7. Butler, P. M. A new interpretation of the mammalian teeth of tripsphenic pattern from the Albian of Texas. *Breviora* **446,** 1–27 (1978).
8. Kielan-Jaworowska, Z. & Dashzeveg, D. Eutherian mammals from the Early Cretaceous of Mongolia. *Zool. Scripta* **18,** 347–355 (1989).
9. Novacek, M. J. The skull of leptictid insectivorans and the higher-level classification of eutherian mammals. *Bull. Am. Mus. Nat. Hist.* **183,** 1–112 (1986).
10. Sigogneau-Russell, D., Dashzeveg, D. & Russell, D. E. Further data on *Prokennalestes* (Mammalia, Eutheria inc. sed.) from the Early Cretaceous of Mongolia. *Zool. Scripta* **21,** 205–209 (1992).
11. Butler, P. M. Early trends in the evolution of tribosphenic molars. *Biol. Rev.* **65,** 529–552 (1990).
12. Clemens, W. A. Jr & Lillegraven, J. A. New Late Cretaceous, North American advanced therian mammals that fit neither the marsupial nor eutherian molds. *Contrib. Geol. Univ. Wyoming* **3,** 55–85 (1986).
13. Lillegraven, J. A., Kielan-Jaworowska, Z. & Clemens, W. A. Jr (eds) *Mesozoic Mammals—the First Two-thirds of Mammalian History* (Univ. of California Press, Berkeley, 1979).
14. Dashzeveg, D. & Kielan-Jaworowska, Z. The lower jaw of an aegialodontid mammal from the Early Cretaceous of Mongolia. *Zool. J. Linn. Soc.* **82,** 217–227 (1984).
15. Rougier, G. W., Wible, J. R. & Novacek, M. J. Implications of *Deltatheridium* specimens for early marsupial history. *Nature* **396,** 459–463 (1998).
16. Nessov, L. A., Sigogneau-Russell, D. & Russell, D. E. A survey of Cretaceous tribosphenic mammals from middle Asia (Uzbekistan, Kazakhstan and Tajikistan), of their geological setting, age and faunal environment. *Palaeovert.* **23,** 51–92 (1994).
17. Slaughter, B. H. Mid-Cretaceous (Albian) therians of the Butler Farm local fauna, Texas. *Zool. J. Linn. Soc.* **50** (suppl.), 131–143 (1971).
18. Wang, Y. Q., Hu, Y.-M., Chow, M.-C. & Li, C.-K. in *Sixth Symposium on Mesozoic Terrestrial Ecosystems* (eds Sun, A.-L. & Wang, Y.-Q.) 221–228 (China Ocean, Beijing, 1995).
19. Fox, R. C. *Paranyctoides maleficus* (new species), an early eutherian mammal from the Cretaceous of Alberta. *Spec. Publ. Carnegie Mus. Nat. Hist.* **9,** 9–20 (1984).
20. Cifelli, R. L. *et al.* in *Vertebrate Fossils of Utah* (ed. Gillette, D. D.) 219–242 (Utah Geological Survey, Salt Lake City, 1999).
21. Jenkins, F. A. Jr & Schaff, C. R. The Early Cretaceous mammal *Gobiconodon* (Mammalia, Triconodonta) from the Cloverly Formation in Montana. *J. Vert. Paleontol.* **8,** 1–24 (1988).
22. Kielan-Jaworowska, Z. Evolution of the therian mammals in the Late Cretaceous of Asia. Part II. Postcranial skeleton in *Kennalestes* and *Asioryctes*. *Palaeontol. Pol.* **37,** 65–83 (1974).
23. Luo, Z. in *In the Shadow of the Dinosaurs—Early Mesozoic Tetrapods* (eds Fraser, N. C. & Sues, H.-D.) 98–128 (Cambridge Univ. Press, Cambridge, 1994).
24. Luckett, W. P. in *Mammal Phylogeny, volume 2—Mesozoic Differentiation, Multituberculates, Monotremes, Early Therians, and Marsupials* (eds Szalay, F. S., Novacek, M. J. & McKenna, M. C.) 182–204 (Springer, New York, 1993).

Supplementary Information is available on *Nature*'s World-Wide Web site (http:www.nature.com) or as paper copy from the London editorial office of *Nature*.

Acknowledgements

I thank W. D. Maxwell and D. Smith for their collaboration in field activities, S. K. Madsen for fossil preparation, N. J. Czaplewski for illustration, M. Kyte for cooperation of the US BLM, W. Helmer and C. Nomee for the cooperation of the Crow Tribe, and P. Butler for various help. Funding was provided by the National Geographic Society and the NSF.

Correspondence and requests for materials should be addressed to R.L.C.

Oldest playable musical instruments found at Jiahu early Neolithic site in China

Juzhong Zhang*†, Garman Harbottle‡, Changsui Wang† & Zhaochen Kong§

* *Institute of Cultural Relics and Archaeology of Henan Province, Zhengzhou, Henan, China 450000*
† *Archaeometry Laboratory, University of Science and Technology of China, Hefei, Anhui, China 230026*
‡ *Chemistry Department, Brookhaven National Laboratory, Upton, New York 11973, USA*
§ *Paleobotany Laboratory, Institute of Botany, Academia Sinica, Beijing, China 100080*

Excavations at the early Neolithic site of Jiahu[1,2] in Henan Province, China have produced what may be the earliest complete, playable, tightly-dated multinote musical instruments. Jiahu was occupied from 7000 BC to 5700 BC, considerably antedating the well known Peiligang culture[3–5]. Here we describe six exquisitely made complete flutes which were found in radiocarbon-dated excavation layers, along with fragments of perhaps 30 more. The flutes are made from the ulnae of the red-crowned crane (*Grus japonensis* Millen) and have 5, 6, 7 and 8 holes. The best preserved flute has been played and tonally analysed. In addition to early musical artefacts, the archaeological record at Jiahu[1,2] contains important information on the very foundations of Chinese society. We describe the archaeological characteristics of the Jiahu site, details concerning its dating, its place in the prehistory of the Chinese Neolithic, the ethnicity of its population and the results of a tonal analysis of a nearly 9,000-year-old musical instrument found there.

Jiahu lies in the 'Central Yellow River Valley'[3] in mid-Henan Province, east of Mount Funiu and bounded by the flood plains of the Ni river to the south and the Sha river to the north. It was discovered by Zhu Zhi in 1962 but its significance was not fully appreciated until other sites related to the Peiligang culture[3–5] had been excavated. Jiahu is an irregular ellipse, 275 m long (east–west) and 260 m wide (north–south). Below a modern agricultural layer of loess 0.3–1.0 m deep lies a layer of the Han Dynasty (206 BC–AD 220), and beneath this Neolithic layers which together are 0.5–0.9 m thick. Of Jiahu's 55,000 m^2, only 2,400 m^2 (4.4%) have been excavated, revealing 45 house foundations, 370 cellars, 9 pottery kilns, more than 300 graves and thousands of artefacts made out of bone, pottery, stone and other materials. There are three sub-periods at Jiahu; during the latest two the site shows distinct areas for residences, workshops and graves[1]. The differential furnishing of the graves provides evidence for early social stratification. Jiahu appears to represent an organized, well established sedentary village of long duration in the very early Chinese Neolithic.

The dating of Jiahu is crucial. So far we have determined twenty ^{14}C dates: nine from charcoal (three in each of the three sub-periods mentioned above), five from plant ash, four from human bone, one from a whole fruit pit and one from a broken grain of carbonized rice. The conventional ^{14}C ages range from 7,017 to 8,285 ^{14}C years BP. After dendrochronological correction the corresponding range is 7,700 to 9,000 calendar years BP or nearly 5700 to 7000 cal. (calibrated) BC. The three sub-periods are dated as follows: the oldest is 6600–7000 cal. BC; the second oldest 6200–6600 cal. BC; and the third ~5700–6200 cal. BC. Thus, Jiahu spans some 1,300 years. If this range of dates is borne out by subsequent research, then Jiahu represents a Neolithic cultural phase distinctly earlier at its inception than the Peiligang culture, where the dates of many of the sites range from 5100 BC to 6300 BC[3–5]. On the basis of these dates, and considering the repertoire of ceramic shapes and stone tools[1], we would tentatively characterize Jiahu as a culture parallel to, overlapping in duration, and very possibly related to, the Peiligang. The same might apply to the site of Houli in the eastern Yellow River Valley (north-central Shandong Province), dated 5000 BC to 6200 BC[3]. For the ^{14}C determinations, see Supplementary Information.

A careful study of the bones of 400 individuals removed from more than 300 graves indicates that the Jiahu ethnic group may be identified with the North Asian Mongolian group, and also with the Xiawanggang and Miaodigou groups in Henan Province and the Dawenkou, Yedian and Xixiahou groups that were later found in Shandong Province. The range of male heights was from 170 to 180 cm. In the late Palaeolithic Zhoukoudian Cave, 'unspecialized'

Table 1 Analysis of intervals of flute M282:20

Location of interval	Average value in cents[14]	Musical description
Between hole 1 and hole 2	284	Minor third
Between hole 2 and hole 3	244	Slightly larger than major second (a whole tone)
Between hole 7 and tube sound	260	Slightly smaller than minor third, slightly larger than a whole note.

Figure 1 Bone flutes from burials at Jiahu. Top to bottom: M341:2, M341:1, M78:1, M253:4, M282:20, M282:21. Scale is in centimetres.

Mongoloids were described[6]. By the Yangshao period (3000 BC–5000 BC)[7], the skull measurements are 'physically Chinese' and 'modern'[6]. The physical similarity of the Jiahu people to the later Dawenkou (2600 BC–4300 BC) indicates that the Dawenkou might have descended from the Jiahu, following a slow migration along the middle and lower reaches of the Huai river and the Hanshui valley.

The discovery of complete, playable multinote flutes at Jiahu presents us with a rare opportunity to hear and analyse actual musical sounds as they were produced nine millennia ago. Earlier flutes have been found in Neanderthal contexts, but they are so fragmentary that it is difficult to do more than guess their tonal production[8–10]. We arranged to test one or more of the six flutes discovered at Jiahu; all are of the vertically held type (Sachs-Hornbostel[11] classification 421.111.12).

The best preserved flute (M282:20; Fig. 1), which was free of cracks, was chosen to be tested using a 'Stroboconn' sound-analysing stroboscope, supervised by Huang Xiangpeng from the Music School of the Art Institute of China. This flute has seven main holes plus a tiny hole near hole 7. Two other seven-holed flutes were considered, but playing tests produced cracking sounds and were promptly discontinued. However, data were recorded for two players blowing twice each with their embouchures angled at 45° up and 45° down across the mouth of flute M282:20 (eight scales altogether).

The music research team did not use the modern standard of A4 = 440 Hz, but instead adopted an arbitrary standard of hole 5 = 'C6'. (Based on A4 = 440 Hz, the actual tone of hole 5 was C6 + 2 Hz(± 20 Hz), averaged over eight trials.) Then the interval relationships of the sounds from hole 3 to hole 7 fitted reasonably well to the note sequence E6, D6, C6, B5, A5, with the tone of hole 1 = A6 and hole 2 = F#6. On this scale, the tone of the whole tube is G5 or F#5. In Table 1 three of the intervals in M282:20 are evaluated numerically.

Tests revealed that the tiny hole next to hole 7 (Fig. 1) was probably drilled to correct the off-pitch tone of the original hole 7; thus a tone of G#5 + 16 Hz was corrected to A5 − 11 Hz, which is much closer to the octave of A6 − 36 Hz.

Without testing more flutes, we cannot say whether the tonal scale of the bone flute of Jiahu (M282:20) is the ancestor of either the six-tone Qing Shan scale or the seven-tone Xia Shi scale; in any case, the latter two scales are only documented six millennia later. It should be possible, by constructing exact replicas of the Jiahu flutes in material whose density approximates bird-bone, to study the tonal sequences of all these instruments without endangering the valuable artefacts themselves. The carefully selected tone scale observed in M282:20 indicates that the Neolithic musician of the seventh millennium BC could play not just single notes, but perhaps even music. It is important in considering the possible role of these flutes in Neolithic society to recall that ancient Chinese tradition held that there were strong cosmological connections with music: that music is part of nature[12]. In this context, the performance of rituals and music were specifically associated with matters of state and sound government[13].

Excavation of only a small fraction (<5%) of the Jiahu site has revealed that, by the unexpectedly early date of 7000 BC, a complex, highly organized Chinese Neolithic society had already begun to evolve employing multinote musical instruments. Future excavation and research should help us to understand the technical aspects of one of mankind's earliest practices of musical expression, which probably took place in a ritual setting.

Note added in proof: Flute M282:20 can be heard on the *Nature* web site. In the recording, made at the Music Institute of the Art Research Institute of China, Taoying Xu plays part of the folk song "*Xiao Bai Cai*" ("The Chinese small cabbage"). Recording engineer was Bobao Gu. Research for the recording was by Xiangpeng Huang (deceased), Xinghua Xiao and Zhongliang Tong. □

Received 15 February; accepted 30 July 1999.

1. Henan Province, Institute of Cultural Relics. Preliminary report for the second through the sixth excavation at the Neolithic site of Jiahu in Wuyang, Henan. *Wenwu* **1,** 1–17 (1989).
2. Zhang, J. & Wang, X. Notes on the recent discovery of ancient cultivated rice at Jiahu, Henan Province: a new theory concerning the origin of *Oryza japonica* in China. *Antiquity* **72,** 897–901 (1998).
3. Underhill, A. Current issues in Chinese Neolithic archaeology. *J. World Prehist.* **11,** 103–160 (1997).
4. An, Z. Radiocarbon dating and the prehistoric archaeology of China. *World Archaeol.* **23,** 193–200 (1991).
5. National Bureau of Cultural Relics Board. *A Compilation of Cultural Areas in China* (Zhongguo Ditu, Press, Henan, 1991).
6. Howells, W. W. in *The Origins of Chinese Civilization* (ed. Keightley, D. N.) (Univ. of California Press, Berkeley, 1983).
7. Barnard, N. in *The Origins of Chinese Civilization* (ed. Keightley, D. N.) (Univ. of California Press, Berkeley, 1983).
8. Marcuse, S. *A Survey of Musical Instruments* (Harper & Row, New York, 1975).
9. Early Music. *Science* **276,** 205 (1997).
10. Lau, B., Blackwell, B. A. B., Schwarcz, H. P., Turk, I. & Blickstein, J. I. B. Dating a flautist? Using ESR

(electron spin resonance) in the Mousterian cave deposits at Divje Babe I, Slovenia. *Geoarchaeology* **12,** 507–536 (1997).
11. Brown, H. M. in *The New Grove's Dictionary of Music and Musicians* (ed. Sadie, S.) 664–681 (Macmillan, London, 1987).
12. Pian, R. C., Kishibe, S. & Yang, B. N. in *The New Grove's Dictionary of Music and Musicians* (ed. Sadie, S.) 245–283 (Macmillan, London, 1987).
13. Needham, N. J. T. M., Wang, L. & Robinson, K. G. in *Science and Civilization in China* **iv/1** (ed. Needham, N. J. T. M.) 126–228 (Cambridge University Press, 1962).
14. Lindley, M. in *The New Grove's Dictionary of Music and Musicians* (ed. Sadie, S.) 277–279 (Macmillan, London, 1987).

Supplementary Information is available at *Nature*'s World-Wide Web site (http://www.nature.com) or as paper copy from the London editorial office of *Nature*.

Acknowledgements

This project was supported by the National Natural Science Foundation of China. In addition, C.W. was supported by the Department of Science & Technology of China, the Chinese Academy of Sciences and the Structure Research Laboratory at USTC. Research at Brookhaven National Laboratory is supported by the US Department of Energy. We thank Huang Xiangpeng of the Music School of the Art Institute of China who supervised these important tests and the personnel of the same Music School who carried them out: Xiao Xinghua, Xu Taoying, Gu Bobao, Tong Zhongliang, Qiu Ping and Liu Haiwang.

Correspondence should be addressed to G.H. (e-mail: garman@bnl.gov) and requests for materials should be addressed to J.Z. For further information see http://www.pubaf.bnl.gov/pr/news releases.html

Incorporating rules for responding into evolutionary games

John M. McNamara*, Catherine E. Gasson† & Alasdair I Houston†

* *School of Mathematics, University of Bristol, University Walk, Bristol BS8 1TW, UK*
† *School of Biological Sciences, University of Bristol, Woodland Road, Bristol BS8 1UG, UK*

Evolutionary game theory[1,2] is concerned with the evolutionarily stable outcomes of the process of natural selection. The theory is especially relevant when the fitness of an organism depends on the behaviour of other members of its population. Here we focus on the interaction between two organisms that have a conflict of interest. The standard approach to such two-player games is to assume that each player chooses a single action and that the evolutionarily stable action of each player is the best given the action of its opponent. We argue that, instead, most two-player games should be modelled as involving a series of interactions in which opponents negotiate the final outcome. Thus we should be concerned with evolutionarily stable negotiation rules rather than evolutionarily stable actions. The evolutionarily stable negotiation rule of each player is the best rule given the rule of its opponent. As we show, the action chosen as a result of the negotiation is not the best action given the action of the opponent. This conclusion necessitates a fundamental change in the way that evolutionary games are modelled.

Most two-player game models with a continuous range of possible actions assume that: (1) each player makes its choice before it has observed the action of its opponent; (2) a player cannot change its action once the opponent's action has been observed; (3) all population members that have a given role in the game are identical. For example, if each member of a pair of animals chooses the proportion of time it spends scanning for predators as opposed to feeding, then each would prefer to feed as much as possible and so would prefer the other to be vigilant. In models of this conflict[3–5], all the above assumptions hold; in particular, assumption (3) holds because the models assume (sometimes implicitly) that all animals are identical in terms of both energy reserves and ability to detect and escape from predators. If population members follow an evolutionarily stable strategy, assumption (3) implies that every player in a given role adopts the same action, so that each player effectively knows the action of its opponent before this action is observed. Thus, given assumption (3), assumption (2) is reasonable. It is, however, not reasonable to assume that players in a given role are identical. Individuals will differ in aspects of quality that influence the costs and benefits of taking an action, and hence the action chosen will depend on quality. If the quality of an opponent cannot be directly observed, then an opponent's action is not known in advance and it will be beneficial to respond to this action once it has been observed. The opponent should respond in turn, and so on, until both players reach a negotiated settlement.

It might be thought that, if the variation in quality is small, this variation, and hence negotiation, can be ignored. We show, however, that this approximation may give quantitatively different predictions even when the variation in quality is vanishingly small.

We present an analysis of negotiation in the context of a pair of animals feeding their young, but the qualitative conclusions apply to a wide class of games. If a parent increases its feeding effort this will reduce its own future reproductive success, but will increase the success of itself and its partner in the current breeding attempt. Thus a conflict of interest exists, with each parent preferring the other to work hard. There is evidence that a parent responds directly to the effort of its partner[6,7], so that a model involving negotiation seems appropriate. In contrast, the standard model of parental effort by Houston and Davies[8] involves a single decision. This game can be summarized as follows. All members of a given sex are identical. Each parent makes a single choice of effort, ignoring the partner's effort, so that there is no negotiation. If the male provides effort u_m and the female provides effort u_f then $B(u_m + u_f)$ young survive to maturity. These efforts reduce the future reproductive success of the male and the female by $K_m(u_m)$ and $K_f(u_f)$, respectively. For a given female effort u_f, the best male effort $\hat{r}_m(u_f)$, is the value of u_m that maximizes

$$B(u_m + u_f) - K_m(u_m) \qquad (1)$$

The best female effort given that of the male, $\hat{r}_f(u_m)$, is defined

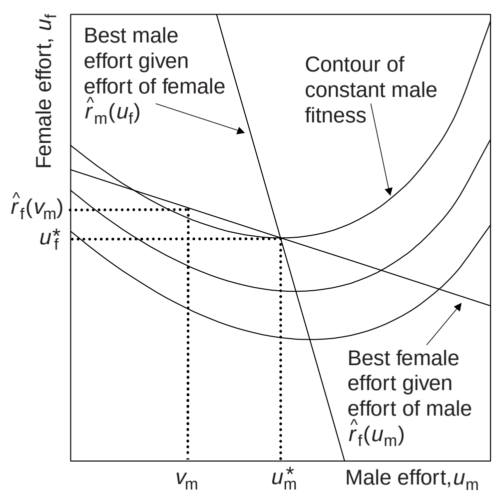

Figure 1 The best effort of a male, $\hat{r}_m(u_f)$, given fixed female effort u_f, and the best effort for the female, $\hat{r}_f(u_m)$ given fixed male effort u_m. The evolutionarily stable levels of effort, u_m^* and u_f^*, are the coordinates of the intersection of these two functions. The contours are lines of constant fitness for the male. For a given male effort, fitness increases with female effort. Assume that the female responds to the male with response rule $\hat{r}_f$. Then if a male provides effort v_m, the female responds with $\hat{r}_f(v_m)$ and the point $(v_m, \hat{r}_f(v_m))$ is above the contour that passes through (u_m^*, u_f^*). Thus the male's fitness is higher than if he had used fixed effort u_m^* or had used $\hat{r}_m$ as a response rule.