

improve the sensitivity of sensors. Consider diamond spin sensors. Rather than using optical resonances, diamond spin sensing relies on the precision measurement of transitions between resonance states that are associated with a quantum property of electrons: spin. Such sensors can be responsive to various quantities, including magnetic¹⁰ and electric fields¹¹, temperature¹², pressure¹³ and strain¹⁴. But the sensitivity of these devices — particularly for temperature and strain — is limited by the nature of the ground-state spin wave function of the electrons used in the sensing mechanism¹³.

It has been proposed¹⁵ that this problem could be overcome by constructing a hybrid sensor using the same magnetostrictive material as that used by Forstner and colleagues. However, the material would function in exactly the opposite way to that reported by these authors: a strain (or an electric field) would generate a magnetic field, which is sensitively detected by the electron spins, which in turn are read out optically. The resulting diamond hybrid sensor is predicted to be about 1,000 times more sensitive for pressure, force or electric field than diamond spins alone, and would retain excellent spatial resolution.

Hybrid sensors thus seem to be an upcoming theme in sensor technology. An important further step will be to use advances in quantum technology to achieve the limits of accuracy.

The resulting quantum hybrid sensors could potentially revolutionize sensor technology in various disciplines, enabling unprecedented opportunities in technology and basic science. ■

Jörg Wrachtrup and Amit Finkler are at the Third Institute of Physics, University of Stuttgart, Stuttgart 70569, Germany. e-mail: wrachtrup@physik.uni-stuttgart.de

1. Forstner, S. *et al. Adv. Mater.* <http://dx.doi.org/10.1002/adma.201401144> (2014).
2. Budker, D. & Romalis, M. *Nature Phys.* **3**, 227–234 (2007).
3. Kotler, S., Akerman, N., Navon, N., Glickman, Y. & Ozeri, R. *Nature* **510**, 376–380 (2014).
4. Kominis, I. K., Kornack, T. W., Allred, J. C. & Romalis, M. V. *Nature* **422**, 596–599 (2003).
5. Lee, S.-K., Sauer, K. L., Seltzer, S. J., Alem, O. & Romalis, V. *Appl. Phys. Lett.* **89**, 214106 (2006).
6. Forstner, S. *et al. Phys. Rev. Lett.* **108**, 120801 (2012).
7. Gavartin, E., Verlot, P. & Kippenberg, T. J. *Nature Nanotechnol.* **7**, 509–514 (2012).
8. Krause, A. G., Winger, M., Blasius, T. D., Lin, Q. & Painter, O. *Nature Photon.* **6**, 768–772 (2012).
9. Bagci, T. *et al. Nature* **507**, 81–85 (2014).
10. Taylor, J. M. *et al. Nature Phys.* **4**, 810–816 (2008).
11. Dolde, F. *et al. Nature Phys.* **7**, 459–463 (2011).
12. Neumann, P. *et al. Nano Lett.* **13**, 2738–2742 (2013).
13. Doherty, M. W. *et al. Phys. Rev. Lett.* **112**, 047601 (2014).
14. Ovarthaiyapong, P., Lee, K. W., Myers, B. A. & Bleszynski Jayich, A. C. *Nature Commun.* **5**, 4429 (2014).
15. Cai, J., Jelezko, F. & Plenio, M. B. *Nature Commun.* **5**, 4065 (2014).

BEHAVIOURAL ECOLOGY

Love thy neighbour

A theoretical model suggests that the cause of female-driven extra-pair mating lies in the spreading of male interests among neighbouring families, creating powerful incentives for male cooperation and concomitant benefits for females.

BEN C. SHELDON & MARC MANGEL

Birds have long served as paragons of contented coupledom, and with apparent justification, given that more than 90% of bird species breed in socially monogamous pairs, with the male and female seemingly cooperating to rear offspring. But appearances can be deceptive. In fact, in the majority of bird species tested — data are available for more than 200 species — a substantial proportion (sometimes exceeding 50%) of offspring are sired by a male other than that providing parental care. A huge, but rather fruitless¹, effort to explain the evolution of female extra-pair mating behaviour in birds has focused on potential genetic benefits to females. Now, writing in *PLoS ONE*, Eliassen and Jørgensen² offer an alternative explanation: that extra-pair mating by females creates an incentive for males to cooperate with their neighbours, generating a

form of collective good that may be a powerful evolutionary force.

The development in the 1980s of genetic markers to assign parentage revolutionized our understanding of mating patterns in many organisms, but nowhere was the effect greater than in birds³. Before this, most birds seemed rather uninteresting from the perspective of sexual selection, because it was expected that social monogamy, reinforced by the need for rapidly growing offspring to receive extensive care from both parents, would limit the extent to which sexual selection could influence fitness (in evolutionary terms, the likelihood of survival and reproductive success). The realization that extra-pair paternity could, in principle, greatly increase the fitness variation among males relative to females, hence creating the potential for strong sexual selection, led to a vigorous interest in testing the causes and consequences of extra-pair copulation



50 Years Ago

‘Obituary: Prof. James Franck’ — I remember his famous lecture ... which gave strong support to Bohr’s new theory of the atom. Einstein said to me: “It’s so lovely, it makes you cry!” ... In 1920 Franck was called to a chair in Göttingen ... many honours ... have come his way, among them the Nobel Prize in Physics in 1926 jointly with Hertz ... Göttingen saw Franck’s happiest and most fruitful period ... Those happy days ended when Hitler came to power. When the racial laws were announced, Franck published a courageous open letter in which he resigned his chair ... He was the most lovable of men because he loved people; kindness shone from his eyes. There must be many beside myself who now feel they have lost one of their best friends.

Lise Mietner

From *Nature* 29 August 1964

100 Years Ago

The Trail of the Sandhill Stag by E. T. Seton; *Wild Game in Zambesia* by R. C. F. Maugham — The first of the books before us aims rather at being a work of art than of natural history ... Never since the days of melancholy Jacques was such an outpour of sentiment upon a stricken deer. To those who like this mood the book may be recommended, for it is curiously wrought and daintily embellished ... The second book on the list strikes quite another strain ... But the list of stores required by two persons for a trip of two months is startling. It almost shakes one’s confidence in the author to learn that he cannot go into camp with a friend for two months without a dozen tins each of lobster and salmon, two dozen tins of sausages, and three dozen tins of fruit in syrup.

From *Nature* 27 August 1914

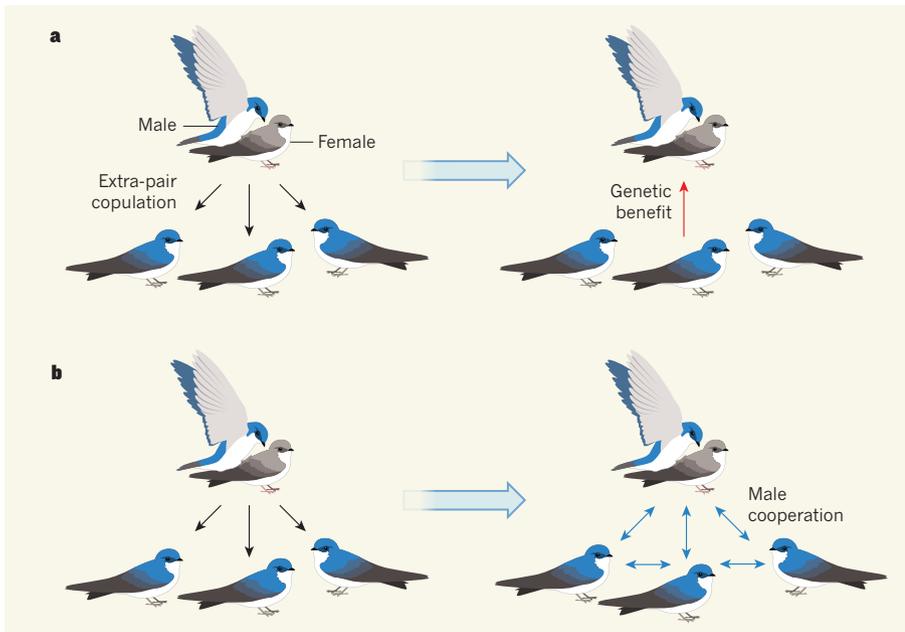


Figure 1 | Potential benefits of extra-pair mating. Genetic analysis of parentage in socially monogamous birds has revealed many cases in which female-driven extra-pair mating leads to males caring for offspring that are not their own. **a**, Previous studies to explain such behaviour focused on the idea that females gain genetic benefits from this behaviour. But the genetic benefit is small (or absent), because it is gained only from extra-pair copulations that result in fertilization. **b**, A new model by Eliassen and Jørgensen² argues that the key force in the evolution of extra-pair mating in birds lies in the way that the matings distribute potential paternity among neighbours and therefore create incentives for cooperation among neighbouring males.

(EPC) behaviour and resulting extra-pair fertilizations.

EPC behaviour in birds is frequently initiated by females, and the only obvious benefit associated with extra-pair fertilizations seemed to be genetic — the provision of genes from the extra-pair partners to offspring. So this seemed an ideal system for testing the ‘good gene’ benefits of sexual selection (Fig. 1a). Over time, however, a large body of empirical work, exemplified by recent comprehensive studies on American song sparrows (*Melospiza melodia*)⁴, led to the conclusion that the genetic benefits of EPCs are at most small. This sparked the suggestion¹ that there has been too much emphasis on adaptive explanations for the evolution of female EPC behaviour, and that non-adaptive explanations, such as inter-sexual genetic constraints (female behaviour resulting from selection in males), should be more rigorously explored. The hypotheses arising from such alternative explanations are difficult to test empirically, although one study⁵ of captive zebra finches was supportive of genetic constraints.

Now, however, Eliassen and Jørgensen use evolutionary modelling to suggest that EPC behaviour in females is indeed adaptive, but that researchers interested in explaining it have simply been looking in the wrong place. The authors’ model (Fig. 1b) argues that female EPC behaviour creates an incentive for males to cooperate with neighbours in a wide range of behaviours that add together to a common good. The incentive occurs because, rather than all of a male’s expected paternity being

limited to a single nest, female EPC spreads the likelihood of paternity among neighbouring nests. Given this uncertain redistribution of a male’s reproductive interests, Eliassen and Jørgensen predict an associated shift by males to invest more in behaviours that benefit neighbouring nests as well.

What form might such behaviours take? In the context of socially monogamous birds, collective behaviour to discourage predators or infanticide by males represents one potentially important mechanism. Equally, this logic might operate through a reduction in territorial or aggressive interactions between neighbours, or by resource sharing during offspring rearing, such as through a relaxation in territorial boundaries. A strength of the new model is that the focus on what type of benefit females gain from extra-pair mating changes from genetic to ecological. Predation and food limitation are commonly identified as contributing to variation in fitness in wild populations, and the effects can be large.

One of the puzzles in understanding EPC behaviour in socially monogamous species is that it occurs in systems that seem likely to be destabilized by such behaviour. Indeed, there is mounting comparative evidence, from social insects⁶ as well as birds⁷, that cooperation is unlikely to evolve within extended families unless there is also genetic monogamy. The perspective offered by Eliassen and Jørgensen is that a different form of cooperation — between unrelated individuals — may actually be promoted by promiscuity. However,

there will inevitably be a trade-off between the group-defence benefits accorded by redistribution of paternity and the expected reduction in a male’s care for offspring in his ‘own’ nest⁸ as his relatedness to these offspring falls; the resolution of this trade-off will probably depend on the relative costs and benefits of the two processes. Thus, their model is as much about the evolution of cooperation as it is about EPC behaviour. Furthermore, because the authors used an adaptive-dynamics method⁹ to build their model, they have laid the groundwork for investigating the broader goal of understanding the emergence of societies as complex adaptive systems¹⁰.

Eliassen and Jørgensen show that many of their model’s predictions, when combined with life-history differences between species, accord well with empirical data from field studies. For instance, the model predicts that extra-pair sires should usually be immediate neighbours, and that exchange of paternity between males will be commonplace — both patterns are commonly seen in the field. Across species, the model explains why extra-pair paternity will be less frequent as longevity increases, a non-intuitive result that accords well with the evidence, but is also predicted by other models. At present, no data exist that could test this model to the exclusion of others, although the model may, as good theory should, challenge empiricists to design more discriminatory tests. Nevertheless, Eliassen and Jørgensen’s work represents a radical shift in focus of tests of the costs and benefits of extra-pair mating in birds, and has broad consequences for our understanding of the evolution of cooperation among interacting, but non-related, individuals. ■

Ben C. Sheldon is at the Edward Grey Institute, Department of Zoology, University of Oxford, Oxford OX1 3PS, UK. **Marc Mangel** is at the Center for Stock Assessment Research, University of California, Santa Cruz, Santa Cruz, California 95064, USA. e-mails: ben.sheldon@zoo.ox.ac.uk; msmangel@ucsc.edu

- Forstmeier, W., Nakagawa, S., Griffith, S. C. & Kempenaers, B. *Trends Ecol. Evol.* **29**, 456–464 (2014).
- Eliassen, S. & Jørgensen, C. *PLoS ONE* **9**, e99878 (2014).
- Griffith, S. C., Owens, I. P. F. & Thuman, K. A. *Mol. Ecol.* **11**, 2195–2212 (2002).
- Sardell, R. J., Arcese, P., Keller, L. F. & Reid, J. M. *Am. Nat.* **179**, 779–793 (2012).
- Forstmeier, W., Marin, K., Bolund, E., Schielzeth, H. & Kempenaers, B. *Proc. Natl Acad. Sci. USA* **108**, 10608–10613 (2011).
- Hughes, W. O. H., Oldroyd, B. P., Beekman, M. & Ratnieks, F. L. W. *Science* **320**, 1213–1216 (2008).
- Cornwallis, C. K., West, S. A., Davis, K. E. & Griffin, A. S. *Nature* **466**, 969–972 (2010).
- Sheldon, B. C. *Phil. Trans. R. Soc. Lond. B* **357**, 341–350 (2002).
- Dercole, F. & Rinaldi, S. *Analysis of Evolutionary Processes* (Princeton Univ. Press, 2008).
- Levin, S. *Proc. Natl Acad. Sci. USA* **111** (Suppl. 3), 10781–10784 (2014).