AI-assisted proof of Riemann Hypothesis passes independent verification

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On Nov. 20, Levent Alpöge, a Turkish-American mathematician at Artificial Intelligence (AI) company Anthropic, announced that he and the company's AI model Claude had found a proof of the Riemann Hypothesis, one of mathematics' most famous unsolved problems.[1] He released approximately 17 million lines of code written in the Lean proof assistant, claiming that the work also established the stronger Generalized Riemann Hypothesis for Dirichlet L-functions.

A day later, on November 21, the Lean and Mathlib communities issued a joint statement, endorsed by the Lean Focused Research Organization (Lean FRO) and the Mathlib Initiative, confirming that the formal proof had passed independent verification (Figure 1).

"We have full confidence that Alpöge's proof of the Riemann Hypothesis is correct," the statement said.[2]

The verification addressed four essential questions: whether the mathematical statement was correctly formulated, whether the code compiled successfully, whether the code proved the intended theorem rather than a weaker or altered statement, and whether the proof itself satisfied the rules of formal logic.

According to the statement, dozens of people successfully compiled the code, reproducing the same raw proof export file. Two independent tools confirmed that the theorem proved by Alpöge's code exactly matched the established formulation of the Riemann Hypothesis in Mathlib, while the exported proof was also checked by Lean's official kernel and several independent proof checkers, which confirmed its logical validity.

Further independent checks were conducted by Michael Rubinstein, a mathematics researcher at the University of Waterloo in Canada. His verification involved compiling all 175,187 Lean modules, auditing the axioms on which the theorems depended, replaying the proof through Lean's official kernel, and checking it with an independently developed proof checker called nanoda.

All four checks were completed without errors. The independent checker verified 1,484,729 declarations required by the theorems.

Lean differs from conventional AI-generated mathematical writing because its proof-checking system verifies each formal logical step rather than relying on the plausibility of natural-language explanations.

Meanwhile, Andrew Sutherland, a mathematician at the Massachusetts Institute of Technology, published detailed independent verification results, reporting that the proof had passed multiple proof checkers and that its central theorems matched the established mathematical formulations.[3]

However, while the successful checks provide strong evidence for its

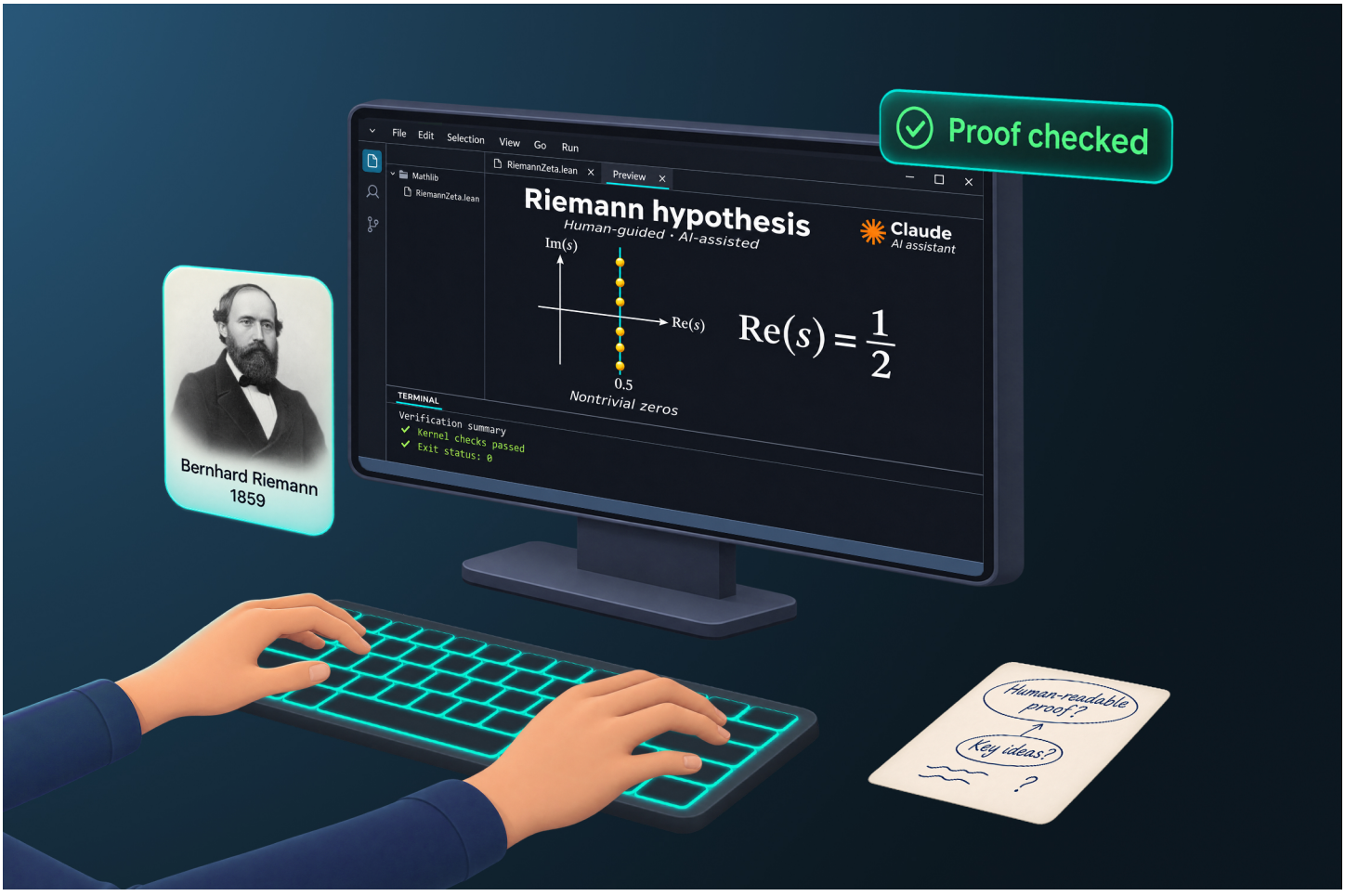

Figure 1. A formal Lean proof of the Riemann and generalized Dirichlet L-function Riemann hypotheses, verified by the Lean/Mathlib community.

mathematical correctness, the formalized result has yet to complete the broader academic recognition process required by the Clay Mathematics Institute (CMI), which administers the $1 million Millennium Prize for the problem. As of this writing, the Riemann Hypothesis is still listed as "unsolved" on the CMI's official website.[4]

A 167-YEAR-OLD MATHEMATICAL CHALLENGE

First proposed by German mathematician Bernhard Riemann in 1859, the Riemann Hypothesis concerns the distribution of prime numbers, integers greater than one that have exactly two positive divisors: one and themselves.

Although prime numbers appear irregularly among the integers, their distribution follows deep mathematical patterns. Riemann discovered that these patterns are closely connected to the zeros of a mathematical function now known as the Riemann zeta function.

The hypothesis states that every nontrivial zero of this function has a real part equal to one-half. Proving this statement would establish tighter bounds on deviations in the distribution of prime numbers from their expected average pattern.

The problem is one of the seven Millennium Prize Problems designated by the CMI, with a $1 million prize offered for a qualifying solution to each problem. The Generalized Riemann Hypothesis extends the central question to a broader family of mathematical functions known as Dirichlet L-functions.

The announcement also comes in 2026, the 200th anniversary of Riemann's birth.

A NEW ERA FOR MATHEMATICS?

The development has prompted mathematicians and technology observers to consider a question extending beyond whether AI can solve exceptionally difficult problems: can humans understand the mathematical ideas discovered with its assistance?

Elon Musk, CEO of Tesla and SpaceX, described the AI-assisted proof as "yet another mind-blowing thing achieved by super intelligence" in a post on X on Saturday. He said its significance lay partly in turning mathematical results previously conditional on the Riemann Hypothesis into unconditional theorems.

Shing-Tung Yau, a Fields Medal-winning mathematician, described the development as potentially marking a new era for mathematics during an online press conference held in connection with a symposium commemorating Riemann's bicentenary in Shenzhen, China.

"I think it will take no more than five years for the entire proof to be fully understood, and for a version that humans can understand to be written," said Yau. "AI has built on mathematical approaches originally developed by humans, combining them to make a major breakthrough. Since these ideas originated with humans, we should also be able to understand them. I don't see this as a major obstacle."[5]

James Maynard, a University of Oxford mathematician and 2022 Fields Medal recipient, expressed strong confidence in the formal verification but distinguished establishing a theorem from understanding why it is true.

"Assuming we do get the corresponding understanding, this will surely be viewed as one of the absolute pinnacles of mathematical results," Maynard said. In his assessment, the next challenge is to identify the essential ideas within the vast formal proof and produce an explanation that mathematicians can study and build upon.

"I imagine the digestion process will take some time," wrote Terence Tao, another Fields Medal-winning mathematician, in his blog.

The breakthrough has also triggered sharply contrasting reactions among technology observers. Eliezer Yudkowsky, an AI safety researcher based in the US, described the solution of the Riemann Hypothesis as a long-anticipated warning sign of potentially dangerous AI capabilities.

Then what about AI's influence upon mathematicians?

"The first step in any scientific discipline is identifying the right direction, and AI can play a crucial role in helping us find it," Yau said, expressing his confidence about AI being a useful tool for mathematicians, providing more opportunities for them.

More mathematicians are also thinking about how mathematics should develop in this age of AI. Alpöge himself described how the roles of human researcher and AI evolved during the project. He said he had guided the research toward a mathematical setting inspired by an earlier simplified model, before Claude began making progress that astonished him.

"Claude far outpaced me near the finish line," he wrote in his announcement.

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DECLARATION OF INTERESTS

The author declares no competing interests.