a classic textbook framework. (Perhaps the publisher was afraid that figures would look too textbooky?) The author is jaunty and hospitable, but his prose, occasionally purple, cannot carry the show alone. Some might blench at being told how complex systems "evolve in both deterministic and stochastic ways"; might 'predictable and random' have sufficed?

The musical analogy does, however, permit some changes of pace. It allows Hazen, for instance, to share anecdotes from his musical life — such as the unfortunate side effects when fog from dry ice (frozen carbon dioxide) drifts into an orchestra pit. He jokes that 'tinnunculite', formed only where gases from a burning coal mine react with falcon excrement, was not one of the carbon minerals predicted by the DCO. More of such leavening would have been welcome.

Popular-science books are often told at least partly through history, and the people we meet there. Yet, despite rich potential, *Symphony in C* is almost history-free. We find no mention of Soviet biochemist Alexander Oparin, whose pioneering 1936 book *The Origin of Life* (published in English in 1938) was the first to draw together the ways in which lifeless carbon could have become living (see T. Hyman and C. Brangwynne *Nature* **491**, 524–525; 2012). An even more surprising no-show is Nobel-prizewinning US chemist Linus Pauling. His intuitive quantum-mechanical explanation of carbon's unique ability to form so many types of atomic bond made him a superstar overnight in the early 1930s.

Thumbnail sketches of DCO researchers emphasize another problem that can afflict some authors who participate in the projects they write about: a heavy hand with panegyrics. These often seem to over-sell the scientist at the expense of their science. Like a cheerful headmaster's end-of-year report, *Symphony in C* seems to mention everyone, but struggles to come alive.

The Geological Society of London (my erstwhile employer) has declared 2019 the 'Year of Carbon'. Meanwhile, the declaration of a climate emergency has spurred school strikes and demonstrations around the world. Thus, ultimately, Hazen's book is a valuable and welcome explanation of why we would do well to pay more attention to the sixth element — and of how much more remains to be discovered about its planetary role through time. ■

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MACHINE LEARNING

Art attribution: AI enters the fray

Can artificial intelligence crack old puzzles in art history? **David Adam** finds out.

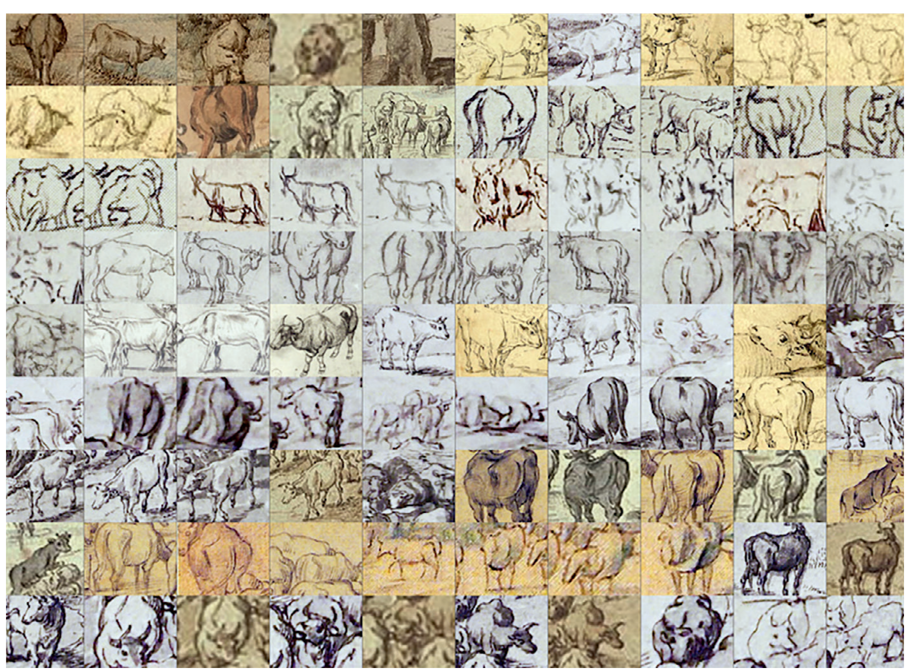
When art thieves broke into a church in northwestern Italy this March, they thought they were stealing a seventeenth-century work by the Flemish painter Pieter Brueghel the Younger. In fact, police in the small Ligurian town of Castelnuovo Magra had been tipped off, and swapped *The Crucifixion*, valued at €3 million (US$3.3 million), for a cheap copy.

In fairness to the gang, a number of Brueghel's works do look nearly interchangeable. A similar *Crucifixion* attributed to the same artist hangs in the Philadelphia Museum of Art in Pennsylvania. And Brueghel probably copied both paintings from another by his trailblazing father, Pieter Bruegel the Elder — whose work also heavily influenced his other son, Jan (known as Jan Brueghel the Elder). With a dynasty of prolific artists, some replicating each other's and their own works, attribution can be nightmarish.

Elizabeth Honig studies these complexities to build up a better picture of who was painting what and influencing whom in northern Renaissance art. And now, she has turned for help to the untiring eye of a computer.

Honig — an art historian at the University of California, Berkeley — has a database of more than 1,500 digitally reproduced Brueghel pictures, most attributed to Jan. In 2016, she initiated an unusual collaboration with artificial intelligence (AI) researchers in France and the United States, deploying state-of-the-art computer vision to help in analysing similarities and tracing them from work to work. Other art historians are also seeing opportunities in harnessing machine learning to provide empirical support for theories and ideas previously confined to the subjective eyes of the beholders.

The computer, says Honig, can pick up "so many more details, so much more easily". Take windmills: hundreds of pictures featuring them fill her Brueghel database. The algorithm has picked up identical images of the structures in multiple paintings. It can even show when a replica has been flipped. And it has helped to pinpoint exact copies of lions, dogs and other figures. The workshops of many Renaissance artists were co-working spaces, so the computer technique helps Honig to piece together how different artists, in the family or not, might ▶



ERIC MONSON/ELIZABETH HONIG

Pictures of cows repeated across a range of paintings attributed to Jan Brueghel the Elder.

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collaborate. "Rubens comes in and does some figures, and then Jan Breughel comes in and does the horses, the dog and the lion, because he's 'Mister Animal'," Honig says. "And so they fit the things together."

Many art historians surmised, on the basis of records and close observation, that this is what happened with numerous paintings by the younger Brueghels. The computer helps to prove it. Hong says: "It addresses a lot of questions about the process of production."

The computer scientists bring their own questions to the project. To them, Honig's collection is a perfect data set with which to stretch their algorithms. Working with paintings challenges a program's pattern-matching capacity, says Mathieu Aubry, a specialist in computer vision and deep learning at École des Ponts ParisTech in France. The difficulty hinges on differences in media and colour. Computer vision can't, he explains, "recognize that a house is the same in a drawing and an oil painting if it has not been trained to do so". The sharp linearity of draughtsmanship and relatively blurred edges in oil painting can confound algorithms.

It would take too long to annotate identical objects or teach the computer to look for certain similarities, such as shape. So Aubry and his colleagues used a technique called unsupervised deep learning, in which the algorithm is shown the pictures and finds similarities for itself. The results could feed into more practical applications of AI vision, he says, such as self-driving cars.

His team posted the results — for instance, a cannon and a chandelier both repeated across five separate pictures — on the arXiv preprint server in March (X. Shen *et al*. Preprint at https://arxiv.org/abs/1903.02678; 2019). And next week, they will present them at the 2019 Conference on Computer Vision and Pattern Recognition in Long Beach, California. Although unsupervised deep learning typically takes a lot of computer power, Aubry says, it is mostly immune from human preconceptions. So it's a good way to avoid biases such as the tendency to focus on the main features of a picture.

> ***"AI allows art history to be treated, for the first time, as a predictive science."***

TELLING TRENDS

Similar technology is being used at Rutgers University in Piscataway, New Jersey, to map how style is defined and develops over time in artists as diverse as Rembrandt van Rijn and the Russian avant-garde artist Kazimir Malevich. "We had theories but they're not provable," says art historian Marian Mazzone, a member of the Rutgers Art and Artificial Intelligence Laboratory. "Computer science may be a tool that can help me empirically answer some of these questions."

Working with lab head Ahmed Elgammal, she has produced a digital analysis of 77,000 of works of art spanning five centuries, from the Renaissance to pop art (A. Elgammal *et al*. Preprint at https://arxiv.org/abs/1801.07729; 2018). To the team's astonishment, the computer — also using unsupervised learning — put the artworks into chronological order.

The project confirmed a theory of eminent twentieth-century art historian Heinrich Wolffin. He argued that shifts in artistic style could be analysed and categorized according to five binary characteristics. One was whether the work was 'linear' (contour-led, as in the work of Sandro Botticelli) or 'painterly' (reliant more on brushstrokes denoting light and shadow, as in the paintings of Tintoretto). Elgammal argues that AI allows art history to be treated, for the first time, as a predictive science that compares theory with observations.

Elsewhere, AI is being harnessed to address a perennial problem of material legacy that underpins art history: deterioration. For instance, the Verus Art system from start-up Arius Technology in Vancouver, Canada, is deploying a 3D scan–print system — initially devised to study damage to Leonardo da Vinci's *Mona Lisa* — to replicate artworks precisely, down to textured brushstrokes and pigment hues. Intended for education, outreach and archives, the 'backed-up' paintings might have another use: foiling thieves more discerning than those fooled by Castelnuovo Magra's cheap copy. ■

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MILITARY TECHNOLOGY

Eyed up: the state of surveillance

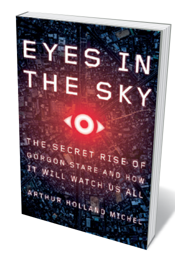
Sharon Weinberger is struck by a book on a technology aimed at capturing everyone's every move.

In the 1998 Hollywood thriller *Enemy of the State*, an innocent man (played by Will Smith) is pursued by a rogue spy agency that uses the advanced satellite "Big Daddy" to monitor his every move. The film — released 15 years before Edward Snowden blew the whistle on a global surveillance complex — has achieved a cult following.

It was, however, much more than just prescient: it was also an inspiration, even a blueprint, for one of the most powerful surveillance technologies ever created. So contends technology writer and researcher Arthur Holland Michel in his compelling book *Eyes in the Sky*. He notes that a researcher (unnamed) at the Lawrence Livermore National Laboratory in California who saw the movie at its debut decided to "explore — theoretically, at first — how emerging digital-imaging technology could be affixed to a satellite" to craft something like Big Daddy, despite the "nightmare scenario" it unleashes in the film. Holland Michel repeatedly notes this contradiction between military scientists' good intentions and a technology based on a dystopian Hollywood plot.

He traces the development of that technology, called wide-area motion imagery (WAMI, pronounced 'whammy'), by the US military from 2001. A camera on steroids, WAMI can capture images of large areas, in some cases an entire city. The technology got its big break after 2003, in the chaotic period following the US-led invasion of Iraq, where homemade bombs — improvised explosive devices (IEDs) — became the leading killer of US and coalition troops. Defence officials began to call for a Manhattan Project to spot and tackle the devices.

In 2006, the cinematically inspired research was picked



Eyes in the Sky: The Secret Rise of Gorgon Stare and How It Will Watch Us All
ARTHUR HOLLAND MICHEL
Houghton Mifflin Harcourt (2019)

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