at the end of my first term, at the beginning of my junior year, Barry Simon called me in, and he says, "You're graduating this year." I said, "Wait, what happened? A year ago, it was like, 'No, you're staying.'" He says, "No. Why should your parents be paying for another year? You should go to graduate school, and have them pay you."

ZIERLER: [laughs] Did they write him a letter?

[55:00]

Did he not know this before? How did he find out that your parents were doing this financial —

PERIWAL: Everyone's parents were paying. So, it's not — so, he said, "No, you should go to graduate school, and people will pay you." So, I said, "Okay." I'm graduating. Okay.

ZIERLER: So, staying in the United States and pursuing graduate school in the United States — this is for sure. There's no question about you going back to India at this point. No question whatsoever.

PERIWAL: Well, I told my parents.

ZIERLER: Are you visiting your family at holidays? I mean, were you just in America?

PERIWAL: I did one year. One year, I did. The first year after the freshman year, I did. But there was nothing to do, and I found —

ZIERLER: Were you able to communicate with them by telephone? Were you writing letters?

PERIWAL: My mom would write me letters, and Caltech was a very good place for a person who was really fresh off the boat, because it was a small place full of weirdos. And you know, it was a very gentle introduction to the U.S. So, I was actually very grateful that I was at Caltech and not Princeton, because I ended up going to graduate school at Princeton, and then I discovered that Princeton undergraduates are very different [laughs] from Caltech undergraduates. I was very happy that I had been to Caltech.

ZIERLER: Yeah. A different world.

PERIWAL: Absolutely, yeah.

ZIERLER: Right. So, what led you to Princeton? Did you have the same sort of pool of applications, and this was your best shot?

PERIWAL: No, I actually — Barry told me — okay. He wanted me to be his graduate student, so he told me to apply to Caltech, and he says, "Normally, we don't want people to stay at the same institution. But I think that you have enough maturity that it's okay for you. And you could work with me." And he was just ridiculously kind to me. So, I applied there, and he told me, "Apply to Princeton." And I said, "Maybe I want to do astrophysics." So, I applied to the University of Chicago, and I applied to Harvard.

ZIERLER: What about Pomona?

PERIWAL: [laughs] Good question. But yeah, so that was my graduate school pool.

ZIERLER: Now, were you thinking at this point in terms of careers? Like, these are the places you want to apply based on the field to pursue, but were you fast-forwarding towards — what are you going to do with a graduate degree?

PERIWAL: No.

ZIERLER: You're not there yet.

PERIWAL: I am a really stupid person in terms of career management. I do not think in terms of — like, I remember a friend of mine in graduate school, at some point, pointed out to me, you know, what oculd he do? I'm a physicist. That was what my friend said to me. And I'm like, I never thought of this as a profession.

ZIERLER: Yeah. Purely an intellectual pursuit.

PERIWAL: Yeah, and this is what I like to do, and this is why I do it. I never thought of it like, you know: I want to be a professor. I never thought of it as a sort of social status thing, as a monetary thing, or anything like that. It was just like: this is what I like to do.

ZIERLER: So what were the branches of — in applying to graduate school, what were the branches of physics that were most exciting to you?

PERIWAL: It was either mathematical physics — it was a little bit astrophysics, because I really [laughs] — it's changed a lot, but I really didn't like interacting with people, and I thought: astrophysics. You know, this might let me sort of stay away from people a lot. So, it was very haphazard, the why and where of graduate school. The University of Chicago - I did get in. I did not get into Harvard.

ZIERLER: They just do not like you at Harvard.

PERIWAL: But Barry told me, "You will get into Princeton, and you will get into Caltech. Then, it'll be your decision." And I said, "How do you know I'm going to get into Princeton?" He said, "They know me." [laughs] So, he's the one who got me into Princeton. And just think about it.

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He wanted me to be his graduate student, but he still got me into Princeton. That's how kind he was. Right? But it was beyond that. So, this is the hardest decision for me, ever. On the one hand, there's this guy who's ridiculously kind to me, who I know I can get along with, and so on. And then, there's Princeton, which I have no idea what it's like.

ZIERLER: But is Barry connecting you with somebody at Princeton to take you under their wing?

PERIWAL: He told me, "I think you might be able to work with Witten." Barry was the director of graduate studies when Edward Witten was a graduate student. So, he said, "You might be able to," but he said, "Edward has a lot of people clamoring for his time. So, that's someone you might think about."

ZIERLER: And this is 1983 when you're making this decision?

PERIWAL: This is 1983. So, that was the hardest phone call I ever had to make — one of the hardest, if not the hardest — was calling up Barry Simon at home to tell him that I was going to go to Princeton instead of staying at Caltech. But, I did do it. So, I get to Princeton, and —

ZIERLER: What was it that they offered you at Princeton that you were so excited about? I mean, you knew…

PERIWAL: No.

ZIERLER: …that you were going to be taken good care of…

PERIWAL: No.

ZIERLER: …at Caltech.

PERIWAL: Yeah. It was again — I was not excited about what Barry's research was. I knew I could do it.

ZIERLER: This was your next challenge.

PERIWAL: Yeah.

ZIERLER: Your next adventure.

PERIWAL: Yeah. I just did not get excited about it.

ZIERLER: Now, did you have contact with Witten before you got to Princeton?

PERIWAL: No, of course not.

ZIERLER: No. So, you just showed up.

PERIWAL: Look, I'm this naïve. I go as a visiting prospective graduate student, and they'll sign me up for a bunch of interviews, right? So, I talked to Arthur Wightman, who was a mathematical physicist, probably one of the most senior mathematical physicists in the U.S., one of the founders of — I talked to David Gross. This is how naïve I am. David Gross — I walk into his office. I sit down. He says, "So, what can I tell you?" So I ask, "Do people do things like the renormalization group here?" And David gives this big grin, like what I later used to call the "shark grin," and he says, "Yeah, we've done a little bit of that." That's how stupid and ignorant I was.

ZIERLER: [laughs] He didn't have to be so generous with his answer. He could have let you have it right then and there.

PERIWAL: Yeah. [laughs] Yeah, that's one of the more embarrassing moments of my life.

ZIERLER: In these interviews though, are you coming in prepared with what it is that you want to pursue?

PERIWAL: I didn't look up anything about what these people do.

ZIERLER: No, but in terms of what you wanted to do.

PERIWAL: No, I had no idea. No idea. [laughs]

ZIERLER: Okay.

PERIWAL: You know, let me put it this way. My son's in graduate school right now. Okay? This is his second year. He just put a paper out on ultracool atoms or whatever, his first paper in this experimental lab that he's in. He knew what he wanted to do before he went to graduate school. He contacted the professor he wanted to work with the summer before, so she actually asked him to come for the summer. So he left right after graduation. He was an undergraduate at Caltech. He left Caltech. He spent his first summer at Stanford, getting into the research in this person's lab, and then she asked him, you know, "You want to continue work as my graduate student?" And he did. So, he was all set with his thesis advisor and so on by the end of the summer when he wasn't even officially there.

ZIERLER: You're saying, this is the right way to do it.

PERIWAL: That's the right way to do it. And then there's my way. [laughs]

ZIERLER: [laughs] Well, it worked. You got in.

PERIWAL: Yeah, it did.

ZIERLER: Now, how does it work at Princeton? Because you got the master's degree in 1984, but do you just get the —

PERIWAL: All that means is —

ZIERLER: You just continue on. If you do well, they just give you the master's, and then you continue on.

PERIWAL: No, no. You pass the qualifying exams, and you get that degree.

ZIERLER: Does anybody leave with just the master's?

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PERIWAL: Yeah. There was a person I knew the year before me who actually only managed to pass the qualifying exams after five attempts, and he took his master's degree, and he left. Princeton does not admit people for just a master's degree. Not at all.

ZIERLER: The expectation is, if we admit you, you're supposed to go all the way.

PERIWAL: Yeah. So, I got to Princeton, and again, I still had no idea what I was going to do.

ZIERLER: Yeah. This is a culture shock. It's probably —

PERIWAL: No, no. In the graduate — now, see again, here in the physics department, there's no culture shock, really.

ZIERLER: Yeah. As an undergraduate, there would be.

PERIWAL: There would have been a huge culture shock.

ZIERLER: But as a graduate student, you're sort of ensconced in the department.

PERIWAL: Yeah, so there was no culture shock.

ZIERLER: There's no eating clubs issue, there's nothing like that.

PERIWAL: There's no eating clubs. There are no drunk people on Prospect. [laughs]

ZIERLER: Yeah. Right.

PERIWAL: So, I used to joke that, you know, this is a party school. [laughs] What kind of school is this? People look at me like, "Wait, Princeton is a party school?" Yeah, it is!

ZIERLER: Yeah. Absolutely.

PERIWAL: [laughs] I've been to a real school. I know.

ZIERLER: Right. And there was not much of that at Caltech among the undergraduates.

PERIWAL: Not at that time. Apparently, there is now more of a binge-drinking culture in certain houses, but still, I don't think it's anywhere near to the extent that it is at other places.

ZIERLER: So, does Witten take you under his wing? Does that actually happen?

PERIWAL: That's another story. So, in 1983, just beginning 1984, I'm sort of sniffing around, like: what am I going to do? Now that I've passed the qualifying exams, what seems exciting? And that's when the string-theory anomaly cancellation happens. And talk about being at the right place at the right time, there we are. So now —

ZIERLER: How did you know this was a big deal? What was the — the buzz? People talking? What was it?

PERIWAL: Yeah. People were talking, and you know, David Gross started giving a course — a lecture series on string theory, and John Schwartz came by and gave a seminar on anomaly cancellation, and so on. I used to go to these seminars. I used to go to seminars at Caltech, too. I didn't understand a word. Right? But I would just go.

ZIERLER: Just for the exposure.

PERIWAL: Just for the exposure. Just curiosity. You know? And there are these funny memories that go along with this, like the time Hans Bethe gave a colloquium at Caltech. And there's Richard Feynman, his old friend, in the front row. And Bethe puts the date on something in the European format, or the format anywhere except in the U.S. [laughs] And Feynman starts teasing him, like, "What, is that the 13th month? What is this?" So, Bethe made a — probably one of the few people who could sort of go toe-to-toe with Richard. "Ah, Dick. I keep hoping you catch up." Without a pause. You know? I used to go to particle theory seminars. What would I know, as an undergraduate, about particle theory. Right? But it was really fun to watch. Feynman would sit in one chair, and he'd be kind of abstractly sort of toying with a pen, or whatever. And then at the end — or in the middle, you know, whatever — he would ask these questions. It would invariably — and they were not mean questions. Okay? They would invariably fluster the person. [laughs] Not intending to. Like, I remember —

ZIERLER: I mean, when you're a genius like Feynman, you're going to ask questions. It's going to fluster the speaker.

PERIWAL: And that's something that I've taken away all my life is, you know, the quality of the questions that a person asks in a seminar are directly correlated with how good a physicist they are. [laughs] And this is really a very, very good correlation. So, I remember a particularly memorable one is when Tony Zee, who is a good

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friend of mine now, came to give a talk at Caltech. And I guess Tony Zee and Steve Adler had this theory of photon-pairing instabilities as the source of gravity. So, Feynman listens, listens, and he keeps asking Tony, "I want to see some big numbers here," because there has to be a big number, right? G, is very small, so somewhere there has to be a big or small number. Right? And Tony was very cool. Tony keeps talking about their calculation, trying to get nonperturbative effects. Feynman is just like, "I don't see the big numbers." Finally, Tony comes up with a number at the end, and Feynman just explodes in laughter. He says, "So, gravity is repulsive?" [laughs] Because the sign — I remember, the sign came out wrong.

ZIERLER: Oh, wow.

PERIWAL: Oh, Feynman found that hilarious. There wouldn't be any other undergraduates there. I would just go there and just listen to the repartee and the —

ZIERLER: So, back to Princeton. Who becomes your mentor at Princeton?

PERIWAL: Then I spent my whole second year at Princeton, trying to persuade David Gross to take me on, because Edward had no room. He'd already — he had students.

ZIERLER: All the grad students he could handle.

PERIWAL: Yeah. So, he had no room.

ZIERLER: Now, was he at the Institute yet, or he was still in the department?

PERIWAL: No, no. All the time I was at Princeton, he was there. Yeah. He left later — moved to the Institute later. So yeah, he'd be there. And so, at that time — this is called "shooting yourself in the foot." So, I'm struggling, trying to find an advisor, and David sort of gave me a toy problem to work on. And I'm working on this toy problem.

ZIERLER: And what was David's research at this point? What was he pursuing?

PERIWAL: String theory. He was just 100 percent in string theory. Right? They just did the heterotic string, and so everyone was — every seminar at Princeton at that time was all string theory. It was all string theory. Curt was working on it, David was working on it. Edward was working on it. Larry Yaffe was probably the only person — no, two people: Larry Yaffe and Ian Affleck were not doing string theory. Not that they couldn't, but they just would not do it.

ZIERLER: Why not? What was your sense?

PERIWAL: I don't know. I have no idea. Ian Affleck actually was transitioning. He took a sabbatical to go work in France, and he came back, and he had converted completely to condensed matter physics. He's

one of the smartest people I know, but he just did not want to do — he did some very nice work with Michael Dine on supersymmetric field theories, supersymmetric Yang-Mills theories. But after that, after his sabbatical in France, he just worked on condensed matter problems. And Larry Yaffe was doing large N at that time, trying to do symbolic computer calculations of solving large N lattice gauge theory. So, he was deep into computational, symbolic calculations, computation for trying to solve lattice gauge theory. And what was funny was at that time, Edward was learning TeX. Everyone was learning TeX. Nobody wanted to give handwritten manuscripts to secretaries to type up. So, what Edward occasionally would do would be that, you know, they had these terminals all hooked up to a little microcomputer, a little VAX it was, or whatever. And occasionally, he would get logged out while he was editing his manuscripts.

ZIERLER: Oh, no.

PERIWAL: And then, he would come looking for help, and I had very weird working hours at that time. So, occasionally, I would end up helping him recover the files that were, you know, left unsaved. So, after having done this a few times,

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he said, "We should talk sometime" — so, unfortunately, right at that time, David had finally agreed that I could be his graduate student.

ZIERLER: Oh, so you have a problem on your hands now.

PERIWAL: So I said, "No, I already started with Gross" — so there was my — what was funny was that in later times, people were so anxious to be in touch with Edward, even through his surrogate graduate students, right, that people have actually asked me, like, "Oh, are you working with Edward?" And I'd say, "No," and they would stop talking to me. [laughs] Which was kind of funny.

ZIERLER: So, was Witten perceived to be in a different league than Gross at this time? Was he just like, his own category of superstar? What were the differences there?

PERIWAL: Well, you know, in terms of the way they do things, Edward was understood to be on a different plane. Right?

ZIERLER: Not just at Princeton, but probably anywhere.

PERIWAL: Yeah, yeah. I remember David once introduced him at a colloquium, and I don't think Edward was that happy about [laughs] the description. It was like, "Some people have said that string theory is like a church. In that case, Edward is the pope." [laughs] David has a very good sense of humor. But of course, it was true that at that time, in Princeton, you could very definitely say that it was [laughs] kind of like a church. And it was a very exciting time. You got all sorts —

ZIERLER: Now, with string theory at this time, did you feel like the field was on the cusp of something major? Was there that excitement building towards something?

PERIWAL: Yeah. Absolutely. Once I understood what all the excitement was about, about anomaly cancellation and so on, it was clear. Wow, the theory of everything. You know, working out consequences, and so on.

ZIERLER: Like the true unified theory. Yeah.

PERIWAL: Right. Yeah. So there was a lot of genuine excitement. People weren't — but you know — and I worked on it for years. Decades. And I think there probably is something there. But what really —

ZIERLER: Not yet achieved, though.

PERIWAL: Not yet achieved, no. In fact, there was a summer conference in Santa Barbara, and some friends and I, who were not invited, went to it. We flew from Princeton to Santa Barbara, and just used to sit in the back of the auditorium, even though we weren't really supposed to be there. And David laid out, in his first lecture there — he laid out some unsolved problems in string theory. And one of those problems was the string perturbation theory. Right? Does it converge? Does it diverge? What is it? Because you know, one of the things was, string theory is this — there's just one diagram, so to say, at any given order in perturbation theory, whereas field theories in perturbation expansions have a very well understood divergence, because there are so many diagrams. So, it's at best, an asymptotic expansion, which we know. And Q.E.D., you get 14, 15 orders of decimal places of accuracy in prediction. And yet, that perturbation theory _in field theory___ diverges, just simply because there are so many diagrams, and the number of diagrams goes up factorially. So, in string theory, somehow — wait, there's just one diagram at any given loop order. Right? But this diagram must be summed over sort of the different shapes of the surface. So actually David suggested, "Okay, you know what? We did this string —

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heterotic string. Why don't you work out the string field theory of heterotic string theory? And I remember asking him why, and David said, "No, we'll be able to do something nonperturbative with it."

ZIERLER: "Why" as in, "Why are you, David, not working on this? Why are you assigning this to me?"

PERIWAL: No. No, "why" as in, like, "What's the interest?" Because I did not see what the interest was, because I had looked at other string field theories. This was light-cone string field theory, which is a ridiculously ugly form of string theory. You take all the beauty of string theory, right, hammer it away, and then you're left with light-cone string field theory. The idea was that if you had this field theory — string field theory, then you'd have a nonperturbative formulation of string theory. And then, you might try to do something with the nonperturbative formulation. To this day, [laughs] there is no nonperturbative formulation of string theory. Right? So, that's what David asked me to do. And I could not get excited about this, because the light-cone formulation was very mathematically ugly— you take all the beautiful parts about string theory, and it's not that. [laughs] So, I wasted a lot of time doing a bunch of reading about other things, and then I took to avoiding David. So, I would sort of like come into the department at like, 6 p.m. and leave at 2 a.m. or 3 a.m. [laughs] And I guess after a few months, I happened to come across David as he was on his way out. And I'm going — he said, "You should come talk to me." I said, "Yeah." And then I again ignored him for a few months. But this was a really stupid thing to do. I'm not proud of it. But you know, I did it.

ZIERLER: This is not a healthy student advisor relationship.

PERIWAL: No. It's a really, really bad — and it wasn't anything he did. It was just, I was not excited about this problem. So eventually, I did finish it.

ZIERLER: Were you making any headway on it?

PERIWAL: Well, working on it maybe two hours a week and reading other stuff the rest of the time, how much headway could I be making on this? [laughs]

ZIERLER: Right.

PERIWAL: At the end of it, I took about a week to finish it. So I did it, but at the end of a year and a half, or whatever it was.

ZIERLER: Way too much time. Way too long.

PERIWAL: Yeah. And then I asked him, "Okay, so here it is. What are you going to do with it?" So, by that time, he says, "Yeah, I guess there's not — you're not going to be able to get much out of it." [laughs] I didn't tell him "I told you so." But you know, yeah. And yes, I have no idea why I felt this. I can't tell you why. It's just something intuitive, that this is too ugly to actually work.

ZIERLER: Now, were you doing anything applied? Were you working in the labs at all, or this is all theoretical?

PERIWAL: All theoretical. Sit in my office and read papers, books. We had a lot of math books. I took a few math courses. Not seriously enough. I should have worked through some of them, but I'd just sort of sit and listen to the lectures, and so on.

ZIERLER: And how'd you develop and pursue your dissertation?

PERIWAL: So, that was one thing, and then I asked David, "Okay, now this is done. What's the next problem?" So he says, "Why don't you try to prove something about string perturbation theory? What is it about it? Can we show that it diverges?" So now, this problem I liked.

ZIERLER: Why?

PERIWAL: Because it was something that would — you know, there was this big puzzle by this time, in mid-1985, 1986. What is string theory? Is it just, you know, a single diagram at every order in perturbation so how can it diverge? But you have to actually figure out, you know, how this single diagram — what is its contribution, ____.

ZIERLER: So you mean, despite at this point all of the work on string theory, there were still existential questions about what string theory was, that remained to be answered?

PERIWAL: There still are.

ZIERLER: Yeah.

PERIWAL: No one has ever figured out what is string theory. I mean, if you go ask all the eminent string theorists, none of them can answer for you this one simple question. Can you show me a consistent string theory, where supersymmetry is broken?

ZIERLER: Yeah. And David was thinking, with your humble little dissertation, maybe you would answer that question?

PERIWAL: No.

ZIERLER: Or, you would contribute to answering that question.

PERIWAL: So, it was a — as I said, one of the

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questions that David put out in Santa Barbara, at the beginning of the string revolution at that time, was: what is the structure, what is the character of string perturbation theory? So, this is the problem he set me. You know? What is — does it diverge? Does it converge? Okay? So that, I could get my teeth into. And so, I came back a week —

ZIERLER: Okay. Was the math more elegant also here? Was that part of it?

PERIWAL: Actually, the first thing I had to do was figure out in string theory, right, what amplitude are you going to calculate that will show the divergence? And so, the first thing I did was, a couple of weeks later, I looked through how it would work, you know, to show something diverges or converges, you need to have the same sign in everything. Right? You can't have things that are going to have alternating signs and so on. So then, I come back to David, and I said, "How about we show that the dilaton two-point function diverges?" And so, that he agreed: yeah, that would be good, because that doesn't have any photon polarization. It was just a scalar particle two-point function. So then, I had to learn a lot of mathematics, as to like — or at least, understand a little bit of the mathematics as to how exactly do you calculate the contribution of a given order of perturbation theory? See, you have these surfaces with a certain number of handles. Right?

ZIERLER: Yeah.

PERIWAL: Okay. And there's only one surface. If I say, "I have a double torus," you know, "It's got two holes in it," right, that's the unique diagram of two-loop order. But it can have many different shapes, meaning that one hole can be small, the other hole big. The holes could be, you know, sort of elongated, etcetera, etcetera. These are called moduli. Okay? "Moduli" meaning "shape parameters." And it turns out that the number of these shape parameters goes up as 6 times the number of handles minus 6. And so, to calculate the contribution of the surface with the G handles, you need to calculate — you know, there's two parts of a contribution. Right? There's the integral, volume, and there's the function that you integrate. So, we had to show two things: one, that the — how did the volume increase with the number of handles, and two, show that the function that you're integrating actually does not go to zero. Provide a lower bound that's independent of the number of handles.

ZIERLER: Which tells you what?

PERIWAL: Which tells you that the function is lower bounded by this constant, so then it becomes all a question of, "What's the volume? How is the volume increasing as a function of the number of handles?" So, it turns out that we could show that the volume is actually increasing faster than G factorial. Okay? And so, string perturbation theory diverges. And that was the paper we wrote.

ZIERLER: And "we" is you and David.

PERIWAL: Yeah. And that is the only one of David's problems that he phrased in 1985 that I think has been answered. [laughs] At least, he said this at a conference, probably in 1990-something.

ZIERLER: So, this was your dissertation, or this is what led to your dissertation?

PERIWAL: That's one of my — that's the string — the heterotic string field theory is one part. The string perturbation theory diverges is another part. And then I did a couple of other calculations with other — just on my own.

ZIERLER: So, the dissertation was really an amalgam of different problems.

PERIWAL: Yeah.

ZIERLER: Is that standard in theoretical physics, not to have one central research focus?

PERIWAL: Yeah.

ZIERLER: Who was on your committee?

PERIWAL: Who was on my committee? David, Lance Dixon,

[1:30:00]

and —

ZIERLER: Witten was not on your committee.

PERIWAL: No. I didn't ask. Lance was my second reader.

ZIERLER: Does Princeton have an outside reader?

PERIWAL: Nope. David, Lance, and usually — there was an experimentalist. I forget. Who was the third person? I don't know if it was Bob Austin. I'm not sure.

ZIERLER: I'll test your memory on this one, too. Do you remember the title of your dissertation?

PERIWAL: Yeah, I do. "Pointless Strings."

ZIERLER: "Pointless Strings."

PERIWAL: Yeah.

ZIERLER: Was that a double entendre?

PERIWAL: Yeah.

ZIERLER: Did the strings not have points, and they were also pointless?

PERIWAL: And the string perturbation theory diverges, so there's the pointless part of that. [laughs]

ZIERLER: Oh, wow. That's a hat trick. That's three. [laughs]

PERIWAL: Yeah, so that was —

ZIERLER: So, you graduate in 1988, and then you're back to Caltech.

PERIWAL: No.

ZIERLER: You're not.

PERIWAL: No.

ZIERLER: The Institute for Theoretical Physics is not —

PERIWAL: Santa Barbara.

ZIERLER: Oh, that's Santa Barbara. Okay.

PERIWAL: That was the NSF-funded Institute for Theoretical Physics.

ZIERLER: So, it was located in the university, or it was its own thing?

PERIWAL: It was on the sixth floor of a university building, but it was its own thing.

ZIERLER: So, NSF was funding this.

PERIWAL: Yeah. So, this was —

ZIERLER: Were you working for Department of Physics professors, or it was totally separate?

PERIWAL: No, no. See, at the best theoretical physics places, postdocs have complete freedom to do whatever they want. So, I was hoping to go to Berkeley, but I didn't get an offer from Berkeley. And David called up once I had an offer from Steve Weinberg at the University of Texas-Austin, and then I was called up by the ITP in Santa Barbara. So, then there are — but once the ITP called me up, then I told Austin that I wasn't going to go. I wasn't going to come.

ZIERLER: What was the big draw with ITP?

PERIWAL: It's just a — it was a very stimulating place, as in, like people going through. And Andy Strominger called me up to try to persuade me to come to ITP. And he said, "You know, we have this new seminar room." And only when I got there did I found out that they didn't actually have seminars. [laughs] They didn't have money to get seminar speakers for this new seminar room. But it was a good place to be a postdoc. It was very stimulating.

ZIERLER: So, was anybody advising the postdocs, or you were like, truly on your own?

PERIWAL: I just did whatever I wanted. I mean, we'd go to lunch with Andy, and John Cardy. John Cardy was at the department, as was Andy, and Gary Horowitz was there, and Mark Srednicki were there. So, they were the particle theorists at the department.

ZIERLER: It was a strong department.

PERIWAL: It was okay. Andy hadn't made his name yet at that time. John Cardy was, of course — and you know, I learned so much watching John Cardy. John Cardy is a physicist's physicist. He was so precise when he explained something. He was so precise. He was very approachable. I just learned a lot.

ZIERLER: What was he working on at this time?

PERIWAL: He was working on conformal field theories. He's one of the pioneers in conformal field theory, before string theory. And John Cardy, in terms of knowing field theory, I doubt anyone knows more field theory [laughs] than John Cardy. So, I learned a lot from watching John Cardy. And the best work I did in Santa Barbara — so, there was a little excitement over these matrix models of string theory

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that were supposedly, you know, exact solutions of toy models in string theory, then maybe they would give us insights into non-perturbative string theory. In fact, see, one of the things that came out of my string perturbation theory divergence paper was that Steve Shenker, who is a ridiculously smart guy — he looked deeper at the result that David and I had, and he said that it's more than just divergence. That actually, what we'd shown was that it was diverging as 2G factorial, not G factorial, but 2G factorial. And Steve said usually the way it diverges tells you about the magnitude of non-perturbative effects. Like, in field theories, there are these instantons that are non-perturbative phenomena that tell you about different vacuums. They're basically tunneling between vacuums, between ground states. And the divergence of perturbation theory, even in quantum mechanics — like, if you take an anharmonic oscillator — not just a harmonic potential, but an X to the 4^{th} term. Then that X to the 4^{th} term, if you try to do perturbation theory for the coupling constant of that, that perturbation theory will diverge as G factorial, coupling constant, as at Nth order as N factorial. Okay? And what that means is that has a non-perturbative effect that goes as E to the -1 over G. So, E to -1 over PPlanck's constant. In string theory, what we had actually shown was that it goes as 2G factorial, or 2N factorial. What that means is that the strength of non-perturbative effects is not just E to the -1 over Planck's constant. It's E to the -1 over square root of Planck's constant. In other words, non-perturbative effects are much stronger in string theory than in standard quantum mechanics perturbation theory.

ZIERLER: So, did Steve turn your findings on its head, or what was the impact of what —

PERIWAL: No, no. He pointed out that this actually indicated something fundamental about string theory, that its non-perturbative effects were going to be much stronger in string theory.

ZIERLER: Yeah. So, this is something he recognized in yours and David's work, that you yourself did not recognize.

PERIWAL: That we didn't know. No.

ZIERLER: Wow.

PERIWAL: And I've been just — ever since then, I've always thought that Steve is a really smart — okay.

ZIERLER: Yeah. And where were you when you had this interaction with him? Was this at Princeton?

PERIWAL: No. The result came out, and people were a little interested, but they didn't know what to do with it. And our way of calculating didn't tell you what to do with it. But what Steve did was point out that this said something deeper about string theory, and how strong non-perturbative effects were. And I only mention this because then, when I was a postdoc in Santa Barbara, Steve and his postdoc, Michael Douglas, they actually found — and there were a couple of other groups that found this — these matrix models, which are sort of toy models of string theory — that showed these kinds of non-perturbative effects. So, I'm stuck in the boondocks in Santa Barbara. It was the boondocks compared to Princeton string theory. Okay?

ZIERLER: Sure.

PERIWAL: And John Cardy comes back from some conference or something, and he proceeds to explain the work that Steve and Mike Douglas and — he explained it in a lunch seminar. And then, I finally understood what they were doing. And so, once I understood it, then I went to the library — then I had the idea — wait, but there are other matrix models that one could solve exactly.

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And I knew that there was a model of unitary matrices that people had used for lattice gauge theories in the large N limit. So then, one of Andy Strominger's_____ graduate students and I solved the unitary matrix model exactly, following John's exposition, it was now clear to me what was going on, which, the original papers, I had not a clue. What is this about? [laughs] But after John's explanation, then it was clear. We wrote this paper, and that paper is actually what got me a job after Santa Barbara. And I'll tell you, all this time, you know, my deal with my parents was always that if I am able to do physics at the highest level, then I'm going to stay in physics. Otherwise, I would not.

ZIERLER: Back to electrical engineering for you, or something like that.

PERIWAL: Yeah. Whatever. I didn't want to do physics except at the best level.

ZIERLER: So, were they happy when you were accepted into the Institute for Advanced Study?

PERIWAL: It didn't mean anything to them.

ZIERLER: But it meant something to you.

PERIWAL: Yeah.

ZIERLER: And you could communicate to them what that meant.

PERIWAL: Yeah. So then, that work got a little bit of notice. We solved a few other models, and then Edward, who had always written me letters —

ZIERLER: Now, at that point, he had switched over to the Institute.

PERIWAL: Yeah. Now, he was at the Institute. And I met him at a conference, and he says, you know, "You should apply to the Institute." And I said, "Of course, I intend to." But he said that, you know, "You'll likely get a junior faculty position, so you should apply for those, too." So, I said, "That's unlikely, but I will." So, I applied to junior faculty positions, and I was interviewed at a couple of places. And it's a long story. I don't want to get into the unpleasant part of it. But in any case, I did not get a junior faculty position. So, I called up Edward and I said that I'd like to come be a postdoc. And Edward —

ZIERLER: So, that's the position at the Institute. It's not a tenure-track position.

PERIWAL: No, no. Not at all.

ZIERLER: There's no such thing as tenure track in the Institute.

PERIWAL: No, no.

ZIERLER: Right.

PERIWAL: The Institute is a pure research thing. There's only these few professors, and everyone else is just a member who is visiting, either for two years or whatever.

ZIERLER: Right. What was your sense of why the junior faculty search was not going well? I mean, you're clearly an up-and-comer in this field.

PERIWAL: I actually know very well why it wasn't, but I don't want to talk about it.

ZIERLER: Okay.

PERIWAL: It's just — no. But yeah, so I go to the Institute, and I was actually extremely depressed, because I really thought that I —

ZIERLER: Had a future in the academic world.

PERIWAL: Had a future, and I didn't really care about the academic world. I just, as I said, I'm only concerned with doing interesting things. And I thought there would be a longer period to do interesting things, whereas this was another postdoc. So, I went to the Institute.

ZIERLER: But it's a different level of postdoc, too. I mean, it is forward motion.

PERIWAL: Not really.

ZIERLER: No?

PERIWAL: I mean, it's a better postdoc than the Santa Barbara postdoc, as in, it's a more stimulating environment. Notice that I'm always interested [laughs] in the stimulating.

ZIERLER: Sure.

PERIWAL: So, this is great. And so, I had the office next to Edward's, and I did a few things there. And then a couple of years later, there was — I had to look for a job again, and I applied to Princeton as an assistant professor, and I got a job there. So, I went to Princeton as an assistant professor.

ZIERLER: So, it worked for you this time, this job search.

PERIWAL: Yeah.

ZIERLER: Did you apply more widely this time, or this was only this particular job to Princeton?

PERIWAL: Not really. No, I only applied to Princeton, actually. Yeah.

ZIERLER: So, what was it like working at the Institute? I mean, did you feel…

PERIWAL: Oh—

ZIERLER: … like the legacy of Einstein — I mean, is that part of it?

PERIWAL: No. It's a very — it's hard to describe. It's a very ethereal place, so to say.

ZIERLER: I get the sense that you're just — you have access to all the greatest geniuses in the world, across the disciplines.

PERIWAL: You don't really have —

ZIERLER: And you can talk to any of them,

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any time.

PERIWAL: No, you don't really have —

ZIERLER: I guess that's the cartoon perspective of the Institute.

PERIWAL: That's the cartoon perspective. But you know, you get these little vignettes. Right? I mean, like Edward had an office on the — I don't know where his office is now. I'm sure he's moved. But his office was on the second floor, and Frank Wilczek was in the office right below him. And across, on the other side of the building, Steve Adler had his office on one side, and below that was Freeman Dyson's office. Right? And then, the rest of the small offices were postdoc offices. So, it was an interesting atmosphere. And you know, as strong as that set of physicists is, right across was the math department, and there you had, you know, Fields medalists of all sorts. You'd see Pierre Deligne in blackface occasionally. Not blackface like a — it was a Halloween costume, half blackface. [laughs] You know, cavorting with his children. I mean, it was just an interesting atmosphere.

ZIERLER: Was it good for your research? Was it a good time for you?

PERIWAL: I don't think I did particularly interesting research. I did — I mean, I did okay, but I'm not particularly proud of anything I did there, except for one little paper I wrote, in which [laughs] — see, this is called the contrarian part — is I showed — people were very excited about the large N limit, so I took this toy model, and I showed that in the large N limit, it actually produced something nonanalytic, as in like, you could not, in any order of 1 over an expansions, ever see what the answer was that was exact at N equals infinity. So, in other words, it was to me a cautionary tale. Like, you think you're doing large N and then getting an intuition for finite N. But here's this very simple model where you can do the calculation exactly, and you can do all your 1 over N expansion as far as you want, and it'll never tell you

[laughs] about what's going to happen at N equals infinity. But you know, it's a — at this point, string theory was already at that time pretty much a sociological thing.

ZIERLER: What do you mean "sociological"?

PERIWAL: So, it's something that was borne home to me gradually, that there's no experimental proof. Like, are you a good physicist or a bad physicist? Who's going to tell? How do you know? Right?

ZIERLER: Yeah.

PERIWAL: I mean, I'd go and give a talk somewhere, and I remember this very clearly. I went and gave a talk at SUNY Stony Brook, what's now called, I guess, Stony Brook University. And at the end of the talk, I was talking to one of the faculty there who'd invited me. And he said, "So, what does XYZ think of this work?" And I was just taken aback. I was like: wait, you're a physicist. I'm a physicist. Why do we need to know what XYZ thinks of this?

ZIERLER: Yeah.

PERIWAL: Right? That's what I mean by sociology.

ZIERLER: I see. It's as much about what a certain group of peers thinks about the theory.

PERIWAL: Yeah, and this really perturbed me. As far as I was concerned, after the string perturbation theory diverges thing, I was not interested in doing perturbative calculations. So, what the solution was that people did was: okay, we'll work on various supersymmetric theories where there is no higher contribution, and under the assumption that there is supersymmetry, you can use holomorphicity to deduce things from the structure of the fact that there's so much supersymmetry. And this really bothered me, as in: okay, there's this really amazingly beautiful structure, and lots of very pretty mathematical results that are coming out — mathematical results that are suggested by these

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correlations. But I just don't get — as a physicist, I don't to want to have to worry about, "What does XYZ think about what I'm doing?"

ZIERLER: Yeah, because you're pursuing a truth, and it's either true or it's not. It doesn't really matter what other people think about it.

PERIWAL: Right. I really don't care. I mean, no matter how much I respect — and I do — Edward, or David, or whoever, I really don't need to know what they think about my work. Right? I just — anyhow —

ZIERLER: How does that attitude serve you in an academic setting, though? Right?

PERIWAL: It doesn't.

ZIERLER: How does that attitude affect you in terms of tenure considerations and things like that?

PERIWAL: Yeah, so when I was — no, so I actually — I mean, when I was — well, I have no — I'm really stupid sociologically, as in, I have no instinct for self-preservation. So, I could see I had role models in front of me of how people with tenure…

ZIERLER: Succeeded.

PERIWAL: …succeed, not just getting tenure at Princeton, but getting tenure at very good places after Princeton, too. And I paid zero attention to all this. So, while I was at Princeton, I tried doing some lattice gauge theory.

ZIERLER: Were you teaching also?

PERIWAL: Yeah. Actually, I taught one in field theory for a few years, because that's what I loved doing.

ZIERLER: Graduate level?

PERIWAL: Yeah. But I did teach undergraduates.

ZIERLER: How did you like teaching?

PERIWAL: So, the first time I taught undergraduates, I did a really terrible job. Then the math department was offering a teaching seminar.

ZIERLER: As in, how to teach?

PERIWAL: Yeah. So, I went to this, and they videotaped me teaching. Right? And once I saw this, I was like — not teaching like, this math professor who was a very good teacher, who was visiting Princeton. He set us problems, and he said, "Okay, how would you teach this? Next class, we'll videotape this." I see this, and I'm like, "Damn, who could possibly get something out of this monkey jumping around on the blackboard, trying to get all this information across?"

ZIERLER: Yeah, to freshman who have like, no basis to understand what it is you're talking about.

PERIWAL: Yeah, and that was such a salutary thing to see this. And I'm like, "Oh, man. This is so terrible." So after that, I completely changed the way I would teach. And the last two years I was at Princeton, I would just tell the class: this week we have one concept. Everything comes from f=ma. We're just going to do this one concept of how to use f=ma. Right?

ZIERLER: This is really basic stuff.

PERIWAL: And this was to pre-med. And I have to tell you that I suddenly went from being a terrible teacher to people switching out of other people's sections to be in my recitation section. Okay? So yeah, unfortunately I only learned how to teach my last two years in Princeton. But yeah, I mean, there was this whole skill of actually saying: one concept.

ZIERLER: Right. And your goal during these years — you were on a tenure track — was your goal to achieve tenure at Princeton?

PERIWAL: No.

ZIERLER: Or again, you're not thinking strategically.

PERIWAL: I'm not thinking about this at all.

ZIERLER: Okay.

PERIWAL: It's hard to say. You know, in hindsight, like, how stupid could you be? I was.

ZIERLER: So, 2001 comes around, and what's happening now? Because this is when you transition from Princeton to NIH. So, is the message you're not getting tenure at Princeton?

PERIWAL: No. Yeah, yeah. Actually, I remember Curt called me up.

ZIERLER: Who called you up?

PERIWAL: Curt Callan was the chairman of the department, and he said, "Vipul, we won't be able to give you tenure." And I said, "I'm not surprised."

ZIERLER: Yeah. But why are you not surprised?

PERIWAL: Because, you know, it's self-obvious. They recommend you for fellowships, and this and that.

ZIERLER: So, you're not commenting on the quality of your work. You're commenting on your perception of how other faculty members are regarding you.

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PERIWAL: Yeah. It was quite obvious to me, and it didn't bother me at all, because I mean, 1 out of 10 people gets tenure. I never went in there saying that my goal is tenure. It's maybe hard to explain.

ZIERLER: Yeah. It is hard to explain. I'm an academic. You think in terms of tenure, for sure.

PERIWAL: Yeah, but I don't. So as far as I was concerned, this was a great environment, very stimulating, and I want to try to do something interesting. So, I have this really kind of stupid, you know, "swing for the fences" attitude in anything I do.

ZIERLER: So, in terms of self-preservation, you're just not preserving yourself.

PERIWAL: No, no. I would be extinct.

ZIERLER: [laughs] Yeah. Okay, so 2001, you get the message you're not getting tenure at Princeton.

PERIWAL: Right.

ZIERLER: You have a "What next?" moment.

PERIWAL: Well, my last couple of years, I'd been doing work on sort of finding patterns in data. Right? It was an application of field theory that got me into this, and so the genomes — the whole genomes were coming out, like the yeast genome.

ZIERLER: That's my question. So far, I'm not hearing this transition.

PERIWAL: Yeah. Where is the biology?

ZIERLER: Yeah. How are you getting to NIH from Edward Witten? This doesn't make sense yet.

PERIWAL: No, it makes no sense to anybody. So, I'm getting interested in these applications of field theory to finding patterns in biological systems.

ZIERLER: I see. And you're attuned to these quantum leaps in computational power that are happening as well at this time. Right?

PERIWAL: I've always been pretty okay at programming. Right? It just never was needed in string theory. So, I'm relearning — oh yeah, in C, this is how we program, and so on. So I did, and then I would be doing things on the yeast genome, finding patterns and whatnot. I halfheartedly looked for other physics department jobs outside Princeton, after Princeton. And to be very honest, no one offered me one, and I was so sort of —

ZIERLER: You didn't have a positive experience your first time around applying for these jobs.

PERIWAL: Yeah, but that was a very special case. This time around, I was like: do I really want to be in the physics department at Syracuse? How stimulating is this going to be? Do I really want to be at UC-Irvine in physics? You know? I don't know. If you spend your whole life basically shuttling between Princeton and Santa Barbara and so on —

ZIERLER: You're spoiled.

PERIWAL: You're spoiled. You're ridiculously spoiled. Right? So, I could just not bring myself to really put in an effort. I did get interviewed a couple places, but I just —

ZIERLER: You were not feeling it, and you were probably conveying you were not feeling it.

PERIWAL: Yeah, I'm sure I was. So then I thought, okay. Let's just do something completely different.

ZIERLER: Alright. But at Princeton, you're talking about two years before you left there, you started to get into some research…

PERIWAL: Yeah.

ZIERLER: …that eventually had a biological component to it.

PERIWAL: I was doing string-theory kind of things, and this. Right?

ZIERLER: So, what was your entrée into this new field? How did you —

PERIWAL: I didn't come straight here to the NIH. Actually, Sol Gruner, who is at Cornell now, he was at Princeton in biophysics. And he said to me, "Vipul, you're looking for something in biology, right?" Because I'd talked to him and Bob Austin. And Bob was always very kind to me. So was Sol. So, he said, "Maybe you want to talk to these people who are trying to set up a systems biology startup, and these are people at Cornell." So, I go talk to these graduate students, who are trying to do a systems biology startup, and they're looking for someone with an impressive scientific resume that they can trot out in front of venture capital people. Right? And I'm wanting to still do interesting things.

ZIERLER: [laughs] Yeah. Yeah.

PERIWAL: So, never mind that these are graduate students. I have no idea how mature they're going to be in running their startup, and so on, and so forth. I have no idea about their funding.

ZIERLER: You have no background in biology.

PERIWAL: I have no background in biology. I just have an impressive resume. And off I go to work at this company

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for a couple of years.

ZIERLER: Now, was your sense — before you even get there and you know what it is that you're getting yourself into, is your sense that you're leaving physics behind, or are you going in thinking, "I'm bringing all of this physics with me, and I'm going to apply it in this new endeavor?"

PERIWAL: No, it's very, very clear that all the string theory I've been doing for two decades has nothing to do with this. Right? All I'm bringing is sort of a generalized, "This is how physicists solve problems." And the good thing here is that while I was doing theoretical physics, I actually worked on a very broad array of problems. A friend of mine once described it like, "You're not a string theorist. You're basically doing a random walk through all of theoretical physics." And that served me in good stead. So, you know, if it's something that can be approached with a physicist's intuition, I can probably do something with it.

ZIERLER: Even though this is all applied, you're operating strictly in a theoretical world up at this point.

PERIWAL: I am operating totally in a theoretical world. And really, they needed a resume to trot out, and I needed a place where I could learn some biology and do something interesting.

ZIERLER: So, this is your next big adventure into the abyss. This is the next one.

PERIWAL: Yeah. I mean, just think about it. My poor family. At this point, I have a kid. Right? My wife and I have never worked within 50 miles of each other.

ZIERLER: When did you get married? When did that happen?

PERIWAL: That happened the year I became an assistant professor.

ZIERLER: You met your wife in Princeton?

PERIWAL: No, I met her in India, actually. And then she came to be a postdoc at UPenn.

ZIERLER: What's her field?

PERIWAL: She was an immunologist. So, she would take the Amtrak from Princeton to Philadelphia every morning and come back. And then we had a kid three years later. And so, I would take my son and drop him off at the university daycare and go on and teach, and so on, and so forth. So, that was 50 miles or so, whatever the distance from Princeton to Philadelphia. Then after five years, she got a job in Wisconsin, so then she would fly out Monday mornings, and fly back Friday nights, and I would have my son, who was three years old at that time. I would take care of him during the week, and then we

moved — when I was denied tenure at Princeton, or it was clear I was going to be denied tenure, we moved to Wisconsin. And then I would fly and teach at Princeton.

ZIERLER: Oh, man. Whoa.

PERIWAL: Oh, it gets better than that. [laughs] So then, my wife got a job at a big pharma near New York City, so then I would be driving down to Princeton from Rockland County. And then I got this job in Ithaca, so then I made a deal with these graduate students. I said, you know, I'm not coming for five days a week. I'll come up three days a week. So, I'd drive up, and they'd put me up at a motel for three days, and then I'd drive back. And those three days I was there, I was basically working 16-hour days. I was actually driving up to Ithaca exactly when 9/11 happened.

ZIERLER: Oh, wow.

PERIWAL: And I had no idea, because my car didn't have a radio working. So, I see all these New York state trooper cars just go zooming by in the opposite direction at ultra-high speeds, with sirens blaring and what not. And I have no idea what's going on. And I get to my workplace in Ithaca, and people said, "Do you know what happened?" And I was like, "What? No, I don't have a working radio. What happened?" And that was 9/11.

ZIERLER: Wow. So, how did you find the work in Ithaca? Was this exciting to you? Was this a new —

PERIWAL: No, you know, I was just learning a lot about it. They were trying to model colon cancer, and so I didn't know anything about colon cancer. I didn't know anything about mutations and DNA repair and this pathway and that pathway, and so on.

ZIERLER: Was there something exciting about transitioning from a theoretical field

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into doing something that more directly is helpful for people?

PERIWAL: You know, they didn't want me to be mucking around with like, the actual modeling. What they wanted was for me to use my pattern recognition, basically, to help with model selection, to automate what models to build, and something.

ZIERLER: Right, but it's still all geared toward that purpose of advancing human health.

PERIWAL: Right, but that wasn't — for me, the intellectual thing was how the heck do you do this? As in, like, there's so little data, so much information. How do you extract something like this?

ZIERLER: Yeah. So intellectually, the end-point was something that you were separate from.

PERIWAL: Right. And you know, this is — yeah, so that's what — and it's come down to this, that now I — so that's basically what I was doing there, was helping them by trying to come up with ways that you could automatically infer actual mechanisms and models from just raw data. This was my job — was to come up with mechanism inference. So, I have a patent on systems for inferring models from — systems, biology models, from data. Which, it was just — I was driving up and down, and I would think

about what we could do, and blah, blah, blah. And I'd drive up, and I'd tell them, "Hey, you know, we could try this," and they would file a patent thing on that, and some of them were granted. [laughs]

ZIERLER: Was it exciting work? Did you enjoy it?

PERIWAL: I didn't enjoy the graduate student immaturity, though. And I think after a couple of years, it was pretty clear there was an impedance mismatch.

ZIERLER: What became of the product of the research?

PERIWAL: I think the company's still alive. I don't really follow this, because then my wife got tired of big pharma, and she got a job here at the NIH. So, she now manages clinical trials for the National Eye Institute. She's one of the program managers for clinical trials for the NEI. And then, she came for a different job first, so when she got a job here, and I wasn't feeling so great about the graduate students anymore, so then I —

ZIERLER: How did that job pay? Was it good? Comparable to junior faculty kind of position?

PERIWAL: Lower. I mean, this was a startup. But they paid me more than they paid any other employee, and I guess I wasn't very convincing, because they didn't really get venture capital funding [laughs] by trotting me out in front of people. But then, I did have a very jaundiced view of venture capital people, like, they really don't know what they're doing. I got a very jaundiced view of this. And similarly, I've never been as insulted, really, as when I was leaving Princeton, and it was suggested to me that "you might want to look into management consulting." So, I go to some seminar where these management consultants are trying to recruit people, and I sit through the seminar, and I'm like, "Do they really think I'm that stupid?" You know, I really could not bring myself to do this kind of thing. Anyhow, so I didn't become a VC, and I didn't become a management consultant.

ZIERLER: And perhaps, you're harboring — you know, way back in your childhood — some negative memories of your father's experience in business.

PERIWAL: No, I have nothing against business. You know, there's all sorts of very, very useful things that come out of entrepreneurship. Right? What I just find — I just found it silly, like, they'd trot me in front of the VCs, and the VCs would say, "Oh, we had this Ph.D. from Harvard, and I have a Ph.D. from MIT, so you can tell us about the technical things." And I'm like, "Okay, great. Let's go." So I start, and they're like, "No, we don't need quite this level of detail." Okay. Whatever. So what I'm trying to say

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is these are basically people who didn't make it as postdocs. Right? And they didn't have imagination enough to go do something else. But they're still very proud of the fact that they were in this lab at Harvard, or this lab at MIT. Right? So, I can't fake it like this. So, what does this mean? You want detail or you don't want detail. You decide.

ZIERLER: Right. So meanwhile, you see your wife. She's doing well at NIH. She's enjoying this.

PERIWAL: So, she was at the NIH, and so I called around, because as I said, I was getting tired of this graduate-student lifestyle at this startup. And I managed to get in touch with my friend Tony Zee who

was on the faculty at the ITP in Santa Barbara. And I asked Tony. He's very well-connected, and he knows a lot of people. So, I asked him, "Do you know anyone at the NIH?" So, Tony put me in touch with Bill Eaton, who is the head of the lab in which Attila works. And Bill Eaton said, "We don't have a job, but this fellow Carson Chow is moving to NIDDK, and he might have a position. So, I called up Carson. I emailed Carson, like: I was referred by Bill Eaton. Do you happen to have a position? And Carson happens to be one of the ultimate softies. Like, he'll help anybody. I mean, seriously. You know? So, between Carson and Artie Sherman. Right? I ended up in this lab as a contractor. I was working on diabetes and obesity. At this point, I'm just trying to get my foothold and get a job, do the modeling, and so on.

ZIERLER: So this is, in a sense, a continuation of the work you were doing up in Ithaca. Same basic field.

PERIWAL: Yeah, except with real scientists.

ZIERLER: [laughs] Right.

PERIWAL: These are serious people, and this was an interesting problem. Like, why exactly do people get obese? That's when I started here, a long time ago.

ZIERLER: So when did you start? 2002?

PERIWAL: 2003, I think. November, 2003. And so, we were trying to model — what is it about obesity? Why is there obesity? And so on, and so forth. And then I got into different aspects, and then there was a sort of tenure-track position here. So, I applied for it after a year and a half or so. Then, I went through the interview process with various people at different institutes who were all on the selection committee. And then, they hired me.

ZIERLER: What was the general reaction to the fact that you had spent how many years doing string theory, and you know, branches of physics that had nothing at all to do with what you were currently doing at NIH?

PERIWAL: You know, it's whatever Artie and Carson saw in me. I mean, they'd seen me working for a year and a half on problems dealing with obesity and diabetes. So, whatever it is that they saw in me — I don't know.

ZIERLER: Right. Now, are you learning biology on the fly? Are you teaching yourself with textbooks?

PERIWAL: No, I learned a lot of biology just sort of on the fly when I was in Ithaca for two years. And you know, the neat thing about biology is it's a very broad field, but it's very shallow.

ZIERLER: Yeah. Keir Neuman made exactly that same point. He said exactly the same thing…

PERIWAL: Really?

ZIERLER: …in almost exactly those words. Yeah.

PERIWAL: Look, I'm a theorist. And when I look at different areas of biology, I'm struck by the similarities.

ZIERLER: Like what? What's an example of the similarities?

PERIWAL: If you look at,

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say, adipose tissue, it has some dynamics. Like, when there's excess fat that needs to be stored, then fat cells get bigger, and they can't really get too big. If they get too big, then they become mechanically very fragile, really. And then, there's kind of a feedback loop, that they recruit new cells. So, this kind of feedback, where there's a demand, there's an adaptation, and then there's further adaptation if that adaptation wasn't enough, recruit new cells. Things like that. Right? Look at beta cells in diabetes, or as you get Type 2 diabetes. So, there starts to be too much glucose, you get higher insulin, and that stresses out beta cells. Unfortunately, beta cells are not that good at recruiting — producing more beta cells. But the feedback — these are systems that are designed to be robust. And so that kind of robustness — how do you inherit that kind of robustness? Because you see —

ZIERLER: Genetically, you mean?

PERIWAL: Yeah. So, there's this theoretical problem, really, in biology that if I become highly tuned to my environment, that doesn't mean that my fine-tuning in my lifetime is going to be inherited by my progeny. What I'm passing on is my germline, which is in your testes and ovaries. That genome is actually not the genome in most of your cells. This is your somatic — any mutation that happens on my skin is not going to affect my children. And so, the question is: any optimization you do, any fine-tuning, is not going to be inherited unless it's actually in your germline. And so, natural selection — this is a big puzzle. How exactly — I mean, natural selection is: everyone has lots of children, and the fittest survive. But the fittest who are actually able to — who actually have the mutations in their germline that can be inherited. As I said, if I become a really good sprinter, my germline doesn't know about this. [laughs] So, this is the Lamarck versus Darwin. So, what makes this robustness heritable? Because in any dynamics, if you do dynamical systems, then you know that things are chaotic, the slightest change in parameters leads to completely different behavior. But what we're talking about is for most mutations, that could happen in your progeny, they're going to function pretty much the same as you do. Why is that? For such a highly complex dynamical system, what principle of organization is there? That homeostatic robustness — me, being able to deal with freezing temperatures or the Sahara — can go along with genetic robustness. You know, there are these few mutations that happen every time people have children, and yet, the children are grossly like their parents. Right? So, there's this balance. You can't think that because I've become a good sprinter that you'll pass that on. It's not going to happen. But nevertheless, the circuitry that you pass on, that is capable of adaptation. And how do you make it? So, that's the kind of question that is very general in biology. It affects everything in biology.

And the other amazing thing about biology is that whether you're a mouse, a human, a rat, a dog, many of your systems are going to function exactly the same. The enzymes will work pretty much the same. It's just little tweaks in the control make it that we don't develop tails, but mice do. Right? Just very little tweaks. So, we made a model of liver regeneration, which is this amazing process. You cut off a certain part of the liver, and the remaining part increases to the same mass as the original mass, plus or minus 10 percent, or whatever. It doesn't become cancerous. Like, it's not uncontrolled proliferation. It's exactly smoothly going back to the same mass. So, we made a model of this, and amazingly enough, with the one parameter change, there's a straight line in the predictions between mouse, rabbit, dog,

rat, human, in one straight line. One parameter change. That parameter change is related to the body mass. And this has the biochemistry of signaling, etcetera, etcetera, in it, but on these vastly different timescales. A mouse regenerates its liver in like, three weeks. Humans take about nine months. The biochemistry is unchanged. So, that's the kind of thing that — I mean, a physicist looks at this, and it's like: what kind of dynamical system can I make, where this kind of robustness — it just, you know, you cut off part of it, it'll just go smoothly, proliferate, come back to the same mass.

ZIERLER: Now, in creating these systems, is the goal that the research will ultimately have clinical value? What's the end product of the research into the systems?

PERIWAL: Oh, we do all sorts of things, some of which have clinical aspects. So, we've gotten into —

ZIERLER: And "we" is who? Who do you mean by "we"?

PERIWAL: My group. I have three postdocs, usually. So, what we do is we've sort of — we do occasionally make detailed models, for instance — we published a model about calcium dynamics and mitochondria meeting the endoplasmic reticulum, and how that gets affected in obesity, and so on and so forth. But in general, a lot of what we're doing these days is almost machine learning, except what we call mechanistic machine learning — like, I don't want any black boxes in the models I make. What I want is to know mechanism. Why does this going up lead to this going down?

ZIERLER: Now, when you say "machine learning," is that because there's so much data to deal with?

PERIWAL: No, it's basically that all of biology is only partially observable. There is nothing, no organism, that you can actually observe in completeness while living.

ZIERLER: What's the limitation?

PERIWAL: You observe everything, it's dead.

ZIERLER: Oh, I see.

PERIWAL: You cannot dynamically follow every protein in any organism over any period of time.

ZIERLER: And this is a limitation of technology? Do you see a point where we can get to that capability, or it's beyond technological solutions?

PERIWAL: Even for a bacterium, we don't even know. There are 4,000 odd genes in E coli. We don't even know the functions of most of those genes — of a lot of those genes. Can you imagine following the protein products of several thousand genes in a single E coli? This is not going to happen.

ZIERLER: So, I guess this is the point in the interview when we get to more philosophical, bigger questions.

PERIWAL: No, no. This is a technical question.

ZIERLER: Yeah?

PERIWAL: You can't do this.

ZIERLER: Well, but the question is: when you look at ultimate mysteries, when you're thinking about string theory or you're looking at E coli, are they equally mysterious? Are they different categories of mystery?

PERIWAL: It's kind of, like,

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diametrically opposite, as in, a string theorist or a fundamental physicist — what they're trying to do is: what is the fundamental law? What is it that would explain everything? Whereas Darwin gave biologists…

ZIERLER: A unified theory.

PERIWAL: …a unified theory.

ZIERLER: So, you accept the theory of evolution as the unified theory of biology?

PERIWAL: But, the point is, how exactly does this lead to this balance between genetic robustness and homeostatic robustness?

ZIERLER: Yeah.

PERIWAL: What is it about the circuitry? How is it implemented? Right? What's the architecture of biological systems that enables this to work? So, people say: oh, you know, it's a miracle. Life is a miracle. If you just put together a random set of chemical reactions, you could never reproduce it. But that's actually — from an information theoretic point of view, that's just stupid. Because actually, by definition of living — which means basically reproducing —

ZIERLER: "Life" means "the capacity to reproduce."

PERIWAL: Yes. So, in that sense, most of these chemical reactions, grab-bags that you might put together, they don't have the capacity to reproduce. So, the universe of possible reactions that you need to look at is much, much smaller than any old random chemical reaction, because by definition, you're only investigating self-reproducing chemical reactions. Right? So, it's a much smaller universe. But now, you want not just that shouldn't — it has to be self-reproducing. So, it has to produce another reaction, or it has to split up into two reactions that are each going to self-reproduce. How can you make this robust? If you come up with a cycling reaction, where it cycles over and over — but it's not robust. If you change the temperature beyond a certain range or something, it doesn't do the cycling anymore. But, living things that can reproduce themselves over and over and over — what's the architecture, and what's the essential architecture, that everything else is just sort of icing. Right? E coli does it. We do it. This reproduction business — but what is the essential aspect of what makes this architecture inheritable?

ZIERLER: That's the big question.

PERIWAL: This is a puzzle. You know, so that's what I mean by diametrically opposite. On the one hand, in string theory, you don't have any idea. What is the law? And in biology: here's the law. How exactly does it work? In other words, what's the inclined plane for this law?

ZIERLER: Yeah. Are you more confident that the question on the architecture in biology is answerable, or that the string theory can be proven?

PERIWAL: I would say that probably both of them require the same sort of approach to answer that. Now, that may seem like a very strange thing.

ZIERLER: I can't wait to hear what you say next.

PERIWAL: Look. You know, if you go back — since I stopped doing string theory, I'm free to think non-stringy thoughts. No, it's a very simple thing, really. When you look at general relativity, Einstein said things about meter sticks and lightbulbs. What was he talking about? Events. Right?

ZIERLER: Yeah.

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PERIWAL: So now, tell me this: how exactly — I asked Gell-Mann this at a colloquium. He was talking about this information gathering and utilization systems that Jim Hartle and he were developing a theory of quantum cosmology. So, he starts — he was giving a colloquium at the ITP. He was visiting the ITP in Santa Barbara, and he was giving a colloquium, so he was talking about this. So, being a very bumptious postdoc, I raised my hand, and I said, "You're assuming that there is a tomorrow." And he became red in the face, and he said, "My doctor won't let me answer such questions." And Frank Wilczek was sitting behind me. And Frank says, "But you didn't answer his question."

ZIERLER: [laughs] Where were you coming from with this question?

PERIWAL: I'll explain. Look, we talk about space-time, Lorentz transformations, and so on, and so forth. Look, we're living on one slice of space. So what's the Lorentz transformation doing, really? There is no time. Okay? So, what's the Lorentz transformation doing? It's actually just "recoordinatizing" our space-like slice. Right?

ZIERLER: Constantly, or once?

PERIWAL: It doesn't matter.

ZIERLER: It doesn't matter.

PERIWAL: Because two seconds ago doesn't exist anymore. Two seconds from now doesn't exist. Well, now it does, but we've lost something. So, when you do a Lorentz transformation, we say: this is X, and this is T. And when we do a Lorentz transformation, the light cone doesn't change, but the X and T relationship changes. There is no T.

ZIERLER: There is no T.

PERIWAL: Okay? So, the Lorentz transformation is doing what? Do you see what I'm saying?

ZIERLER: Yeah.

PERIWAL: And when we do quantum field theory, we're doing this — you know, we're integrating Feynman diagram momenta. We're doing all these Fourier transforms, which include Fourier transforms in the time direction, and so on. Right?

ZIERLER: Right.

PERIWAL: Is there a tomorrow? [laughs]

ZIERLER: Yeah. Yeah. So, how did he answer?

PERIWAL: No, he couldn't.

ZIERLER: He couldn't.

PERIWAL: You can't. Okay? Because if you claim you're doing quantum cosmology, you're basically assuming that there is a tomorrow. But actually, in quantum gravity, the whole momentum of tomorrow is encoded in the variables on a slice.

ZIERLER: Is it fair to assume that there was a yesterday, because it happened?

PERIWAL: Not really.

ZIERLER: Does it work — so it works both ways.

PERIWAL: Yeah. You only get artifacts of the fact that there was a yesterday. It's some history that's built into whatever slice you're on.

ZIERLER: But in biology —

PERIWAL: Why am I saying — let me — so what I'm trying to say is that something that's event-driven, in trying to deduce "What is space-time?" — that's basically — you have to figure out: these are the events. You have to figure out, "What is the causal relationship between them?" Right? That's what's going to define time. So, if you like, it's an artificial intelligence learning problem of — these are the events. What space-time structure might be consistent with these events? And that should give you a prediction for what you might expect at the next instant. But there are no meter sticks and candles anywhere. So it's only the events that exist, that you have to weave a dynamical prediction of what might happen later. And I know, this is like a really, hand-wavy completely generic problem.

ZIERLER: Well —

PERIWAL: But, you know, the issue is that nobody who does quantum gravity or string theory will say any such thing, because you don't actually have a handle

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on how you're going to answer this question. In biology, what my group does is try to make models from — in the limit of very little data. Everyone talks about big data. So, here's a thought. The genome has 3 billion base pairs. If I'm trying to understand the interactions or correlations between these 3 billion base pairs, how many human beings do I need?

ZIERLER: One?

PERIWAL: What are you talking about? I'm talking about possible correlations between, you know, an A here at position 200 million on the 5th chromosome, and position 25 million on the 18th chromosome. Right? If this is an A, will this be a T? C? You know, what's the probability? So in other words, I have to calculate some sort of correlation matrix that is 3 billion by 3 billion. And that's just talking about correlations. Not even talking about non-linear interactions. So, if I have a 3 billion by 3 billion matrix, how many genomes do I need to be able to fill it out?

ZIERLER: [laughs] You'd better tell me.

PERIWAL: 3 billion squared, at least! How many human beings exist? Maybe 10 billion.

ZIERLER: Ah. Right.

PERIWAL: So, you could sequence every human being…

ZIERLER: And still get a fraction, a tiny fraction.

PERIWAL: …and still not be able to tell. So, it's really — statisticians don't like these problems. Statisticians work in the limit, like — in the limit of infinite data, we can prove that we will converge to the right answer. So, my group works on — with very little data, what's the best inference you can do?

ZIERLER: Yeah. Right. So, to get back to this question of mysteries, you know, whether it's string theory or it's fundamental questions of biology — so, the Socratic idea that the more you know about something, the more you know you don't know. Right? Do you find that to be more true here in your work at NIH than it was in your previous life in string theory?

PERIWAL: Yeah, because in string theory, there's the physicist's prior expectation that you're going to find the next f=ma. Right? So that's always guiding you towards —

ZIERLER: The fundamental laws of physics is always your baseline.

PERIWAL: Yes.

ZIERLER: There's no deviation from that.

PERIWAL: It's got to become simpler. If it's not simpler, it's not right.

ZIERLER: Right. But in biology, life, there's no limit.

PERIWAL: There's no limit. Well, there's no limit to how many interactions there can be. Biologists — when I started out, they used to think in terms of: there's this pathway, so there's this input, and it cascades through this molecule, this, this, this, and then it affects this. Then they realized fairly quickly — not fairly quickly, actually. When they started doing large-scale measurements in systems biology 20 years ago, then they realized that, whoops, all these pathways actually interact. So, it's not really one pathway, another pathway. There are all sorts of interactions between them. And when I came into biology, they were really into — it's got to be modular, the design of biology. Biological systems, they have to be modular.

ZIERLER: Why? Why do they have to be modular?

PERIWAL: I couldn't tell. So, I've been in arguments with people. Like, you keep telling me it's got to be modular.

ZIERLER: So, this is orthodoxy that you just don't accept.

PERIWAL: Yeah. I don't accept it, and now they've come to the point where they don't accept it, either. I read a paper a couple of weeks ago. It was like, people not realizing that maybe the resiliency of biological things is because of all the interactions. And it's like, "You don't say!"

ZIERLER: Right.

PERIWAL: But, you know, the whole point was they were trying to explain things.

ZIERLER: But don't biological systems also have to accord with fundamental laws of physics?

PERIWAL: Oh, they do, but that's not useful information.

ZIERLER: Aha. It's not what, it's not clinically useful?

PERIWAL: It's not clinically useful. It doesn't explain the function, because yes, quantum mechanics underlies every molecule. Okay?

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At the same time, a big protein interacting with another protein, it has possibly an active residue that is going to make sure that some ligand binds and then it changes conformation then it can go dock on some other protein or DNA, whatever. Right? So yeah, somewhere in there, there is that little quantum mechanical interaction that's going to cause it to flip. But it does not help you understand — quantum mechanics is pretty irrelevant to the rest of the protein structure, and probably the DNA binding, etcetera, etcetera. So, you can't actually — the problem with biology is that there is no scale separation. There is no scale separation. Things that happen at an amino acid or atomic level will affect the function of your liver, which will affect the function of the whole organism. So, this business of scale separation, it really conflicts with biological function, and that's one of the things that makes biology incredibly hard to model, is: where are you going to put the scale separation? So, what we try to do is we try to make effective models, as in like, this is your data. This is the model we made without any assumptions, just using the data. So, what we want is to say, okay, it's some predictive model that says that if you tweak this, this will change. And we'll tell you what interactions are going to take place for this to happen. But these aren't molecular interactions. They're some sort of effective interactions, because there are bunches of hidden things that you didn't see, or you didn't observe, because you can't observe everything.

So, it might be that there's some hidden molecule that interacts between A and C, called B, which you didn't observe, so we're going to say in our effective model that there's an interaction from A to C, but actually, it's through B. Right? But we didn't see B. But we can still make this prediction. So, our goal is to make predictive models of disease that are useful, but that give you some mechanistic understanding at the effective model level. I mean, biology is not easy if you want to do it right. So, if you want to do it right, I mean, to make a predictive model, and you know, physicists have a lot of hubris. They do. There's no doubt about it. Yes, our physical principles will guide everything. Yeah. You know? Physical principles

do guide everything. But at the same time, physical principles at the atomic level are not going to explain to you what the conformations of chromosomes are inside a nucleus.

ZIERLER: And they're certainly not going to help develop a treatment that's going to —

PERIWAL: No, they're not. So, if you can make a predictive model that someone can test again with the predictions, and you can refine the model, at some point, we hope it's a useful model that can be used for something that has a consequence. That's what I would ideally like.

ZIERLER: So, last question, as we're thinking toward the future. The language that you're using right now, it's very much forward-looking in terms of how all of this work will lead to some eventual success. Does that mean that so far in your time at NIH, you haven't achieved this satisfying moment of creating this model that for sure establishes a predictive basis for one thing leading to another?

PERIWAL: Actually, our liver regeneration model is predictive.

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ZIERLER: Is it clinically valuable?

PERIWAL: Well, we're trying to make it clinically valuable. I just got — I'm negotiating for access to clinical data from some group in Dallas that took repeated measurements on liver donor patients that I would like to correlate with our liver model to make it clinically relevant. But for the last few years, what we have been trying to do is develop techniques that we can apply to any old data.

ZIERLER: That can be universally applied.

PERIWAL: Yeah.

ZIERLER: So, there's some breakthrough that you're working toward, that can be applied in any number of systems.

PERIWAL: Right. Yeah. We really do best when we think in general terms, because these problems occur everywhere.

ZIERLER: Yeah. Everywhere in the body.

PERIWAL: Everywhere in biology.

ZIERLER: Everywhere in biology. Right.

PERIWAL: And if we can solve it from an abstract point of view — like, we invented a technique for how you deduce how many hidden variables there are in some data. Right? You observe some interactions. You observe the consequences of certain interactions. But there are things that you did not measure. Can you get an estimate for what those things are and how they're interacting? So, that kind of thing is trying to make a better predictive model, getting at the things that you couldn't observe in biology. But of course, it's all in a statistical physics framework, so it actually applies to anyplace where you'll do this. Like, all of machine learning, or all of artificial intelligence. But we're motivated, really, by biological data sets, because even in this era of big data, as I tried to convince you, that [laughs] there's not enough data for the complexity of biological things. So, if there isn't —

ZIERLER: How can that be? How can there be not enough data? I mean, isn't the data representative of the biology?

PERIWAL: Well, let me put it this way: if you think that a Twitter feed, or even the Twitter deluge — like, if you get every tweet being sent — tells you about human psychology.

ZIERLER: Aha. I see. It's a fair metaphor.

PERIWAL: That's a lot of data, right? How much information does it tell you about neuroscience?

ZIERLER: Alright. So, really, the last question: what does the big breakthrough moment look like for you? How would you conceptualize this in terms of putting all of this together? What does that big breakthrough look like?

PERIWAL: If I could make a prediction that was clinically testable, that would make me very happy.

ZIERLER: Do you think you'll get there? It's the thing that motivates you.

PERIWAL: Yeah. I want — you know, I said this once. We had someone visiting when I was managing the physics seminar at Princeton once, as an assistant professor. So, this guy asked me, "So, Vipul, what are you working on?" And I was very jaundiced at that time about making a prediction. So, I said, "Well, lattice gauge theory," which, you know, nobody at Princeton did lattice gauge theory. You were all supposed to be doing string theory. I said, "Yeah, I want a number before I die." [laughs] People are looking at me like, "What kind of lunatic is this?" But you know, a number. That would be nice.

ZIERLER: [laughs] Yeah. Well, Dr. Periwal, this has been an absolute delight.

PERIWAL: I'm sorry. It's — you know, you ask me questions close to [laughs] —

ZIERLER: This is the idea. And it's just such a remarkable — I mean, a career trajectory from being a kid in India, reading the lectures of Feynman, Caltech, string theory, and now here at NIH, it's just a — what a wild ride it's been for you.

PERIWAL: It has. And I tell my children, you know, that I don't care what you do. But you know, you'd be very lucky if you manage to amuse yourself as long as I have.

ZIERLER: And apparently have a sense of adventure along the way.

PERIWAL: Yeah. Who wants to be a dweeb, going to a desk job, and doing — I mean, I have friends who work on Wall Street, and they've

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asked me — not for the last 15, 20 years, but when I was leaving physics, they asked me, "Hey, do you want to come work on Wall Street?" And I actually went and talked to one or two of them and asked them, "What would I be doing?" And they were my friends. They were very honest. They said, "You'll be doing this, or this." And you know, yes, it's very remunerative, but I can't quite see myself doing this.

ZIERLER: Yeah.

PERIWAL: You know, low pay and long hours, that's me. [laughs]

ZIERLER: That's you. [laughs]

PERIWAL: That's right.

ZIERLER: Well, thank you so much. This has been great.

PERIWAL: You're very welcome.

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[END]