



Emily Riehl

Johns Hopkins University

Human mathematics in the age of machine mathematics

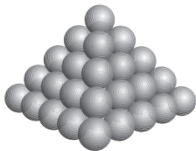
Natural Philosophy Symposium

Recent developments in human mathematics

In 1998, Thomas Hales announced a proof of a 1611 conjecture of Johannes Kepler, via a “**proof by exhaustion**” involving the checking of many individual cases using a computer to solve linear programming problems. After four years, a panel of 12 referees reported they were 99% certain that the proof was correct, but could not check all the computer calculations.

THEOREM 1.1 (The Kepler conjecture). *No packing of congruent balls in Euclidean three space has density greater than that of the face-centered cubic packing.*

This density is $\pi/\sqrt{18} \approx 0.74$.



The unabridged version of the paper, which was published in 2005 in the *Annals of Mathematics*, came to 339 pages, with around 3 gigabytes of computer artifacts.

Recent developments in human mathematics



In 2016, Maryna Viazovska, resolved the analogous question in eight dimensions, proving that the optimal packing of spheres in 8-dimensional spaces positions their centers on the points of the E_8 -lattice.

A week later, she and four collaborators generalized these results to dimension 24.



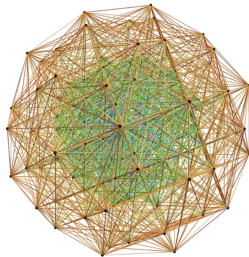
Annals of Mathematics **185** (2017), 991–1015
<https://doi.org/10.4007/annals.2017.185.3.7>

The sphere packing problem in dimension 8

By MARYNA S. VIAZOVSKA

Abstract

In this paper we prove that no packing of unit balls in Euclidean space \mathbb{R}^8 has density greater than that of the E_8 -lattice packing.



Visualization by J.G. Moxness (CC BY-SA 3.0).



Article

Advancing mathematics by guiding human intuition with AI

<https://doi.org/10.1038/s41586-021-04086-x>

Received: 10 July 2021

Alex Davies^{1,2,3}, Petar Veličković⁴, Lars Buesing⁵, Sam Blackwell¹, Daniel Zheng¹, Nenad Tomašević¹, Richard Tanburn¹, Peter Battaglia¹, Charles Blundell¹, András Juhász², Marc Lackenby², Georgie Williamson³, Demis Hassabis¹ & Pushmeet Kohli^{1,2,3}

PatternBoost: Constructions in Mathematics with a Little Help from AI

François Charton*

Jordan Ellenberg[†]

Adam Zsolt Wagner*

Geordie Williamson[§]

November 4, 2024

Abstract

We introduce PatternBoost, a flexible method for finding interesting constructions in mathematics. Our algorithm alternates between two phases. In the first “local” phase, a classical search algorithm is used to produce many desirable constructions. In the second “global” phase, a transformer neural network is trained on the best such constructions. Samples from the trained transformer are then used as seeds for the first phase, and the process is repeated. We give a detailed introduction to this technique, and discuss the results of its application to several problems in extremal combinatorics. The performance of PatternBoost varies across different problems, but there are many situations where its performance is quite impressive. Using our technique, we find the best known solutions to several long-standing problems, including the construction of a counterexample to a conjecture that had remained open for 30 years.

MACHINE LEARNING

Machine Learning Becomes a Mathematical Collaborator

5 | ■

Two recent collaborations between mathematicians and DeepMind demonstrate the potential of machine learning to help researchers generate new mathematical conjectures.

Constructions in combinatorics via neural networks

Adam Zsolt Wagner*

Abstract

We demonstrate how by using a reinforcement learning algorithm, the deep cross-entropy method, one can find explicit constructions and counterexamples to several open conjectures in extremal combinatorics and graph theory. Amongst the conjectures we refute are a question of Brualdi and Cao about maximizing permanents of pattern avoiding matrices, and several problems related to the adjacency and distance eigenvalues of graphs.

MACHINE LEARNING

In New Math Proofs, Artificial Intelligence Plays to Win

3 | ■

A new computer program fashioned after artificial intelligence systems like AlphaGo has solved several open problems in combinatorics and graph theory.

A question from my linear algebra practice exam



does the set of orthogonal matrices define a subspace of the vector space of all square mat X



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AI Overview

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Yes, the set of orthogonal matrices of a fixed size does define a subspace of the vector space of all square matrices of the same size.

Explanation:

Closure under addition:

If you add two orthogonal matrices, the resulting matrix will also be orthogonal, satisfying the closure property for addition in a subspace.

Closure under scalar multiplication:

Multiplying an orthogonal matrix by a scalar preserves the orthogonality condition, meaning the set is closed under scalar multiplication.

Contains the zero vector:

The zero matrix is considered an orthogonal matrix, ensuring the zero vector is included in the set.

Key point: An orthogonal matrix is a square matrix where the transpose is equal to its inverse, which guarantees that the rows (or columns) form an orthonormal set of vectors.



4.11: Orthogonality - Mathematics LibreTexts

Sep 16, 2022 — The span of these vectors is a subspace W of \mathbb{R}^n Thus a matrix is orthogonal if its rows (or...

Math LibreTexts



Orthogonal Matrix - an overview | ScienceDirect Topics

Any set of n nonzero orthogonal [orthonormal] vectors in \mathbb{R}^n is an orthogonal [orthonormal] basis for \mathbb{R}^n If $a...$

ScienceDirect.com



Orthogonal Matrix: Definition, Types, Properties and Examples

A square matrix with real numbers or values is termed as an orthogonal matrix if its transpose is equal to the...

toppr.com



Do orthogonal matrices form a subspace?



My student asked Gemini:

“Does the set of orthogonal matrices define a subspace of the vector space of all square matrices?”

In the 2×2 case, orthogonal matrices have the form

$$\begin{bmatrix} s & -t \\ t & s \end{bmatrix} \quad \text{or} \quad \begin{bmatrix} s & t \\ t & -s \end{bmatrix} \quad \text{with} \quad s^2 + t^2 = 1,$$

while square matrices have the form $\begin{bmatrix} a & b \\ c & d \end{bmatrix}$ for any real numbers a , b , c , and d .

The set of 2×2 matrices forms a vector space because you can add them and multiply them by a real number to get another 2×2 matrix.

This question asks whether the sum or scalar multiple of orthogonal matrices is again orthogonal and whether the zero matrix is an orthogonal matrix.

Gemini's illogical "thinking"



"Does the set of orthogonal matrices define a subspace of the vector space of all square matrices?"

Gemini answered "Yes" with the following explanation:

- "If you add two orthogonal matrices, the resulting matrix will also be orthogonal, satisfying the closure property for addition in a subspace."
This is incorrect.
- "Multiplying an orthogonal matrix by a scalar preserves the orthogonality condition, meaning the set is closed under scalar multiplication."
This is incorrect.
- "The zero matrix is considered an orthogonal matrix, ensuring the zero vector is included in the set."
This is incorrect.

Despite the fact that Gemini gave correct definitions of **subspace** and of **orthogonal matrices** (as those matrices whose transpose is the inverse), it answered **wrong**.

Vibe proving

Is it true that an ∞ -category is idempotent complete (in the ∞ -categorical sense) if and only if its homotopy category is idempotent complete (in the 1-categorical sense)?

◆ Show thinking ▼

Yes, it is true that an ∞ -category \mathcal{C} is idempotent complete (in the ∞ -categorical sense) if and only if its homotopy category $ho(\mathcal{C})$ is idempotent complete (in the 1-categorical sense).

Let's establish the definitions and then prove the equivalence.

...

Conclusion:

The two conditions are equivalent. The definitions of idempotent completeness are "homotopy-invariant" in a way that translates directly between the ∞ -category and its homotopy category. This result is also confirmed by the fact that $h(Kar(\mathcal{C})) \cong Kar(h\mathcal{C})$, where $Kar(-)$ denotes the Karoubi envelope (idempotent completion) and $h(-)$ denotes taking the homotopy category. An (∞) -category is idempotent complete if and only if the canonical functor into its Karoubi envelope is an equivalence.

The omitted text contains a clearly written argument with a subtle error, the sort of optimistic mistake often made by human mathematicians. **The conclusion is incorrect.**

Your answer uses the "incoherent" definition of an idempotent in an ∞ -category? Can you answer the same question using the coherent definition of an idempotent in an ∞ -category?

◆ Show thinking ▼

You're right to press on the subtleties of "coherence" in ∞ -categories. Let's clarify how these definitions are typically handled and why the previous conclusion still holds.

...

If a framework requires a more elaborate "coherent idempotent object" (e.g., an object in a category of idempotents, or an algebra for a certain monad), the definition of "idempotent completeness of \mathcal{C} " itself usually still boils down to the splitting condition for any e satisfying $e \circ e \simeq e$. The power of ∞ -category theory is that such "weak" conditions, when interpreted within a coherently structured environment, often suffice and lead to robust theories.

Thus, the answer remains the same: Yes, an ∞ -category is idempotent complete (in the standard ∞ -categorical sense) if and only if its homotopy category is idempotent complete (in the 1-categorical sense). The "coherence" is sufficiently handled by the definitions used.

How do we defend the mathematical literature against vibe proving?

A lot of the mathematical text generated by top “reasoning” models is pretty good and all of it looks good.*

*Caveat: large language models tend to get even the simplest numerical calculations horribly wrong.

But pretty good is not good enough: one minor error could make an entire logical argument reach the wrong conclusion: true instead of false.

As a journal editor specializing in a subfield where papers tend to be long, technical, and difficult to referee, I am **extremely concerned** about AI generated mathematical “proofs.”

Proof as peer review

“A technical argument by a trusted author, which is hard to check and looks similar to arguments known to be correct, is hardly ever checked in detail.”

— Vladimir Voevodsky

Why has mathematics largely avoided the replication crisis
that has confronted other fields?

Peer review in theory: careful refereeing should lead to an error-free publications.

Unfortunately, the mathematical literature contains famous mistakes as well as
contradictory theorems.

Peer review in practice: in theory any proof should be **reproducible** by any reader —
allowing the reader to understand for themselves why the result is true.

When papers have enough readers, mistakes are eventually caught.

Importantly: human mathematicians are careful in claiming they have a proof.

A new paradigm for mathematical proof?

THE EQUIVARIANT MODEL STRUCTURE ON CARTESIAN CUBICAL SETS

STEVE AWODEY, EVAN CAVALLO, THIERRY COQUAND, EMILY RIEHL, AND CHRISTIAN SATTLER

ABSTRACT. We develop a constructive model of homotopy type theory in a Quillen model category that classically presents the usual homotopy theory of spaces. Our model is based on presheaves over the cartesian cube category, a well-behaved Eilenberg-Zilber category. The key innovation is an additional equivariance condition in the specification of the cubical Kan fibrations, which can be described as the pullback of an interval-based class of uniform fibrations in the category of symmetric sequences of cubical sets. The main technical results in the development of our model have been formalized in a computer proof assistant.

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Software programs called **computer proof assistants** can certify the correctness of a mathematical proof that has been written in a precise formal language.

- Today such proofs are laboriously encoded by human mathematicians (**formalization**).
- In principle, generative AI could be trained to output text in a format that could be checked by a computer proof assistant (**autoformalization**).

Computer proof verification

```
{-
```

```
-----  
Formalization of an equivariant cartesian cubical set model of type theory  
-----
```

This formalization accompanies the article

The equivariant model structure on cartesian cubical sets.
Steve Awodey, Evan Cavallo, Thierry Coquand, Emily Riehl, & Christian Sattler.
<https://arxiv.org/abs/2406.18497>

The contents of the formalization are outlined in Appendix A of the article.

The formalization defines a model of homotopy type theory inside an extensional type theory augmented with a flat modality and axioms postulating *shapes* (among them an *interval*) and a cofibration classifier. The results can in particular be externalized in the category of cartesian cubical sets.

The code has been tested with Agda version 2.6.4.
The source is available at

github.com/ecavallo/equivariant-cartesian

and there is an HTML interface at

ecavallo.github.io/equivariant-cartesian

For reference (see the file `equivariant.agda-lib` in the source), the formalization is compiled with the flags

```
--with-K  
--cohesion --flat-split  
--no-import-sorts  
--rewriting
```

In particular, the `--with-K` flag enables axiom K (uniqueness of identity proofs), while the `--cohesion` and `--flat-split` flags enable the flat modality (see the module `axiom.flat` for more information).

```
-}
```

The main definition takes just a few lines to encode:

Our 87 page preprint is accompanied by a library of formalized proofs checked by the computer proof assistant **Agda**.

The paper, submitted to a journal in September, is still awaiting a referee report.

```
--+ The equivariance condition on local filling structures associated to a shape  
--+ homomorphism  $\sigma : S \rightarrow T$ . Filling an open box over  $T$  and then composing with  $\sigma$  should be  
--+ the same as composing the box with  $\sigma$  and then filling over  $S$ .
```

```
LocalEquivariance : {S T : Shape} ( $\sigma : \text{Shape}[S, T]$ ) {A : (T)  $\rightarrow$  Type  $\ell$ }  
   $\rightarrow \text{LocalFillStr } T A \rightarrow \text{LocalFillStr } S (A \circ \langle \sigma \rangle) \rightarrow \text{Type } \ell$   
LocalEquivariance  $\sigma \text{ liftT liftS} =$ 
```

```
   $\forall r \text{ box } s \rightarrow$   
    reshapeFiller  $\sigma (\text{liftT } (\langle \sigma \rangle r) \text{ box}) .\text{fill } s .\text{out}$   
   $= \text{liftS } r (\text{reshapeBox } \sigma \text{ box}) .\text{fill } s .\text{out}$ 
```

```
Equivariance : {S T : Shape} ( $\sigma : \text{Shape}[S, T]$ ) { $\Gamma : \text{Type } \ell$ } {A :  $\Gamma \rightarrow \text{Type } \ell'$ }  
   $\rightarrow \text{FillStr } T A \rightarrow \text{FillStr } S A \rightarrow \text{Type } (\ell \cup \ell')$ 
```

```
Equivariance (T = T)  $\sigma \{ \Gamma \} A \text{ fillT fillS} =$   
  ( $\gamma : \Gamma \wedge T$ )  $\rightarrow \text{LocalEquivariance } \sigma (\text{fillT } \gamma) (\text{fillS } (\gamma \circ \langle \sigma \rangle))$ 
```

```
--+ Definition of an equivariant fibration structure.
```

```
record FibStr { $\Gamma : \text{Type } \ell$ } (A :  $\Gamma \rightarrow \text{Type } \ell'$ ) : Type ( $\ell \cup \ell'$ ) where  
  constructor makeFib  
  field
```

```
    --+ We have a filling structure for every shape.
```

```
    lift : (S : Shape)  $\rightarrow \text{FillStr } S A$ 
```

```
    --+ The filling structures satisfy the equivariance condition.
```

```
  vary :  $\forall S T (\sigma : \text{Shape}[S, T]) \rightarrow \text{Equivariance } \sigma A (\text{lift } T) (\text{lift } S)$ 
```



By **computer formalization**, I am referring to a new and not yet widely practiced method of developing and communicating rigorous mathematical proofs, using a computer program called a **computer proof assistant**.

- The mathematician inputs each line of their proof in a precise syntax.
- The computer verifies the logical reasoning produces a valid deduction of the claimed mathematical statement.
- Depending on the sophistication of the computer program, it might also “assist” the mathematician in various ways:
 - By catching errors of reasoning (unjustified assumptions, missing cases, etc).
 - By keeping track of where they are in a complicated logical argument.
 - By suggesting or even automatically generating proofs (“auto-formalization”).

Norms for machine-generated mathematical proof

Despite well-known imperfections, the mathematical community can take deep pride in our overwhelmingly reliable and continually improving standards for mathematical proof.

We should demand the same for AI when it comes to the mathematical realm.

Maintaining high standards will frustrate near term progress, delaying the arrival of a machine we validate as having “artificial mathematical intelligence,” but should be beneficial for overall reliability in the long run, in mathematics and beyond.

Specifically, I want to propose the following norm for the mathematical community when it comes to original mathematics produced by an AI system:

Any artificially generated mathematical text will **not be considered as a proof** unless:

- It has been communicated in both a natural language text paired with a computer formalization of all definitions, theorems, and proofs.
- The formalization has been accepted by the proof assistant and human expert referees have vetted both the formalization and the paired text.

Obstacles to computer-verified proof: resource demands

When human referees failed to fully certify his proof of the Kepler conjecture, Hales launched a project to verify the result himself in a computer proof assistant. Eleven years later, the full proof was formally verified in the proof assistants **Isabelle** and **HOL Light**. The formalization was described in an accompanying 29 page paper with 22 authors.

A FORMAL PROOF OF THE KEPLER CONJECTURE

THOMAS HALES¹, MARK ADAMS^{2,3}, GERTRUD BAUER⁴,
TAT DAT DANG⁵, JOHN HARRISON⁶, LE TRUONG HOANG⁷,
CEZARY KALISZYK⁸, VICTOR MAGRON⁹, SEAN MCCLAUGHLIN¹⁰,
TAT THANG NGUYEN⁷, QUANG TRUONG NGUYEN¹,
TOBIAS NIPKOW¹¹, STEVEN OBUA¹², JOSEPH PLESO¹³, JASON RUTE¹⁴,
ALEXEY SOLOVYEV¹⁵, THI HOAI AN TA⁷, NAM TRUNG TRAN⁷,
THI DIEP TRIEU¹⁶, JOSEF URBAN¹⁷, KY VU¹⁸ and
ROLAND ZUMKELLER¹⁹



Last year, Kevin Buzzard launched a project to verify a modern proof of Fermat's last theorem—that there are no positive integer solutions to the equation $x^n + y^n = z^n$ for $n \geq 3$ —in the computer proof assistant **Lean**, with the aim of reducing the problem to results known in 1980 by 2029

Moral: proofs at the frontier of mathematics are formalizable
...but only with monumental human effort.

The gameification of mathematical research



In my experience at least, computer formalization very much activates the reward mechanisms that I imagine make computer gaming so intoxicating.

- During a typical research day, I make no quantifiable progress towards proving anything.
- While computer formalizing, you can periodically ask the proof assistant whether what you've done so far is correct. When it says yes, this feels great.

For me at least, part of what I find so seductive is how formalization makes it easier to get into and sustain a flow state of deep focus.

- The rigor demands of computer formalized proofs are so high, there is no point in attempting to write anything if you aren't thinking perfectly clearly.
- Paradoxically, this much steeper demand of my attention makes it easier for me to achieve that level of focus.

A paradigm shift?

Right now computer proof assistants are very difficult for the working mathematician to use in an expedient way: the gap between the “post-rigorous” mathematics of pen-and-paper works and fully formal mathematics is enormous. However, if:

- more mathematicians learn to reason in alternative foundation systems such as dependent type theory, which bring the formal definitions of the central mathematical objects much closer to mathematician’s intuitions,
- or if AI-powered autoformalization continues to advance,

it seems entirely plausible to me that the everyday practice of mathematics will change dramatically in the coming decades as proof assistants become easier to use and more powerful.

- What will it feel like to be a human mathematician collaborating with a computer?
- How will human mathematicians keep up with the latest advances as the pace at which new theorems are proven accelerates?
- What sort of mathematics will the mathematical community most value?