The Dreams Stuff is Made Of

a skit by the *Science 1 Staff*

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CAST (in order of appearance)

- Max **Planck** (Mark)
- Philipp **von Jolly** (Marty)
- **Narrator** (Marty)
- Michael **Faraday** (Tony)
- James Clerk **Maxwell** (Jess)
- Johann Jakob **Balmer** (Kevin)
- Johannes Robert **Rydberg** (Elliott)
- Albert **Einstein** (Michael)
- Ernest **Rutherford** (Jess)
- Max **Born** (Domingo)
- Niels Henrik David **Bohr** (Douw)
- Louis Victor **de Broglie** (Neil)
- Werner **Heisenberg** (Mark)
- Erwin **Schroedinger** (Elliott)
- Wolfgang **Pauli** (David)

The chalk is the "baton" in this relay.

1 A Few Loose Ends

The classroom is darkened and three "experiments" are represented on stage: on the left is Neil with a flashlight and a piece of metal, simulating the PHOTOELECTRIC EFFECT; in the centre are Elliott and Kevin with an actual blowtorch and a nichrome wire, demonstrating both blackbody radiation and ATOMIC SPECTROSCOPY (with various salts); and on the right is Douw drawing the BLACKBODY SPECTRUM and the "ultraviolet catastrophe" theory. The others also put plots and/or equations on the blackboard as the following action takes place:

Enter **Planck** followed by **von Jolly**.

von Jolly: "So you want to study Physics, do you, Mr. Planck?"

Planck: "Yes sir, Professor von Jolly, I wish to study nature at its most fundamental level."

von Jolly: "Well, forget it! The fundamentals have all been worked out, and there's nothing particularly interesting left to do. Physics will be finished in just a few more years."

Planck [to audience, on exit] "Great, then I'll work out the loose ends and settle into a cushy professorial life like this guy."

von Jolly $\longrightarrow$ **Narrator** [turning toward demos] "Indeed, all we have left are a few nagging discrepancies between theory and these experiments.

[referring to blackbody radiation graph] "We know a body should emit radiation when heated," [indicates Rayleigh-Jeans theory curve] "but our spectrum doesn't look quite right." [Douw superimposes experimental curve.]

[referring to line-spectra demo] " Also, it seems that the elements absorb and emit light only at discrete frequencies, in a manner we can't quite put our finger on."

[referring to photoelectric simulation] "Finally, the photoelectric effect shows the number of electrons kicked out of a metal increasing *not* with the *intensity* of the radiation, but with its *frequency*.

"These experiments show there are a few holes left in our understanding of matter, which stems from our understanding of *atoms*, its most fundamental constituents. Surely, with the kind of collaboration we've seen between theory and experiment, these problems will go away. We'd like them to go away. They're nasty and embarrassing. Faraday and Maxwell serve as a shining example of what can happen when the experimentalists and theorists talk to each other, and we just need more of this sort of thing."

2 Electrodynamics

Faraday walks onto stage as an old man with a cane, addresses audience with a freil English voice:

"My name is Michael Faraday. I don't care what anyone says about these newfangled theories about the nature of matter, it seems to me that it all started with some experiments I did back in 1831. I was always an experimentalist by nature. Spent all day in my laboratory in London — even slept there sometimes. I did a great deal of work on magnets in those days. I found out that if I moved a conductor across the field of a powerful magnet...

[illustrates on the board]

"...then an electric current was produced in the conductor! Nobody had ever witnessed this before.

"I tried to develop some ideas to explain this process. It seemed to me that the empty space between the poles of the magnet must contain some type of lines of force. I was inclined to compare the diffusion of magnetic forces from the poles to waves like the vibrations upon the surface of water.

"Not only that, but the vibrations in the magnet might have induced similar vibrations in the matter of the conductor.

"Since I was (and still am) a believer in the uniformity of the forces of nature, I thought that these waves might be commonplace, not only in the case of electromagnetism, but a general property of all matter.

"I am no mathematician — I was originally trained as a bookbinder's apprentice — but I was convinced that the vibrations whose existence I had inferred could be best described in a mathematical manner. Some Europeans had developed certain formulas on the subject, but they did not impress me. However, I knew a bright young mathematician, a Scot by name of James Clerk Maxwell, whom I consulted on this problem, and he gladly agreed to put his mind to it."

Maxwell is writing MAXWELL'S EQUATIONS on the board as Faraday speaks:

$$\begin{aligned}
\vec{\boldsymbol{\nabla}} \cdot \vec{\boldsymbol{D}} &= \rho \\
\vec{\boldsymbol{\nabla}} \cdot \vec{\boldsymbol{B}} &= 0 \\
\vec{\boldsymbol{\nabla}} \times \vec{\boldsymbol{E}} + \frac{\partial \vec{\boldsymbol{B}}}{\partial t} &= 0 \\
\vec{\boldsymbol{\nabla}} \times \vec{\boldsymbol{H}} - \frac{\partial \vec{\boldsymbol{D}}}{\partial t} &= \vec{\boldsymbol{J}}
\end{aligned}$$

Faraday: [turning to look at Maxwell's equations] “Hmmm. . . . I am sorry to say that your formulas look like hieroglyphics to me. Is there no way that these same conclusions can be expressed in common language as fully and clearly? It would be a great boon to such as I, so that I might work upon them by experiment. However, I must grudgingly admit that these formulas seem to be the beginnings of a theory that can account for many of the general properties of matter.”

Maxwell [reading a letter] “I was aware that there was supposed to be a difference between Faraday’s way of conceiving phenomena and that of the mathematicians, so that neither he nor they were satisfied with each other’s language. I had also the conviction that this discrepancy did not arise from either party being wrong.”

[Looks up.]

“. . . we have strong reason to conclude that light itself — including radiant heat, and other radiations if any — is an electromagnetic disturbance in the form of WAVES propagated through the electromagnetic field according to electromagnetic laws.”

[Draws a wave on the blackboard.]

3 Hot Atoms

Narrator: “Faraday has elucidated the nature of electrical phenomena, Maxwell has formulated the physical laws, and Joseph John **Thomson** has found the ELECTRON. It seems to be a fundamental particle, tied up in the atom. Electrons are discrete pointlike things with negative electric charge, and moving them around creates esoteric phenomena like magnetism, so the atoms that make up everyday stuff must look something like this (holds up a RAISIN BUN) with the mushy brown part embodying most of the mass and the positive charge required to make the overall atom electrically neutral. We just need to nail down the details of how jiggling raisin buns explain everything.”

Balmer and **Rydberg** [conducting experiments with a Bunsen burner and a nichrome wire]

Balmer scratches head mumbles: “This darn high school teaching is driving me crazy,” and writes on board near H atom spectrum:

$$\lambda = \frac{hm^2}{m^2 - 4} \quad \text{for integer } m > 2.$$

Rydberg: “Dr. Balmer, I decided to visit you in Basel because I am so very excited with your equation for the H atom lines. If I turn it upside down I can write it:

$$\frac{1}{\lambda} = R_H \left(\frac{1}{m_2^2} - \frac{1}{m_1^2} \right) \quad \text{with } m1 > m2.$$

“It then fits additional hydrogen lines.” [pointing to spectrum from sun] “But more importantly, with a slight modification I can fit lines from other atoms as well. This seems to be a universal equation to fit all spectral lines. I cannot understand why they won’t grant me tenure back in Lund. Just to get at them, I’m naming the new fundamental constant R_H the Rydberg constant — after me!”

Narrator: “These empirical formulas are certainly useful. But what do they *mean*?”

Planck: Enters, takes chalk from Balmer’s hand, walks to blackbody spectrum on next blackboard panel and fills in corrected theoretical spectrum.

“I was able to get rid of the so-called *ultraviolet catastrophe* and make the theoretical BLACKBODY SPECTRUM agree with the experimental data by assuming that the energy of electromagnetic waves was not a continuous property, but came *quantized* in fixed multiples of . . . ”

[writes on board]

$$E = h\nu$$

"... where ν is the *frequency* of the light. I have no idea what this *means* either, but it seems to work."

[Leaves chalk under PHOTOELECTRIC EFFECT.]

4 Swiss patent office, 1905

Narrator: "In 1902 Philipp E.A. von Lenard discovered that you can't excite electrons out of a metal using low frequency light, no matter how high you turn up the intensity. But if you use even a little bit of *higher frequency* light, out pop lots of electrons. So it isn't the *power* of the electromagnetic radiation, it's the *frequency*.

"Meanwhile, isolated from the scientific community and twiddling his thumbs in a Swiss patent office, we have a bit of a flunky. He had some problems in high school, his friends dragged him through his undergrad finals, he couldn't get into grad school when he tried, and finally couldn't land an academic position anywhere. He was poking away at a few problems here and there, in between stamping his approval on new and improved mousetraps. In 1905, Albert Einstein published a thing or two ... or three."

Einstein: [writing on blackboard]

$E = ma^2$ ... no, $E = mb^2$ ... no ....

Leaves relativity on side board, fixes up photoelectric effect behind demo. Emphasizes quantization of radiation, doesn't like it.

5 McGill, 1905

Narrator: "So the theorists are working on it, and surely with a little more mathematical sophistication all these temporary fixits will reveal their sensible character. Sadly, the experimentalists are at it again too, and are generating more embarrassing problems. In a quaint backwater town of the snowy Canadian wilderness, Ernest Rutherford is visiting McGill University and tinkering with Marie Curie's *alpha rays*."

Rutherford: "It's amazing how many of these heavy elements decompose spontaneously, giving off *alpha* particles, which I have discovered are actually the nuclei of helium atoms."

"I believe I'll move back to England to do some more experiments with these things."

[Walks across stage to signify this.]

"Here in Manchester I tried scattering alphas off a thin gold foil.

[Uses chalk in demo of scattering.]

'Most of the time we see just what you'd expect: the alphas shoot right through the foil and out the other side, with only a little deflection. But occasionally — very rarely — one will bounce straight back from the foil. *It is like firing shells at a piece of paper handkerchief and having them bounce back at you.*

"The only way this could possibly happen is if most of the mass of the atom is contained in a small, hard, positively charged NUCLEUS about which the electrons orbit like planets about the sun!"

Born: [jumping up and down, ears steaming, foaming at the mouth]

"That's insanity! Orbiting electrons are accelerating and thus radiate away their energy!"

Grabs chalk, draws spiraling orbit; classical calculations show electron falls into nucleus in ~ 1 ns.

Bohr: [takes chalk to blackboard]
"... so we're forced to postulate discrete orbits

and energy levels in atoms."

$$L_n = n\hbar$$
$$E_n = -\frac{R}{n^2}$$

[Connects all three problems by quantization of angular momentum, thus also emitted and absorbed energy.]

6 The Roaring 20's

Narrator: "And here the revolution really begins. Bohr's *Ansatz* is not yet an explanation, but the unifying power of his atomic model demonstrates that we need to take this quantization business seriously. So far none of these old-school scientists wanted to take their treatment physically, but rather as mathematical patchwork.

"Now a younger school of upstart hotshots is to take the reigns. They consider these fresh and wild ideas on their own merits, with flagrant disregard for stuffy notions of physical intuition. Louis de Broglie was a young aristocrat whose academic reputation wasn't going to determine whether his kids were fed, so his doctoral work went out on a limb:"

de Broglie: [takes chalk from Bohr]
At $E = h\nu$, adds $\nu = c/\lambda \Longrightarrow \lambda = hc/E$.

"But for light, we know that $E/c = p$, the *momentum* of the photon. Therefore..."

$$\lambda = \frac{h}{p}$$

"If this is true for a *photon*, why not also for an *electron*?"

Narrator: "Now the paradigm really begins to shift. It seems we need to start taking seriously these strange ideas that matter may be *both waves and particles*. Indeed, experiments have already been done demonstrating that X-rays scattered like particles, and electrons like waves, but de Broglie's interpretation was not believed for some time.

"Another two kids are also busy exploring some theory along these lines, one thinking about particles and the other about waves. Both take advantage of the perks involved in theoretical work, and do their thinking in comfort and style. Werner Heisenberg takes a vacation to an island and writes a paper...."

Heisenberg:

[matrices, commutativity, leading to the UNCERTAINTY RELATION]

$$\Delta x\, \Delta p \;\geq\; \frac{\hbar}{2}$$

"But I'm not sure about that, I'd better send it to Pauli to have a look, he knows more about this matrix stuff...."

Narrator: "Meanwhile, a fetching young lad named Erwin Rudolf Josef Alexander **Schrödinger** takes the wife of a colleague (named Weyl) on retreat to a mountainside cabin. He also takes a stack of papers and two pearls with which plug his ears while he works, and she ... uh ... waits. He mixes work and pleasure, but in discrete packets. He also uses Weyl's mathematics to formulate *wave mechanics*."

Schroedinger: [Flirts with several "consenting" females on his way onstage.] "Ahh, Frau Weyl, I hardly recognized you with your cloths on!" [Looks at her — ponders in great thought.] "Your curves ... your curves ... *that's it!* — your curves explain all! What we need is a WAVE EQUATION." [Goes to board and writes.]

$$\mathcal{H}\psi \;=\; E\psi$$

"That's it! Now Frau Weyl, may I sit next to you?"

"...though if they don't work out a better theory than this, I'll wish I hadn't had anything to do with the whole affair."

Narrator: "And he *doesn't* have much more to do with the affair. He is photographed at conferences (flocked by other physicist's wives) and writes a little ditty called *What is life?*"

Pauli: [aside] "This paper is so bad it is not even wrong."

"The fact that the author thinks slowly is not serious, but the fact that he publishes faster than he thinks is inexcusable."

7 End of the Beginning

Narrator: "Now a brilliant fellow named Paul **Dirac** comes along and shows Heisenberg and Schroedinger's formulations are equivalent. He even formulates a relativistic equation for the wavy electron that yields a thing called SPIN, which Heisenberg's old friend Pauli uses to turn chemistry into a mere consequence of quantum physics.

Narrator: "It all works! Unbelievably! And I mean that. Quantum mechanics now explains all the old experimental problems as well as a lot of new things, like ... oh ... chemistry. But what does it all *mean*?"

Born: Interpretation of $\psi^*\psi$ fundamentally changes our notion of quantities like position and momentum, and forces us to think very delicately about the role of MEASUREMENT.

"I am now convinced that theoretical physics is actual philosophy."

Bohr: [The Copenhagen interpretation.]

Enter **Einstein:** "God does not play dice."

[Proposes experiment violating uncertainty relation.]

Bohr: [Refutes it, triumphantly using Einstein's own arguments. Draws some big nuts and bolts on the board and reminds us they're really important, even fundamental.]

"And Albert, stop telling God what to do."