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A Veritable Menagerie of Heritable Bacteria from Ants, Butterflies, and Beyond: Broad Molecular Surveys and a Systematic Review

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Abstract

Maternally transmitted bacteria have been important players in the evolution of insects and other arthropods, affecting their nutrition, defense, development, and reproduction. *Wolbachia* are the best studied among these and typically the most prevalent. While several other bacteria have independently evolved a heritable lifestyle, less is known about their host ranges. Moreover, most groups of insects have not had their heritable microflora systematically surveyed across a broad range of their taxonomic diversity. To help remedy these shortcomings we used diagnostic PCR to screen for five groups of heritable symbionts—*Arsenophonus* spp., *Cardinium hertigii*, *Hamiltonella defensa*, *Spiroplasma* spp., and *Wolbachia* spp.—across the ants and lepidopterans (focusing, in the latter case, on two butterfly families—the Lycaenidae and Nymphalidae). We did not detect *Cardinium* or *Hamiltonella* in any host. *Wolbachia* were the most widespread, while *Spiroplasma* (ants and lepidopterans) and *Arsenophonus* (ants only) were present at low levels. Co-infections with different *Wolbachia* strains appeared especially common in ants and less so in lepidopterans. While no additional facultative heritable symbionts were found among ants using universal bacterial primers, microbes related to heritable enteric bacteria were detected in several hosts. In summary, our findings show that *Wolbachia* are the dominant heritable symbionts of ants and at least some lepidopterans. However, a systematic review of symbiont frequencies across host taxa revealed that this is not always the case across other arthropods. Furthermore, comparisons of symbiont frequencies revealed that the prevalence of *Wolbachia* and other heritable symbionts varies substantially across lower-level arthropod taxa. We discuss the correlates, potential causes, and implications of these patterns, providing hypotheses on host attributes that may shape the distributions of these influential bacteria.


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Introduction

Insects colonize nearly every terrestrial habitat on the planet, having diversified into millions of extant species. Their roles as pollinators, herbivores, predators, parasites, and mutualists make them integral parts of terrestrial ecosystems, and their biomass within these habitats is largely unrivaled by other animals. Across these invertebrates, the evolutionary innovations enabling adaptation, niche shifts, and diversification have primarily been driven by mutations in their endogenous genomes. Yet, exogenous agents have also played roles in these processes, as many insects harbor maternally transmitted bacteria that provide an additional source of genetic variation with adaptive potential [1].

The variety of these heritable symbionts is impressive, with bacteria from multiple families, orders, and phyla having evolved this highly specialized lifestyle [1]. Several have also independently evolved similar strategies to spread within host populations, making their living through manipulation of host reproduction, or through benefits to host nutrition, defense, or environmental tolerance [2–7]. These effects have enabled heritable symbionts to shape the ecology and evolution of their hosts, and occasional instances of horizontal transfer between species [8–12] have allowed their impacts to be disseminated across the insects and beyond.

*Wolbachia* are by far the best known of the maternally transmitted symbionts. These intracellular members of the Alphaproteobacteria infect a majority of the world’s insect species, and they are also found in isopods, arachnids, and nematodes [13–16]. Other heritable bacteria are typically less prevalent across the arthropods, with lower frequencies and seemingly patchier
Wolbachia lineages are primarily confined to a limited range of arthropod taxa. A systematic review of symbiont frequencies across arthropod taxa, place our results into a broader context, we also conducted a meta-analysis incorporating results from 115 prior studies that used diagnostic PCR (Table S1). This meta-analysis revealed high rates of Wolbachia infection; 114 of the 115 studies each screened a subset of their insect or arachnid specimens for Wolbachia using diagnostic PCR. The majority of surveyed arthropod taxa were insects that are symbiotic with ants, suggesting the possibility for horizontal transfer. However, when we consider that Wolbachia frequencies can differ considerably across related host families, and even related genera [29], it becomes apparent that this lack of information has hindered our understanding of the factors that shape symbiont distributions. Given the known effects of heritable bacteria, surveys for such microbes are likely to identify bacterial species with profound impacts on the nutritional ecology, defensive interactions, reproduction, development, and genome evolution of their host arthropods [2,29].

To further elucidate their distributions, we utilized a series of molecular approaches to study five heritable symbionts across the moths, butterflies (Insecta: Lepidoptera) and ants (Insecta: Hymenoptera: Formicidae). Targeted bacteria included 1) *Aveno-phonous* spp., 2) *Cardinium hericiti*, and 3) *Spiroplasma* spp. found previously across 4–7% of insect and arachnid species [17]; 4) *Hamiltonella defensa*, a heritable symbiont primarily known from whiteflies and approximately 10–15% of surveyed aphid species [4,30,31]; and 5) *Wolbachia* spp., found typically at levels ranging from 15–35% in most diagnostic screening studies [16]. While these bacteria differ in their range of phenotypic effects, all are typically non-essential associates, infecting less than 100% of the individuals within infected species. Additionally, all five symbionts execute at least one type of reproductive manipulation in some host backgrounds, and all but *Cardinium* have been implicated as defensive mutualists [32–36]. With the exception of *Hamiltonella*, all symbionts have been previously targeted in systematic screening studies, including a recent study across a wide variety of arthropods [17]. These prior efforts provide a wealth of data on symbiont frequencies for comparison with our results. *Hamiltonella*, in contrast, was targeted due to its presence in some sap-feeding insects that are symbiotic with ants, suggesting the possibility for horizontal transfer.

For a subset of the targeted ants, we also searched for heritable symbionts through surveys of 16S rRNA libraries amplified with universal primers, focusing on species known to harbor maternally transmitted symbionts (from the tribe Camponotini) and those screening ambiguously with diagnostic PCR. Our molecular screening and sequence analyses allowed us to estimate symbiont incidence across species, prevalence within host taxa, and both diversity and dominance of bacteria within single individuals. To place our results into a broader context, we also conducted a systematic review of symbiont frequencies across arthropod taxa, compiling results from 115 prior studies that used diagnostic PCR to screen for heritable bacteria. Combined, our efforts have yielded one of the most comprehensive examinations of symbiont distributions to date.

### Methods

#### Insect specimens

In total, our surveys targeted 987 specimens of ants, moths, and butterflies. A total of ~250 lepidopteran species (approximation due to the presence of unidentified species from the same genera and, thus, possible redundancy) from 13 families, 37 subfamilies, and 195 genera were surveyed for one or more of the targeted bacteria using diagnostic PCR. The majority of surveyed Lepidoptera hailed from the butterfly families Lycaenidae and Nymphalidae. Sampling within the Lycaenidae targeted 93 genera across 30 of 33 tribes, and six of seven subfamilies. Within the Nymphalidae we screened across 77 genera from 9 out of 12 subfamilies and 33 of 40 tribes. Ants targeted in diagnostic PCR screening came from ~406 ant species spanning 19 of 21 known subfamilies, and 124 genera. A large percentage of the targeted ants were those used to construct the first major ant phylogeny [37], comprising a good representation of the diversity across this family. In addition, high representation within the genus *Pheidole*, the army ants, and the genus *Polyrhachis* (from the Australian Wet Tropics) enabled us to screen extensively within several focal groups of ants. This allowed us to estimate intraspecific infection frequencies for some species, while also enabling infection frequency comparisons among related groups of ants. Surveys in the genus *Polyrhachis* were of special interest due to the group’s known associations with heritable *Blachmanani* symbionts and the possible presence of facultative, “secondary” symbionts.

Collections were made previously from a number of temperate and tropical locations across all continents except Antarctica. All necessary permits were obtained for the described field studies. Army ant samples from Uganda were collected under a permit from the Uganda National Council for Science and Technology (EC483), while from Kenya were collected under permits from the National Museums of Kenya (NMK/CBD/10/VOL:2) and the Kenya Ministry of Education, Science and Technology (MOEST/13/001/31C168/5 and MOEST/13/001/31C168/2). Additional collection information can be found within previously published papers on the specimens used in this study [26,37,38].

#### General molecular methodologies

Information on DNA extractions, PCR conditions, primer design, electrophoresis, positive and negative controls, template quality assays, PCR product purification, cloning, and sequencing can be found in Information S1 and Table S1. Specific details on the primers utilized for diagnostic screening, universal PCR, and sequencing can be found in Table S2.

#### General phylogenetic methodologies

Sequences generated with universal or diagnostic PCR primers (along with their closest relatives) were aligned on the RDP website [39]. Maximum likelihood phylogenies were constructed on the CIPRES web portal [40] using the program GARLI [41]. Each of our analyses employed a GTR + G + I model of nucleotide substitution, and parameters for this model were estimated during each run. For taxon-specific phylogenetics (see below), bootstrap analyses with 100 replicates were performed for each dataset using GARLI (with the above-described approach) or RAXML 7.2.8 Black Box [42]. Analyses using this latter program utilized default parameters with the exception that the proportions of invariant sites were estimated during all runs. All phylogenies were visualized on the Interactive Tree Of Life (iTOl) website [43].
Diagnostic PCR assays

Diagnostic PCR screening was used to assess the presence/absence of *Arsenophonus*, *Cardinium*, *Hamiltonella*, *Spiroplasma*, and *Wolbachia* across ants and lepidopterans. Screening for the former four symbionts ranged across our insect collections, while surveys for *Wolbachia* were more limited due to prior surveys of some of our targeted insects [26]. Nearly all screening assays were conducted on extractions from single individuals.

PCR results were only tallied for runs in which the positive controls amplified with the proper diagnostic primers and for which negative controls were clearly negative. Templates were scored positive when: 1) they yielded a product of the expected size in at least two separate reactions (for all samples), and (for all but two of our declared positives) 2) when BLASTn searches with the amplified sequences yielded a top hit to a bacterium from the expected taxon. Alternatively, templates were scored negative when they did not give rise to products of the expected size or if the top BLASTn hit was to a bacterium from outside the targeted clade (e.g., for three butterfly species with microbes BLAST'ing to *Providencia* instead of *Arsenophonus*). Those giving rise to non-repeatable amplification were scored as ambiguous and were not included in our frequency/incidence estimates.

Systematic review of symbiont incidence

To place our screening results into a broader context, we performed a systematic review of symbiont incidence across the arthropods (see Figure 1 for PRISMA flow diagram, and supplementary files for the PRISMA checklist). We began with a literature search, identifying published diagnostic PCR surveys for the five heritable symbionts targeted in this study. These studies were found through the Web of Science database by using the genus names of all five symbionts, separately, as queries. Literature searches were performed in 2009, and again in July 2011 and July 2012.

After scanning abstracts for terms indicative of molecular symbiont screening, the Methods sections of candidate papers were read to determine suitability. Only those using diagnostic PCR with species- or genus-specific primers were included. To avoid bias within individual studies we ensured that all species surveyed were fully listed (rather than only those with the symbiont) and that PCRs included negative controls.

For all suitable publications, we extracted data on the presence/absence of symbionts in individual arthropods (or pools of individuals) from tables, text, or supplementary files, compiling this into a spreadsheet that listed the names and taxonomy of surveyed arthropod species, and the presence/absence of the five symbionts screened for in this study. Our focus was limited to the species level, and we ignored data on intraspecific frequency when symbionts screened for in this study. Our focus was limited to the surveyed arthropod species, and the presence/absence of the five heritable symbionts was used to suggest the potential for heritability among the novel bacteria identified from ants and lepidopterans.

Wolbachia wsp sequence analyses

To study the diversity of *Wolbachia* strains infecting ants and lepidopterans, we sequenced the highly variable *wsp* gene for nearly all infected hosts. Chromatograms generated from direct sequencing were examined, and those with clean, single peaks were used to infer likely single infections. The *wsp* sequences from these single infections were submitted to GenBank (Accession #s below). Otherwise clean chromatograms that gave rise to multiple peaks at some positions were used to infer the presence of multiple *Wolbachia* strains in the targeted insects. *Wolbachia* is the most striking example of a heritable symbiont considered in this review.
these hosts were subsequently studied by cloning and sequencing wsp fragments.

Sequences from wsp clone libraries were separately aligned using ClustalW on the EMBL-EBI website (http://www.ebi.ac.uk/Tools/msa/clustalw2/), and alignments were manually adjusted in MacClade [48]. Uncorrected pairwise distances were then computed for each alignment in PAUP v4.0b10 [49]. Distance matrices for each clone library were inspected to identify 99% phylotypes—groups of related sequences that were ≤1% divergent from all other members of their cluster and greater than 1% divergent from all sequences in other clusters. Using the same approach, 97% phylotypes were also identified for each library. To illustrate the diversity of Wolbachia strains found in single ant and lepidopteran hosts we calculated the number of phylotypes from each insect host and the number of sequence reads from each phylotype.

For each wsp library, one representative sequence per 99% phylotype was chosen for subsequent analyses and for submission to GenBank. Each of these representatives, and all of those from direct sequencing were queried against the wsp database on the Wolbachia MLST website (http://pubmlst.org/Wolbachia), identifying the closest relatives of the wsp alleles sampled in our study. Accession numbers for GenBank all wsp submissions were KC137149–KC137234.

**Results**

**Infection across host species and populations—diagnostic PCR**

Ants were frequently colonized by Wolbachia (28.6%), showing fewer associations with Spiroplasma (4.6%) and Arsenophonus (1.6%). Lepidopterans did not harbor Arsenophonus; but like the ants, these insects frequently possessed Wolbachia (24.7%), while few were colonized by Spiroplasma (2.5%). Neither Cardinium hertigi nor Hamiltonella defensa were found among any of the insects screened in this study (see Table 1 for summarized screening results and sample sizes, and Table S3 for details on all surveyed insects).
Wolbachia prevalence varied extensively between army ant genera. Species from the genus *Aenictus* (subfamily Aenictinae) exhibited the highest infection rate, with 10 infected species out of the 12 that were surveyed. Only *Neivamyrmex* species were found to be infected among the five surveyed genera from the subfamily Ecitoninae, with all five surveyed species from this genus harboring *Wolbachia*. In contrast, *Wolbachia* were not found among 19 ant species from the genus *Dorylus* (subfamily Dorylinae). Among well-sampled lepidopteran families (i.e. \( n \geq 10 \) species surveyed), Hesperiidae species were the most commonly infected (aphids), Culicidae (mosquitoes), Tephritidae (true fruit flies), and Hemiptera (kissing bugs), though they were not extensively surveyed across other hemipteran families. And although *Cardinium* appeared common among the Hemiptera, this largely resulted from high prevalence within the Delphacidae (planthoppers), compared to lower infection rates within the Aphiidae (based on limited screening). Across well-sampled Hymenoptera families, *Cardinium* were only found in the Aphelinidae, while findings of *Cardinium* among dipterans were confined to species from the Ceratopogonidae (biting midges).

Infection across the arthropods—a systematic review of diagnostic screening studies

To place our findings from ants and lepidopterans into context, we summarized the frequencies of the five focal symbionts—*Arsenophonus*, *Cardinium*, *Spiroplasma*, and *Wolbachia*—across 4,366 arthropod species based on the results from 115 diagnostic PCR screening studies (Table S3). Infection frequencies within the insect orders Coleoptera, Diptera, Hymenoptera, and Lepidoptera were found to mirror the results from our diagnostic screening, with \( \sim 20\% - 35\% \) of species infected by *Wolbachia* and \( \sim 6\% \) or less harboring *Arsenophonus*, *Cardinium*, and *Spiroplasma* (Figure 2). The Lepidoptera exhibited no instances of infection with any symbionts except *Spiroplasma* (2.4% of species infected) and *Wolbachia* (29.1% species infected), again matching results from our screening.

The Hemiptera deviated from other insect groups, showing higher instances of *Arsenophonus*, *Cardinium*, and *Spiroplasma*. Outside of the insects, arachnids were common hosts of *Cardinium*, with frequencies ranging from 14–44% outside of the Ixodid (ticks), which showed 0% infection in the targeted studies. The Araneae (spiders) were especially enriched for *Spiroplasma* (23.1% of species infected) in addition to *Cardinium and Wolbachia* (44.2% and 31.7% infected species, respectively).

Examination of symbiont prevalence within arthropod families (with \( n \geq 10 \) sampled species) provided further insight into the taxa shaping trends seen at the ordinal level (Figure 3). For instance, within the Hemiptera *Arsenophonus* were enriched within the Cicadellidae (leafhoppers) and Reduviidae (specifically, the kissing bugs), though they were not extensively surveyed across other hemipteran families. And although *Cardinium* appeared common among the Hemiptera, this largely resulted from high prevalence within the Delphacidae (planthoppers), compared to lower infection rates within the Aphiidae (based on limited screening). Across well-sampled Hymenoptera families, *Cardinium* were only found in the Aphelinidae, while findings of *Cardinium* among dipterans were confined to species from the Ceratopogonidae (biting midges).

Variation in *Wolbachia* prevalence also existed among genera from the same families, most notably within the Aphiidae (aphids), Culicidae (mosquitoes), Tephritidae (true fruit flies), and Formicidae (ants) (Table S6). In the former case, *Wolbachia* were found in only 10% of species from the genus *Aphis* (\( n = 30 \)) compared to 50% of the surveyed *Cinara* species (\( n = 14 \)). Within the Tephritidae, infection ranged from 29.5% (\( n = 44 \)) of species from the genus *Bactrocera* to 100% (\( n = 10 \)) within the genus *Anastrepha*. Among the mosquitoes, the genus *Aedes* had no infected species out of 35 surveyed, while the genera *Anopheles* and *Culex* had *Wolbachia* infection rates of 26.5% (\( n = 34 \)) and 50% (\( n = 34 \)), respectively. Finally, the ant family Formicidae had infection frequencies ranging from 0% (*Dolichoderus* and *Dorylus* with \( n = 15 \) and \( n = 22 \) surveyed species, respectively) to over 80% within the genera *Tetraponera* (\( n = 10 \)), *Aenictus* (\( n = 16 \)), and *Formica* (\( n = 10 \)).

It should be mentioned that our criteria for the inclusion of symbiont screening data (i.e. diagnostic PCR surveys across two or more species) led to exclusion of several confirmed infections. In fact, some of the hosts with 0% reported infection in our figures and tables are known to harbor the microbes in question. This is true for ticks (Ixodidae), for example, which harbor *Arsenophonus* [52]. It is also true for ants (Formicidae), where at least one species is known to harbor *Cardinium* [53].
Infection across ant and lepidopteran species—universal PCR and phylogenetic analysis

While diagnostic screening permitted surveys across a diverse range of ants, moths, and butterflies, sequencing of universal 16S rRNA products provided a second molecular approach for symbiont surveys across the ants (see Table S7 for summary statistics of clone libraries and a list of sampled species). Based on this dataset, RDP classification revealed that *Wolbachia* were present in 28/74 sampled ant species. This same approach identified heritable *Blochmannia* symbionts in all but one of nine sampled species from the tribe Camponotini. *Spiroplasma* symbionts were found in two of these nine camponotine species (genus *Polyrhachis*), and in two of the 65 other ant species surveyed with the universal approach. Aside from potentially heritable symbionts from the Enterobacteriaceae (see below), universal PCR and sequencing did not identify maternally transmitted bacteria from other common groups (e.g., *Rickettsia* sp., *Hamiltonella defensa*, *Serratia symbiotica*, *Regiella insectcola*, *Cardinium hertigii*, etc.) either from ants or from the one butterfly sampled with universal primers. Overall, ants harbored heritable symbionts from six, and possibly eight, lineages of heritable symbionts (*Arsenophonus, Blochmannia, Spiroplasma, and Wolbachia*—shown here; *Cardinium hertigii* and *Serratia symbiotica*—shown elsewhere [33,34]; and two candidate symbionts from fire ants [55]; see Figures 4 and S1). The presence of bacteria clustering within clades of other heritable bacteria from the Enterobacteriaceae (Figure S2) suggests that this number could be even higher. These results contrast with what we see in the Lepidoptera, with only two heritable lineages (*Spiroplasma* and *Wolbachia*) being reported to date.

**Taxon-specific phylogenetic analyses**

Maximum likelihood phylogenies showed that *Arsenophonus* (Figure S4) and *Spiroplasma* (Figure 3) from ants clustered with heritable bacteria from other ant or arthropod hosts, although several ant-associated *Spiroplasma* grouped into lineages without known heritable relatives. As seen in our universal 16S rRNA phylogeny (Figure 4), a number of other ant-associates (identified with universal 16S rRNA PCRs) clustered within a gammaproteobacterial clade comprised almost entirely of insect-associated symbionts (Figure S2), including heritable bacteria from tsetse flies, scale insects, psyllids, and aphids, as well as gut bacteria from ants. Among these, several were related to coevolved *Blochmannia* symbions from carpenter ants (Figure S3). Although the long branches separating ant-associates from known symbionts prevent us from making stronger conclusions, these Enterobacteriaceae microbes could potentially be heritable symbions or specialized residents of ant guts.

**Within-host infection trends—relative symbiont densities**

When considering hosts infected with microbes from vertically transmitted clades, we found a tendency for heritable symbions to dominate bacterial communities (Table S7). In *Camponotus* and *Polyrhachis* species, *Blochmannia* (an essential heritable symbiont) comprised a median of 50% of the universal sequence reads across eight worker ants from seven species (with n≥4 sequence reads each). In two *Polyrhachis* species, sequence reads BLAST'ing to *Spiroplasma* comprised 50% and 57.1% of our clone libraries, respectively equaling and exceeding the numbers of *Blochmannia* reads in the same hosts. Interestingly, in the one camponotine with *Wolbachia* and n≥4 sampled sequences, 9/9 reads belonged to this bacterium. Looking across all ants with n≥4 sequence reads, *Wolbachia* made up anywhere from 20% to 100% of sequence libraries when present (n = 6 sampled ant species), with a median representation of 68.33%. In addition, clean *Wolbachia* sequences have been generated from direct sequencing of 20 other universal 16S rRNA
products from different ants (two new to this study), suggesting high abundance compared to co-infecting microbes within the same hosts. When we consider that Wolbachia were detected in 37.8% (28/74) of the ant species surveyed with universal primers, and that 16.5% (78/474) of all universal sequence reads came from Wolbachia, it is clear that this symbiont is a dominant member of microbial communities within many ants.

Within-host infection trends—Wolbachia co-infection

Prior research suggested that Wolbachia communities from individual insects may themselves consist of multiple strains [28], hinting at even more diversity within hosts than can be appreciated through 16S rRNA analyses. In this study we generated 32 clean wsp sequence reads (i.e. no multiple peaks) from Wolbachia-infected Lepidoptera out of direct sequencing attempts from 35 species. Multiple peaks within the remaining...
chromatograms suggest that roughly 8.6% of lepidopteran infections involved more than one strain. Among the Polyrhachis ants that were newly discovered to have Wolbachia, we had difficulty generating quality wsp sequences. Instead, we sampled two MLST genes, \textit{gatB} and \textit{hcpA}, observing that 6/8 samples (from five ant species) likely harbored multiple Wolbachia strains.

Sequencing of \textit{wsp} from Wolbachia in Aenictus and Neivamyrmex army ants identified eight likely multiple infections out of direct sequencing attempts from 22 different workers (spanning 13 species, with direct sequencing from 1–5 workers per species).

To better assess the diversity of Wolbachia within ant and butterfly hosts, we targeted several of those yielding multiple
Symbiont Distributions across the Arthropods

- Mycoplasma genitalium U39694
- Spiroplasma chrysoplasticola AY189127 (tabanid fly)
- Spiroplasma syphidicola AY189309 (syphid fly)
- *Lasius alienus* CS0268 GQ275102 (ant)
- Spiroplasma sp DC017753 (crab)
- Spiroplasma sp DC300669 (shrimp)
- Spiroplasma of Ixodes uriae EU727106 (tick)
- Trapetzites elenae HM96746 (skipper)
- Spiroplasma of Anthidiom florentinum EU727107 (wasp)
- Spiroplasma sp LB-12 AY189313 (green leaf bug)
- Spiroplasma sp NS25 Leucoma salisic DQ186442 (moth)
- *Poritia sumatranae* butterfly HM96745 (butterfly)
- Spiroplasma of Drosophila hydei DQ412092 (fruit fly)
- Spiroplasma of Drosophila melanogaster FJ657180 (fruit fly)
- Spiroplasma of Drosophila simulans FJ657181 (fruit fly)
- Spiroplasma sp DW1 of Drosophila willistoni M24483 (fruit fly)
- Spiroplasma of Drosophila melanogaster AY519996 (fruit fly)
- Spiroplasma panzei AY771927 (shrimp)
- *Spiroplasma insolitum* AYL19313 (flower-butterfly)
- Spiroplasma phoenicuri AY771935 (plant)
- Spiroplasma melilobi AY323304 (honeybee)
- Spiroplasma of Pardosa lugubris EU727108 (spider)
- Spiroplasma Ch-1 DQ452375
- *Rhetus nr* Periander HM96751 (butterfly)
- *Mesone phareus* HM96752 (butterfly)
- Spiroplasma olhi X33761 (plant)
- *Lycana arata* HM96756 (butterfly)
- *Polyphagis* sp CS07671 (ant)
- *Polyphagis* sp CS07673 clone 191-5 (ant)
- *Myrmica incompleta* HM96744 (ant)
- *Polyphagis* ornata clone 190-5 (ant)
- Spiroplasma of Drosophila mojavensis FJ657219 (fruit fly)
- Spiroplasma of Drosophila hydei DQ412094 (fruit fly)
- Spiroplasma of Drosophila wheeleri FJ657225 (fruit fly)
- Spiroplasma of Drosophila aldrichi FJ657229 (fruit fly)
- 13 strains of Entomoplasm, Mesospora, & Mycoplasma (3 from ants)
- *Polyphagis* sp KC-A021-01 (ant)
- *Polyphagis* sp RA0732 (ant)
- Mesospora lactucae AF303132 (plant)
- *Calyptonymex becari* HM96748 (ant)
- *Acronymyx octospinosus* AF491679 (ant)
- *Neivamyrmex nigrescens* HM96773 (ant)
- Spiroplasma sp TIUS-1 AY189318 (typhlid wasp)
- Spiroplasma lampyricolli AY189314 (firefly)
- *Neivamyrmex alleni* AY188823 (scorpion fly)
- *Neivamyrmex diminutus* AY189304 (mosquito)
- Spiroplasma sp CB1 AY189315 (insects-flowers)
- Entomoplasm melanaceae AS35990 (flower)
- *Spiroplasma floridica* AYL19313 (flower)
- *Alicides zodiacus* HM96749 (moth)
- Spiroplasma sp BARC-1901 AY189320 (tabanid fly)
- *Spiroplasma tabanidica* GU58690 (tabanid fly)
- *Polyphagis* robonisi CS07120 (ant)
- Trachymyrmex jamaicensis RA0247 GQ275127 (ant)
- Vollenhovia sp RA0294 GQ275136 (ant)
- Vollenhovia sp KC-A026-01 HM96763 (ant)
- Dorylus molestus Q16-12 HM96767 (ant)
- Pheidole sp HM96747 (ant)
- *Pheidole sortis* HM96754 (ant)
- *Spiroplasma platyheix* DQ998101 (dragonfly)
- *Neivamyrmex carolinensis* N51401 HM96770 (ant)
- *Neivamyrmex gibbatus* HP107 HM96776 (ant)
- *Spiroplasma of Drosophila tenebrosa* FJ657245 (fruit fly)
- uncultured bacterium EU136790 (rainwater)
- uncultured bacterium EU136790 (rainwater)
- *Spiroplasma of Nerene clambrata* EU727102 (spider)
- *Spiroplasma of Meta mengei* EU727103 (spider)
- *Spiroplasma of Meta segmentata* EU727104 (spider)
- *Spiroplasma of Tetragnatha montana* EU727105 (spider)
- *Spiroplasma of Tipula olivacea* EU727101 (crane fly)
- *Spiroplasma Hg5-41 of Hepalis gonggaienss* EU344951 (moth)
- *Spiroplasma of Chrysolina varians* EU727100 (beetle)
- *Spiroplasma of Araneus diadematus* EU727099 (spider)
- *Spiroplasma of Adalia bipunctata* AJO00775 (beetle)
- *Spiroplasma clones 02-2-14 AY837731 (mosquito)
- *Spiroplasma of Drosophila ananassae* FJ657247 (fruit fly)
- *Spiroplasma of Laodelphax striatellus* AB553862 (plant hopper)
- *Spiroplasma of Acyrthosiphon pisum* AB404463 (pea aphid)
- *Spiroplasma of Antonina crawby AB030022 (scale insect)
- *Spiroplasma of Notostira elongata* EU727096 (grass bug)
- *Spiroplasma of Cricada virginis* EU727097 (leaf hopper)
- *Spiroplasma of Fannia manica* AYL388899 (house fly)
- *Polyphagis sokolovia* CS08654 (ant)
- *Spiroplasma of Danaus chryssippus* AJO25996 (butterfly)
- *Spiroplasma of Ep121346 (flora)
- *Spiroplasma of Drosophila atipex* FJ657246 (fruit fly)
- *Spiroplasma of Anisosticha novedecipunctata* AJO00775 (beetle)
- *Spiroplasma of Harmonia axyridis* AJO32412 (beetle)
chromatogram peaks in prior direct sequencing attempts [26]. The wsp gene was amplified, cloned, and sequenced from 15 ants and two lycaenid butterflies, with an average of 8.6 reads per individual ant (range: 3–22) and 4.5 per butterfly (range: 4–5). Among the two Wolbachia wsp libraries from butterflies, two phylotypes were detected from the host with a suspected multiple infection, while just one phylotype was found in a host with a suspected single infection (true for both 99% and 97% phylotype criteria). In only two ant libraries did we detect just one wsp variant (99% and 97% phylotype criteria); the first of these had been selected a priori due to its suspected single infection status, while the other was sampled at low depth (n = 3 reads). As such, 13 out of 14 suspected instances of multiple Wolbachia infection were confirmed (99% phylotype results; see Table 2).

When using 99% wsp sequence identity as the cut-off for phylotype assignment, the median number of strains detected per studied ant with suspected multiple infection was three. One worker of the species Megalomyrmex feae harbored six different Wolbachia strains. Five strains were detected in a single Temnothorax triarchanuus worker, while single workers from two other species (Labidus spinosus and Formicaexus provancheri) each harbored four different strains. Results were nearly identical when using the 97% criterion—there were 40 detected strains using this measure across all 14 ants with suspected multiple infections, compared to 43 with the 99% criterion.

We should note that the existence of singleton OTUs in several of the sampled libraries leaves open the possibility that either sequencing error or PCR artifacts (i.e. chimeras) were responsible for a small proportion of the detected diversity. Indeed, two alleged strains out of the 40 detected from ants (based on the 97% criterion) appeared to harbor wsp alleles that were likely recombinants of others from the same host. While these could represent examples of novel allele generation facilitated by multiple infections, they could also have stemmed from chimeric PCR products. Aside from these instances, it is unlikely, however, that non-recombinant singleton sequences with over 3% divergence from others in the same host arose frequently due to sequencing or PCR error.

Trends of host-association inferred from wsp alleles

To ascertain whether wsp alleles from co-infecting strains showed similar trends of host association as seen for singly infecting Wolbachia strains of ants [26,36], a representative sequence from each 99% phylotype was used to perform a query search against the Wolbachia MLST database (http://pubmlst.org/wolbachia/). Eleven wsp sequences were identical to alleles in the database (Table S8). All of these were derived from Wolbachia strains of ants, with only one (allele 18) that was also found outside of ants (in lepidopterans). A slim majority (23/42) of the remaining wsp alleles from multiply infected ant hosts had highest similarity to those from ant-associated Wolbachia strains established as single infections. Alleles from New World ants were most similar to those from Wolbachia found in various New World locations. And those from ants in the Old World and Oceania regions were, likewise, most similar to wsp alleles of Wolbachia from ants in these same regions. Trends from army ants with single Wolbachia infections largely mirrored those described above. Similarly, 17/35 wsp alleles from lepidopterans were most closely related to those found previously in other moths and butterflies (Table S8).

Discussion

Microbial menageries—players within bacterial communities from ants and lepidopterans

Over the past decade, the cataloging of microbial communities across the insects has begun to accelerate. Long-known to play important nutritional roles in groups such as termites [57,58] and sap-feeding hemipterans [59], more recent discoveries also hint at common microbial roles in defense against natural enemies [33–36,60] and tolerance of abiotic conditions [61–63]. Although metagenomic approaches can provide powerful insight into the functions of microbial communities [64,65], surveys of animal-associated bacteria often lack the ability to determine lifestyles and functions of the identified bacteria and fungi. It is partially for this reason that surveys for widespread microbes with conserved lifestyles—like those employed here—are especially useful, as they enable researchers to identify symbionts within a range of plausible phenotypic effects.

In this study we have characterized microbial associates of two diverse and important groups of insects, looking broadly across the ants while focusing mostly on the Lycadaeidae and Nymphalidae families within the Lepidoptera. Ants, moths, and butterflies are found across most terrestrial habitats and can vary functionally as herbivores, generalists, and predators; as pollinators and seed dispersers; as contributors to nutrient recycling; as defensive mutualists of plants and plant pests; and as major plant pests themselves through their abilities to defoliate vegetation. Symbiotic microbes could play roles in several of these functions, while shaping other lifestyle attributes that influence the fate of their host species.

Microbial communities of ants and lepidopterans have been assessed previously, though typically with less depth and breadth. For instance, gut bacteria of lepidopteran larvae and adults have been documented for a small number of species [66–68], while recent studies have also chronicled the distributions and evolution of bacteria from the guts [46,69–71] and cuticles [72,73] of various ants. Such research is of interest given the hypothesis that gut bacteria have facilitated the evolution of herbivory across the ants [44], and also given their proposed use [74], or actual function [66], in biological control. Studies on these insects have also focused on heritable symbionts. Facultative heritable symbionts such as Wolbachia, Spiroplasma, Cardinium, Seratia, and Arsenophonus have been documented from ants [47,53,54,75–78], with only the former two groups being reported from lepidopterans [79,80].

When combined with our findings, it appears that the Lepidoptera harbor a more limited array of common heritable symbionts (thus far, just two), when compared to the ants, for reasons that are currently unknown. While we estimate six species of heritable symbionts across the ants, this number may be higher. For instance, fire ant queens harbor bacteria in their hemolymph that are also found in eggs and ovaries [55], while other ants harbor bacteria from a symbiotic clade within the Gammapro-
Table 2. The diversity of Wolbachia strains from single insect hosts as inferred through sequencing of wsp libraries.

<table>
<thead>
<tr>
<th>Common host name</th>
<th>Host genus and species</th>
<th>Total # of phylotypes</th>
<th># reads in phylotype 1</th>
<th># reads in phylotype 2</th>
<th># reads in phylotype 3</th>
<th># reads in phylotype 4</th>
<th># reads in phylotype 5</th>
<th>Total # sequence reads</th>
</tr>
</thead>
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<td>Ant</td>
<td>Aenictus sp. 2</td>
<td>2</td>
<td>5</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td>6</td>
</tr>
<tr>
<td>Ant</td>
<td>Cardiocondyla emeryi</td>
<td>2</td>
<td>4</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td>6</td>
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<tr>
<td>Ant</td>
<td>Formica wheeleri</td>
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<td>7</td>
<td></td>
<td></td>
<td>13</td>
</tr>
<tr>
<td>Ant</td>
<td>Formicaeus provanekeri</td>
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<td>4</td>
<td>2</td>
<td>1</td>
<td>4</td>
<td></td>
<td>11</td>
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<tr>
<td>Ant</td>
<td>Formicaeus provanekeri</td>
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<td>2</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>Ant</td>
<td>Heteroponera microps</td>
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<td>2</td>
<td>2</td>
<td></td>
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<td></td>
<td>4</td>
</tr>
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<td>Labidus spinipodus</td>
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<td>4</td>
<td>1</td>
<td>1</td>
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<td></td>
<td>6</td>
</tr>
<tr>
<td>Ant</td>
<td>Myrmelachista sp.</td>
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<td>3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3</td>
</tr>
<tr>
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<td>3</td>
<td></td>
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<td>1</td>
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<td>1</td>
<td></td>
<td></td>
<td>4</td>
</tr>
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<td>9</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>9</td>
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<td></td>
<td></td>
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<td>1</td>
<td></td>
<td></td>
<td></td>
<td>5</td>
</tr>
</tbody>
</table>

Phyotypes described based on 99% sequence similarity, as described in the methods. doi:10.1371/journal.pone.0051027.t002
teobacteria (Figure S2). More work is needed to elucidate the lifestyles of these bacteria, to explore the possibility of non-canonical or rare heritable symbionts across ants and lepidopterans, and to confirm the lifestyles of Arsenophonus and Spiroplasma, which come from lineages where heritability is not ubiquitous [81].

It should be noted that while our screening assays could have plausibly missed some of the targeted bacteria (e.g. due to primer-annealing site mismatches), screening and sequencing with universal 16S rRNA primers across several dozen ants identified no candidate heritable bacteria other than Blochmannia and those detected through diagnostic screening. For this reason, our findings that Cardinium and Hamiltonella are rare across the ants are unlikely to be the result of methodological bias. This rarity is at least mildly surprising, in light of the frequent trophic interactions between ants and insects known to host such bacteria (i.e. aphids and whiteflies).

Similar to our growing, but limited, knowledge of microbial diversity in the insects targeted here, our understanding of the functions and consequences of identified bacteria is also in the budding stages. A few exceptions can be seen for lepidopterans, in which Wolbachia can manipulate reproduction [79,80,92]. Among the ants, members of the tribe Attini are known to harbor antibiotic-producing bacteria on their cuticles that help to defend their fungal gardens [83], while those from the Camponotini harbor nutritional Blochmannia symbionts in specialized cells of their midgut [84–86]. Aside from indirect evidence for nutritional roles of gut symbionts in herbivorous ants [44,70], the vast majority of the remaining bacteria described thus far from ants remain uncharacterized, including many related to free-living microbes detected from ants in our own work (Figure S1).

Certainly, then, discoveries of heritable symbionts with a potential for nutrition, defense, or reproductive manipulation [1] suggest areas for investigation. Our findings suggest that such roles should be especially studied for Wolbachia, given their notable prevalence and infection patterns among the insects studied here. Currently, Wolbachia are known to induce male-killing (MK), feminization, and cytoplasmic incompatibility (CI) in lepidopterans [80,92,87,88]. While CI and MK are consistent with patterns from Wolbachia-infected ants [89], we know little about the explicit effects of these bacteria on their ant hosts [28,90,91]. Like Hamiltonella [35], Spiroplasma [34,60] and possibly Arsenophonus [32], Wolbachia can also defend some insects against natural enemies [33,36], raising an unexplored possibility for the ants and lepidopterans.

Wolbachia steal the show…but not on all stages

In addition to characterizing the heritable microbial communities of ants, butterflies, and moths, our work synthesizes the current state of knowledge on the distributions and frequencies of these bacteria across the arthropods. While a good deal was previously known about these distributions, prior efforts had not approached the depth or breadth of sampling attained here within insect taxa. Our screening efforts and systematic review, therefore, facilitate some of the broadest and most comprehensive examinations of 1) variation in symbiont prevalence across host taxa and 2) the diversity of symbionts within well-sampled host taxa. In turn, these examinations allow initial glimpses of the correlates of infection—both phylogenetic and ecological—which may suggest causes and consequences of symbiont proliferation.

As noted above, our results indicate that Wolbachia are by far the most prevalent heritable symbionts found across the ants and within some butterflies, followed by Spiroplasma (both) and Arsenophonus (only in ants). Only one surveyed host group among these organisms, provided an exception to this rule, with the genus Polyrhachis showing a high prevalence of Spiroplasma. However, the originisation of most targeted Polyrhachis species from one general location (i.e. the Australian Wet Tropics) suggests a need for further studies across a broader geographic range. Furthermore, four of the six identified Polyrhachis infections came from species in the subgenus Chariomyrma (4/6 species infected, compared to 2/17 in species from other subgenera). This indicates that Spiroplasma enrichment could be a specific feature of these close relatives, rather than a genus-wide attribute.

Similar to our results for the focal insects, Wolbachia appears to be the predominant heritable symbiont among the Coleoptera, Diptera, and Hymenoptera. Yet Wolbachia dominance is not seen across all arthropod orders. Notably, some groups within the Hemiptera show a pronounced enrichment for Arsenophonus, while several groups of arachnids are enriched for this bacterium and/or Cardinium, trends that have generally been recognized through prior reports [76,92–94].

It is important to note that most of the sub-taxa within the different orders and families highlighted in Figures 2 and 3 have not been sampled with sufficient depth. In fact, trends gleaned for high Arsenophonus and Cardinium frequencies among the arachnids are based largely on in-depth sampling within single families in the Prostigmata (mites), Mesostigmata (mites), and Araneae (spiders). And while the Hemiptera have been sampled with greater depth and breadth for some symbionts, high incidence of Arsenophonus is driven by results from only two families (Cicadellidae and Reduviidae), while high Cardinium levels are promoted by frequent infection in the Delphacidae. So given that related taxa can differ drastically in symbiont infection frequencies (e.g. Table S6), it is clear that apparent differences in symbiont prevalence across host taxa should be interpreted cautiously until a larger portion of diversity from lower-level taxa can be sampled.

But even after accounting for sporadic and/or limited sampling of different groups, Wolbachia is nevertheless dominant amongst the heritable symbionts—a result that has been appreciated previously on smaller scales [17,19,21]. This raises the question of why Wolbachia symbionts have been so much more successful in obtaining broad host ranges and high incidence. Possibilities include their capacity for rapid molecular evolution through recombination or perhaps their abilities to persist in many types of hosts due to their wide range of conferred phenotypes (discussed further in Information S1).

Side-shows or show-stealing stars?—What host factors govern symbiont prevalence?

While Wolbachia are the most prevalent among the heritable symbionts found across the arthropods, this obscures the fact that their frequencies vary between various host groups, something seen also for less prevalent and more host-range-restricted bacteria such as Hamiltonella, Cardinium, and Arsenophonus. This indicates that phylogeny is a correlate of prevalence for several symbionts (see also Table 3). Such a trend could extend from multiple symbiont acquisitions by a particular host group, or a limited number of acquisitions followed by codiversification, a scenario proposed for Arsenophonus and their blood-feeding hosts [76].

In addition to phylogenetic correlates of symbiont prevalence, similar biological attributes can be found in some unrelated hosts enriched for the same symbionts, including diet (i.e. blood-feeding, for Arsenophonus), genetic system (i.e. haplodiploidy, for Cardinium), and modes of ant colony founding (i.e. dependent-founding, for Wolbachia [28,51]). While exceptions to these biological correlates reveal a need for further examination, these trends do suggest hypotheses for symbiont function and for host attributes favoring...
the spread of facultative symbionts (see Table 3 for an overview, and Information S1 for more details).

### A profile of the ants’ symbiotic menageries

In addition to our focus on bacterial distributions across host taxa, we have also characterized features of heritable symbionts that are evident at other hierarchical levels. To summarize: 1) ant hosts commonly harbor multiple *Wolbachia* strains within single workers; 2) heritable symbionts are abundant, if not dominant, members of ants’ microbial communities (resembling trends from some [95–97], but not all [98] prior studies); 3) *Wolbachia* may be found at high frequencies within some ant species (raising questions about the prevalence of loss from adult workers [89,90,99]); and 4) heritable symbionts from related hosts appear closely related themselves, suggesting host specificity. While these observations are not entirely novel, the scope of our surveys does newly allow for generalizations across the ants. Below, we finish with a brief discussion of one of these findings.

### High levels of multiple infection across the ants—trends and implications

While analyses of 16S rRNA genes allow us to decipher the varieties of bacterial species from animal hosts, sequencing of more rapidly evolving genes is needed to distinguish among related strains co-infecting the same hosts. Interestingly, such efforts in this study make it clear that ants are especially predisposed toward co-infection with multiple strains of *Wolbachia*. This trend had been seen before in a limited range of wood ants, fire ants, and leaf-cutter ants [89,100,101]. Furthermore, in a previous study spanning a broader range of the Formicidae, we observed that 37.9% (33/87) of *wsp* chromatograms from ants had multiple peak patterns suggestive of multiple *Wolbachia* infections. In contrast, this total was considerably lower for surveyed butterflies (16.7% from 3/18 species with *wsp* sequence confirmation) [26]. When combined with chromatogram observations here, the number of *Wolbachia* infections estimated to consist of two or more strains reaches 40.2% (47/117) for the ants and 11.3% (6/53) for lepidopterans. The methodological basis for these estimates becomes more sound when we note that all but one of 15

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**Table 3.** Prevalence, ranges of infected hosts, and correlates of symbiont prevalence as inferred from our systematic review.

| Symbiont     | Prevalence and Host Range | Host Taxonomy | Life History
|--------------|---------------------------|---------------|--------------
| Arsenophonus | % species infected: 7.50 (n = 733) Enriched among some hemipterans, including leafhoppers and kissing bugs Enriched among unrelated blood-feeding arthropods |
|             | # infected arthropod families: 18 (n = 113) |
|             | # infected arthropod orders: 6 (n = 16) Dominant symbiont within 1 of 10 well-sampled arthropod orders |
| Cardinium    | % species infected: 9.28 (n = 1250) Enriched among mites and spiders Enriched among some unrelated haplodiploids (mites, armored scale insects, parasitic wasps) |
|             | # infected arthropod families: 22 (n = 191) |
|             | # infected arthropod orders: 9 (n = 29) Dominant symbiont within 3 of 10 well-sampled arthropod orders |
| Hamiltonella | % species infected: 2.74 (n = 585) Enriched among aphids No identified trends |
|             | # infected arthropod families: 3 (n=19) |
|             | # infected arthropod orders: 1 (n=3) Dominant symbiont within 0 of 10 well-sampled arthropod orders |
| Spiroplasma  | % species infected: 3.77 (n = 982) Enriched among *Polyrhachis* ants from the subgenus *Chariomyrma* from the Australian Wet Tropics; rare among related *Camponotus* ants |
|             | # infected arthropod families: 15 (n = 95) |
|             | # infected arthropod orders: 6 (n = 14) Dominant symbiont within 0 of 10 well-sampled arthropod orders |
| Wolbachia    | % species infected: 31.25 (n = 3994) Enriched among *Aenictus* army ants; rare among *Dorylus* army ants Rare in two groups of cyclical parthenogens (aphids and oak gall wasps) |
|             | # infected arthropod families: 183 (n = 356) Enriched among *Culex* mosquitoes; rare among *Anopheles* mosquitoes Possibly more common among ant species with dependent colony founding, with exceptions in some groups. |
|             | # infected arthropod orders: 24 (n = 38) Dominant symbiont within 5 of 10 well-sampled arthropod orders |

*Focusing on traits found in two or more unrelated groups enriched for the given symbiont.

[doi:10.1371/journal.pone.0051027.t003]
examined multiple infections inferred from chromatogram viewing was confirmed through wsp cloning and sequencing in this study (Table S4), with a median number of 3 strains per multiply infected host. While insects such as lice and tephritid fruit flies have been found to harbor multiple Wolbachia strains [102,103], up to eight strains have been detected within single worker ants, revealing a high diversity of these symbionts at the individual level [100].

So what are the implications of multiple infections? Clearly these should provide an avenue for the exchange of genetic material. Could ants, then, serve as a common group of melting pot hosts, facilitating genetic exchange among various Wolbachia lineages [28]? Such a role would be most far-reaching if multiply infected ants served as a cross-roads for generalist Wolbachia strains coming from numerous host taxa. Yet our inferences from wsp relatedness do not suggest this to typically be the case. Instead, we find that the wsp alleles sampled in multiply infected ants are most often related to those of strains grouping into ant-specific lineages on MLST phylogenies (Table S8). While we recognize the limitations of wsp as a phylogenetic marker, this finding matches previous trends seen for Wolbachia strains found as single infections within ants, trends seen among the lepidopteran associates identified here and elsewhere, and broader patterns of host-symbiont specialization that appear to characterize symbiotic associations in general [9,25,26,47,56].

An important exception to this pattern involves a clade of wsp alleles found commonly in ants and lepidopterans. Since many Old World ants harbor Wolbachia strains with wsp alleles from this clade, it stands to reason that their Wolbachia symbionts may have opportunities for genetic exchange amongst a wider gene pool. Whether this does happen, or whether any melting pot effects of multiple infections are more insular, is a question awaiting further investigation.

Conclusions

The frequencies of heritable symbionts vary across arthropod taxa. Wolbachia are the dominant symbionts within several groups, including ants and butterflies, suggesting that this bacterium has likely had a relatively large impact on their ecology and evolution. Correlates of symbiont prevalence provide several clues regarding forces that shape their distributions, identifying promising areas for future research on these pervasive and influential microbes.

Supporting Information

Checklist S1  PRISMA 2009 Checklist.

Figure S1  Maximum likelihood phylogeny of ant-associated bacteria, their relatives, and heritable symbionts of arthropods. This full phylogeny is the counterpart to Figure 3 and illustrates relatedness among nearly all known lineages of heritable bacterial symbionts from arthropods, representative sequences from each ant-bacterial 16S rRNA library (i.e. one per 97% phylotype) generated with universal primers, Arsenophonus sequences identified with enteric-specific primers, top SeqMatch hits of all representative sequences from ants, and sequences from bacteria previously detected in ants. Symbionts are labeled with their names, and those from larger clades are enclosed by brackets colored the same as the corresponding clade name. Bacterial taxonomy is indicated in the inner color strip. Ant-association (maroon or red) is indicated with branch coloration and with the middle color strip. Symbiont lifestyle (heritable vs. free-living/non-heritable) is indicated with the outer color strip. See second page for figure legend. Notice the large fraction of ant-associated bacteria that do not group with heritable symbionts.

Figure S2  16S rRNA maximum likelihood phylogeny of other Gammaproteobacteria. Bootstrap values exceeding 60% are indicated near their respective nodes. Sequences highlighted in red are from ants. Those generated from ants in this study are indicated with “*”. Included in this analysis, in addition to ant-associates, were known members of the larger symbiotic clade including Sodalis, Buchnera, Blochmannia, etc. along with top BLASTn hits and members of related clades from throughout the enteric bacteria. Note that unlike the other phylogenies, this topology (along with bootstrap values) was generated using RaXML.

Figure S3  16S rRNA maximum likelihood phylogeny of Blochmannia and relatives. Bootstrap values exceeding 60% are indicated near their respective nodes. Sequences generated from ants in this study are indicated with “*”. Those highlighted in red are from ants. Subclades of Blochmannia are indicated with labels. Included here, in addition to nearly all known Blochmannia sequences, are close relatives identified through BLASTn searches—all are symbionts of other ants.

Figure S4  16S rRNA maximum likelihood phylogeny of Arsenophonus. Bootstrap values exceeding 60% are indicated near their respective nodes. Sequences generated from ants in this study are indicated with “*”. Those highlighted in red are from ants, and those in blue are from lepidopterans. Included in this analysis, in addition to ant-associates, were nearly all known Arsenophonus sequences >700 bp in length and representative sequences from clades known to be closely related to Arsenophonus.

Information S1  Details on molecular work, including PCR reactions, purification, cloning, and sequencing, can be found in this section. Also described are methods for sequence alignment and phylogenetics. This section additionally includes detailed results of taxon-specific phylogenetic analyses and a discussion of the phylogenetic and lifestyle attributes correlating with symbiont distributions.

Table S1  PCR conditions used in this study. See separate file.

Table S2  PCR and sequencing primer information. See separate file.

Table S3  Detailed results of diagnostic PCR screening new to this study. “+” positive; “−” negative; “?” ambiguous. Screens for Arsenophonus involved two primer pairs. Pair 1 (Ars2F & 1513R) results are indicated to the left of the slash and pair 2 (Ars23S-1 & Ars23S-2) results to the right. Note that “+” indicates that one of the two aforementioned pairs was not used. All Spiroplasma screen results followed by a “*” were performed with primer pair 63F & TKSSsp; the remaining Spiroplasma results were inferred based on BLASTn/phylogenetic results of sequences generated with primer pair cute493F & 1513R. See Excel file.

Table S4  Intraspecific screening performed for this study. Numbers of infected individual ants out of the total number with unambiguous screening results are indicated for
Table S5  Compiled screening results from this study and those in the systematic review. Each surveyed species is listed only once in this file, and results are a compilation for each species. ‘−’ indicates species thus far testing negative in all studies; ‘+’ indicates species with at least one sample testing positive in at least one study. Blank cells indicate no (or ambiguous) screening results in our study or those from our systematic review. Cited references performed a diagnostic PCR survey for at least one of the symbionts mentioned within the same row. See Excel file.

Table S6  Variation in Wolbachia infection frequencies across well-sampled host genera. Proportions of infected species and sample sizes are indicated for arthropod genera with n>10 species screened for Wolbachia. Colors are used to highlight taxa from the same orders. See Excel file.

Table S7  Results of 16S rRNA sequencing with universal vs. enteric primers. This table provides information on the aut and butterfly hosts whose bacterial communities were targeted with this sequence-based approach. Details on the methodologies used (e.g. cloning vs. direct sequencing, universal vs. enteric primers), the depth of sampling (e.g. cloning vs. direct sequencing, universal vs. enteric specific primers), and those in the systematic review. Cited references performed a diagnostic PCR survey for at least one of the symbionts mentioned within the same row. See Excel file.

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Author Contributions

Conceived and designed the experiments: JAR CSM NEP. Performed the experiments: JAR CSM BGH DS. Analyzed the data: JAR. Contributed reagents/materials/analysis tools: DJCK CSM NEP. Wrote the paper: JAR CSM BGH DS DJCK CSM NEP.

References


