

Gamete competition, gamete limitation, and the evolution of the two sexes

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ABSTRACT: Males and females are a fundamental aspect of human reproduction, yet procreation is perfectly possible without this division into two sexes. Biologically, males are defined as the sex that produces the smaller gametes (e.g. sperm), implying that the male and female sexes only exist in species with gamete dimorphism (anisogamy). Our ancestors were isogamous, meaning that only one gamete size was produced. The question of the evolutionary origin of males and females is then synonymous to asking what evolutionary pressures caused gamete sizes to diverge. Studying the ancestral evolutionary divergence of males and females relies largely on mathematical modelling. Here, we review two classes of models explaining the evolutionary origin of males and females: gamete competition and gamete limitation. These seemingly alternative explanations are not mutually exclusive, but two aspects of a single evolutionary process. Once evolved, anisogamy and the two sexes are evolutionarily very stable. This explains the maintenance of anisogamy in organisms with internal fertilization, which can cause large decreases in both gamete competition and gamete limitation. The ancestral divergence and maintenance of gamete sizes subsequently led to many other differences we now observe between the two sexes, sowing the seeds for what we have become.

Key words: isogamy / anisogamy / sexes / gamete / reproduction

Introduction: a fundamental asymmetry in reproductive biology

It is difficult to envisage human reproduction without thinking of male and female sexes. Although the female provides the physical resources for the development of a zygote, ova must be fertilized by sperm before development begins. It is then easy to take for granted the existence of these separate sexes, with their morphologically differentiated gametes. Yet such a differentiation is not a prerequisite for reproduction, and if we look across the entire tree of life, it turns out to be only one of many possibilities. It is entirely possible to imagine life on earth without separate male and female sexes.

Although not the topic of this review, it is worth noting that reproduction is possible even in the complete absence of sex (for which there are many alternative definitions; see glossary, [Losos et al., 2013](#); [Lehtonen and Kokko, 2014](#)). Although sexual reproduction prevails in complex forms of life, asexual reproduction is not rare in nature (e.g. [Maynard Smith, 1978](#); [Schön et al., 2009](#)). Most cells in a living organism contain a complete set of 'instructions' for building a new individual, and there

is no fundamental reason why a single cell could not develop into an offspring without fertilization. On the contrary, it has proved very difficult to find a convincing, fundamental and general reason for why sexual reproduction is so common. Asexual reproduction has many advantages compared with sex ([Williams, 1975](#); [Maynard Smith, 1978](#); [Lehtonen et al., 2012](#); [Meirmans et al., 2012](#)), and the reason for the prevalence of sexual reproduction remains one of the major open questions in evolutionary biology ([Otto, 2009](#); [Hartfield and Keightley, 2012](#)).

Here, we will discuss a different, but related question: when genomes from two individuals do combine (i.e. sex happens), why are the two individuals engaging in sexual reproduction so often clearly different? Why are there girls and why are there boys? We review theoretical work which suggests that divergence into just two sexes is an almost inevitable consequence of sexual reproduction in complex multicellular organisms, and is likely to be driven largely by gamete competition. In this context we prefer to use the term gamete competition instead of sperm competition, as sperm only exist after the sexes have already diverged ([Lessells et al., 2009](#)). To see this, we must be clear about how the two sexes are defined in a broad sense: males are those individuals that produce the smaller gametes (e.g. sperm), while females are defined as those that produce the larger gametes (e.g. [Parker et al., 1972](#); [Bell, 1982](#);

Lessells *et al.*, 2009; Togashi and Cox, 2011). Of course, in many species a whole suite of secondary sexual traits exists, but the fundamental definition is rooted in this difference in gametes, and the question of the origin of the two sexes is then equal to the question of why do gametes come in two different sizes. This gamete size dimorphism is called anisogamy, and it is the dominant gametic system among multicellular organisms (Lessells *et al.*, 2009). Isogamy occurs when all gametes are morphologically the same. Isogamy was very likely to have been the gametic system in the common ancestor of sexually reproducing eukaryotes (Maynard Smith, 1982; Lessells *et al.*, 2009), and it is also common (but not universal) in extant, unicellular organisms (Parker *et al.*, 1972; Lessells *et al.*, 2009; Togashi and Cox, 2011).

Why is such a strong asymmetry so common in reproductive systems? This does not seem at all obvious, as in many other respects sexual reproduction is a very symmetrical process. First, there is symmetry in reproductive output: the total number of offspring produced by males must be exactly equal to the total number of offspring produced by females, because every offspring must have exactly one mother and exactly one father (Düsing, 1884; Fisher, 1930). This symmetry in the reproductive fitness of the sexes is commonly called the Fisher condition, and it has many surprisingly complex and far-reaching evolutionary consequences (e.g. Houston and McNamara, 2005; Kokko and Jennions, 2008). Secondly, there is genetic symmetry: half of the genes in offspring tend to come from the mother and half from the father (Williams, 1975; Maynard Smith, 1978). Third, there is symmetry in the abundance of the two sexes: the average number of male offspring is usually equal or close to the number of female offspring (Fisher, 1930; Hardy, 2002; West, 2009; but see, e.g. Hamilton, 1967 for exceptions). The same prediction, but with more frequently expected deviations applies to allocation into male and female functions in simultaneous hermaphrodites (Charnov, 1982; Schärer, 2009). These can be regarded as two sexes in one individual that can play the roles of 'sperm donor' and 'sperm recipient' (Charnov, 1979; Schärer *et al.*, 2014) when they meet another individual of the same species. Symmetries like this are very common in nature, which makes it all but clear why a strong dimorphism in gamete sizes is almost ubiquitous in multicellular eukaryotes.

Furthermore, when gamete sizes are differentiated, there are typically exactly two sexes, no more and no less: males that produce small gametes and females that produce large ones; why not, say, 5 or 7 sexes? From a mammal point of view, one may say that this is very easy to answer: the mammalian XY sex determination system inevitably results in two sexes. But this is a 'proximate' solution—it outlines how we end up with males and females, and in equal numbers, with this particular sex determination mechanism. In reality, there are many different ways in which sex determination and two sexes can be achieved in the plant and animal kingdoms (Bull, 1983). This implies that these mechanisms do not tell us the ultimate evolutionary reason behind the number of sexes, or the evolution of gamete sizes.

Features of the hypothetical ancestor

Understanding the origin of two sexes encounters the problem that anisogamy could have first arisen well over a billion years ago. Eukaryotic multicellular forms appear to have arisen from unicells in the ancient oceans, and unicells are often (but not always) isogamous (Parker,

2011). The evolutionary transition from isogamy to anisogamy has left no trace in the fossil record, which is why understanding this transition relies heavily on mathematical modelling (Lessells *et al.*, 2009). The starting point for most models is a hypothetical isogamous marine ancestor that shed its gametes into the seawater, where fertilization took place after two compatible gametes from different parents collided randomly and fused. They assume that all parents have a fixed resource budget for gamete production (say M units), and that there is a size-number trade off so that if a parent produces gametes of size m , the number of gametes is $n = M/m$. In other words, the budget is simply split into n equal pieces. The final assumption is that the viability, f , of the fertilized zygote relates to its size, S . Precisely, how f relates to S varies depending on the analysis. The first models, by Kalmus (1932) and Scudo (1967), assumed that a fixed zygote size S was required to enable the zygote to survive, and that in a given population the sizes of the two fusing gametes could vary continuously, provided that when they fused their mass summed to the fixed value, S . Later models, beginning with Parker *et al.* (1972), allowed parents to vary their gametes sizes independently and relaxed the assumption that zygote size is a fixed constraint: instead, a zygote's viability increased continuously with its size, following a zygote survival function, $f(S)$, whose form varied with the model. The general theme of all these approaches is that if parents make smaller gametes, they can make more of them, but larger gametes contribute more to provisioning the zygote, increasing its survival prospects. Under certain conditions this can result in disruptive selection (e.g. Bulmer and Parker, 2002; Lessells *et al.*, 2009), leading to divergence into two different gamete sizes.

In most unicellular eukaryotes, gametes do not fuse randomly when shed into the sea water, even in the absence of size dimorphism (Maynard Smith, 1982; Czárán and Hoekstra, 2004); instead, gamete fusion (syngamy) occurs between + and – 'mating types', such as in the volvocine green alga *Chlamydomonas* (Wiese *et al.*, 1979; Nozaki *et al.*, 2006). Thus, disassortative syngamy between mating types probably arose before the evolution of anisogamy and persists in advanced anisogamous organisms where it is associated with gamete size (fusion is ova-sperm, and never sperm-sperm or ova-ova; Lessells *et al.*, 2009).

Anisogamy takes various forms and appears to have arisen several times independently (Wiese *et al.*, 1979; Kirk, 2006; Ferris *et al.*, 2010). For example, even in the volvocine green algae, anisogamy may have arisen twice from ancestral isogamy (see Kirk, 2006), and there is variation ranging from isogamy with motile gametes (e.g. the unicellular *Chlamydomonas reinhardtii*; Wiese *et al.*, 1979; Nozaki *et al.*, 2006) to weak anisogamy with motile gametes (e.g. *Pandorina morum*, which forms colonies of 8 or 16 *Chlamydomonas*-like cells by asexual cell division; Knowlton, 1974), to pronounced anisogamy (oogamy) in which the female gamete is non-motile and much larger than the motile male gamete (e.g. *Volvox aureus*, which lives in large, asexually produced colonies of thousands or even tens of thousands of *Chlamydomonas*-like cells; Kudo, 1966). Thus, hypothetical ancestors are usually envisaged to be marine organisms, possibly unicellular or primitively multicellular, releasing gametes into the sea, where fusion is random, with or without the constraint of mating types. Existing theoretical models indicate that similar evolutionary processes could have led to the evolution of anisogamy, regardless of whether mating types preceded the transition (e.g. Charlesworth, 1978; Maynard Smith, 1982; Bulmer, 1994; Bulmer and Parker, 2002; Lehtonen and Kokko, 2011) or not (Parker *et al.*, 1972; Bell, 1978; Charlesworth, 1978; Maynard Smith, 1978; Parker, 1978).

Did early anisogamy result in hermaphrodites or separate sexes? Again, we do not have a conclusive answer to this question. The strongly anisogamous green alga, *Volvox*, includes both single-sex and hermaphroditic (monoecious) species (Isaka *et al.*, 2012). It is usually assumed that the separate sexes arose first, with hermaphroditism (which can take various forms) being favoured later under certain ecological conditions (e.g. Charnov *et al.*, 1976; Heath, 1977). Nevertheless, some models examine the possibility of the evolution of anisogamy in hermaphrodites (Wiese, 1981; Iyer and Roughgarden, 2008; Matsuda and Abrams, 2011; Roughgarden and Iyer, 2011). However, one argument why separate sexes may be ancestral is that the simplest way to alter gamete size would be to alter the number (or rate) of cell divisions during gamete formation. Thus, a mutant with a different rate of cell division would produce all its gametes of a different size from the rest of the population, resulting in separate sexes (Parker, 2014).

The first evolutionary models of anisogamy evolution: gamete limitation

Although the focus of this special issue is on sperm competition, we begin by briefly reviewing the first evolutionary explanations for the divergence of the male and female gametes, as they do have a connection to the later, sperm competition-based models (see the next two sections). We do not cover the third main class of hypotheses for the evolution of anisogamy, ‘intracellular conflicts’, as they are outside the topic of this special issue. These are discussed in a recent review (Lessells *et al.*, 2009) and book (Togashi and Cox, 2011), with many references contained therein. The evolution of sex-specific gamete motility (e.g. motile sperm, non-motile ova) is likewise not covered here, because such differences are likely to have evolved after size dimorphism (Lessells *et al.*, 2009; but see Hoekstra, 1984 for a theoretical analysis of a possible interaction between the evolution of motility and size dimorphism).

The earliest theoretical model for the evolution of anisogamy that we are aware of is that of Kalmus (1932), which is based on an idea now often called ‘gamete limitation’. Kalmus’ model showed that under certain conditions, the highest population-wide rate of successful gamete fusions (i.e. gamete collision resulting in a surviving zygote) is reached if both small and large gametes are produced. The latter provides the majority of the resources needed by the zygote, and the former is produced in large numbers to increase the fertilization rate via ‘mass action’ (Otto and Day, 2007), i.e. the collision rate of gametes is proportional to their numbers. These arise from the size-number trade off—the aim being to find the combination of gamete sizes, m_1 , m_2 , resulting in most fusions at the population level. Since the size of the zygote was constant at $S = m_1 + m_2$, Kalmus’ model assumed that if the parents producing the m_1 -sized gametes switch to producing gametes of size $m_1 + d$, then parents producing m_2 -sized gametes perform a balancing change to gametes of size $m_2 - d$. This idea was developed further by Scudo (1967), who added gamete mortality and gamete depletion due to previous fusions to a similar framework. These models, however, implicitly assumed that evolution by natural selection works at the species, or population level, maximizing the reproductive output of the entire population. Since then, it has been shown that evolutionary phenomena must generally be explained by an individual level advantage (Williams, 1971; Dawkins, 1976; Maynard Smith, 1982). The primary reason for this is

that if a trait supposedly exists for the good of the species or group, in many cases a ‘selfish’ mutant would be at a selective advantage, and would invade the population (e.g. Maynard Smith, 1982). Therefore, adaptations requiring selection to act on groups or populations (group selection) are generally evolutionarily unstable, and in this sense these early anisogamy models are obsolete. The idea of maximizing gamete fusion rates is nevertheless important and has been resurrected (sometimes controversially) in more recent models (e.g. Cox and Sethian, 1985; Dusenbery, 2006; Togashi *et al.*, 2007; Iyer and Roughgarden, 2008; Yang, 2010; Lehtonen and Kokko, 2011; Roughgarden and Iyer, 2011).

Gamete competition can explain the evolution of anisogamy under individual selection

The model by Parker *et al.* (1972; often now referred to as the PBS model) was the first attempt to explain how two sexes might have originated by individual selection. It assumed the same size-number trade off for gamete production as Kalmus (1932), but, importantly, allowed parents to alter their gamete sizes independently; thus a population could consist of parents producing many gamete sizes, m_1 , m_j , m_k ... etc. Thus zygote size, $S = m_i + m_j$, now varied depending on the sizes of the two fusing gametes, m_i and m_j , and the resulting zygote’s viability, f , was assumed to increase continuously with its size, following a zygote survival function, $f(S)$. PBS used the increasing form $f(S) = S^x$, the steepness of which depends on the value of the exponent x . Subsequent developments have used various increasing functions, something that has attracted (largely unwarranted) controversy (see Bulmer and Parker, 2002). PBS made their analyses by computer simulation of a large population of parents with different alleles determining a range of gamete sizes. The population started with parents that released their gametes, which then fused randomly (there were no mating types; all gametes fused on encounter). After a number of generations, provided that $x > 1$ in the function $f(S) = S^x$, the result was anisogamy—only alleles for producing the largest and the smallest gametes remained and the other alleles were lost by selection. But if $x < 1$, the result was isogamy with the persistence of only the alleles for producing the smallest gametes. This indicated a possible explanation for the origin of gamete dimorphism, as well as for the fact that there are exactly two sexes.

The reason that PBS generates anisogamy is that ‘proto-females’ (parents producing large gametes) have zygotes that survive well, while ‘proto-males’ (producing many small gametes) ‘capture’ most of these valuable large gametes, effectively parasitizing their investment. Because of gamete competition, the small gametes become ever smaller and more numerous, so that eventually all of the resources for the zygote are provided by the large gametes. Intermediate ‘proto-sexes’ are lost from the population by disruptive selection. Without the assumption of pre-existing mating types, many of the ‘proto-males’ waste their gametes fusing with other tiny gametes by producing inviable zygotes, which helps to explain the evolution of microgametes that selectively fuse with macrogametes (reasons why macrogametes should not favour fusions with other macrogametes are more complex; see Parker, 1978).

If the evolution of disassortatively fusing mating types preceded the evolution of anisogamy, selection is predicted to favour linkage

between the loci determining mating types and gamete size (Charlesworth, 1978), and there is now some empirical support for this (Charlesworth and Charlesworth, 2010; Ferris *et al.*, 2010). It seems likely that mating types did indeed precede the evolution of anisogamy (Wiiese *et al.*, 1979; Maynard Smith, 1982; Charlesworth and Charlesworth, 2010). Subsequent analyses of PBS therefore usually start from mating types, in which gamete size mutations linked to the mating type locus can arise independently in + and - mating type strains. This makes theoretical analyses more tractable, and can instantly generate two sexes and fusions only between microgametes and macrogametes. (The fact that + / - mating-type behavior is likely to be ancestral does not mean that it must necessarily be maintained during the evolution of anisogamy, should selection act against it; Maynard Smith, 1982; Parker, 2011). They confirm the basic PBS result that gamete competition can readily generate two sexes by individual selection under a wide range of conditions where zygote viability increases with its size; the remaining conditions for increasing $f(S)$ generate isogamy (e.g. Charlesworth, 1978; Maynard Smith, 1982; Bulmer, 1994; Bulmer and Parker, 2002; Lehtonen and Kokko, 2011). Similar results have been reached using very different modelling approaches, including simulations (Parker *et al.*, 1972; Parker, 1978), game theory (Maynard Smith, 1978; Maynard Smith, 1982; Bulmer, 1994; Bulmer and Parker, 2002; Lehtonen and Kokko, 2011) and population genetics (Bell, 1978; Charlesworth, 1978).

Two sides of the same coin: unifying gamete limitation and gamete competition

In gamete limitation models, pressure to increase the overall number of successful fertilizations results in the evolution of gamete dimorphism. In contrast, with gamete competition models, each male 'selfishly' aims to increase its own share of the available female gametes, at the expense of other males—this is essentially sperm competition driving and maintaining the two sexes. Some recent work has argued against conflict and 'selfish' evolution as a driver of the evolution of anisogamy (Iyer and Roughgarden, 2008; Yang, 2010; Roughgarden and Iyer, 2011) to the extent of claiming that competition-driven hypotheses are entirely misguided.

However, the seemingly alternative explanations for the origin of the sexes (gamete limitation and gamete competition) are not as separate as they may seem, nor are they mutually exclusive (Lehtonen and Kokko, 2011). In gamete limitation, a mutant male (or proto-male) with a slightly increased number of gametes can gain access to a pool of female gametes that would have otherwise died (or in some other way permanently disappeared from the pool of available gametes) before being fertilized. In this way, the mutant increases its own individual fitness. In gamete competition, an identical mutant can gain access to a pool of female gametes that would have otherwise been fertilized by a different male. In this way, this mutant also increases its own individual fitness. This suggests that gamete limitation and gamete competition can be considered two aspects of a single evolutionary process under individual selection (Fig. 1): selection for increased fertilization efficiency. This was shown mathematically in a recent model (Lehtonen and Kokko, 2011) where the intensity of gamete competition could be adjusted by varying the size of the local group of ancestral broadcast spawners. With increasing group size the results of this model are compatible with earlier gamete

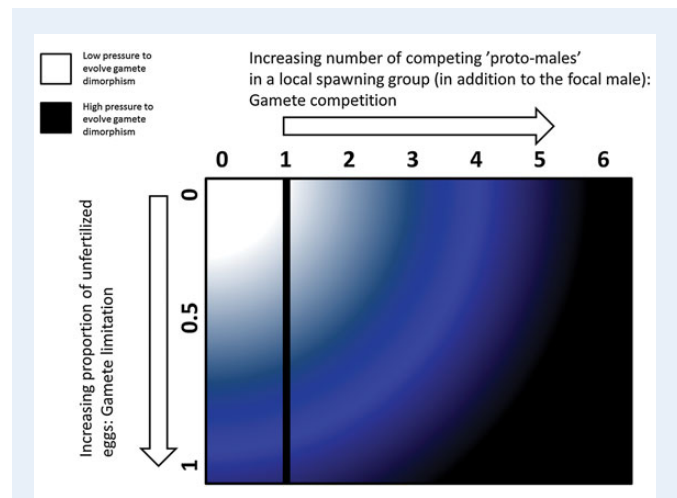


Figure 1 Gamete competition and gamete limitation as evolutionary forces in the evolution of anisogamy. Both act in the same direction, i.e. they promote the production of increased numbers of sperm, at the expense of sperm size. If the resource requirements of the zygote are high, eggs must remain large to enable zygote survival, leading to anisogamy. Gamete competition is a very potent evolutionary force, and is stronger than gamete limitation if there is always at least one competing 'proto-male' in a local spawning group, in addition to the focal male (to the right of the black vertical line; Parker and Lehtonen, 2014). Note that this simplified figure is only intended to qualitatively illustrate the two evolutionary pressures. It is not intended to be an exact mathematical representation, which would necessarily depend on several factors (e.g. Lehtonen and Kokko, 2011; Parker and Lehtonen, 2014). It should also be noted that not all combinations of competition and limitation are equally likely in real-world scenarios. For example, if gamete competition is very high, then gamete limitation is generally unlikely to be very high because gametes are produced by several individuals. The region in the lower right area would then only be likely if there were other factors which made fertilization inefficient, such as very high gamete mortality or conditions where individuals are widely dispersed.

competition models based on PBS (e.g. Bulmer and Parker, 2002), but anisogamy can also evolve even in spawning groups that consist of only one proto-male and one proto-female (implying zero gamete competition). This requires gamete limitation (i.e. a significant proportion of gametes remain unfertilized), which can be increased in the model by increasing gamete mortality or by decreasing gamete fusion rates or the resources available for gamete production.

These two selective pressures therefore both act at the level of individual selection, and they also always act in the same direction, in that they select for an increased number of gametes. The conditions dictate which one prevails. The question remains which one was stronger at the time of the ancestral divergence of the two sexes, and which one is more important in maintaining anisogamy. Given that the first divergence happened long ago, establishing the relative importance of the two selective pressures at the origin of anisogamy is very difficult. We can, however, make some observations based on mathematical principles. A comparison of the strengths of these two selective pressures using techniques adapted from evolutionary game theory showed that under fairly general conditions, the presence of just one competing 'proto-

male' is sufficient to make gamete competition the stronger evolutionary force, regardless of the strength of gamete limitation (Parker and Lehtonen, 2014). This suggests that gamete limitation could only have been the prevailing force selecting for the evolution of anisogamy if the spawning groups of the isogamous ancestor were very small and isolated.

Nevertheless, we may never know the ancestral breeding biology to this level of detail, and this may be a question that is impossible to answer conclusively. Given that anisogamy has evolved multiple times (Wiese et al., 1979; Kirk, 2006; Ferris et al., 2010) the conditions may also have been different in each case. But perhaps more importantly, other empirically testable predictions of these models do not depend on which was the stronger evolutionary pressure. As mentioned before, the two forces act in the same direction reinforcing each other, and regardless of the relative strengths of competition and limitation, the model in Lehtonen & Kokko (2011) makes the same overall prediction as the PBS models (Parker et al., 1972; Maynard Smith, 1978; Parker, 1978; Maynard Smith, 1982; Bulmer and Parker, 2002): an increase in zygote provisioning requirements, probably connected to organismal complexity and the evolution of multicellularity, was required to trigger the divergence of gamete sizes.

Multicellularity and complexity as a potential trigger for the evolution of anisogamy

The predominance of isogamy among unicells and the almost universal prevalence of oogamy in complex multicells suggests a link between the origin of anisogamy and multicellularity and its associated increases in organismal complexity. Such a link has been shown empirically many times, beginning with Knowlton (1974) for volvocine algae (see the *Chlamydomonas-Pandorina-Volvox* sequence above). However, the suitability of the volvocine algae for testing the PBS models has been criticized, due to apparent violation of the assumptions of freely mixing gametes and external fertilization (Randerson and Hurst, 2001a, b). It would therefore be useful to relax the assumptions of theoretical models to see if the results hold regardless of these issues. A very recently discovered 'missing link' in the volvocine algae (Nozaki et al., 2014) may also prove useful in such comparative studies. Parker et al. (1972) suggested that the reason why the zygote size/viability relation shifted into the zone where anisogamy would replace isogamy was that complex multicells require greater zygotic reserves for development to adulthood than simple unicells. This link was investigated further by Bulmer and Parker (2002), who added a gamete viability/size relation, $g(m)$, to the PBS model. Thus, a gamete's viability g increases with its size m , and (as PBS) zygote viability f also increases with its size S . The stable solution is isogamy when these two functions, $g(m)$ and $f(S)$, are rather alike, as may apply to unicells where gametes are often a similar order of magnitude in size to adults. But when the size of the zygote must be much greater than the size of the gamete to achieve a similar relative viability, isogamy becomes evolutionarily unstable and anisogamy is stable. So these models predict that as multicellular complexity develops, and the requirements for the survival of a zygote become much greater than those for the survival of a gamete, isogamy becomes unstable and anisogamy is generated. However, since some unicells show anisogamy, and a few multicells show isogamy (Parker, 2011), there cannot be an

exact parallel between this divergence of gamete and zygote survival requirements.

The evolutionary stability of anisogamy under external and internal fertilization

The conditions required for the evolutionary maintenance of anisogamy are not necessarily the same as those required for its origin. The origin models discussed above assume a hypothetical ancestor with features that obviously do not apply to all sexually reproducing organisms today. Most vertebrates are far from sessile broadcast spawners, yet a gamete size ratio of 10^6 is not uncommon (Parker, 1982). Internal fertilization is perhaps the most obvious deviation from the model assumptions, but conditions can change even under external fertilization. For example, a more targeted and localized sperm release could decrease both gamete competition and gamete limitation. However, theory shows that even a very low level of gamete competition is sufficient for maintaining anisogamy once it has evolved. This has been shown for small groups (i.e. low sperm competition) of external fertilizers with no gamete limitation (Parker, 1982, 2011), and remains true in a model that allows for both gamete competition and gamete limitation (Lehtonen and Kokko, 2011). These models show that the necessary conditions for the evolutionary maintenance of the two sexes are much less stringent than those for their initial evolution, especially as the difference in mass of the sperm and egg becomes huge. This is intuitively understandable. As soon as gamete sizes have diverged and one gamete type outnumbers the other, many gametes of the more numerous type (e.g. sperm) are destined to remain unfertilized. Because it is not known in advance which male gametes will be successful, a relatively small increase in the reserves of the few successful sperm would require wasting the same amount of extra provisioning on a large number of unsuccessful sperm. On the other hand, even a relatively large change in the size of a tiny sperm size can still be very small in relation to the size of the egg, therefore contributing little to the survival of the zygote. The result is that increasing zygote provisioning by a significant amount requires a large decrease in microgamete numbers, with a corresponding decrease in sperm competition ability. All of this makes the evolution of anisogamy almost a one-way path and, according to these models, exceptional biological circumstances would be required to reverse it: either a reversal of organismal complexity, or an almost complete elimination of both gamete competition and limitation (e.g. a return to panel a in Fig. 5 in Lehtonen and Kokko, 2011) would be necessary.

The importance of this stability becomes even clearer when we consider internal fertilization. Internal fertilization, together with the development of genitalia and behavioral patterns such as mate guarding, could, in principle, abolish both gamete competition and gamete limitation almost completely, yet anisogamy prevails. The reason is basically the same as that for external fertilization: once anisogamy has evolved, it is easily maintained even by very low levels of sperm competition.

Consider, for example, an animal where almost all females are inseminated with one single mating, and double inseminations happen very rarely (implying very low risk of sperm competition). If two males that mate with one female have equal probability of fertilization, anisogamy is stable if the probability of a double mating q is greater than $2m_{\text{sperm}}/m_{\text{ovum}}$ (Parker, 1998). The ovum–sperm size ratio commonly

exceeds 10^6 (Parker, 1982), so that here only a 0.0002% risk of double mating should, in theory, be sufficient to maintain anisogamy and minimal provisioning in sperm. This result is altered slightly if the assumption of equal fertilization probability is broken, but does not change the main result that anisogamy is very stable, even under very low sperm competition (Parker, 1982). A recent analysis shows that, under internal fertilization, gamete limitation can also play a significant role in the maintenance of anisogamy (Parker and Lehtonen, 2014), potentially making extreme anisogamy even more stable.

The sexual cascade and the legacy of anisogamy

The basic asymmetry of anisogamy has immense consequences for subsequent evolution. It forms an integral part of what has been termed 'the sexual cascade' (Parker, 2014), the consequential sequence of events in the evolution of sex that flows from the origin of sexual recombination and syngamy in the earliest eukaryotes to what we now see in vertebrates, such as ourselves, with all its complex implications of sexual dimorphism and sex roles.

As explained, ancestral isogamy may have been replaced by anisogamy in the drive towards multicellular complexity. Once two sexes arise, selection quickly favours a 1 : 1 ratio of males and females through 'Fisher's principle': under random mating, the sex that is rarer in the population has a fitness advantage that is lost only when equality is attained (Fisher, 1930). Ancestral multicellular animals may have been relatively immobile broadcast spawners, so that sexual selection (Darwin, 1871; Jennions and Kokko, 2010; Kuijper *et al.*, 2012) would have been post-ejaculatory, and mainly by sperm competition. Thus, organisms such as coelenterates and echinoderms typically show large bodily expenditures (in both sexes) on gonads and gametes (Parker and Pizzari, *in press*). Darwin (1871) dismissed these 'lower forms' in his account of sexual selection (apparently unaware of sperm competition as a mechanism in sexual selection), but stressed that mobility and behavioral complexity were vital for sexual competition for mates (pre-ejaculatory, or pre-copulatory sexual selection). As soon as mobility became advanced, selection on males to reduce sperm competition by moving closer to females to release sperm ('female-targeting') may have played an important part in the evolution of copulation and internal fertilization itself, permitting pre-ejaculatory sexual selection (the form of sexual selection recognized by Darwin) to generate a suite of changes in male body form and behavior to outcompete other males for matings, at the expense of expenditure on gamete production (Parker, 2014).

Thus, the primeval asymmetry of anisogamy set the intriguing legacy for what we now have become, with all the genetically determined differences between males and females.

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J.L. and G.A.P.: conception and design, drafting manuscript, revising manuscript for critical comments and final approval of manuscript.

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Glossary

Anisogamy

Anisogamy refers to gametic systems where the gametes are dimorphic in size: one gamete type is larger (e.g. ova) than the other (e.g. spermatozoa), and gametic fusion occurs only between the larger and the smaller gametes.

Female

Biologically, the female sex is defined as the adult phenotype that produces the larger gametes in anisogamous systems.

Group selection

Evolutionary hypotheses that assume, either explicitly or implicitly, that evolution results in adaptations that benefit the species or group. See individual selection.

Hermaphroditism (in animals), monoecy (in plants)

Systems in which male and female sexes exist in the same individual, i.e. a single individual produces both small and large gametes.

Individual selection

The evolutionary mechanism of natural selection envisaged by Darwin, in which certain characteristics spread throughout a population because the individuals carrying those characteristics produce more progeny than individuals lacking them. Individual selection need not result in adaptations beneficial to the group or species, and indeed in many cases results in adaptations that reduce the reproductive output of the group or species.

Isogamy

All gametes in isogamous gametic systems are of similar size. However, isogamy is almost always associated with mating types (see below).

Male

Biologically, the male sex is defined as the adult phenotype that produces the smaller gametes in anisogamous systems.

Mating types

Mating types are gamete genotypes for molecular mechanisms that regulate compatibility between fusing gametes. Mating types enable disassortative fusion in both isogamous and anisogamous gametic systems: if the gametes are composed of + and - mating types, then only fusions of + and - gametes are possible. All anisogamous species feature mating types and disassortative fusion, as do most isogamous species. This

suggests that mating types may have evolved before the divergence of gamete sizes. Isogamous species can have several mating types, even up to hundreds, but anisogamous species always have only two.

Oogamy

Oogamy is essentially extreme anisogamy, where the two gamete types have diverged to such an extent that the larger specializes in provisioning, while the smaller specializes in 'searching' for the larger gametes. This is the gametic system that is most familiar to us. Oogamy is generally associated with non-motile macrogametes and motile microgametes, but this is not necessarily always true (e.g. the non-motile microgametes of many plants).

Separate sexes, gonochorism (in animals), dioecy (in plants)

Systems in which the two sexes (males and females) are separate, i.e. male individuals produce small gametes and female individuals produce large gametes.

Sex

The definitions of 'sex' and 'sexes' vary. Here we define 'sex' as the union of gametes and genomes from two individuals (or in some hermaphrodites, from the same individual), and 'sexes' (male, female) are defined by the type of gamete an individual produces (see above).

Syngamy

The fusion of two gametes to form a zygote.

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