

15. Wang, D., and Dubois, R.N. (2010). Eicosanoids and cancer. *Nat. Rev. Cancer* 10, 181–193.
16. North, T.E., Goessling, W., Walkley, C.R., Lengerke, C., Kopani, K.R., Lord, A.M., Weber, G.J., Bowman, T.V., Jang, I.H., Grosser, T., *et al.* (2007). Prostaglandin E2 regulates vertebrate haematopoietic stem cell homeostasis. *Nature* 447, 1007–1011.
17. Wolfe, M.M., Lichtenstein, D.R., and Singh, G. (1999). Gastrointestinal toxicity of nonsteroidal antiinflammatory drugs. *N. Engl. J. Med.* 340, 1888–1899.
18. Colotta, F., Allavena, P., Sica, A., Garlanda, C., and Mantovani, A. (2009). Cancer-related inflammation, the seventh hallmark of cancer: links to genetic instability. *Carcinogenesis* 30, 1073–1081.

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<http://dx.doi.org/10.1016/j.cub.2012.05.037>

## Evolution: Sociality as a Driver of Unorthodox Reproduction

**An unusual reproductive system was discovered in desert ants, in which daughter queens are produced asexually via parthenogenesis, whereas workers develop from hybrid crosses between genetically divergent lineages. The system appears to be doomed to extinction.**

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Although species are commonly defined as groups of shared reproduction, many species do form hybrids in nature. In most cases, these hybrids are infertile and perish in one generation, but some hybrid species have escaped this constraint by acquiring unusual reproductive modes. Several hybrid species of fish, stick insects and frogs consist only of females and rely on males of closely related species to fertilize their eggs. When such hybrid females produce eggs themselves, they selectively discard the chromosomes inherited from their father to only transmit the genetic material of their mother [1]. In such cases, referred to as 'hybridogenesis', females thus asexually transmit their maternal genome to the next generation, while males are only used as 'sperm donors' for the production of the soma.

A new paper in this issue of *Current Biology* [2] now describes a social version of hybridogenesis. In the desert ant *Cataglyphis hispanica* (Figure 1A), queens use alternative modes of reproduction to produce reproductive daughter queens and the non-reproductive workers, which are necessary for the maintenance and survival of the colony. All daughter queens are produced

asexually via parthenogenesis while workers are sexually produced from hybrid crosses between two genetically distinct lineages. Each of the two lineages has a set of private microsatellite alleles, indicating that they are independently evolving entities with little or no gene flow between them.

**Social and Non-Social Hybridogenesis**  
There are striking similarities between this system of 'social hybridogenesis' and the known systems of (non-social) hybridogenesis. In both systems, sperm is used only to produce individuals (the workers) or cells (somatic cells) that do not contribute to the transmission of genetic material between generations. However, two important features distinguish the system of social hybridogenesis in *C. hispanica* from its non-social version: first, instead of having one species depending on the presence of males of another species to reproduce (normal hybridogenesis), both lineages of *C. hispanica* need each other to obtain the sperm required for the production of workers; second, both *C. hispanica* lineages still produce males while males are entirely absent from non-social hybridogenetic species.

Although the *C. hispanica* reproductive system most closely mirrors non-social hybridogenesis, the term social hybridogenesis was originally coined for a reproductive

system in *Pogonomyrmex* harvester ants [3,4] where at least eight divergent lineages co-occur in specific lineage-pairs [5]. Queens mate multiply with males of their own and of the alternative lineage; offspring produced from same-lineage matings always develop into queens, whereas inter-lineage hybrids develop into workers [3,4,6,7]. Thus, while in both *C. hispanica* and *Pogonomyrmex* workers are produced from crosses between divergent lineages, the two systems differ in how queens are produced: by normal sexual reproduction in *Pogonomyrmex* and via parthenogenesis in *C. hispanica*.

Four additional ant species have been shown to have reproductive systems relying on hybridization between species or lineages for worker production. Similarly to *Pogonomyrmex*, *Solenopsis xyloni* workers are produced from matings with a different species (*S. geminata*) while within-species fertilizations give rise to new queens [8]. The difference is that *S. xyloni* colonies comprise multiple queens each mated with a single male. Thus, queens produce exclusively new queens or workers depending on the male they mated with. In the three remaining species — *Wasmannia auropunctata*, *Vollenhovia emeryi* and *Paratrechina longicornis* — the situation is even more baroque [9–11]. New queens are also produced via parthenogenesis and workers are produced sexually via hybrid crosses. However, the hybrid crosses take place between the maternal lineages and a species consisting exclusively of males. These males reproduce by using females as 'egg donors': instead of developing from unfertilized eggs, as is usually the case in ants, the sperm most likely eliminates the maternal

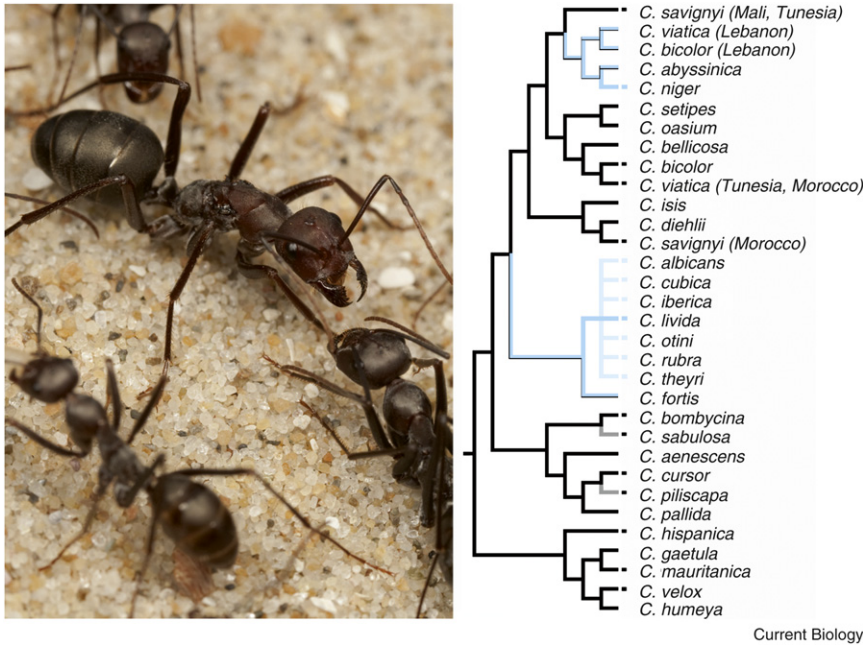


Figure 1. *Cataglyphis* and female parthenogenesis.

(A) *Cataglyphis hispanica* queen and workers (picture courtesy of Hugo Darras). (B) *Cataglyphis* molecular phylogeny adapted from [15], with clades inferred to have female parthenogenesis in black and clades inferred to have lost it in blue (assuming equal costs for acquiring or losing female parthenogenesis in a maximum parsimony framework requires at least five independent gains or two independent losses; the latter is thus more likely). The presence or absence of parthenogenesis cannot be inferred for branches with split colors. Workers in species labeled with squares have been reported to have the capacity for female parthenogenesis (black squares) or lack of it (blue squares). Information on worker parthenogenesis combined from [12,16–20]. Branches with lighter shades of blue and grey were added to the phylogeny following species-group classifications by [16].

genome upon fertilization, thus leading to the production of a haploid male identical to the father instead of a worker [9].

#### Evolution of Social Hybridogenesis

These unusual reproductive systems raise questions about the proximate and ultimate mechanisms underlying their evolution. In the case of *C. hispanica*, the evolution of social hybridogenesis requires two features: facultative parthenogenesis for the production of queens and inter-lineage hybrids developing into workers. Facultative parthenogenesis is most likely an ancestral feature of *Cataglyphis* ants, as it is present in at least 11 distantly related species (Figure 1B). Furthermore, in at least one species (*C. cursor*) there is a seasonal switch between parthenogenetic and sexual reproduction, such that new queens are produced parthenogenetically in spring and workers produced sexually during the remaining season [12]. A system as in *C. cursor*

thus represents a possible intermediate step from normal sexual reproduction to social hybridogenesis as in *C. hispanica* (Figure 2). Importantly, there are no genetically differentiated lineages in *C. cursor*, because two routes maintain gene flow between the female lineages. First, a minority of queens is still produced by sexual reproduction [12]. Second, workers can also sometimes produce new queens parthenogenetically when their mother queen dies [13]. Together, these two sources of sexual reproduction are sufficient to prevent significant genetic differentiation between the female lineages. However, if queens were exclusively produced parthenogenetically, and if workers were unable to produce replacement queens, gene flow between maternal lineages would cease, eventually giving rise to genetically differentiated lineages (Figure 2).

While there are alternative routes that could lead to social hybridogenesis in

*C. hispanica*, our model shows how a few relatively minor evolutionary steps could lead to a complex reproductive system. Along the same lines, a system like in *C. hispanica* may be an intermediate step towards the systems uncovered in *W. auropunctata*, *V. emeryi* and *P. longicornis*. Male clonal reproduction might have evolved in these systems in response to the parthenogenetic production of queens as a mechanism for males to achieve any reproductive success [9]. Indeed, the situation where all queens are produced asexually, and workers are sterile, as is the case in the three species, leads to males only contributing genes to sterile individuals and thus having no reproductive success.

#### Doomed to Extinction

Over evolutionary time, the *C. hispanica* reproductive system seems transitory, given that males do not contribute genes to the next generation — they only sire workers, not reproductive offspring — and thus represent an unnecessary energy expenditure for colonies. However, if one lineage greatly reduces or ceases male production, the second lineage will become sperm-limited, leading to two possible outcomes. The first is a shift from between- to within-lineage matings. This would result in a transition to a reproductive system similar to the one in *C. cursor*. Alternatively, this shift might be impossible if workers can only be produced from between-lineage matings. This is the case in the *Pogonomyrmex* system where pure-lineage individuals have lost the capacity to develop into workers [14]. It is likely that such a loss of plasticity has also occurred in *C. hispanica* lineages, given that, without apparent exception, all pure-lineage (parthenogenetically produced) females are queens and all hybrid individuals are workers, and there seems to be no gene flow between the lineages. If a similar loss of plasticity has occurred within the *C. hispanica* lineages, the system is doomed to become extinct given the selection on each lineage to stop the production of males.

The discovery of so many unusual reproductive systems in ants raises the question of whether unconventional systems of reproduction are more

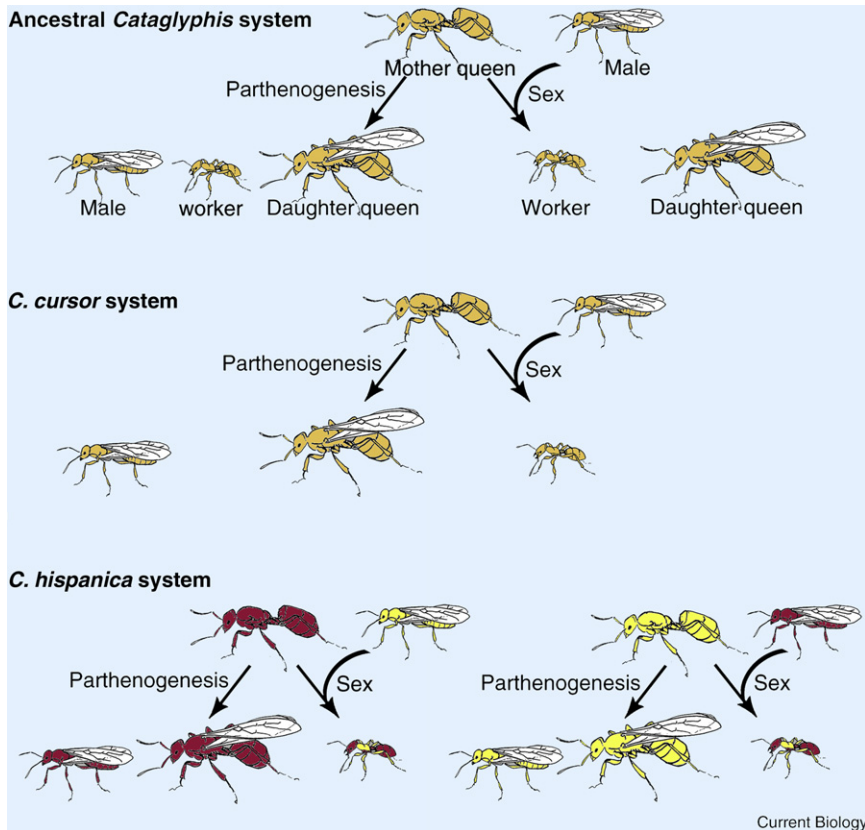


Figure 2. Transitions in the evolution of social hybridogenesis.

The *Cataglyphis hispanica* system could have evolved from a hypothetical system of facultative parthenogenesis, where both queens and workers can be produced alternatively via sexual or asexual reproduction and males develop from haploid, unfertilized eggs as typical in ants. In species with discrete production of queens and workers (usually queens in spring and workers during other seasons), a shift towards a seasonal use of each reproductive mode (with parthenogenesis only in spring) would give rise to a system as in *C. cursor*. If all queens are exclusively parthenogenetically produced and if workers are sterile, gene flow between maternal lineages would cease, resulting in a gradual transition from a *C. cursor* to a *C. hispanica* system as the maternal lineages diverge with two, or most likely several, genetically differentiated lines.

common in animals than had been realized or whether there are factors predisposing ants to evolve such systems. Parthenogenesis is expected to evolve more readily in species with haplodiploid sex determination than in diplo-diploid species. In haplodiploid species, males develop from unfertilized eggs, so that the developmental machinery for spontaneous male-embryo development without paternal contributions may be co-opted for female-producing parthenogenesis. Thus, with haplodiploidy as a stepping stone to parthenogenesis, it may well be that the combination of sociality and parthenogenesis creates the opportunity for unusual systems to arise. In addition, as outlined in the

case of *C. hispanica*, the proximate changes required for 'social hybridogenesis', with different genomes represented in different individuals, may be simpler and thus more likely to evolve than non-social hybridogenesis where genomes have to be differentially transmitted (or eliminated) depending on the parent of origin.

#### References

1. Burt, A., and Trivers, R. (2006). *Genes in Conflict: The Biology of Selfish Genetic Elements* (Cambridge, MA: Harvard University Press).
2. Leniaud, L., Darras, H., Boulay, R., and Aron, S. (2012). Social hybridogenesis in the clonal ant *Cataglyphis hispanica*. *Curr. Biol.* 22, 1188–1193.
3. Helms Cahan, S., Parker, J.D., Rissing, S.W., Johnson, R.A., Polony, T.S., Weiser, M.D., and Smith, D.R. (2002). Extreme genetic differences

- between queens and workers in hybridizing *Pogonomyrmex* harvester ants. *Proc. R. Soc. Lond.* 269, 1871–1877.
4. Julian, G.E., Fewell, J.H., Gadau, J., Johnson, R.A., and Larrabee, D. (2002). Genetic determination of the queen caste in an ant hybrid zone. *Proc. Natl. Acad. Sci. USA* 99, 8157–8160.
5. Schwander, T., Helms Cahan, S., and Keller, L. (2007). Characterisation and distribution of *Pogonomyrmex* harvester ant lineages with genetic caste determination. *Mol. Ecol.* 16, 367–387.
6. Volny, V.P., and Gordon, D.M. (2002). Genetic basis for queen-worker dimorphism in a social insect. *Proc. Natl. Acad. Sci. USA* 99, 6108–6111.
7. Helms Cahan, S., and Keller, L. (2003). Complex hybrid origin of genetic caste determination in harvester ants. *Nature* 424, 306–309.
8. Helms Cahan, S., and Vinson, S.B. (2003). Reproductive division of labor between hybrid and nonhybrid offspring in a fire ant hybrid zone. *Evolution* 57, 1562–1570.
9. Fournier, D., Estoup, A., Orivel, R.M., Foucaud, J., Jourdan, H., Le Breton, J., and Keller, L. (2005). Clonal reproduction by males and females in the little fire ant. *Nature* 435, 1230–1234.
10. Kobayashi, K., Hasegawa, E., and Ohkawara, K. (2008). Clonal reproduction by males of the ant *Vollenhovia emeryi* (Wheeler). *Entomol. Sci.* 11, 167–172.
11. Pearcy, M., Goodisman, M.A.D., and Keller, L. (2011). Sib mating without inbreeding in the longhorn crazy ant. *Proc. R. Soc. B. Biol. Sci.* 278, 2677–2681.
12. Pearcy, M., Aron, S., Doums, C., and Keller, L. (2004). Conditional use of sex and parthenogenesis for worker and queen production in ants. *Science* 306, 1780–1783.
13. Pearcy, M., Hardy, O., and Aron, S. (2006). Thelytokous parthenogenesis and its consequences on inbreeding in an ant. *Heredity* 96, 377–382.
14. Helms Cahan, S., Julian, G.E., Rissing, S.W., Schwander, T., Parker, J.D., and Keller, L. (2004). Loss of phenotypic plasticity generates genotype-caste association in harvester ants. *Curr. Biol.* 14, 2277–2282.
15. Knaden, M., Tinaut, A., Stokl, J., Cerda, X., and Wehner, R. (2012). Molecular phylogeny of the desert ant genus *Cataglyphis* (Hymenoptera: Formicidae). *Myrmecol. News* 16, 123–132.
16. Agosti, D. (1990). Review and reclassification of *Cataglyphis* (Hymenoptera, Formicidae). *J. Nat. Hist.* 24, 1457–1505.
17. Cagniant, H. (2009). Le genre *Cataglyphis* Foerster, 1850 au Maroc (Hyménoptères Formicidae). *Orsis* 24, 41–71.
18. Leniaud, L., Hefetz, A., Grumiau, L., and Aron, S. (2011). Multiple mating and supercoloniality in *Cataglyphis* desert ants. *Biol. J. Linn. Soc.* 104, 866–876.
19. Timmermans, I., Grumiau, L., Hefetz, A., and Aron, S. (2010). Mating system and population structure in the desert ant *Cataglyphis livida*. *Insectes Soc.* 57, 39–46.
20. Timmermans, I., Hefetz, A., Fournier, D., and Aron, S. (2008). Population genetic structure, worker reproduction and thelytokous parthenogenesis in the desert ant *Cataglyphis sabulosa*. *Heredity* 101, 490–498.

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