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LETTERS

Calendars with Olympiad display and eclipse prediction on the Antikythera Mechanism

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Previous research on the Antikythera Mechanism established a highly complex ancient Greek geared mechanism with front and back output dials[1–7]. The upper back dial is a 19-year calendar, based on the Metonic cycle, arranged as a five-turn spiral[1,6,8]. The lower back dial is a Saros eclipse-prediction dial, arranged as a four-turn spiral of 223 lunar months, with glyphs indicating eclipse predictions[6]. Here we add surprising findings concerning these back dials. Though no month names on the Metonic calendar were previously known, we have now identified all 12 months, which are unexpectedly of Corinthian origin. The Corinthian colonies of northwestern Greece or Syracuse in Sicily are leading contenders—the latter suggesting a heritage going back to Archimedes. Calendars with excluded days to regulate month lengths, described in a first century BC source[9], have hitherto been dismissed as implausible[10,11]. We demonstrate their existence in the Antikythera calendar, and in the process establish why the Metonic dial has five turns. The upper subsidiary dial is not a 76-year Callippic dial as previously thought[8], but follows the four-year cycle of the Olympiad and its associated Panhellenic Games. Newly identified index letters in each glyph on the Saros dial show that a previous reconstruction needs modification[6]. We explore models for generating the unusual glyph distribution, and show how the eclipse times appear to be contradictory. We explain the four turns of the Saros dial in terms of the full moon cycle and the Exeligmos dial as indicating a necessary correction to the predicted eclipse times. The new results on the Metonic calendar, Olympiad dial and eclipse prediction link the cycles of human institutions with the celestial cycles embedded in the Mechanism's gearwork.

This extraordinary astronomical mechanism from about 100 BC employed bronze gears to make calculations based on cycles of the Solar System[1,6] (Supplementary Notes 1). Recovered in 1901 by Greek sponge-divers, its corroded remains are now split into 82 fragments—7 larger fragments (A–G) and 75 smaller fragments (1–75)[6]. Data, gathered in 2005[6,7], included still photography, digital surface imaging[12] and, crucially for this study, microfocus X-ray computed tomography (CT)[6,13] (Figs 1–3)—details are in Supplementary Notes 2 (and at www.antikythera-mechanism.gr).

The main upper back dial is now established as a Metonic calendar[1,6,8] (Figs 1 and 2, Supplementary Box 1). The calendar dial bears inscriptions, only viewable using X-ray CT. We have now identified all 12 months of this calendar (Fig. 2, Supplementary Notes 3), providing conclusive evidence of the regulation of a Greek civil calendar by a Metonic cycle, and clues to the instrument's origin. Whereas the Babylonian calendar followed a Metonic cycle from about 500 BC, it has commonly been assumed that the intercalary months of the numerous lunisolar calendars of the Greek cities were determined arbitrarily—Metonic and Callippic cycles (Supplementary Box 1) only being used by astronomers[14]. The month names on the Metonic spiral, however, belong to a regional calendar unassociated with technical astronomy, suggesting that it may have been common for Greek civil calendars to follow the Metonic cycle by about 100 BC.

The inscriptions show that not only the names and order of the months were regulated, but also which years had 13 months, which month was repeated in these years, and which months had 29 or 30 days. The rules are similar to those given by the first century BC writer Geminos[9], whose accuracy has hitherto been in doubt[10,11]. Years are numbered 1 to 19, and intercalary months are spread as evenly as possible over the cycle, such that each year begins with the first new moon following solstice or equinox[15]. In a Metonic cycle, 110 of the 235 months must have 29 days (Supplementary Box 1). The divisibility of both 110 and 235 by 5 explains the five turns of the spiral: months on the same radius across all five turns are equal in length. The numbers on the inside of each 29-day radius indicate which day in these months is skipped (Fig. 2). The skipped days are spread uniformly at intervals of 64 or 65 days across successive Metonic periods, improving on Geminos' scheme, which had uniform 64-day intervals followed by a run of 74 unskipped days at the end.

The month names and order in Greek regional calendars vary widely[16]. The months on the Mechanism belong to one of the Dorian family of calendars, with practically a complete match (11 or 12 names) with Illyria and Epirus in northwestern Greece and with Corcyra (Corfu)—all Corinthian colonies. The calendars of Corinth and its other important colonial foundation, Syracuse, are poorly

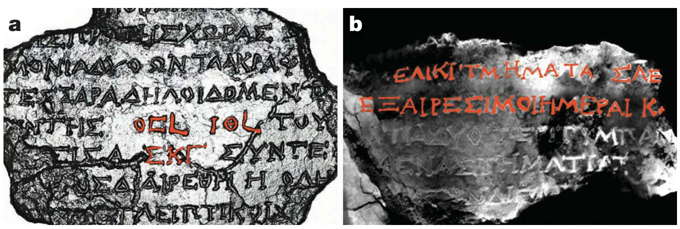

Figure 1 | The 'instruction manual'. Previously identified inscriptions[1,6] reveal remnants of an instruction manual, describing the Mechanism's cycles, dials and functions, as seen in two examples from the Mechanism's back door. **a**, Polynomial texture mapping of fragment 19 shows fine surface detail, with text about 2 mm high. Highlighted in red are "76 years, 19 years" for the Callippic and Metonic cycles (Supplementary Box 1), and "223", for the Saros cycle (Supplementary Box 2). **b**, X-ray CT of fragment E reveals text about 2 mm high. Highlighted are "on the spiral subdivisions 235", confirming the Metonic dial (Supplementary Box 1); and "excluded days 2…", the final "K" presumably standing for the number 20—part of the 22 excluded days round each of the five turns of the Metonic calendar—though "B" that would complete "KB" (22) remains speculative.

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documented. Seven of the Mechanism's months, however, coincide in both name and sequence with the calendar of Tauromenion in Sicily, which was probably originated by settlers from Syracuse in the fourth century BC. The Mechanism's calendar is thus from Corinth or one of its colonies. Moreover, the estimated date of the Mechanism falls after the Roman devastation of Corinth (146 BC) and Epirus

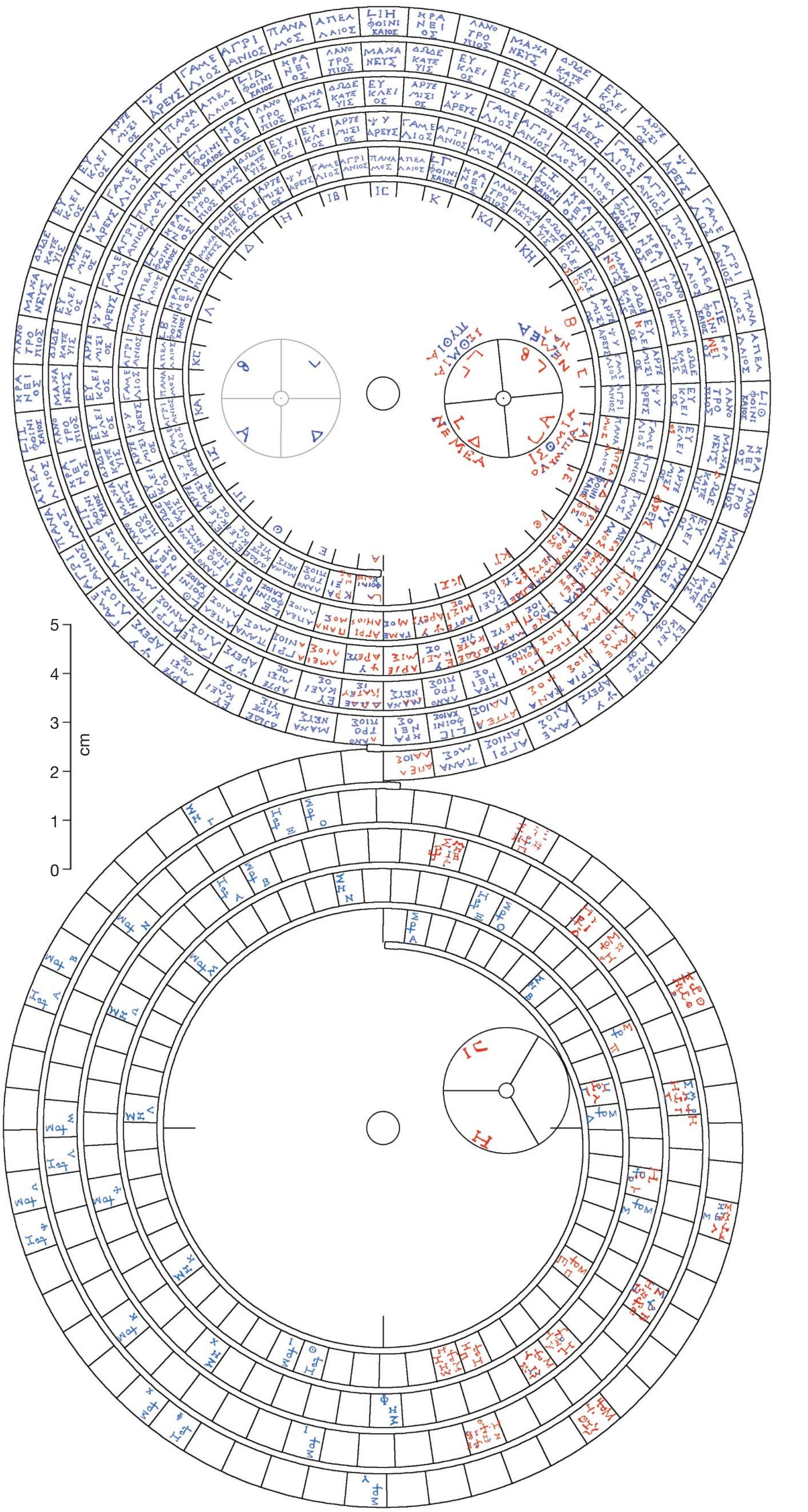

Figure 2 | The back dials. Text in red is traced from X-ray CT; text in blue is reconstructed. Top, the Metonic dial is the main upper dial: a 19-year calendar with 235 months round a five-turn spiral. Though the evidence is scant, we have fortunately been able to decipher all the month names because of their repetition round the dial. With reasonable assumptions about which years have 13 months and which months are repeated in these years, we can then reconstruct the whole of the calendar because of its cyclical nature. The newly identified Corinthian months, written over two or three lines in each cell, are: 1, ΦΟΙΝΙΚΑΙΟΣ; 2, ΚΡΑΝΕΙΟΣ; 3, ΛΑΝΟΤΡΟΠΙΟΣ; 4, ΜΑΧΑΝΕΥΣ; 5, ΔΩΔΕΚΑΤΕΥΣ; 6, ΕΥΚΛΕΙΟΣ; 7, ΑΡΤΕΜΙΣΙΟΣ; 8, ΨΥΔΡΕΥΣ; 9, ΓΑΜΕΙΛΙΟΣ; 10, ΑΓΡΙΑΝΙΟΣ; 11, ΠΑΝΑΜΟΣ; 12, ΑΠΕΛΛΑΙΟΣ. The numbers Α (1), Ε (5), Θ (9), ΙΓ (13)… around the inside of the spiral specify the excluded days to be skipped in each of the five 29-day months on the same radius. Within the Metonic dial are shown two subsidiary dials. Right, the Olympiad dial (see Fig. 3), which is identified here for the first time. It is a four-year dial, representing the cycle of the Panhellenic Games, a central part of ancient Greek culture and a common basis for chronology. Left, the hypothetical Callippic dial, which follows a 76-year cycle, indicated on the back door inscriptions (Fig. 1). Bottom, the Saros dial is the main lower dial: an 18-year (223-lunar month) scale over a four-turn spiral, for predicting eclipses. Predictions are shown in the relevant months as glyphs (see Fig. 4), which indicate lunar and solar eclipses and their predicted times of day. This new reconstruction has 51 glyphs, specifying 38 lunar and 27 solar eclipses. The glyph times are incomplete as their generation remains obscure. The divisions on the inside of the dial at the cardinal points indicate the start of a new full moon cycle (Supplementary Box 2). Within the Saros dial is shown a subsidiary dial, the Exeligmos dial: this is a 54-year triple Saros dial, whose function is now understood. The first sector is blank (representing 0) and the following are labelled with numbers Η (8) and Ις (16). The dial pointer indicates which number must be added to the glyph times in hours to get the eclipse times.

(171–168 BC). Syracuse's candidacy suggests a possible mechanical tradition going back to Archimedes (died 212 BC), who invented a planetarium described by Cicero[17] (first century BC) and wrote a lost book on astronomical mechanisms[18].

The subsidiary dial (Fig. 3) inside the Metonic spiral was formerly believed to be a 76-year Callippic dial[8] (Supplementary Box 1). We have now established from its inscriptions that it displays the 4-year Olympiad cycle—a suggestion made previously for the main upper back dial[19]. The four sectors are inscribed anticlockwise with each sector containing a year number and two Panhellenic Games: the 'crown' games of Isthmia, Olympia, Nemea and Pythia and two lesser games: Naa (at Dodona) and a second game not yet deciphered[20,21]. As biennial games, Isthmia and Nemea occur twice. The Olympiads were a common framework for chronology, with years normally beginning in midsummer. But here the year must start between early autumn and early spring, because the Isthmian Games are in the years preceding their usual positions in the cycle (Fig. 3). Several month names favour a start following the autumnal equinox. The small ($\sim 8^{\circ}$, that is, one month) offset of the dial took account of the variation in the start of the lunisolar calendar and so ensured that the next Olympiad year would never start before the current year's games were over.

The Olympiad dial must be turned from the existing gearing[6] at a rate of one-quarter turn per year. Underneath the Olympiad dial are the remains of an isolated gear with 60 teeth[1,6]. Engaging this with a single additional gear with 57 teeth on the shaft of the Metonic pointer provides the correct anticlockwise rotation. Sizing this gear, with tooth pitch equal to the 60-tooth gear, gives a gear radius exactly as required by the interaxial distance: strong supporting evidence both for the Olympiad dial and this mechanical arrangement. The "76 years" inscription (Fig. 1) and other factors favour a Callippic dial, as a second subsidiary, symmetrical with the Olympiad dial—though loss of evidence means confirmation is unlikely. Might a fourth subsidiary, symmetric with the Exeligmos dial (Figs 1 and 2) complete the dial system? An existing shaft here does not penetrate the back plate and does not appear to rotate at any meaningful rate. So this seems doubtful.

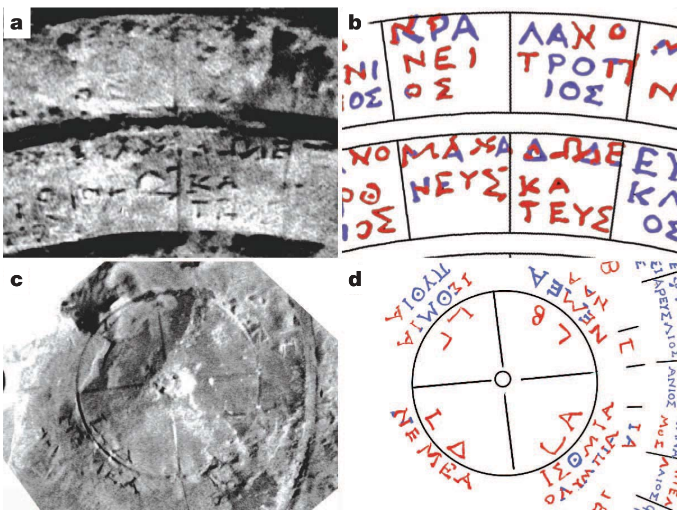

Figure 3 | Deciphering the Metonic and Olympiad dials. a, Representative CT slice of fragment B, showing part of the Metonic dial. The scales are 7 mm wide and the text 1.7 mm high (Supplementary Notes 3). **b**, Text in red was traced from the CT—just enough being deciphered to discover all the month names; text in blue is reconstructed (colouring in **d** follows this convention). The months here are ΚΡΑΝΕΙΟΣ, ΛΑΝΟΤΡΟΠΙΟΣ, ΜΑΧΑΝΕΥΣ and ΔΩΔΕΚΑΤΕΥΣ. **c**, CT slice through fragment B, showing the Olympiad dial. LΔ and NEMEA can be seen faintly on the left-hand side. **d**, The four sectors of the Olympiad dial are labelled LA, LB, LΓ and LΔ—years 1, 2, 3 and 4. Outside are the Panhellenic Games: year 1: ΙΣΘΜΙΑ, ΟΛΥΜΠΙΑ; year 2: NEMEA, NAA; year 3: ΙΣΘΜΙΑ, ΠΥΘΙΑ; and year 4: NEMEA, and undeciphered text. To the right of the dial are the numbers ς (6) and IA (11) for the excluded days.

We have increased the number of identified eclipse glyphs[6] (Figure 4, Supplementary Notes 4) from 16 to 18. The decoding of these glyphs is extended here with the observation of 'N\$^{\Upsilon}$' abbreviating 'ΝΥΚΤΟΣ' ('of the night') for solar eclipses and index letters at the bottom of each glyph in alphabetical order. These mean that the Saros dial starts at the top (as initially suggested[4]) with index letter 'A' rather than at the bottom (as in a later model[6]). With any other dial start, extrapolation of the index letters back to the first glyph would force them to begin in the middle of the alphabet. The alphabetic index letters also constrain the number of glyphs. If the 18 glyphs are aligned with lunar and solar eclipses in the last four centuries BC[22], they give a perfect match for 100 start dates, suggesting an excellent prediction scheme. However, we do not believe that the glyphs were based primarily on observations: even extensive observations over decades would miss a high proportion of the 65 estimated eclipse predictions (Supplementary Box 2). The glyphs appear to have been generated by a scheme of eclipse possibilities, similar to Babylonian schemes with an 8-7-8-7-8-pattern[23,24] (Supplementary Box 2), which can be generated from a simple arithmetical model of nodal elongation at syzygy[25]. However, these schemes have 5- or 6-month gaps between all predictions, whereas the index letters imply that the Antikythera scheme has some longer gaps.

We consider kinematic models for glyph generation, defined by different nodal elongation criteria and computable either with similar technology to the Mechanism or an arithmetic method. With suitable criteria, these models generate all the Antikythera glyphs and no glyphs which are observably absent—whether the model uses mean months or first anomaly months (incorporating lunar and solar anomalies). However, none of these models exactly match the index letters. Because of parallax, the likelihood of a solar eclipse depends not only on a syzygy's nodal elongation, but also on whether it occurs north or south of the ecliptic, as was recognized in antiquity[11]. Introducing this asymmetry produces models (both using mean and first anomaly months) that exactly match all 18 definite glyphs with a single index letter error, caused by the only instance where the models generate two adjacent lunar glyphs—something which never featured in Babylonian schemes. Discarding the second of these gives a perfect match. These kinematic models provide a persuasive explanation of the glyph sequence.

Matching the glyph times with actual eclipse times over the last four centuries BC has not discovered close correlations, suggesting they were not accurate. Five out of the eight definite glyph times that include 'H\$^{M}$' ('ΗΜΕΡΑΣ', 'of the day'; Fig. 4) conform to a model that calculates glyph times from mean lunar months—but two others certainly do not. Introducing the first lunar and solar anomalies into the analysis of the glyph times should reveal a periodic cycle of corrections following the full moon cycle (Supplementary Box 2). But the glyph times do not conform to this pattern. We conclude that the process of generation of glyph times was not sound and may remain obscure.

We have discovered why the Saros dial is a four-turn spiral: each quarter-turn of the dial covers a full moon cycle (Supplementary Box 2). So the apparent diameter of the Moon, which mediates the duration and type of an eclipse, is indicated by the angle of the pointer within each quarter turn of the dial.

Each Saros series eclipse occurs about 8 hours later in the day (Supplementary Box 2). After three Saros cycles (the Exeligmos) the eclipse is at nearly the same time of day. The Exeligmos dial[6] is divided into three sectors, with no inscription in one sector and the numbers 8 and 16 in successive sectors (Fig. 2). We conclude that these numbers tell the user how many hours to add to the glyph time to get the time of the predicted eclipse.

The newly discovered inscriptions reveal that the Antikythera Mechanism was not simply an instrument of abstract science, but exhibited astronomical phenomena in relation to Greek social institutions. It is totally unexpected that it was made for use

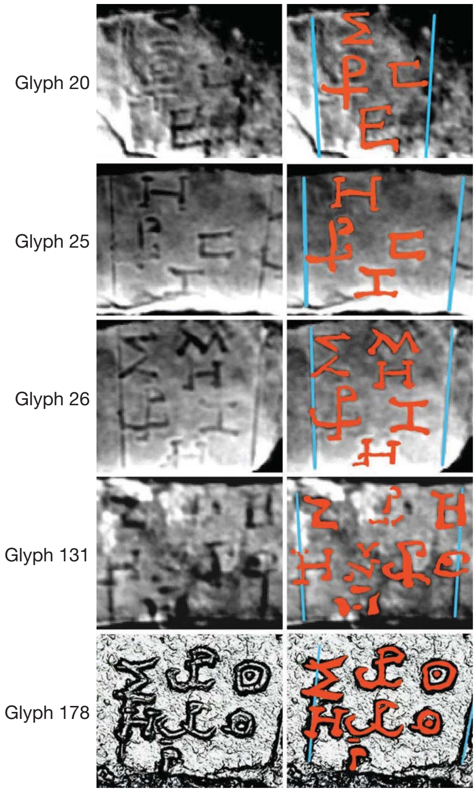

Figure 4 | The glyphs. A selection of the 18 known eclipse prediction glyphs (Supplementary Notes 4). Left, the raw data; X-ray CT for glyphs 20, 25, 26 and 131, and polynomial texture mapping for glyph 178. Right, the text traced in red. Most of the glyph symbols were previously decoded[6]. Σ, ΣΕΛΗΝΗ (Moon); Η, ΗΛΙΟΣ (Sun); $\mathrm{H}\backslash^{\mathrm{M}}$, ΗΜΕΡΑΣ (of the day); $\omega\backslash^{\rho}$, ωρα (hour) and the text that follows is the eclipse time in hours. Here we add $\mathrm{N}\backslash^{\Upsilon}$, ΝΥΚΤΟΣ (of the night), as seen in glyph 131, and the identification of index letters at the bottom of each glyph in alphabetical order. In the consecutive glyphs 20, 25 and 26 the index letters Ε, Ζ and Η can be seen. (Ζ is always written on the Mechanism as an Ι with long serifs.) Some of the glyphs have unexplained bars over the index letter, as in glyphs 131 and 178. The index letters have profound consequences for the design of the glyph sequence.

in northwestern Greece or Sicily, rather than Rhodes as is often suggested. The Metonic calendar, the Olympiad dial and the Saros eclipse prediction scheme add new insights into the sophisticated functions of this landmark in the history of technology.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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Author Contributions T.F. and A.J. carried out the CT analysis of the inscriptions and A.J. provided most of the interpretation and historical analysis, with input from Y.B. A.J. identified the excluded days on the Metonic dial, the Olympiad dial and the index letters in the glyphs. T.F. proposed how the Olympiad dial was turned. J.S., T.F. and A.J. contributed ideas about the glyphs and T.F. carried out the analysis of glyph sequence generation and glyph times and explained why the Saros dial has four turns. J.S. identified the role of the Exeligmos dial. All the authors contributed to the written manuscript. T.F collated and condensed the text and designed the illustrations.

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