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Evolutionary Conflict

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Abstract

Evolutionary conflict occurs when two parties can each affect a joint phenotype, but they gain from pushing it in opposite directions. Conflicts occur across many biological levels and domains but share many features. They are a major source of biological maladaptation. They affect biological diversity, often increasing it, at almost every level. Because opponents create selection that can be strong, persistent, and malevolent, conflict often leads to accelerated evolution and arms races. Conflicts might even drive the majority of adaptation, with pathogens leading the way as selective forces. The evolution of conflicts is complex, with outcomes determined partly by the relative evolvability of each party and partly by the kinds of power that each evolves. Power is a central issue in biology. In addition to physical strength and weapons, it includes strength from numbers and complexity; abilities to bind and block; advantageous timing; and abilities to acquire, use, and distort information.

1. INTRODUCTION

Joint phenotype: a trait or outcome that can be affected, and potentially evolve, under the influence of two or more parties

Actual conflict: when two individuals actually strive to push a joint phenotype in opposite directions because of past evolutionary history of conflicts of interest

Potential conflict: when two parties should be selected to push a joint phenotype in opposite directions; also known as a conflict of interest

Cooperation and conflict are the yin and yang of biological interactions. The past few decades have seen a surge of interest in the fundamental puzzle of how evolution can solve cooperative dilemmas. Research on evolutionary conflict has also flourished during this period, with book-length treatments of many subareas including animal conflicts and aggression (Huntingford & Turner 1987), sexual conflict (Arnqvist & Rowe 2005), sibling conflict (Mock & Parker 1997), within-genome conflicts (Burt & Trivers 2006), communication conflict (Bradbury & Vehrencamp 1998, Maynard Smith & Harper 2003, Searcy & Nowicki 2005), parasite–host conflict (Zuk 2007), macroevolution of predator–prey conflict (Vermeij 1987), and social parasite conflict (Davies 2000). However, although students of cooperation have been reaching for syntheses across many levels and domains of life (Bourke 2011, Buss 1987, Maynard Smith & Szathmáry 1995), there have been fewer such efforts for conflict (Brockhurst et al. 2014, Dawkins 1982, Dawkins & Krebs 1979). We suggest that conflict poses an equally important set of puzzles across levels: How does evolution proceed under conflict, who wins, and why? Ironically, after 50 years of excellent work on cooperation, how conflict evolves may now represent the greater unsolved question.

2. WHAT IS CONFLICT?

Conflict is actually rarely defined in evolutionary biology, perhaps because it is often so obvious (but see table 7.1 in Arnqvist & Rowe 2005). Conflict can be easily recognized when a lion kills a zebra or a male langur chases away a harem owner and acquires the harem. The challenge is to define conflict for less obvious cases, as when a fetus pulls nutrients from its mother.

2.1. Joint Phenotypes

We suggest a general definition of evolutionary conflict based on the concept of a joint phenotype (Queller 2014), a trait or outcome affected by two parties. The joint phenotype is the object of conflict when changes in it help one party at the expense of the other. **Table 1** lists a selection of conflict types, parties, and joint phenotypes. A joint phenotype is influenced by the genes of both interacting parties. For example, human genes pack red blood cells with hemoglobin to carry oxygen. The genes of the malarial parasite *Plasmodium* turn the red blood cell phenotype instead into a factory for producing *Plasmodium*. Selection works on each party to impose its favored state on red blood cells.

For at least one of the two parties (here the *Plasmodium*), the joint phenotype is an extended phenotype, a trait that an actor can influence outside of its own body (Dawkins 1982). Though extended phenotypes can be inanimate like a beaver's dam or a spider's web, they can also be traits of another individual (Dawkins 1982). Genes in an offspring can evolve to influence its mother's feeding rate, so feeding rate is a joint phenotype that can evolve by selection on either party's genes. This remains true even when the offspring is a cuckoo chick parasitizing another species. When a cheetah chases an impala, each is striving to impose different states (alive or dead) on the joint phenotype of the impala's flesh. Some may prefer the word "outcome" to "phenotype," but the latter stresses the crucial point that effects on others can evolve, just like any other phenotype.

2.2. Potential and Actual Conflict

There are two different senses of conflict: potential and actual (Ratnieks & Reeve 1992, Ratnieks et al. 2006). Actual conflict is the conflict we actually see between individuals, whereas potential conflict is why it evolves. Potential conflict, or a conflict of interest, is when two parties should

Table 1 Levels and domains of conflict

Type of conflict	Joint phenotype example	Example of party 1 and strategy	Example of party 2 and strategy
Predator–prey	Use of impala flesh	Cheetah speed	Impala turning
Plant–herbivore	Use of plant tissue	Plant toxic compounds	Detoxification
Social parasitism	Which offspring are raised by the host	Cuckoos lay eggs similar to the host	Host rejects anomalous eggs
Host–pathogen	Use of host red blood cells	Produces malarial merozoites	Produces hemoglobin to carry oxygen
Mutualistic	Use of seed resources	Fig wasps oviposit into ovules	Figs make ovules less accessible
Resource competition	Capture of sunlight	Plants grow tall	Shade tolerance
Male–male	Who mates with the female	Stickleback nest builder	Stickleback sneaker
Male–female	Egg production and remating of the female	Male *Drosophila* delays female remating	Female *Drosophila* remates
Parent–offspring	Blood flow to the placenta	Maternal spiraling of arteries	Placental cells digest lining of arteries
Parent–offspring	Sex ratio of colony	Ant workers kill males	Ant queen produces excess males
Among siblings	Who is fed by the parent	Large egret chicks harass small ones	Small chicks try to avoid blows
Among gametes	Who survives and fertilizes eggs	Sperm with toxin alleles kills other sperm	Suppressor loci
Organelle–nucleus	Production of pollen	Mitochondria suppress pollen	Nuclear genes restore pollen
Mother–father genes in offspring	Embryo growth rate	Mouse paternal IGF2 increases growth	Maternal IGF2R receptor degrades IGF2
Between chromosomes	Sex ratio	The X chromosome produces females	Autosomes produce males and females
Transposon–host	Replication within host	Transcription of transposon	Small interfering RNAs

For each conflict type, an example is given for the joint phenotype and a strategy for each of the two parties.

be selected, given sufficient genetic variation, to push a joint phenotype in opposite directions. It can be written in terms of the Price equation (Frank 2012). The Price equation states that for a phenotype z, including a joint phenotype, selection on party i can be written as $\mathrm{cov}(w_i,z)$ and selection on party j as $\mathrm{cov}(w_j,z)$ with the w's being fitnesses (or inclusive fitnesses if kin are affected) (Queller 2014). Potential conflict occurs for values of z for which these two covariances differ in sign. Note that two genes within an individual commonly have joint phenotypes—let us say they both help build hair follicles—but normally no conflict exists between them.

Actual conflict is when two individuals actually strive to push a joint phenotype in opposite directions because of an evolutionary history of conflicts of interests. It is not readily defined in terms of the Price equation because it is about the result of selection rather than the process and because it pertains to individual parties rather than to populations. Even if current cheetahs had little genetic or phenotypic variation for speed, so that selection is not currently operating, the chase of an impala is still an actual conflict.

Our definitions exclude several phenomena sometimes described as conflict (see the sidebar titled What Is Not Conflict?). Our intent is to include phenomena that share certain important properties and to exclude those that do not. Our definition groups together phenomena that are important for similar reasons, undergo special kinds of evolutionary dynamics, and raise a set of shared evolutionary issues, for example, about power.

WHAT IS NOT CONFLICT?

Conflict is not equivalent to all Darwinian competition. Faster cheetahs may competitively replace slower ones, but this is not actual conflict between the cheetahs except when they contest a joint phenotype. It is conflict if two cheetahs race to catch a particular prey, as they jointly affect their phenotypes of prey possession.

It is not conflict when one selected locus overshoots an optimum and another compensates by returning it toward the optimum. Both loci, if they had the appropriate variation, would be selected to the same optimum, so there is no potential conflict. For the same reason, it is not conflict when an allele is favored but has a harmful pleiotropic effect that is then reduced by other loci.

We also exclude conflicts that are really evolutionary trade-offs. A cheetah might have a trade-off between building muscles and building brain tissue, but this is a design conflict, not a conflict of interest between (metaphorical) designers. More subtly, intralocus sexual conflict, in which a gene is beneficial when expressed in males but detrimental in females, is also a trade-off that happens to be expressed in different individuals. Trade-offs resemble Hamlet's indecision, whereas conflicts are analogous to his fight with his uncle.

3. THE IMPORTANCE OF CONFLICT

3.1. The Organismal Divide

The organism is one of the key concepts in biology. We have suggested that the organism is characterized, and even defined, by two features (Queller & Strassmann 2009, Strassmann & Queller 2010). Within an organism, there is very high cooperation with very little conflict. Between organisms there is typically rather little cooperation and mostly conflict (or indifference). Major transitions in evolution often involve how organismality transitions from one level to another, and mechanisms that reduce conflict are essential to this process (Maynard Smith & Szathmáry 1995).

Both cooperation and conflict can lead to complexity, but complexity of very different kinds (Strassmann & Queller 2007). Cooperation within organisms leads to harmonious intricate adaptations directed at a common purpose. Conflict between organisms can lead instead to a complex pattern of moves and countermoves.

3.2. Maladaptation

Natural selection should bring its target ever closer to perfection, as predicted by Fisher's fundamental theorem of natural selection (Fisher 1930). But organisms are far from perfect, which Fisher attributed to a deterioration of the environment, something his theorem did not include. This deterioration can result from changes in the physical environment, but these changes tend to be slow in pace, limited in range, and in random directions. In contrast, changes in a joint phenotype by an enemy are seemingly malevolent—usually pulling away from the organism's optimum. When an organism's fitness is modeled as a joint phenotype affected by others, its rate of change also depends on the additive genetic variance of opponents (Queller 2014). If we are going to use adaptive landscapes and peak climbing as metaphors for adaptation, we might imagine that each climber is yoked to others who are trying to climb their own peaks, so that sometimes little progress is made and other times the climber gets dragged down toward the valleys (**Figure 1**).

Maladaptation is especially clear when manipulation causes an opponent to behave actively against its own interests (Heil 2016, Moore 2002). Classic cases include the apicomplexan

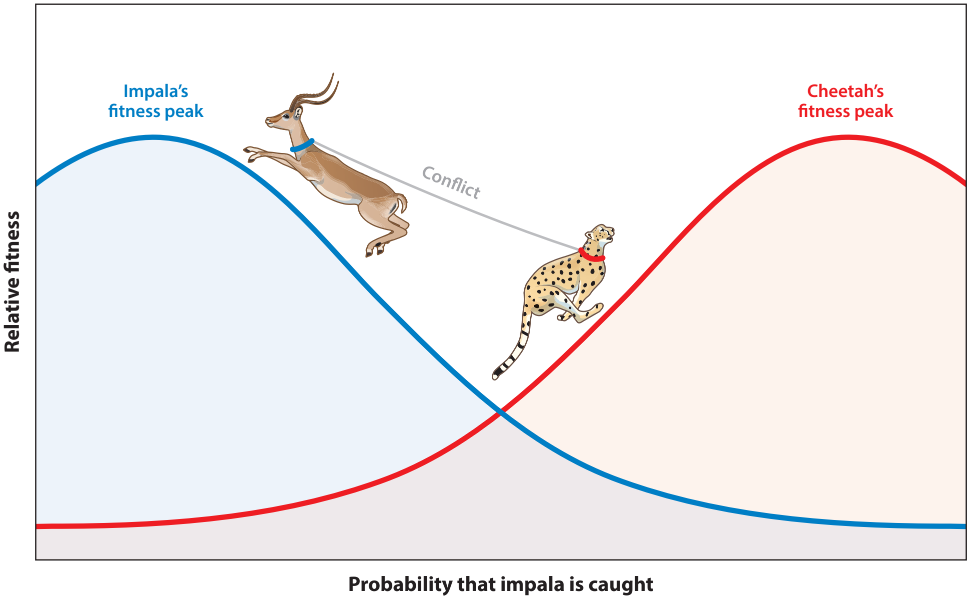

Figure 1

Cheetahs and impalas are in conflict over how the impala's flesh is used. Both parties can affect that joint phenotype, here the probability of the impala being caught. Any evolutionary gains by one party that take it toward its fitness peak cause its partner to slip farther down its fitness peak, as if the two parties were yoked together. Illustration by Noel Sirivansanti.

parasite *Toxoplasma gondii* that makes rats less afraid of cats, thereby facilitating the next step of its life cycle, transmission to cats. Crickets infected by a hairworm jump into water, aiding the worm while drowning the cricket (Heil 2016). Haldane's famous quip about altruism should be modified: One would jump into a river to save two brothers or eight cousins or because of any effective manipulator.

Maladaptation is not just from losing conflicts. Selection on conflict phenotypes can also cause harm to winners, owing to costs and trade-offs. The cost of theft among humans is not limited to the value of the things stolen. There are the costs of theft deterrence, including locks, fences, alarms, lighting, police forces, security guards, and prisons. There are also opportunity costs, such as avoiding risky areas. Even organisms that are winning or holding their own in conflicts may have high costs of weapons, defenses, or foregone opportunities. These costs are sometimes exposed in species introductions. Birds on Guam that shed their presumably costly predator defenses in the absence of predators were annihilated with the introduction of the brown tree snake (Fritts & Rodda 1998).

An unanswered question is how much conflict contributes to extinction. Conflict presumably is not the major factor in mass extinctions, but it might be a major contributor to the background rate of extinctions. Indeed the Red Queen metaphor of conflict evolution (see Section 3.4) originated in an attempt to explain constant background extinction rates (Van Valen 1973).

Arms race: an increased rate of reciprocal adaptive evolution in two conflicting parties specifically due to their conflict

3.3. Extravagant Adaptations

Conflict can lead to adaptations that have a notably extravagant nature. Darwin was struck by the apparent excess of many male weapons and ornaments. For weapons, this excess can make sense

Red Queen evolution: an increased rate of adaptive evolution in at least one party due to conflicts with other parties, usually with the additional implication that there may be little net improvement

in terms of arms races in which males with relatively larger weapons (or greater defenses) defeat those with relatively lesser ones. Similar kinds of excesses arise even more readily from between-species conflict. Traits like the speed of cheetahs and the thickness of mollusk shells are far in excess of what would be needed in the absence of antagonists. The same is true at the molecular level. Newts evolve to produce more tetrodotoxin in areas where their garter snake predators have evolved sodium channels that are resistant to it (Hanifin et al. 2008).

As for ornaments, Darwin believed them to be favored by female choice. Though he did not explicitly invoke conflict, and ornaments could evolve via honest signaling, excesses seem most easily explained by a feedback between partially deceptive male salesmanship and increasing female resistance (Gavrilets et al. 2001). Escalation of salesmanship and resistance seems most likely in systems with a mix of conflict and cooperation, like mating, offspring provisioning, and mutualisms. In such cases, signals may be important enough not to be ignored even when they sometimes mislead. For example, begging signals from an offspring like a canary nestling to its mother can be exploited, because the signals can also convey important information on nestling needs (Trivers 1974). Similar salesmanship and resistance have apparently led to human placentas releasing very high amounts of placental lactogen compared with amounts of typical human hormones not involved in conflict (Haig 1993).

3.4. Accelerated Evolution and Arms Races

In any ongoing conflict, at least one partner is kept away from its optimum by its malevolently evolving opponent. So, genes underlying conflict phenotypes may face selection that is unusually persistent and strong. Provided underlying genetic variance exists for the trait, this persistent selection can lead to evolutionary arms races (Brockhurst et al. 2014, Dawkins & Krebs 1979) and Red Queen evolution in which, like Lewis Carroll's Red Queen, you have to keep running fast to stay in the same place (Van Valen 1973). In Section 4, we delve into this important hypothesis and suggest that the majority of adaptive evolution may be due to conflict.

3.5. Population Diversity

Certain kinds of conflict drive within-population diversity. Nonadditive genetics like overdominance or sign epistasis can generate diversity without conflict, but conflict can add in nonadditive interactions between individuals. The so-called matching alleles model is a kind of between-individual sign epistasis: The two alleles in each party match, in opposite ways, the two alleles of the other party, in the sense of defeating one allele and losing to the other (Nuismer 2017). This epistasis causes a form of negative frequency dependence: Any allele that becomes common selects for the opponent's allele that defeats it and is then itself selected against. With time lags, oscillations can also be seen—so-called fluctuating arms races (Brockhurst et al. 2014). Maintenance of diversity by negative frequency dependence also emerges in models of social conflict, such as the classic hawk–dove game (Van Cleve & Akçay 2014).

A few such cycles have been recorded in nature, including for three male-lizard mating morphs (Sinervo & Lively 1996) and for scale-eating fish morphs adapted to attack from the left versus the right (Hori 1993). Indirect evidence can be obtained from tests of resistance and infectivity of opponents collected at different times—so-called time shift experiments (Gaba & Ebert 2009). Cyclic behavior has been inferred by testing an artificially stored time series of Australian native flax (*Linum marginale*) with its fungal pathogen (*Melampsora lini*) (Thrall et al. 2012) as well as by testing samples of *Daphnia magna* and its bacterial parasite *Pasteuria ramosa*, stored naturally in time-ordered sediments (Decaestecker et al. 2007). Conflict-generated diversity is consistent with the high diversity and incidence of balancing selection in human immunity genes (Andrés et al. 2009) and plant resistance genes (Borevitz et al. 2007). In the social domain, a set of cheating/cooperation loci in a social amoeba shows unusual polymorphism and signatures of balancing selection (Ostrowski et al. 2015).

Spatial structure and gene flow can further enhance selection for variation at the metapopulation level. Conflict interactions can vary across sites, giving even more complex dynamics and a shifting geographic mosaic of coevolutionary hot spots and cold spots (Thompson 2005).

3.6. Speciation and Macroevolutionary Diversity

If conflict drives much of adaptive evolution, it may also promote speciation (Althoff et al. 2014, Schluter 2000). Geographic mosaics of quickly diverging populations (see Section 3.5) speak to the potential for allopatric speciation, potential that has been realized in some crossbills (*Loxia curvirostra* complex) in conflict with lodgepole pines (*Pinus contorta latifolia*), which have themselves diverged owing to the presence and absence of conflict with pine squirrels (*Tamiasciurus hudsonicus*) (Smith & Benkman 2007). Rapid accumulation of conflict differences could drive Dobzhansky–Muller incompatibilities. Evidence for this comes from experimental evolution of *Tribolium* beetles (Bérénos et al. 2012). Crosses between replicate lines coevolved with a microsporidian parasite showed significant postzygotic reproductive isolation, whereas lines evolved without the parasite did not. However, such a result has also been obtained with an abiotic selective force (Dodd 1989), so the relative importance of conflict is uncertain.

Three classes of conflict may have special roles in speciation. First, accelerated evolution via male–female conflict, perhaps enhanced by runaway sexual selection under female choice, may drive differences in mating traits or behaviors that could lead directly to the inability to successfully mate (Gavrilets 2014, Servedio & Boughman 2017, West-Eberhard 1979). Genital evolution is often extremely rapid (Eberhard 1985) and may affect compatibility between populations. Experimental evolution in flies in populations with more sexual conflict evolved more incompatibilities than those with less conflict (Martin & Hosken 2003), but studies in other organisms did not duplicate this result (Gavrilets 2014). In some but not all taxa, sexual conflict is associated with higher species numbers (Gavrilets 2014).

Similarly, incompatibilities could arise from rapid evolution of mother–offspring conflict, which might explain why viviparous mammals lose the ability to hybridize much more quickly than birds and frogs (Zeh & Zeh 2000). A similar comparison of angiosperms, which provision seeds after fertilization, with gymnosperms, which provision them before, would be interesting.

Examples of genes involved in speciation include a surprising number that are implicated in within-individual conflicts, such as meiotic drive genes, transposable elements, and imprinted genes (Crespi & Nosil 2013, Presgraves 2010, Wolf et al. 2014). Presgraves (2010) pointed out that the evolution of meiotic drive loci is often followed by evolution of suppressor loci, such that subsequent hybridization with a species lacking both unleashes harmful meiotic drive. This argument also seems plausible for many within-genome conflicts but less so for between-species conflicts in which hybrid progeny contain genes for only one side of the conflict.

Conflict can promote speciation in an additional way. When a species evolves a novel solution to a conflict, it can open up major new adaptive opportunities. This hypothesis, due to Ehrlich & Raven (1964), is now called the escape and radiate hypothesis. Their original evidence, based on radiation of butterflies that had escaped host defenses, has been supported by modern phylogenetic analysis (Fordyce 2010). This process does not directly explain reproductive isolation itself, but it may increase opportunities for speciation by increasing geographical or host plant ranges (Janz 2011).

3.7. Ability to Respond to Novel Challenges

The large, persistent, and malevolent pressures applied by antagonists can also select for abilities to respond to novel challenges. Some of these enhance evolvability. For example, experimental evolution of the bacterium *Pseudomonas fluorescens* in the presence of a phage led to the evolution of a heightened rate of mutation (Pal et al. 2007). Similarly, the long-suspected role of host–pathogen conflict in selection for recombination and sex (Hamilton 1980, Lively 2010) is supported by increases in these traits observed under experimental evolution with partners but not without them (Kerstes et al. 2012, Morran et al. 2011).

Phenotypic plasticity can also be favored as a way to respond to conflict novelty. The vertebrate adaptive immune system allows for rapid phenotypic adjustment to specific pathogen attacks. Moreover, the identities of the attackers are essentially learned and remembered so that they can be dealt with better the next time. The CRISPR/Cas systems of bacteria perform a similar function against phages (Garneau et al. 2010).

Finally, true learning and intelligence might be favored by the challenges of conflict. It has been hypothesized that primate brains evolved to be larger in the context of social complexity, the intricate negotiation of cooperation and conflict in large groups (Dunbar 1998). The most recent comparative analysis does not support this hypothesis for primates in general (DeCasien et al. 2017), though it could still apply uniquely to humans.

3.8. Practical Relevance

Learning can bring a radical new dimension to conflicts. Humans now engage in coevolutionary battles in which our behavior evolves by cultural evolution. By this means, we have largely defeated our predators, who cannot evolve quickly enough to counter our guns, traps, and poisons. We have also used cultural evolution to battle pathogens and pests, though they are fighting back by evolving resistance to antibiotics and pesticides. Taking things one step further, it should not be forgotten that humans also engage in strictly cultural arms races, including the literal arms races that gave rise to the evolutionary metaphor.

Conflict plays a role in medicine. Cancer is evolution at the somatic level that is in conflict with evolution at the individual level over phenotypes like replication rate and resource use (Aktipis & Nesse 2013). Some disorders of fertility, pregnancy, and birth appear to be related to sexual conflict, mother–offspring conflict, and within-genome imprinting conflict between maternal and paternal genes in an offspring (Crespi 2010, Haig 1993), and imprinting conflict may also be responsible for some psychiatric disorders (Crespi 2008). Some of these problems probably arise from rope dropping. In an evolutionary tug-of-war, with a balance struck between two parties pulling hard, what happens when one party reduces pulling, perhaps because of a mutation? An impala mutated so it cannot run results in a cheetah victory. However, in a cooperative system, conflict may not result in any winners. For instance, if a mutation causes an embryo to reduce its signals to its mother that it needs food, the distorted balance means the mother may now feed it too little for it to survive (Frank & Crespi 2011, Moore & Haig 1991).

4. ACCELERATED CHANGE AND ARMS RACES

> It takes all the running you can do, to keep in the same place.
>
> —The Red Queen in *Through the Looking-Glass* by Lewis Carroll

Because selection on conflict can be unusually persistent, strong, and malevolent, it is expected to sometimes cause evolutionary arms races (Dawkins & Krebs 1979) or Red Queen evolution

(Van Valen 1973). In this section, we ignore cycling or fluctuating arms races to focus on directional change–escalatory and chase arms races (Brockhurst et al. 2014). But we also note some potential for conflict-generated accelerated evolution without classic arms races.

4.1. Theory

There are many models of evolution under conflict (Nuismer 2017). A common approach is to write a mathematical expression for the joint phenotype. For example, the probability that the impala is caught by the cheetah might be set as $z = 1/(1 + e^{y-x})$, where y and x are their respective running speeds (Nuismer 2017). This expression is substituted into equations for each party's fitness, and the model is solved. Population–genetic models with one locus for each party have provided many insights into cycling but do not easily address the key issue of directional selection. For any selection type—be it conflict, cooperation, competition, or adaptation to the abiotic environment—one can specify a selective advantage, and the allele causing it will go to fixation. The real question here concerns whether conflict creates such situations more often than other regimes.

Polygenic models provide some additional insight. Here too, equations for the joint phenotype are substituted into fitness equations but are followed by application of the tools of quantitative genetics, game theory, or adaptive dynamics (Nuismer 2017), usually assuming small effects of genes. Such models can easily show escalatory arms races, for example, cheetahs and impalas both evolving to get faster and faster. These arms races can in principle be unbounded, but adding costs can arrest the escalation.

But these models still generally do not get at the question of whether conflict creates more opportunities for selection across many dimensions. Cheetahs and impalas can each get faster, but each might also innovate in agility, alertness, sensory abilities, activity patterns, and habitat choice, resulting in a multidimensional arms race (Brockhurst et al. 2014). Population genetic models with multiple loci evolving at the same time may be relevant, but they rapidly become very complex (Kopp & Gavrilets 2006).

A little-explored alternative is Fisher's geometric model of adaptation, which allows mutational novelty and tracks successive fixations (Tenaillon 2014). In general, populations move up fitness peaks, taking more and larger steps when they are far away (because close to the optimum, many larger mutations will overshoot). They then stay at or near the optimum.

The geometric model has not yet been formalized for conflict, but it is easy to anticipate some predictions. The trick is to consider a joint phenotype, for example, the probability the impala gets caught, for which each party can fix mutations that get it closer to its own optimum. Each party has its own fitness function or adaptive landscape, but they share the joint phenotype so that evolution by one party along this dimension affects the fitness of the other. It seems clear that the trait would often be held away from one or both parties' optima (maladaptation) because of the opponent's fixations (**Figure 1**). Fixations would therefore keep occurring, often running to stay at more or less the same fitness (Red Queen). Being away from the optimum means that a higher percentage of mutations would be favored (rapid adaptation, arms race), and they would have larger effects on average (Tenaillon 2014). A meta-analysis of plant quantitative trait loci modestly supports the latter prediction, showing greater effect size for biotic traits (Louthan & Kay 2011). Two complications are that the study relied heavily on *Arabidopsis thaliana* and that floral traits were classified as biotic, and they might involve both conflict and cooperation. But if correct, this point injects a note of caution with respect to the small-effect assumption frequently made in other models. But the main point is more positive: The model confirms that conflict can generate long-term chase arms races in many dimensions. And it reinforces the view (Queller 2014) that much of life may be on the slopes and valleys rather than at the peaks.

More complex models incorporate many complexities that can sometimes alter outcomes (Nuismer 2017). Ecological feedbacks can sometimes mean that improvements in one party may not select for counteradaptations of the other (Abrams 2000). For example, if a predator improvement reduces prey numbers, reduced encounter rates could eliminate the need for prey response. One of the hallmarks of conflict seems to be that it leads to complex and varied outcomes, but it is nevertheless important to seek possible generalizations, such as conflict generating accelerated adaptive evolution.

4.2. Data

Substantial evidence is accumulating that conflict accelerates the rate of adaptive evolution. Field studies of selection in nature suggest that conflict, including changes in hosts, food plants, and predators, is often an important selective force (Reznick & Ghalambor 2001). Classic field experiments include those introducing guppies from stream pools with predators to those with no predators. However, the importance of conflict is uncertain because there are also many nonconflict examples involving competition, abiotic factors, and especially anthropogenic changes (Reznick & Ghalambor 2001). If we ignore anthropogenic factors, which have been relevant over only recent evolutionary history, the relative importance of biotic factors increases.

Accelerated evolution is also commonly seen in experimental coevolution (Brockhurst & Koskella 2013). When compared with a no-partner control, more accelerated evolution may simply reflect the presence versus absence of any selective force, and nonbiotic forces might work just as well. A better control for the effect of partner evolution is to contrast conflict lines with controls lines evolved with nonevolving opponents, for example, by removing opponents periodically and replacing them with ancestral stock. Phage Φ coevolved with *P. fluorescens* evolved twice the genetic distance from the ancestor as phage evolved with nonevolving *P. fluorescens* (Paterson et al. 2010), demonstrating the key role of an evolving opponent. More examples of this kind of work are needed.

Genomic data coupled with population-genetic tests of selection have begun to allow a much wider exploration of accelerated evolution. Initial clues came when genes identified to be under selection, usually by having a high ratio of nonsynonymous to synonymous substitutions (dN/dS), often fell into gene ontology categories suggesting conflict, usually host–pathogen or male–female interactions (Castillo-Davis et al. 2004). But, of course selected genes fell into other categories as well, and gene ontology categories do not generally provide very precise indicators of conflict.

More targeted results are emerging from studies that make more specific a priori identifications of sets of conflict genes. The placenta is involved in mother–offspring conflict over nourishment, and as predicted, genes preferentially expressed in the placenta show accelerated dN/dS (Chuong et al. 2010). In the social amoeba *Dictyostelium discoideum*, some cells die to aid in the dispersal of related cells (Strassmann & Queller 2011). Genes that are differentially expressed with nonrelatives versus relatives are likely to function in conflict, and these genes show higher rates of adaptive evolution (Noh et al. 2018). The same is true for genes changing in a different form of conflict between cells, cancer. Cancer cells show very high average dN/dS values but, interestingly, so do noncancerous somatic cells (Martincorena et al. 2017). This finding suggests a high level of competition or conflict among cells that does not rise to the level of tumors.

Thus, evidence is accumulating for rapid evolution under conflict. It remains difficult to assess its overall importance, but this is beginning to change with host–pathogen studies. Ebel et al. (2017) identified 490 mammalian genes known to interact with *Plasmodium* and its close relatives. These genes made up 5% of all conserved mammalian proteins and showed approximately three times more adaptive substitutions than the controls. A similar study examined 1,300 conserved mammalian proteins involved in interactions with viruses. These genes showed much higher rates of adaptive change than other genes, including an estimated 30% of all adaptive amino acid changes in the conserved part of the human proteome (Enard et al. 2016). These results from malaria and viruses make it plausible that, if we could add in interactions with bacteria and other pathogens or parasites, not to mention other kinds of conflicts, they might account for the majority of adaptive amino acid substitutions.

Many of these studies of accelerated evolution examine only one party and thus allow room for skepticism about two-sided arms races (Carmona et al. 2015). Indeed, how often any reciprocal coevolution occurs has been debated (Thompson 1997); however, good examples of reciprocal arms races have been identified. These examples come from multiple kinds of conflicts and types of evidence but have the common feature that the interacting traits are well understood.

For example, geographical studies often show correlated evolution, for example, in the degree of newt toxicity and the resistance of their garter snake predators (Hanifin et al. 2008). Such correlations are also seen at the phylogenetic scale for male graspers and female antigrasping devices. For example, male *Gerris* water striders use grasping adaptations like strong forelegs to hold reluctant females, who counter with adaptations like abdominal spines (Arnqvist & Rowe 2002). Antigrasping structures are particularly important in dytiscid diving beetles, because males hold females below water, where they are unable to replenish oxygen. Innovations in male suction cups and female devices that defeat them, such as furrowed backs, evolved at common points in the dytiscid phylogeny (Bergsten & Miller 2007). In bruchid seed beetles, males have genital spines for anchoring themselves during mating, but these spines also harm their mates and have coevolved with increased protective connective tissue in females (Rönn et al. 2007).

One can also see reciprocal rapid evolution at the molecular level in pairs of genes that interact in conflict (Elde & Malik 2009). For example, a poxvirus makes a K3L protein that competitively blocks host protein kinase R antiviral pathways, and both proteins evolve at high adaptive rates (Elde & Malik 2009). Fertilization in abalone depends on sperm lysin opening a hole in egg VERL proteins, and both of these evolve rapidly (Vacquier & Swanson 2011).

But the prediction of conflict-generated accelerated evolution does not rest completely on tight reciprocal coevolution of two species. Coevolution may also be diffuse (Thompson 1997), with one party responding to the changes in multiple contemporary antagonists. In between-species interactions, partner switching makes the interaction less reciprocal, but it adds new conflicts to adapt to (Brockhurst et al. 2014). Accelerated evolution in one party might not even require any real evolution in antagonists, arising instead because of a constant ecological shuffling in the mix of antagonist species. For these reasons, we suggest that conflict-generated accelerated evolution may be a broader phenomenon than true arms races.

5. WINNING AND POWER

> "I don't know what you mean by your way," said the Queen: "all the ways about here belong to me . . ."
>
> —The Red Queen in *Through the Looking-Glass* by Lewis Carroll

5.1. What Does Winning Mean?

The Red Queen became the metaphor for conflict evolution because of her rapid running that went nowhere. Less well known is that Alice learned this as she was trying to climb a hill and was magically forestalled at every turn, ending up back at the base. Climbing fitness peaks can be hard if others control the path.

Power: the mechanisms by which individuals exert influence on disputed joint phenotypes

What does it mean to win or lose an evolutionary conflict? We speak of predators winning against prey or males winning against females, but each actual conflict is between individuals over their joint phenotype. For example, a *Drosophila* male can win its conflict with a female if his seminal fluid prevents her from remating with another male. But this is not a collective win for males. Each male's victory is a loss for any other male who is prevented from mating. The disconnect between individual and group success is particularly clear here because males as a class cannot outreproduce females. In other conflicts, such as between hosts and pathogens, fitnesses are not equalized in this way, but it is still true that frequency dependence and density dependence often cause disconnects between the individual and its class. If predator individuals win so often that they drive a prey species extinct, the predators as a whole do not gain.

Nevertheless, it can be useful to ask which class has more power to win on average. Given that individual conflicts are over a joint phenotype, measures of power should reflect where the joint phenotype ends up in relation to the two preferred outcomes. We propose two such measures: phenotypic power, P_z, and fitness power, P_w. If the joint phenotype is z and the optima are $\hat{z}_1$ and $\hat{z}_2$, a natural measure for the phenotypic power of party 1 depends on the proportional distance to the two optima: $P_{z1} = 1 - |z - \hat{z}_1|/|\hat{z}_2 - \hat{z}_1|$, at least if z is between the optima. (If a party pulls z past its optimum, one can debate whether that implies power that is greater than, lesser than, or equal to its power at its optimum.) Suppose the joint phenotype is latency to remating, and a female fly remates after 4 days, with her optimum being 2 days and her first mate's optimum being that she not remate for her whole life—let us say 18 days. P_z for the female is 7/8 and for the male is 1/8. But it may often be better to express winning in terms of fitnesses. Suppose the male fly who is losing in terms of phenotype is gaining a lot by delaying remating by just 2 days, whereas it harms the female rather little. A natural fitness measure would use Maynard Smith's lag load (Kokko & Jennions 2014) or proportional distance from the optimum, $L_1 = (\hat{w}_1 - w_1)/\hat{w}_1$ and $L_2 = (\hat{w}_2 - w_2)/\hat{w}_2$, where the w's are current fitnesses and the $\hat{w}$'s are optimum fitnesses. To retain a zero-to-one scale, the fitness power of party 1 is $P_{w1} = 1 - L_1/(L_1 + L_2)$.

Conflicts are won or lost through two major means. First, the outcomes of individual contests are determined by various dimensions of power, with strength and weaponry being canonical examples. Second, collective parties may have asymmetries in evolvability—the ability to evolve changes that lead to power. We consider each in turn.

5.2. Levers of Power

As noted by Alexander (1974) for parent–offspring conflict, the outcome of conflict is determined by various types of power. Conflicting parties should evolve to exploit any form of leverage that is effective and to evolve any effective strategy or counterstrategy, so power is likely to become complex and multidimensional. Perhaps for this reason, there have not been many attempts to systematize the levers of power, which ought to be a central topic in the biology of adaptation. Exceptions include Leigh's (1977) parliament of the genes, which invokes the power of the collective of all of an individual's genes over the interests of any single gene. Dawkins & Krebs (1979) proposed a dinner-life principle and a rare-enemy effect. A thorough review of power in social insects added physical presence, strength, access to resources, information, and various idiosyncratic features (Beekman & Ratnieks 2003). Below we expand the list to 10 general, but not mutually exclusive, categories.

5.2.1. Power of proximity or distance. The first issue is engagement. A party may have a potential conflict with another, but it usually needs to be physically present to engage in an actual conflict. Male social Hymenoptera have an interest in how their progeny behave in the colony, but their power is limited by the fact that they are dead by the time the progeny are born (Beekman & Ratnieks 2003). But the ability to imprint their sperm DNA in ways that alter offspring behavior (Galbraith et al. 2016) shows that presence is not absolutely required.

In many conflicts, one party seeks to engage, while the other tries to avoid engagement. The speed and agility of cheetahs and impalas (Wilson et al. 2018) is one among many examples. But escape can also come through camouflage, hiding, stealth, mimicry, and wariness. Countermeasures include better senses, searching strategies, and ambush. Engagement can be increased by extended body parts: hummingbird beaks, woodpecker tongues, the aye-aye's finger, and wasp ovipositors. A few species use extended phenotypes like the webs or bolas of spiders, or the spitballs of archerfish. Engagement can also be increased inside a body. Invasive haustoria of parasitic plants invade their hosts to extract resources (Kuijt 1977), as do the haustoria of some endosperms growing into maternal tissue (Queller 1983). Mammalian placental cells invading the maternal bloodstream may function similarly in manipulating the mother (Haig 1993).

Attachment or bonding is a special case of proximity that merits special mention, because probably all conflict at the direct molecular level is initiated in this way. Newt tetrodotoxin binds to garter snake sodium channels, thereby impeding nerve and muscle function, but snakes can escape by evolving conformational changes to their channels (Hanifin et al. 2008). At the macro scale, examples include the attachments of tapeworms and other parasites to hosts and male claspers for holding females.

5.2.2. Power of timing. Before moving to closer spatial scales, note that timing can also matter. Sometimes an advantage can be gained by striking first; for example, social amoebas that enter the social phase before others have a higher probability of getting into reproductive spores (Kuzdzal-Fick et al. 2010). In certain stingless bees, when a worker-laid egg is in the same cell as a queen-laid female egg, the former hatches earlier and kills the latter (Beekman & Ratnieks 2003). In other cases, getting the last word can be more decisive. Although a queen ant sets the initial sex ratio, the workers then have control over subsequent investment in the two sexes (Beekman & Ratnieks 2003).

5.2.3. Power of size and strength. Perhaps the most obvious type of power in animal contests comes from size and strength (Huntingford & Turner 1987). Predators overpower prey. Larger individuals can defend resources and territories from smaller and weaker ones. Parents can often control weaker offspring (Alexander 1974).

5.2.4. Power of weapons. Predators often evolve weapons to weaken, disable, dismember, or kill their prey (Emlen 2014). Here is where nature is most often red in tooth and claw, not to mention horns, stings, clubs, and beaks. Prey sometimes fight back with defensive weapons—porcupine quills, social wasp stings, termite glue, and thorns on plants. Weapons are also used within species (Huntingford & Turner 1987). They may be used less frequently in interactions among kin or mutualists, but there are many exceptions. The honeybee queen's sting is used only to kill her sister-rivals for the queenship. Siblicide even occurs in utero, as when pronghorn embryos pierce their siblings with a special uterine horn (O'Gara 1969).

Poisons, toxins, and noxious deterrents might be included as chemical forms of weaponry. Predators like venomous snakes and cone snails use these to quickly immobilize prey that might otherwise escape, but toxins are probably more common in prey, especially those like plants that cannot escape. Chemical combat is common in the microbial world, for example, in bacteriocins released to kill competitors. Bacteriocin and colicin genes are usually directly coupled with immunity genes (Cascales et al. 2007), as are meiotic drive genes (Burt & Trivers 2006).

These examples raise the general point that chemical weapons generally require that the user be immune. Targets can also acquire immunity, sometimes allowing them to use the toxin themselves, as when milkweed insects sequester their milkweed host's cardiac glycosides (Petschenka & Agrawal 2016) or poison dart frogs acquire and use alkaloids from their prey (Darst et al. 2004).

5.2.5. Power of blocking and barriers. If weapons are used more on offense, barriers are used more in defense. The first line of defense against pathogens and parasites is usually the external covering of the organism. This function can be reinforced by scales, feathers, fur, and mucus or other coatings. Examples include thick mollusk shells or insect exoskeletons, the horny skin of male elephant seals, tree bark, and even bacterial cell walls. Some organisms build or utilize structures that can function as barriers—for example, hermit crab shells or mammal burrows. Social insect colonies construct barriers ranging from paper wasp envelopes to earthen termite towers. And others, from tiny endosymbionts to gall-forming wasp larvae, gain refuge inside other organisms. Mating plugs are another form of blocking, and the molecular blocking of sodium channels by tetrodotoxin has already been mentioned.

5.2.6. Power of information. Acquiring information is important in any conflict in which actions need to be adjusted. Prey must generally be sensed and distinguished from nonprey. Often self must be distinguished from nonself or kin from nonkin. Slave ants typically lack the information that they are in a foreign colony, being fooled by their mechanism of waiting until adulthood to learn their colony signature (Blatrix & Sermage 2005).

Somewhat more subtly, power can also be gained by hiding information. Crypsis, camouflage, and stealth work by denying information to predators. If male hymenopteran larvae evolve to mask differences from females, they will not be killed by workers who prefer sisters (Nonacs & Carlin 1990).

Giving false information is a prime way to manipulate opponents (Dawkins & Krebs 1978). This tactic should work best when the deceived party cannot easily evolve to ignore the signal. A predator using lures to bring in prey usually mimics important information—the presence of food (snapping turtle tongues) or mates (orchids mimicking wasps, fireflies giving the mating flash of other species) (Bradbury & Vehrencamp 1998). Batesian mimics that falsely tell predators that they are unpalatable gain from the honesty of the unpalatable model species.

Mimicry is now seen as common and important at the molecular level (Elde & Malik 2009). For example, some pathogenic bacteria produce a structural homolog of a human Toll-like receptor domain. The mimic protein competes for binding the model's receptor ligand, inhibiting host inflammatory response. Such mimics can be difficult to counter when the exploited host factor is conserved and hard to change (Elde & Malik 2009).

5.2.7. Power of flexibility. Using information also requires changing behavior appropriately in response. The advantage of changing behavior is often about paying costs only when necessary. Cheetahs cannot run full speed all day. Inducible chemical defenses in plants in other organisms are made as needed because they are costly.

The most sophisticated plasticity systems provide huge advantages. The adaptive immune system flexibly shifts attacks toward specific current threats. Regardless of whether conflict has driven the evolution of larger brains (Dunbar & Shultz 2007), intelligence and learning can clearly provide advantages in conflicts. But microbes also have flexible responses, including the multiple phenotypes of *Plasmodium* (malaria) cells and the widespread use of quorum sensing in bacteria.

5.2.8. Power of complexity. Flexibility is one form of complexity, but it is not the only one. One version of Leigh's (1977) parliament of the genes might posit that meiotic drive elements are generally suppressed because they always consist of nonrecombining elements that are small and cannot build anything very complex, while they are opposed by many genes that can collectively build complex mechanisms, like those that promote a fair meiosis. Though pathogens have an advantage over their hosts owing to rapid reproduction, it seems likely that hosts often have a compensating advantage of complexity. This is particularly true because pathogens are on offense and must unlock every one of the host's morphological, physiological, and behavioral defenses (Gilman et al. 2012). Even in the Avida digital evolution system, in which digital organisms compete for central processing unit cycles, virtual parasites drive virtual host complexity (Zaman et al. 2014). Finally, complexity power is sometimes acquired via alliances as in the many plants that offer special structures and rewards for ants that drive off intruders (Bronstein et al. 2006).

5.2.9. Power of numbers. A second interpretation of Leigh's parliament of the genes, perhaps the more usual one, is that when a meiotic drive element arises, there are simply many other genes that could individually evolve to stop it. This advantage is simply a matter of numbers and not complex interactions. Numbers matter in ant wars and patrolling chimpanzee groups looking to attack and overwhelm lone males. Much as wolves hunt as a group to bring down large prey, bacteria typically must exceed some threshold number to infect a host (De Kievit & Iglewski 2000). Acting collectively to gain this advantage is easiest in cooperative societies but can sometimes occur in otherwise nonsocial groups, as exemplified by predator mobbing in birds (Davies et al. 2012).

5.2.10. Power of choice. Numbers matter in an entirely different way in some systems that resemble markets (Noë & Hammerstein 1995). Being able to choose among multiple potential partners can give the chooser a better deal. The classic example is female choice of males, which can cause males to evolve incentives: nuptial gifts, territories, and defense or feeding of young. Mutualistic systems also involve markets in which partner choice can mean power. For example, bobtail squids apparently select for costly light production in their symbiotic *Vibrio* bacteria by producing antimicrobial compounds when the bacterial luciferase enzyme is not functioning (Schwartzman & Ruby 2016). In another kind of choice, which is not really a market, predators are thought to win more conflicts by being able to choose to go after prey that are weak or old.

5.3. Evolvability

Each aspect of power has to be evolved, and parties that evolve more readily have a long-term advantage. We discuss four types of evolvability.

First, a party can have a general evolvability advantage if it can generate more variants via large population size, short generation times, high gene number, or high mutation rate. Most of these advantages typically accrue to pathogens over their hosts, though hosts often gain evolvability through recombination and sex (Hamilton 1980, Lively 2010). Within-species opponents do not usually have asymmetries in these features (although within-genome opponents can). Age structure can matter; pathogens that attack mainly old hosts will face less counterselection (Thompson 1985), as will predators that preferentially take the old or weak. Although high evolvability is normally advantageous, it can be disadvantageous in certain mutualism bargaining games in which it is beneficial to have one's hands tied (Bergstrom & Lachmann 2003).

Second, parties that experience the strongest fitness effects will experience stronger selection to evolve. Dawkins's life-dinner principle (Dawkins & Krebs 1979) falls into this category; a prey individual suffers far more from losing an encounter than does a predator. However, a more complete accounting would have to consider that the success over all encounters could be a life-or-death matter for the predator as well. Dawkins's rare-enemy effect is probably sounder; opponents will evolve less readily to counter a party that they rarely encounter (Dawkins & Krebs 1979).

Third, the selection focus on conflict can be diluted by other types of selection. For example, for a party for which conflict varies across the landscape, the optimal response in any given area may be impeded (Thompson 2005). Similarly, effects due to pleiotropy and to correlation with other traits will often be negative and impede selection. For example, in the social amoeba *D. discoideum* a gene that cheats by ignoring the signal to become a sterile stalk is nevertheless pleiotropically excluded from spores, and another gene that uses reduced adhesion to avoid the stalk region fails because adhesion is also necessary to get into aggregations (Strassmann & Queller 2011). Another evolvability advantage can result from high modularity, in which subsets of highly focused traits are connected only loosely to the other subsets (Wagner et al. 2007). We speculate that rapidly evolving conflict traits may be more modular than average. In other words, strong selection under conflict will preferentially favor traits that are not too constrained by connections with other traits. For example, mammalian embryos must be quite constrained in their disputes over maternal provisioning due to the demands of early development, so they have evolved a special module—the placenta—that can specialize on the conflict.

Finally, a sort of retrospective evolvability difference comes from the amount of time that has been available to adapt to new conditions. Opposing parties necessarily evolve in direct response to each other for the same amount of time, but it is possible to have asymmetries with respect to general exposure to relevant conflict. The brown tree snake could devastate Guam birds because it has a long history of contending with birds as prey, but the birds of Guam have had no recent history with snakes (Fritts & Rodda 1998). In novel mutualisms in which each party provides something to the other, each party's long history of control of its own resource may put it in charge over that aspect of the interaction. In cancer, every new cancer is a neophyte that must begin from scratch, evolving itself from a lineage with no prior adaptations to be an effective cancer (Greaves & Maley 2012), putting it at a disadvantage in conflicts against a body that has numerous evolved mechanisms to thwart cancers (Crespi & Summers 2005).

5.4. Conflict Reduction

In some circumstances, conflicts can be reduced. Even for fully antagonistic interactions, there can be a shared interest in not engaging in pointless conflict. When a stotting gazelle shows that it is alert and fit, and the predator registers that information, both the gazelle and the predator are saved the trouble of a fruitless chase.

Reduction of conflict is thought to be essential in the major evolutionary transitions such as to the eukaryotic cell, multicellular organisms, or social insect societies (Bourke 2011, Maynard Smith & Szathmáry 1995). This conflict reduction can be due to either reduction of potential conflict or control of actual conflict. Factors limiting potential conflict are high relatedness, as in social insects and multicellular organisms, and shared reproduction, as in endosymbionts and their hosts. Mutualists, even if they do not co-reproduce, share an interest in their partner's fitness when more fit partners provide more mutualistic benefits than less fit ones. Shared interest can build up over time as partners become more dependent on each other. But all of these means are imperfect, and some potential conflicts usually remain—for example, when elements transmitted more through females, such as mitochondria, chloroplasts, or X chromosomes, can gain through biasing sex investment. Potential conflict remains even among autosomal genes given the possibility of meiotic drive. Thus, power and the ability of one party to suppress another are usually still needed for full control of conflicts even in highly cooperative organismal entities (Strassmann & Queller 2010). Some conflicts generally remain, because absolute power to suppress is hard to achieve.

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LITERATURE CITED

Abrams PA. 2000. The evolution of predator-prey interactions: theory and evidence. *Annu. Rev. Ecol. Syst.* 31:79–105

Aktipis C, Nesse RM. 2013. Evolutionary foundations for cancer biology. *Evol. Appl.* 6:144–59

Alexander RD. 1974. The evolution of social behavior. *Annu. Rev. Ecol. Syst.* 5:325–83

Althoff DM, Segraves KA, Johnson MT. 2014. Testing for coevolutionary diversification: linking pattern with process. *Trends Ecol. Evol.* 29:82–89

Andrés AM, Hubisz MJ, Indap A, Torgerson DG, Degenhardt JD, et al. 2009. Targets of balancing selection in the human genome. *Mol. Biol. Evol.* 26:2755–64

Arnqvist G, Rowe L. 2002. Antagonistic coevolution between the sexes in a group of insects. *Nature* 415:787–89

Arnqvist G, Rowe L. 2005. *Sexual Conflict*. Princeton, NJ: Princeton Univ. Press

Beekman M, Ratnieks FLW. 2003. Power over reproduction in social Hymenoptera. *Philos. Trans. R. Soc. B* 358:1741–53

Bérénos C, Schmid-Hempel P, Wegner KM. 2012. Antagonistic coevolution accelerates the evolution of reproductive isolation in *Tribolium castaneum*. *Am. Nat.* 180:520–28

Bergsten J, Miller KB. 2007. Phylogeny of diving beetles reveals a coevolutionary arms race between the sexes. *PLOS ONE* 2:e522

Bergstrom CT, Lachmann M. 2003. The Red King effect: when the slowest runner wins the coevolutionary race. *PNAS* 100:593–98

Blatrix R, Sermage C. 2005. Role of early experience in ant enslavement: a comparative analysis of a host and a non-host species. *Front. Zool.* 2:13

Borevitz JO, Hazen SP, Michael TP, Morris GP, Baxter IR, et al. 2007. Genome-wide patterns of single-feature polymorphism in *Arabidopsis thaliana*. *PNAS* 104:12057–62

Bourke AFG. 2011. *Principles of Social Evolution*. Oxford, UK: Oxford Univ. Press

Bradbury JW, Vehrencamp SL. 1998. *Principles of Animal Communication*. Sunderland, MA: Sinauer

Brockhurst MA, Chapman T, King KC, Mank JE, Paterson S, Hurst GD. 2014. Running with the Red Queen: the role of biotic conflicts in evolution. *Proc. R. Soc. B* 281:20141382

Brockhurst MA, Koskella B. 2013. Experimental coevolution of species interactions. *Trends Ecol. Evol.* 28:367–75

Bronstein J, Alarcón R, Geber M. 2006. The evolution of plant–insect mutualisms. *New Phytol.* 172:412–28

Burt A, Trivers R. 2006. *Genes in Conflict: The Biology of Selfish Genetic Elements*. Cambridge, MA: Belknap Press

Buss LW. 1987. *The Evolution of Individuality*. Princeton, NJ: Princeton Univ. Press

Carmona D, Fitzpatrick CR, Johnson MT. 2015. Fifty years of co-evolution and beyond: integrating co-evolution from molecules to species. *Mol. Ecol.* 24:5315–29

Cascales E, Buchanan SK, Duche D, Kleanthous C, Lloubes R, et al. 2007. Colicin biology. *Microbiol. Mol. Biol. Rev.* 71:158–229

Castillo-Davis CI, Kondrashov FA, Hartl DL, Kulathinal RJ. 2004. The functional genomic distribution of protein divergence in two animal phyla: coevolution, genomic conflict, and constraint. *Genome Res.* 802:802–11

Chuong EB, Tong W, Hoekstra HE. 2010. Maternal–fetal conflict: rapidly evolving proteins in the rodent placenta. *Mol. Biol. Evol.* 27:1221–25

Crespi B. 2008. Genomic imprinting in the development and evolution of psychotic spectrum conditions. *Biol. Rev.* 83:441–93

Crespi B. 2010. The origins and evolution of genetic disease risk in modern humans. *Ann. N.Y. Acad. Sci.* 1206:80–109

Crespi B, Nosil P. 2013. Conflictual speciation: species formation via genomic conflict. *Trends Ecol. Evol.* 28:48–57

Crespi B, Summers K. 2005. Evolutionary biology of cancer. *Trends Ecol. Evol.* 20:545–52

Darst CR, Menéndez-Guerrero PA, Coloma LA, Cannatella DC. 2004. Evolution of dietary specialization and chemical defense in poison frogs (Dendrobatidae): a comparative analysis. *Am. Nat.* 165:56–69

Davies NB. 2000. *Cuckoos, Cowbirds and Other Cheats*. London: A&C Black

Davies NB, Krebs JR, West SA. 2012. *An Introduction to Behavioural Ecology*. Chichester, UK: Wiley-Blackwell

Dawkins R. 1982. *The Extended Phenotype*. Oxford, UK: Freeman

Dawkins R, Krebs JR. 1978. Animal signals: information or manipulation. In *Behavioural Ecology: An Evolutionary Approach*, ed. J Krebs, N Davies, pp. 282–309. Sunderland, MA: Sinauer

Dawkins R, Krebs JR. 1979. Arms races between and within species. *Proc. R. Soc. B* 205:489–511

De Kievit TR, Iglewski BH. 2000. Bacterial quorum sensing in pathogenic relationships. *Infect. Immun.* 68:4839–49

Decaestecker E, Gaba S, Raeymaekers JA, Stoks R, Van Kerckhoven L, et al. 2007. Host–parasite 'Red Queen' dynamics archived in pond sediment. *Nature* 450:870

DeCasien AR, Williams SA, Higham JP. 2017. Primate brain size is predicted by diet but not sociality. *Nat. Ecol. Evol.* 1:0112

Dodd D. 1989. Reproductive isolation as a consequence of adaptive divergence in *Drosophila pseudoobscura*. *Evolution* 43:1308–11

Dunbar RIM. 1998. The social brain hypothesis. *Evolutionary Anthropology* 6:178–90

Dunbar RIM, Shultz S. 2007. Evolution in the social brain. *Science* 317:1344–47

Ebel ER, Telis N, Venkataram S, Petrov DA, Enard D. 2017. High rate of adaptation of mammalian proteins that interact with *Plasmodium* and related parasites. *PLOS Genet*. 13:e1007023

Eberhard WG. 1985. *Sexual Selection and Animal Genitalia*. Cambridge, MA: Harvard Univ. Press

Ehrlich PR, Raven PH. 1964. Butterflies and plants: a study in coevolution. *Evolution* 18:586–608

Elde NC, Malik HS. 2009. The evolutionary conundrum of pathogen mimicry. *Nat. Rev. Microbiol.* 7:787

Emlen DJ. 2014. *Animal Weapons: The Evolution of Battle*. New York: Henry Holt

Enard D, Cai L, Gwennap C, Petrov DA. 2016. Viruses are a dominant driver of protein adaptation in mammals. *eLife* 5:e12469

Fisher RA. 1930. *The Genetical Theory of Natural Selection*. Oxford, UK: Oxford Univ. Press

Fordyce JA. 2010. Host shifts and evolutionary radiations of butterflies. *Proc. R. Soc. B* 277:3735–43

Frank SA. 2012. Natural selection. IV. The Price equation. *J. Evol. Biol.* 25:1002–19

Frank SA, Crespi BJ. 2011. Pathology from evolutionary conflict, with a theory of X chromosome versus autosome conflict over sexually antagonistic traits. *PNAS* 108:10886–93

Fritts TH, Rodda GH. 1998. The role of introduced species in the degradation of island ecosystems: a case history of Guam. *Annu. Rev. Ecol. Syst.* 29:113–40

Gaba S, Ebert D. 2009. Time-shift experiments as a tool to study antagonistic coevolution. *Trends Ecol. Evol.* 24:226–32

Galbraith DA, Kocher SD, Glenn T, Albert I, Hunt GJ, et al. 2016. Testing the kinship theory of intragenomic conflict in honey bees (*Apis mellifera*). *PNAS* 113:1020–25

Garneau JE, Dupuis M-È, Villion M, Romero DA, Barrangou R, et al. 2010. The CRISPR/Cas bacterial immune system cleaves bacteriophage and plasmid DNA. *Nature* 468:67

Gavrilets S. 2014. Is sexual conflict an "engine of speciation"? *Cold Spring Harb. Perspect. Biol.* 6:a017723

Gavrilets S, Arnqvist G, Friberg U. 2001. The evolution of female mate choice by sexual conflict. *Proc. R. Soc. B* 268:531–39

Gilman RT, Nuismer SL, Jhwueng D-C. 2012. Coevolution in multidimensional trait space favours escape from parasites and pathogens. *Nature* 483:328

Greaves M, Maley CC. 2012. Clonal evolution in cancer. *Nature* 481:306

Haig D. 1993. Genetic conflicts in human pregnancy. *Q. Rev. Biol.* 68:495–532

Hamilton WD. 1980. Sex versus non-sex versus parasite. *Oikos* 35:282–90

Hanifin CT, Brodie ED Jr., Brodie ED III. 2008. Phenotypic mismatches reveal escape from arms-race coevolution. *PLOS Biol*. 6:e60

Heil M. 2016. Host manipulation by parasites: cases, patterns, and remaining doubts. *Front. Ecol. Evol.* 4:80

Hori M. 1993. Frequency-dependent natural selection in the handedness of scale-eating cichlid fish. *Science* 260:216–19

Huntingford FA, Turner AK. 1987. *Animal Conflict*. New York: Chapman and Hall

Janz N. 2011. Ehrlich and Raven revisited: mechanisms underlying codiversification of plants and enemies. *Annu. Rev. Ecol. Evol. Syst.* 42:71–89

Kerstes NA, Bérénos C, Schmid-Hempel P, Wegner KM. 2012. Antagonistic experimental coevolution with a parasite increases host recombination frequency. *BMC Evol. Biol.* 12:18

Kokko H, Jennions MD. 2014. The relationship between sexual selection and sexual conflict. *Cold Spring Harb. Perspect. Biol.* 6:a017517

Kopp M, Gavrilets S. 2006. Multilocus genetics and the coevolution of quantitative traits. *Evolution* 60:1321–36

Kuijt J. 1977. Haustoria of phanerogamic parasites. *Annu. Rev. Phytopathol.* 17:91–118

Kuzdzal-Fick JJ, Queller DC, Strassmann JE. 2010. An invitation to die: Initiators of sociality in a social amoeba become selfish spores. *Biol. Lett.* 6:800–2

Leigh EG. 1977. How does selection reconcile individual advantage with the good of the group? *PNAS* 74:4542–46

Lively CM. 2010. A review of Red Queen models for the persistence of obligate sexual reproduction. *J. Hered.* 101:S13–20

Louthan AM, Kay KM. 2011. Comparing the adaptive landscape across trait types: larger QTL effect size in traits under biotic selection. *BMC Evol. Biol.* 11:60

Martin OY, Hosken DJ. 2003. The evolution of reproductive isolation through sexual conflict. *Nature* 423:979

Martincorena I, Raine KM, Gerstung M, Dawson KJ, Haase K, et al. 2017. Universal patterns of selection in cancer and somatic tissues. *Cell* 171:1029–41.e21

Maynard Smith J, Harper D. 2003. *Animal Signals*. Oxford, UK: Oxford Univ. Press

Maynard Smith J, Szathmáry E. 1995. *The Major Transitions in Evolution*. Oxford, UK: Freeman

Mock D, Parker GA. 1997. *The Evolution of Sibling Rivalry*. Oxford, UK: Oxford Univ. Press

Moore J. 2002. *Parasites and the Behavior of Animals*. Oxford, UK: Oxford Univ. Press

Moore T, Haig D. 1991. Genomic imprinting in mammalian development: a parental tug-of-war. *Trends Genet*. 7:45–49

Morran LT, Schmidt OG, Gelarden IA, Parrish RC, Lively CM. 2011. Running with the Red Queen: host-parasite coevolution selects for biparental sex. *Science* 333:216–18

Noë R, Hammerstein P. 1995. Biological markets. *Trends Ecol. Evol.* 10:336–39

Noh S, Geist KS, Tian X, Strassmann JE, Queller DC. 2018. Genetic signatures of microbial altruism and cheating in social amoebas in the wild. *PNAS* 115:3096–101

Nonacs P, Carlin N. 1990. When can ants discriminate the sex of brood? A new aspect of queen-worker conflict. *PNAS* 87:9670–73

Nuismer SL. 2017. *Introduction to Coevolutionary Theory*. New York: Freeman

O'Gara BW. 1969. Unique aspects of reproduction in the female pronghorn (*Antilocapra americana* Ord). *Dev. Dyn.* 125:217–31

Ostrowski EA, Shen Y, Tian X, Sucgang R, Jiang H, et al. 2015. Genomic signatures of cooperation and conflict in the social amoeba. *Curr. Biol.* 25:1661–65

Pal C, Maciá MD, Oliver A, Schachar I, Buckling A. 2007. Coevolution with viruses drives the evolution of bacterial mutation rates. *Nature* 450:1079–81

Paterson S, Vogwill T, Buckling A, Benmayor R, Spiers AJ, et al. 2010. Antagonistic coevolution accelerates molecular evolution. *Nature* 464:275–78

Petschenka G, Agrawal AA. 2016. How herbivores coopt plant defenses: natural selection, specialization, and sequestration. *Curr. Opin. Insect Sci.* 14:17–24

Presgraves DC. 2010. The molecular evolutionary basis of species formation. *Nat. Rev. Genet.* 11:175–80

Queller DC. 1983. Kin selection and conflict in seed maturation. *J. Theor. Biol.* 100:153–72

Queller DC. 2014. Joint phenotypes, evolutionary conflict and the fundamental theorem of natural selection. *Philos. Trans. R. Soc. B* 369:20130423

Queller DC, Strassmann JE. 2009. Beyond society: the evolution of organismality. *Philos. Trans. R. Soc. B* 364:3143–55

Ratnieks FLW, Foster KR, Wenseleers T. 2006. Conflict resolution in insect societies. *Annu. Rev. Entomol.* 51:581–608

Ratnieks FLW, Reeve HK. 1992. Conflict in single-queen hymenopteran societies: the structure of conflict and processes that reduce conflict in advanced eusocial species. *J. Theor. Biol.* 158:33–65

Reznick DN, Ghalambor CK. 2001. The population ecology of contemporary adaptations: what empirical studies reveal about the conditions that promote adaptive evolution. In *Microevolution: Rate, Pattern, Process*, pp. 183–98. Dordrecht, Neth.: Springer

Rönn J, Katvala M, Arnqvist G. 2007. Coevolution between harmful male genitalia and female resistance in seed beetles. *PNAS* 104:10921–25

Schluter D. 2000. *The Ecology of Adaptive Radiation*. Oxford, UK: Oxford Univ. Press

Schwartzman JA, Ruby EG. 2016. A conserved chemical dialog of mutualism: lessons from squid and vibrio. *Microbes Infect*. 1:1–10

Searcy WA, Nowicki S. 2005. *The Evolution of Animal Communication: Reliability and Deception in Signaling Systems*. Princeton, NJ: Princeton Univ. Press

Servedio MR, Boughman JW. 2017. The role of sexual selection in local adaptation and speciation. *Annu. Rev. Ecol. Evol. Syst.* 48:85–109

Sinervo B, Lively CM. 1996. The rock–paper–scissors game and the evolution of alternative male strategies. *Nature* 380:240

Smith JW, Benkman CW. 2007. A coevolutionary arms race causes ecological speciation in crossbills. *Am. Nat.* 169:455–65

Strassmann JE, Queller DC. 2007. Insect societies as divided organisms: the complexities of purpose and cross-purpose. *PNAS* 104:8619–26

Strassmann JE, Queller DC. 2010. The social organism: congresses, parties, and committees. *Evolution* 64:605–16

Strassmann JE, Queller DC. 2011. Evolution of cooperation and control of cheating in a social microbe. *PNAS* 108:10855–62

Tenaillon O. 2014. The utility of Fisher's geometric model in evolutionary genetics. *Annu. Rev. Ecol. Evol. Syst.* 45:179–201

Thompson JN. 1985. Constraints on arms races in coevolution. *Trends Ecol. Evol.* 1:105–7

Thompson JN. 1997. *The Coevolutionary Process*. Chicago: Univ. Chicago Press

Thompson JN. 2005. *The Geographic Mosaic of Coevolution*. Chicago: Univ. Chicago Press

Thrall PH, Laine AL, Ravensdale M, Nemri A, Dodds PN, et al. 2012. Rapid genetic change underpins antagonistic coevolution in a natural host-pathogen metapopulation. *Ecol. Lett.* 15:425–35

Trivers RL. 1974. Parent-offspring conflict. *Am. Zool.* 14:249–64

Vacquier VD, Swanson WJ. 2011. Selection in the rapid evolution of gamete recognition proteins in marine invertebrates. *Cold Spring Harb. Perspect. Biol.* 3:a002931

Van Cleve J, Akçay E. 2014. Pathways to social evolution: reciprocity, relatedness, and synergy. *Evolution* 68:2245–58

Van Valen L. 1973. A new evolutionary law. *Evol. Theory* 1:1–30

Vermeij GJ. 1987. *Evolution and Escalation: An Ecological History of Life*. Princeton, NJ: Princeton Univ. Press

Wagner GP, Pavlicev M, Cheverud JM. 2007. The road to modularity. *Nat. Rev. Genet.* 8:921

West-Eberhard MJ. 1979. Sexual selection, social competition, and evolution. *Proc. Am. Philos. Soc.* 123:222–34

Wilson AM, Hubel TY, Wilshin SD, Lowe JC, Lorenc M, et al. 2018. Biomechanics of predator–prey arms race in lion, zebra, cheetah and impala. *Nature* 554:183–88

Wolf J, Oakey R, Feil R. 2014. Imprinted gene expression in hybrids: perturbed mechanisms and evolutionary implications. *Heredity* 113:167

Zaman L, Meyer JR, Devangam S, Bryson DM, Lenski RE, Ofria C. 2014. Coevolution drives the emergence of complex traits and promotes evolvability. *PLOS Biol.* 12:e1002023

Zeh DW, Zeh JA. 2000. Reproductive mode and speciation: the viviparity-driven conflict hypothesis. *Bioessays* 22:938–46

Zuk M. 2007. *Riddled with Life: Friendly Worms, Ladybug Sex, and the Parasites That Make Us Who We Are*. San Diego: Harcourt