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**Acknowledgments:** We thank two anonymous reviewers for carefully reviewing the manuscript. Supported in part by Deutsche Forschungsgemeinschaft, Helmholtz Gemeinschaft, and Schweizerischer Nationalfonds. This work is a contribution to EPICA, a joint European Science Foundation/European Commission (EC) scientific program, funded by the EC under the Environment and Climate Program and by national contributions from Belgium, Denmark, France, Germany, Italy, the Netherlands, Norway, Sweden, Switzerland, and the UK. The main logistic support at Dome C was provided by the Institut Polaire Français–Paul Emile Victor (IPEV) and PNRA. Ice core material was also used from TALDICE, a joint European program led by Italy and funded by national contributions from Italy, France, Germany, Switzerland, and the UK. The main logistical support at Talos Dome was provided by PNRA. This is EPICA publication 284. The data are accessible online at http://doi.pangaea.de/10.1594/PANGAEA.772713.

**Supplementary Materials**
www.sciencemag.org/cgi/content/full/science.1217161/DC1
Materials and Methods
Figs. S1 to S7
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References (*36–49*)

28 November 2011; accepted 19 March 2012
Published online 29 March 2012;
10.1126/science.1217161

# Ancient Maya Astronomical Tables from Xultun, Guatemala

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**Maya astronomical tables are recognized in bark-paper books from the Late Postclassic period (1300 to 1521 C.E.), but Classic period (200 to 900 C.E.) precursors have not been found. In 2011, a small painted room was excavated at the extensive ancient Maya ruins of Xultun, Guatemala, dating to the early 9th century C.E. The walls and ceiling of the room are painted with several human figures. Two walls also display a large number of delicate black, red, and incised hieroglyphs. Many of these hieroglyphs are calendrical in nature and relate astronomical computations, including at least two tables concerning the movement of the Moon, and perhaps Mars and Venus. These apparently represent early astronomical tables and may shed light on the later books.**

The Maya have long been noted for their astronomical proficiency, believed by many to be on par with that of the cultures of the ancient Middle East. Most of what we know about Maya astronomical methodology, and the precision of their understanding of the movement of the Sun, Moon, and planets, comes from studies of the codices, painted bark paper documents dated to a century or two before Spanish contact. Here we report on a source several centuries earlier, a wall painting accompanied by a numerical table and a series of long numbers that appear to have functioned like those found in astronomical tables in the codices.

Though systematic archaeological investigations began only in 2008 (*1*), the Maya ruins of Xultun, Guatemala, were first reported in 1915 (*2*). Despite formal scientific expeditions to map and record the site's monuments in the 1920s (*2*) and again in the 1970s (*3, 4*), illicit excavations have left the largest mark on the site. In March 2010, Maxwell Chamberlain identified the presence of a heavily eroded mural painting on the west wall of a small masonry-vaulted structure exposed by looting (*5*). The structure (Fig. 1), designated 10K-2, is located within a residential compound and was modified by the Maya over several construction phases. The most recent of these phases saw the room filled with rubble and earth, and the final phase built over it, effectively preserving its interior paintings. The looters' excavation broke through this final-phase veneer and exposed the southernmost portion of the room's west wall. They later abandoned their excavation, and the exposed painting began to weather.

We continued excavating this structure in 2010 and 2011, revealing that three of the structure's interior walls (west, north, and east), as well as its vaulted ceiling, were once covered by mural paintings. The fourth (south) wall consisted mainly of a doorway, with the remainder destroyed by the looters. The state of preservation of the murals varies considerably, owing to the damaging effects of water, roots, and insects. The east wall, located closest to the exterior surface of the covering mound, has eroded the most.

The paintings on the east wall include a large number of small, delicately painted hieroglyphs, rendered in a variety of sizes and in black or red line near the two (possibly three) seated figures that once dominated the imagery. Thin coats of plaster were reapplied over existing texts to provide a clean slate for others. Still other texts are incised into the plaster surface. Given their arrangement around and on the figural painting and

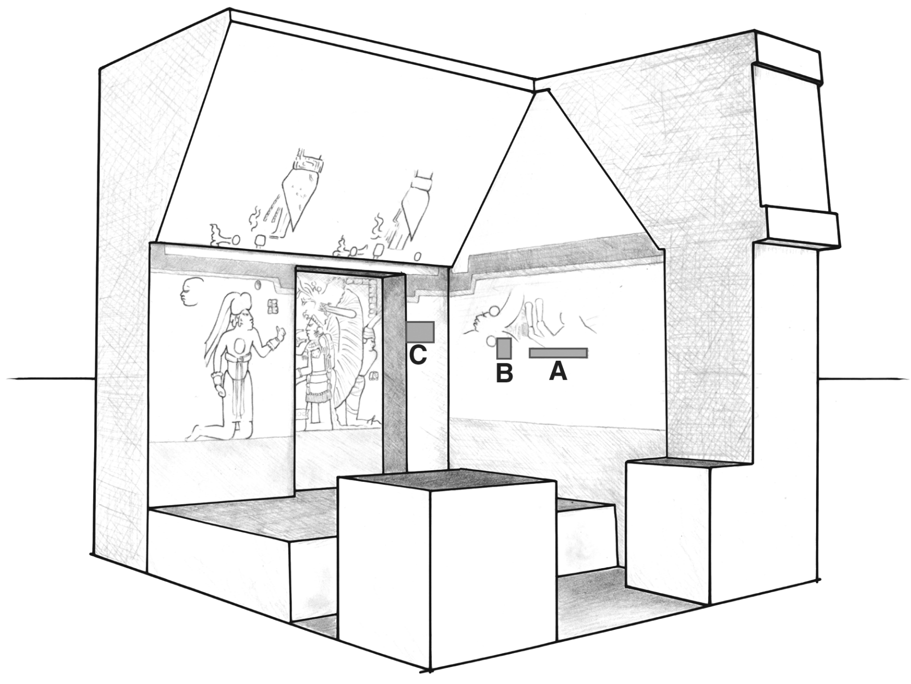


**Fig. 1.** Artist's reconstruction of Structure 10K-2, Xultun, Guatemala, showing painted figures from the north and east walls, as well as the locations of numerical arrays discussed in the text. (**A**) Lunar table. (**B**) "Ring Number." (**C**) Intervals. [Drawing by H. Hurst]

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earlier texts, as well as the variety of sizes and method of execution of the preserved glyphs, there is little doubt that texts were not integral to the original design of the chamber's mural decoration, but were created during the room's continual use.

The remains of many bar-and-dot numbers arranged in vertical columns can be seen along the southern portion of the east wall. Only a handful of legible columns are left (Fig. 2 and fig. S2), but faint remains of other bar-and-dot numbers can be seen, suggesting a lengthy array of columns spanning some 48 cm (fig. S3). The columns contain no more than three numerals, and they resemble calendrical and astronomical tables in the *Dresden Codex*, an ancient Maya hieroglyphic manuscript composed centuries later (*6*, *7*).

Visible atop at least five of the columns are individual "Moon" glyphs combined with facial profiles. Enough detail is visible on two of these glyphs to see that they are deities. Elsewhere, similar hieroglyphs are used to record Moon ages in Maya date records—as part of the so-called Lunar Series identified by Teeple (*8*). Lunar months, as Teeple showed, are grouped into sets of six, forming the 177- or 178-day Maya lunar "semester" (~29.5 days × 6) (*8*–*10*). The presence of these lunar deity heads suggests that the number columns also have a lunar meaning.

The final three number columns are:

| | | |
|---|---|---|
| 12 | 12 | 13 |
| 5 | 14 | 5 |
| ? | 6 | 4 |

Given their similarity to numerical records in the *Dresden Codex* and other hieroglyphic manuscripts, we take these numbers to represent records of elapsed days using periods of the Long Count calendar. The upper number would therefore represent multiples of the 360-day "tun" unit, the middle number multiples of 20-day units known as the "winal," and the final number would represent units of single days, known as "k'in." These three columns thus represent a progression of ever-increasing quantities of days with the last two columns equal to 4606 (12.14.6) and 4784 (13.5.4) days, respectively. The bottommost number of the previous column is eroded, but enough remains to indicate that it must be a number between 7 and 9 (12.5.?), implying that the column's quantity is between 4427 and 4429.

The span between the final two columns is a lunar "semester" of 178 days. Subtracting either 177 or 178 from the penultimate number (4606), we arrive at 4429 (12.5.9) or 4428 (12.5.8) days, both of which fit with what remains of the third-from-last column. In this light, it is reasonable to suggest that the Xultun number array represents a running sequence of consecutive multiples of 177 or 178 with only the last three totals well preserved. The numbers 177 and 178 are important in ancient Maya astronomy. The eclipse tables on pages 51 to 58 of the *Dresden Codex* are based on these same intervals. The *Dresden* tables use this basic unit, along with an interspersed correction span of 148 days, or five lunations, to represent patterns in both lunar and solar eclipses (*8*, *11*). The 4784-day Xultun array represents 162 cumulative 6-month lunations (162 × 29.530589 = 4783.9554), or twice that of the Palenque lunar reckoning system (*8*). Moreover, the layout of the Xultun table closely resembles the successive columns of cumulative totals in the *Dresden* Eclipse Table. However, unlike the *Dresden* tables, the Xultun array does not seem corrected to correlate with precise eclipse phenomena. It would seem rather to be a simpler tally spanning a period of roughly 13 years. This end point is suggestive, because years and other time periods grouped in thirteens were of deep cosmological significance to the ancient Maya, forming the foundation of their "Grand Long Count" calendar (*12*).

Additional similarity between the Xultun paintings and codical tables emerges in the form of an incised "Ring Number" on the east wall (fig. S5). Ring Numbers typically serve to establish the temporal starting points for various tabulations and almanacs, including astronomical tables. The relationship between this Ring Number and the other Xultun texts is at present unclear.

A second array consisting of four columns painted in red is found on the eastern portion of the north wall (Fig. 3 and fig. S4). Each column begins with a tzolk'in day station in the uppermost hieroglyph, followed in a vertical line by a series of five numbers, as follows:

| A | B | C | D |
|---|---|---|---|
| 1 Kawak (Kaban?) | 9 K'an | 13 Chikchan | ? Manik' |
| 8 | 2 | 17 | 12 |
| 6 | 7 | 0 | 5 |
| 1 | 9 | 1 | 3 |
| 9 | 0 | 3 | 3 |
| 0 | 0 | 0 | 0 |

Unfortunately, the tzolk'in stations are not all legible. The middle two are fairly clear as 9 K'an and 13 Chikchan, respectively. The day record atop the first column bears the coefficient 1 with what looks to be Kawak or Kaban, and the final column shows a clear Manik' day sign without a legible coefficient.

The columns of five numbers appear at first glance to be Long Count dates, yet they are not—at least not in the conventional sense. By their nature, standard Long Count dates reckon elapsed

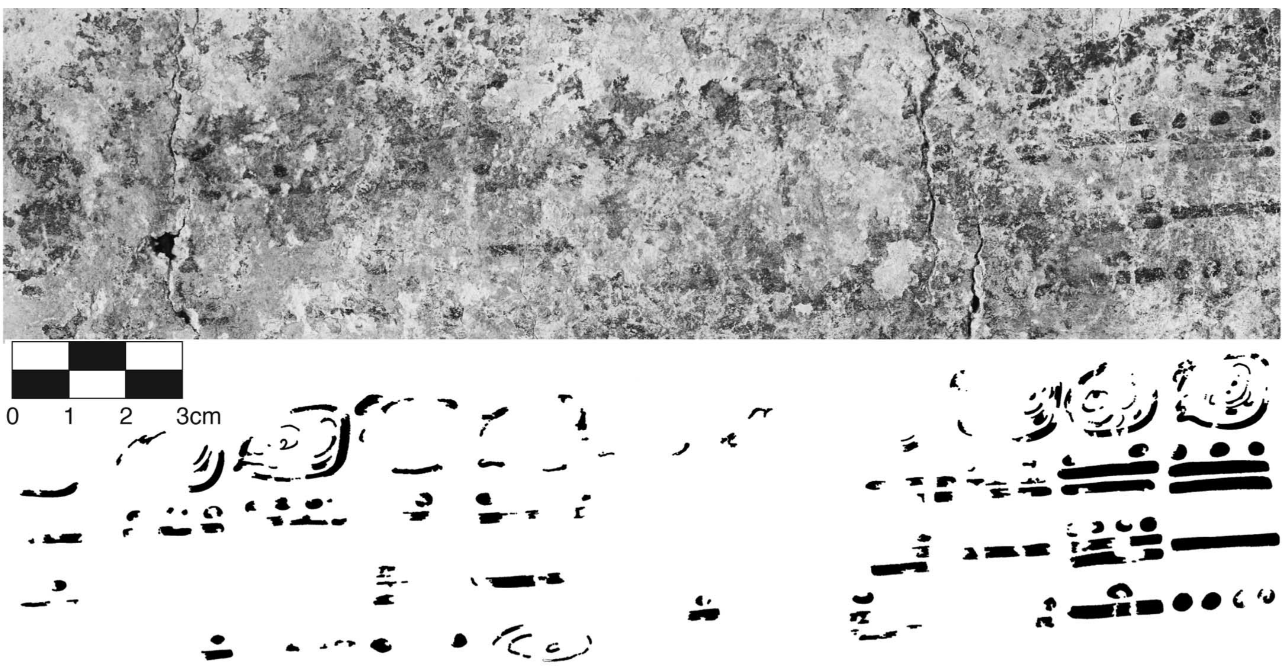


**Fig. 2.** Portion of lunar table, Structure 10K-2, Xultun, Guatemala. [Image by W. Saturno, drawing by D. Stuart]

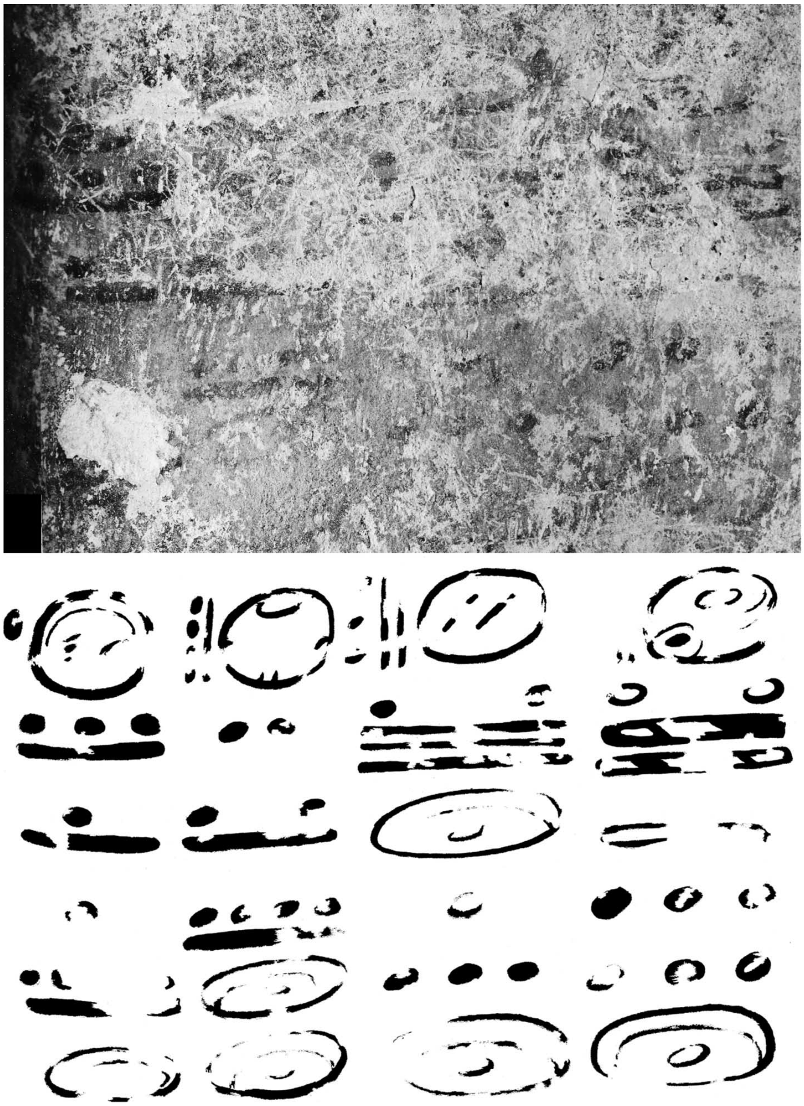

**Fig. 3.** Numerical array. [Image by W. Saturno, drawing by D. Stuart]

time from the base of 13.0.0.0.0 4 Ahaw 8 Kumk'u. These spans are usually between 3000 and 4000 years. The Xultun columns, by contrast, appear different, expressing a wide range of accumulated time, some smaller and others considerably larger. Similar lengthy tallies of days appear as so-called Distance Numbers in both the monumental inscriptions and in the *Dresden Codex*, often involving periods above the Bak'tun (*13–15*). In addition, the Xultun intervals do not link the different tzolk'in day stations noted at the top of each column, suggesting that each column is self-contained, expressing accumulations of days wedded, for reasons still undetermined, to the individual tzolk'in days recorded at the top.

The intervals might be commensurate with other canonic astronomical periods and significant computational numbers found in the much later codices, where they were contrived to perform long-term corrections to astronomical tables and to provide schemes for ordering tabulated base dates. One of the likenesses to the Xultun numbers is on page 24 of the Venus Table in the *Dresden Codex*. The so-called Long Round (LR) number (*16*), 9. 9. 16. 0. 0—which may be added to a date prior to the era beginning 13. 0. 0. 0. 0 to reach a date in the historical era—is a whole multiple not only of the 260-day tzolkin, the 365-day haab, and the 584-day Venus canonic synodic cycle, but also of the 18,980-day Calendar Round, the length of the Venus Table (37,960 days; also a double Calendar Round), and the 2340-day cycle, which commensurates the table with the 9 × 13 = 117-day cycle associated with the nine Lords of the Night (*17*). The number 117 is also an approximation to the synodic period of Mercury (115.9 days), for which there is some documented reference in codical texts (*18*). The largest common divisor of each of the four Xultun intervals, 56,940, is a whole multiple of both the Calendar Round (3 × 18,980) and the canonic Mars period (73 × 780).

Although the Xultun intervals and the aforementioned submultiples can be generated solely

**Table 1.** Maya calendrical and astronomical commensurabilities with the Xultun intervals. Explanation of entries: 1, Xultun intervals (base 20); 2, base-10 equivalent; 3, tzolkin or 260-day round of 13 × 20 days; 4, haab or 365-day year (the Maya did not use leap years); 5, Calendar Round (CR), 18,980 days, which commensurates tzolkin and haab: 52 × 365 = 73 × 260 days; 6, computing year, or 364 days, a conveniently factorable approximation to the 365-day year used to facilitate calculations; 7, canonic Venus period (VP), 584 days (actual 583.92 days); 8, five canonic VP, or 2920 days, the length of one pass of five stations through the Venus table, which commensurates VP and haab: 5 × 584 = 8 × 365; 9, 2340 days, a cycle commensurating the cycle of the nine lords of the night, the 13-day numbers, the VP, and possibly the period of Mercury (actual 115.9 days): 9 × 13 = 117 days; 20 × 117 = 2340 = 4VP + 4 days; 10, length of the Venus table = 37960 = 65 × 584 = 2CR; 11, canonic Mars period (MP) = 780 days (actual 779.9 = 2 × 260 – 0.1 days); 12, 56,940 = largest common divisor of CR and MP = 3 × 18,980 = 73 × 780; 13, length of the Eclipse Table in the Dresden Codex = 11960 = 46 × 260 = 405 lunar synodic months. d, days.

| No. | (1) Interval | (2) Decimal equivalent | (3) Tzolkin | (4) Haab | (5) CR | (6) Computing year | (7) (VP) Canonic Venus period | (8) 5VP | (9) 2340-day cycle | (10) Length of Venus Table | (11) (MP) Canonic Mars period | (12) 56,940-day cycle | (13) Length of Eclipse Table |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| A | 8.6.1.9.0 | 1,195,740 | 4599 | 3276 | 63 | 3285 | 2047+0.5VP | 409.5 | 511 | 31+1CR | 1533 | 21 | 100–260$^{d}$ |
| B | 2.7.9.0.0 | 341,640 | 1314 | 936 | 18 | 938+4×52$^{d}$ | 585 | 117 | 146 | 9 | 438 | 6 | 28.5+780 |
| C | 17.0.1.3.0 | 2,448,420 | 9417 | 6708 | 129 | 6726+3×52$^{d}$ | 4192+0.5VP | 838.5 | 1046+780$^{d}$ | 64+1CR | 3139 | 43 | 204.5+10×260 |
| D | 12.5.3.3.0 | 1,765,140 | 6789 | 4836 | 93 | 4849+2×52$^{d}$ | 3022+0.5VP | 604.5 | 754+780$^{d}$ | 46+1CR | 2263 | 31 | 147.5+4×260 |

as a consequence of their relationship to the Calendar Round, it is also possible that these long numbers were designed at least in part to serve astronomical ends (Table 1). That the Xultun numbers are divisible by integral and half-integral multiples (give or take additive or subtractive small multiples of 52 and 260) is reminiscent of the character of numbers one finds in the upper portions of multiplication tables that accompany astronomical reckonings in the codices. The latter were developed to place canonic events in closer proximity to the occurrence of actual sky phenomena, e.g., an eclipse, the start of a retrograde loop of Mars, or a heliacal rise of Venus.

Though the *Dresden Codex* dates to ca. the 15th century, there are Long Count entry dates to the Eclipse table on the same page as the multiplication table dated to 755 C.E. (*19*), which corresponds well with the 800 C.E. date for Xultun 10K-2. Codical tables were likely copied and recopied over many generations, with updates, based on observational data, incorporated periodically. Thus, the known Postclassic written documents derived from others of classical origin.

One goal of the Maya calendar keepers, gleaned from studies of the codices, was to seek harmony between sky events and sacred rituals. The Xultun paintings may represent an expression of the same ambition several centuries earlier. Although the higher multiples in the multiplication table attached to the *Dresden Codex* Venus Table consist of near whole multiples of important Venus numbers, and the Mars and Eclipse tables exhibit similar properties with respect to Mars and Eclipse periods, respectively, the four (undoubtedly carefully contrived) Xultun numbers may have been devised to create schemes for synchronizing predictable events connected with the movement of Mars, Venus, the Moon, and possibly Mercury. Why these four particular numbers were used, which range in duration from 935 to 6703 years, is uncertain.

Though human portraits adorn most of the interior space, painted when the room was built and decorated in the early 9th century C.E. (texts associated with the main figures of the mural and their actions seem to cluster around 814 C.E.), the smaller, more ephemeral texts represent the continued use and modification of the room up until the time it was intentionally buried. To date, 12 painted or incised texts (not including the presented tables), ranging in length from 5 to 30 glyphs, have been identified. This continued astronomical and calendrical writing is confined to the area along the sunlit portions of east and north walls. These repeatedly replastered sections may have been used as a kind of reference for the preparation of other more permanent or public monuments. The tidy hand-writing on the wall might even have been copied from Classic period screenfold books, the plastered and replastered surfaces reflecting a perpetual negotiation and elaboration in Maya reckonings of time, astronomical cycles, and the written words that conveyed them.

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**Acknowledgments:** The data reported in this paper are available in the supplementary materials. Excavations by the Proyecto Regional San Bartolo–Xultun between 2008 and 2012 were supported by Boston University as well as through grants from the National Geographic Society, Committee for Research and Exploration (grants 8782-10, 8931-11, 9091-12), and the National Geographic Society, Expeditions Council (EC0497-11). We also thank the Guatemalan Ministerio de Cultura, Instituto de Antropología e Historia, and the Departamento de Monumnetos Prehisánicos for their support.

**Supplementary Materials**

www.sciencemag.org/cgi/content/full/336/6082/714/DC1
Materials and Methods
Supplementary Text
Figs. S1 to S5

5 March 2012; accepted 5 April 2012
10.1126/science.1221444

# A Stem Cell–Based Approach to Cartilage Repair

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Osteoarthritis (OA) is a degenerative joint disease that involves the destruction of articular cartilage and eventually leads to disability. Molecules that promote the selective differentiation of multipotent mesenchymal stem cells (MSCs) into chondrocytes may stimulate the repair of damaged cartilage. Using an image-based high-throughput screen, we identified the small molecule kartogenin, which promotes chondrocyte differentiation (median effective concentration = 100 nM), shows chondroprotective effects in vitro, and is efficacious in two OA animal models. Kartogenin binds filamin A, disrupts its interaction with the transcription factor core-binding factor β subunit (CBFβ), and induces chondrogenesis by regulating the CBFβ-RUNX1 transcriptional program. This work provides new insights into the control of chondrogenesis that may ultimately lead to a stem cell—based therapy for osteoarthritis.

Over 70% of Americans between the ages of 55 and 70 are affected by osteoarthritis (OA), which is characterized by the progressive breakdown of articular cartilage (*1*) and ultimately leads to the functional failure of synovial joints. OA is mediated by several pathogenic mechanisms, including enzymatic degradation of extracellular matrix, deficient new matrix formation, cell death, and abnormal activation and hypertrophic differentiation of cartilage cells (*2*). The only current therapeutic options for OA are pain management and surgical intervention (*3*). Mesenchymal stem cells (MSCs), which reside in bone marrow and many adult tissues, are capable of self-renewal and differentiation into a variety of cell lineages, including chondrocytes, osteoblasts, and adipocytes (*4*, *5*). MSCs have been identified in healthy and diseased cartilage and appear to retain at least some potential to regenerate cartilage in vivo (*6*, *7*). Here we