

# One Entangled Evening A Celebration of Feynman's Quantum Legacy

TUESDAY, JANUARY 26, 2016



Welcome to the California Institute of Technology. We are delighted to have you join us for this special evening of exploration, wonder, and celebration.

Caltech scientists and engineers probe the secrets of the universe and translate their discoveries into life-changing inventions. There is no more fundamental paradigm of nature than quantum mechanics – the microscopic rules of the road – and no more impactful technological arena. Advances in quantum science underlie 50 years of spectacular progress in computers, communication, and imaging.

The best is yet to come. Tonight we are only constrained by our imaginations. In the spirit of Richard Feynman, we aim to capture the playful spirit of adventure that animates discovery.

# Thomas F. Rosenbaum

President, California Institute of Technology Sonja and William Davidow Presidential Chair and Professor of Physics



# **RICHARD P. FEYNMAN**

Richard P. Feynman was born in 1918 and grew up in Far Rockaway, Queens, where he earned a reputation among his neighbors as the boy who "fixes radios by thinking." Feynman attended MIT, and received his PhD in Physics at Princeton in 1942, supervised by John Wheeler. While at Los Alamos during World War II working on the Manhattan Project, he drew attention for his prowess at both theoretical physics and safecracking.

Feynman joined the Caltech faculty in 1950, and spent the rest of his career here as the Richard Chase Tolman Professor of Theoretical Physics. His lectures to freshmen and sophomores in 1961-63 were published as The Feynman Lectures on Physics, one of the most popular physics books ever written.



Feynman shared the 1965 Nobel Prize in Physics for his work on quantum electrodynamics. He foresaw the promise of nanotechnology in his 1959 lecture "There's plenty of room at the bottom," and in 1981 he proposed the idea of a quantum computer that can solve problems beyond the reach of conventional digital computers. Feynman's fame expanded in 1986 due to his critical role in the Presidential commission investigating the explosion of the space shuttle Challenger.

A brilliant teacher, Feynman had a rare talent for conveying the excitement of science to the general public. He was a skilled painter and bongo player, who once performed onstage as the Chief of Bali Ha'i in a Caltech production of South Pacific.

Even among scientists, Feynman was revered for his intellectual gifts. As the mathematician Mark Kac put it:

There are two kinds of geniuses: the "ordinary" and the "magicians." An ordinary genius is a fellow whom you and I would be just as good as, if we were only many times better. There is no mystery as to how his mind works. Once we understand what they've done, we feel certain that we, too, could have done it. It is different with the magicians. Even after we understand what they have done it is completely dark. Richard Feynman is a magician of the highest caliber.

Richard Feynman died in 1988 at age 69 after a long battle with abdominal cancer. He is sorely missed.

THIS STUFF IS IMPORTANT (IN SPITE OF APPEARANCES)

> PLEASE DO NOT DESTROY

R.P. Feynman



Caltech

The Division of Physics, Mathematics and Astronomy The Institute for Quantum Information and Matter

The Division of Engineering and Applied Science

and

The Kavli Foundation

Present



Executive Producers

John Preskill Oskar Painter

Artistic Director & Producer Crystal Dilworth

Producers

Cindi Dale Leslie Maxfield Spiros Michalakis

Production Design Margaret Sanchez Live Show Video Director Director Michelle Attebery Jodie Lee

Illustrator Jorge Cham

### **Production Team**

Ed Brown, Marcia Brown, Gina Chen, Erik Ferguson, Mary Herrera, Adam Jacob, Jeff Lewis, Dwayne Miles, James Muro, Gina Marie Napolitan, Jackie O'Sullivan, Robin Puri, Randy Rose, Cara Stemen

 Graphical depiction of a holographic code, which models the emergence of spacetime from quantum entanglement.

# ACT

# The Character of Physical Law

The Messenger Lecture, "Probability and Uncertainty" • 1964 Steve Collins as Richard P. Feynman

# Michelle Feynman

Daughter of Richard P. Feynman

# The Best Teacher I Never Had

Bill Gates, Co-founder, Microsoft and Co-chair, Bill & Melinda Gates Foundation

Video courtesy of the office of Bill Gates

# Quantum is Different, Part 1

John Preskill Director, Institute for Quantum Information and Matter, Caltech Richard P. Feynman Professor of Theoretical Physics

# Quantum Computing: Beyond the Digital Age

Krysta Svore, Senior Researcher, Microsoft Quantum Architectures and Computation Group

# **Tiny Machines**

Richard P. Feynman Excerpt from Idiosyncratic Thinking Workshop · 1984

# Quantum Computing and Schrodinger's Cat

David Wineland, Nobel Prize, Physics 2012 Scientist, National Institute of Standards and Technology

# ACT II

One Entangled Evening Performance by John Preskill & Gia Mora

# Quantum is Different, Part 2

John Preskill Director, Institute for Quantum Information and Matter Richard P. Feynman Professor of Theoretical Physics, Caltech

# Greater than its Parts

Institute for Quantum Information and Matter Video by Iram Parveen Bilal

Breakthrough Initiatives Yuri Milner, Founder, DST Global

# Anyone Can Quantum

Stephen Hawking & Paul Rudd Narrated by Keanu Reeves

Video by Trouper Productions, Inc. Christopher Cantwell · Creator, Quantum Chess

## Suppositions and Superpositions

Thomas F. Rosenbaum, President, Caltech Sonja and William Davidow Presidential Chair and Professor of Physics

# The Character of Physical Law

Richard P. Feynman The Messenger Lecture, "Seeking New Laws" • 1964

# INTERMISSION

Video from tonight's performance will be made available online at IQIM.caltech.edu



TACIT South Pacific · 1982 >

# To the tune of Some Enchanted Evening. Adapted by John Preskill, with apologies to Rodgers & Hammerstein.

< TACIT Guys and Dolls · 1977

One entangled evening We will see a qubit, And another qubit Across a crowded lab,

And somehow we'll know, We'll know even then, This qubit's entangled Aligned with its friend!

One entangled evening We'll cool down a circuit. See if we can work it At 20 milli-K.

A circuit that cold Is worth more than gold 'Cause qubits within it Will do as they're told! Quantum's inviting Just as Feynman knew. The future's exciting If we see it through!

One Entangled Evening

One entangled evening Anyons will be braiding And thereby evading The noise that haunts the lab.

Then our quantum goods Will work as they should, Solving the problems No old gadget could!

Once we have dreamt it We can make it so. Once we have dreamt it We can make it so!

Arrangement by Charles Barnett



## **Steve Collins**

Steve Collins is a guidance and control engineer at Caltech's Jet Propulsion Laboratory. He has worked on numerous NASA/JPL missions including Mars Curiosity, Dawn, Deep Impact, and MER. Steve has degrees in both Physics and Theater from the University of California, Santa Cruz and has performed on stage for over 20 years with TACIT, Caltech's resident theater ensemble. Steve previously appeared as Dr. Feynman as part of the 2011 Caltech TEDx.



### **Bill Gates**

Bill Gates is a technologist, business leader, and philanthropist. He grew up in Seattle, Washington, and dropped out of college to start Microsoft with his childhood friend Paul Allen. He first saw Dr. Feynman's Messenger Lectures while on vacation in the 1980s and enjoyed them so much that he eventually initiated Microsoft's Project Tuva, which made the lectures available online for free. Today, Bill and his wife, Melinda, co-chair the charitable foundation bearing their names and are working together to give their wealth back to society.



#### Michelle Feynman

Michelle Feynman is the daughter of Richard Feynman. A graduate of Art Center College of Design, Michelle works as a communications officer and photographer at Polytechnic School, where she captures moments with students in kindergarten through twelfth grade and shares them with the school community.

She has edited a collection of her father's quotes called The Quotable Feynman, as well as Perfectly Reasonable Deviations from the Beaten Track: The Letters of Richard P. Feynman, a collection of letters to and from her father. Michelle has also gathered a compilation of her father's artwork in a book entitled The Art of Richard P. Feynman: Images by a Curious Character.



# **Stephen Hawking**

Stephen Hawking is the Dennis Stanton Avery and Sally Tsui Wong-Avery Director of Research at the Department of Applied Mathematics and Theoretical Physics, and Founder of the Centre for Theoretical Cosmology at Cambridge. Along with A Brief History of Time, his books for the general reader include A Briefer History of Time, the essay collection Black Holes and Baby Universes, and The Universe in a Nutshell.

In 1963, Hawking contracted motor neuron disease and was given two years to live. Yet he went on to Cambridge to become a brilliant researcher and Professorial Fellow at Gonville and Caius College. From 1979 to 2009 he held the post of Lucasian Professor at Cambridge, the chair held by Isaac Newton. A Fellow of the Royal Society and a Member of the US National Academy of Science, Hawking is regarded as one of the most brilliant theoretical physicists since Einstein. He continues to combine family life with research, along with an extensive program of travel and public lectures. He still hopes to make it into space one day.



### Yuri Milner

Yuri Milner founded Mail.ru Group in 1999 and under his leadership it became one of Europe's leading internet companies. Yuri took that business public in 2010 and founded DST Global to focus on global internet investments. DST Global became one of the world's leading technology investors and its portfolio has included some of the world's most prominent internet companies, such as Facebook, Twitter, WhatsApp, Snapchat, Airbnb, Spotify, Alibaba, Xiaomi, Flipkart and others.

Yuri graduated in 1985 with the advanced degree in theoretical physics and subsequently conducted research in quantum field theory. In 2012 Yuri and Julia Milner, together with Sergey Brin and Anne Wojcicki, Mark Zuckerberg and Priscilla Chan, and Jack Ma and Cathy Zhang launched the Breakthrough Prizes - the largest scientific awards in the world, honoring important, primarily recent, achievements in Fundamental Physics, Life Sciences and Mathematics. In July 2015 Yuri launched the \$100 million Breakthrough Initiatives to reinvigorate the search for extraterrestrial intelligence in the Universe. Yuri lives in Silicon Valley with his family.



# John Preskill

John Preskill is the Richard P. Feynman Professor of Theoretical Physics at the California Institute of Technology, and Director of the Institute for Quantum Information and Matter at Caltech. A graduate of Princeton (B.A. 1975), and Harvard University (Ph.D. 1980), Preskill began his career in particle physics and cosmology, but in the 1990s he got excited about the possibility of solving otherwise intractable problems by exploiting quantum physics. He is especially intrigued by the ways our deepening understanding of quantum information and quantum computing can be applied to other fundamental issues in physics, such as the quantum structure of space and time.



www.GiaMora.com

# Gia Mora

Gia Mora is a multifaceted performer and writer. Her critically acclaimed one-woman show, Einstein's Girl, has played to sold out houses on both coasts and continues to tour the country. She has appeared on True Detective, Impress Me, and Castle among others, and she boasts an extensive theatre resume having received four Helen Hayes nominations. Modern Songbook Records released her second album, Gia Mora Sings Charlie Barnett, in 2015. When she's not working, Miz Mora is a "wannabe theoretical physicist," promoting STEAM education and science literacy with the screen sirens for science, Scirens. She also serves on the board of the SoCal Science Café.

# Keanu Reeves

Keanu Reeves is one of Hollywood's most versatile actors. Best known for "The Matrix" trilogy, Reeves began his acting career on the stage, moving quickly to television and the big screen where he has tackled a broad range of roles including his iconic appearance as Ted in "Bill & Ted's Excellent Adventure." The role of Bill was played by Alex Winter, director of the Quantum Chess video. Reeves made his directorial debut in 2012 with the documentary "Side By Side," which explores the history of filmmaking.



# Thomas F. Rosenbaum

Thomas F. Rosenbaum, Caltech's ninth president, is the Sonja and William Davidow Presidential Chair and professor of physics.

Dr. Rosenbaum is an expert on the quantum mechanical nature of materials—the physics of electronic, magnetic, and optical materials at the atomic level—that are best observed at temperatures near absolute zero. He conducted research at Bell Laboratories, IBM Watson Research Center, and the University of Chicago before joining Caltech as its president on July 1, 2014.

At Chicago, Dr. Rosenbaum was the John T. Wilson Distinguished Service Professor of Physics, and served as the University's provost for seven years. In that role, he had responsibility for a broad range of institutions and intellectual endeavors across the sciences, arts, and professional schools. He was the University's vice president for research and for Argonne National Laboratory from 2002 to 2006.

Dr. Rosenbaum is an elected fellow of the American Physical Society, the American Association for the Advancement of Science, and the American Academy of Arts and Sciences. He received his bachelor's degree in physics with honors from Harvard University and an MA and PhD in physics from Princeton University.



# Krysta Svore

Krysta Svore is a Senior Researcher at Microsoft Research in Redmond, Washington, where she manages the Quantum Architectures and Computation group. She received her Ph.D. in Computer Science with highest distinction from Columbia University in 2006 and her **B.A. from Princeton University in Mathematics** and French in 2001. Dr. Svore's research includes the development and implementation of quantum algorithms, including the design of a scalable, fault-tolerant software architecture for translating a high-level quantum program into a low-level, device-specific quantum implementation, and the study of quantum error correction codes and noise thresholds. She has also developed machine-learning methods for web applications, including ranking, classification, and summarization algorithms.

# David Wineland

David Wineland received the 2012 Nobel Prize in Physics for "his ground-breaking experimental methods that enable measuring and manipulation of individual quantum systems." A graduate of the University of California, Berkeley (B.A. 1965) and Harvard University (Ph.D. 1970), he has been a member of the Time and Frequency Division of NIST (National Institute of Standards and Technology) in Boulder, Colorado since 1975, where he is a group leader and NIST Fellow. A long-term goal of his work has been to increase the precision of atomic spectroscopy, the measurement of the frequencies of atoms' characteristic vibrations. This research has applications to making better atomic clocks and has led to experiments showing precise control of atomic energy levels and motion. Such control can be applied to measurements whose precision is limited only by the constraints of quantum mechanics and to demonstrations of the basic building blocks of a quantum computer.



# Paul Rudd

Paul Rudd is a stage, television, and film actor who studied theatre at the University of Kansas, Lawrence. After graduation he continued his studies with the American Academy of Dramatic Arts/West in Los Angeles and the British American Drama Academy at Oxford University, UK. Rudd's most recent role was as the title character in Marvel's 2015 movie, Ant-Man. Marvel recently confirmed the sequel, Ant-Man and the Wasp, will be released in 2018.

# ACKNOWLEDGMENTS



The Kavli Foundation was established in 2000 by its founder and benefactor, Fred Kavli, a prominent California business leader and noted philanthropist. The Foundation has established major research institutes at leading universities and institutions in the United States, Europe and Asia, including Caltech's Kavli Nanoscience Institute.



The mission of the California Institute of Technology is to expand human knowledge and benefit society through research integrated with education. We investigate the most challenging, fundamental problems in science and technology in a singularly collegial, interdisciplinary atmosphere, while educating outstanding students to become creative members of society.



Caltech's Division of Physics, Mathematics and Astronomy (PMA) creates and uses the most ambitious and technologically advanced tools in an effort to explore and understand all aspects of our universe. PMA is proud to support One Entangled Evening and the Quantum Summit.



Caltech's Division of Engineering and Applied Science (EAS) works at the leading edge of fundamental science to invent the technologies of the future. EAS is pleased to be able to provide support for One Entangled Evening and the Quantum Summit.



GORDON AND BETTY

OUNDATION

The Institute for Quantum Information and Matter (IQIM) at Caltech is a National Science Foundation Physics Frontiers Center with support from the Gordon and Betty Moore Foundation.



Caltech recognizes the National Science Foundation for generous support of campus programs, enabling Caltech researchers to demonstrate the broader impact of their work to the public through multimedia, lectures, and demonstrations.