Genes involved in convergent evolution of eusociality in bees

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Eusociality has arisen independently at least 11 times in insects. Despite this convergence, there are striking differences among eusocial lifestyles, ranging from species living in small colonies with overt conflict over reproduction to species in which colonies contain hundreds of thousands of highly specialized sterile workers produced by one or a few queens. Although the evolution of eusociality has been intensively studied, the genetic changes involved in the evolution of eusociality are relatively unknown. We examined patterns of molecular evolution across three independent origins of eusociality by sequencing transcriptomes of nine socially diverse bee species and combining these data with genome sequence from the honey bee *Apis mellifera* to generate orthologous sequence alignments for 3,647 genes. We found a shared set of 212 genes with a molecular signature of accelerated evolution across all eusocial lineages studied, as well as unique sets of 173 and 218 genes with a signature of accelerated evolution specific to either highly or primitively eusocial lineages, respectively. These results demonstrate that convergent evolution can involve a mosaic pattern of molecular changes in both shared and lineage-specific sets of genes. Genes involved in signal transduction, gland development, and carbohydrate metabolism are among the most prominent rapidly evolving genes in eusocial lineages. These findings provide a starting point for linking specific genetic changes to the evolution of eusociality.

social evolution | social insects | sociogenomics | molecular phylogenetics

The evolution of eusociality, the phenomenon in which female offspring forgo personal reproduction to care cooperatively for their siblings, is one of the major transitions of life on Earth (1). This evolutionary transition has occurred multiple times, but only in a small number of lineages, primarily in the insects (11 or more times; ref. 2). The evolution of eusociality has long fascinated biologists because it requires that the balance between cooperation and conflict shift in favor of cooperation, despite strong selective pressure for individual reproductive success (3).

Despite a rich history of theoretical work on the evolution of eusociality (4, 5), relatively little is known about the molecular changes associated with eusocial evolution (6). These molecular changes have the potential to inform us about the evolutionary processes involved in the evolution of eusociality, such as types and levels of selection (7). Some insights have been gained about molecular mechanisms underlying eusociality in individual eusocial lineages (6), but a broad comparative framework for exploring common principles of the molecular basis of eusocial evolution is lacking. One major unresolved question is whether independent evolutionary trajectories of eusociality involved similar or different genetic changes.

We explored the genetic basis of eusocial evolution in bees, an ideal group for comparative studies of social evolution. There is a wide diversity of social lifestyles within this group, from solitary to intermediately social to elaborate eusociality (8). Additionally, eusociality has been gained independently at least six times (9–12) in the bees, more than in any other group. These features make it possible to compare multiple, independent origins of different social lifestyles among relatively closely related species. Furthermore, the extensive knowledge of bee natural history (8, 13, 14) provides a valuable framework for developing hypotheses about the adaptive significance of genetic changes detected in eusocial bee lineages.

To study patterns of molecular evolution associated with eusociality in bees, we generated ~1 Gbp of expressed sequence tags (ESTs) from a set of nine bee species (Table S1). This set of species reflects the remarkable social diversity in bees by including eusocial and non-eusocial species; three origins of eusociality (9, 10); and two different forms of eusocial lifestyle, "highly eusocial" and "primitively eusocial" (ref. 8; Fig. 1*A*). We combined the ESTs with genome sequence from the highly eusocial honey bee *Apis mellifera* (15), and created manually curated, 10-species, partial gene sequence alignments. We searched among the alignments for genes with accelerated rates of amino acid substitution in eusocial relative to non-eusocial lineages. Accelerated rates of protein evolution can reflect a molecular signature of positive natural selection (16), and shared patterns of acceleration among lineages can suggest an association between genetic changes and the evolution of shared traits.

Results

Characterization of Alignments. Our alignments corresponded to ~33% of the genes (n = 3,647; 3,638 after removal of alignments showing evidence of saturation) in the *A. mellifera* Official Gene Set (Dataset S1). To improve the utility of this genomic resource for evolutionary analysis, we used stringent criteria for assessing orthology to minimize misclassification of paralogous sequences within the alignments (*SI Text*). We also looked for functional biases in the set of genes represented by our alignments by performing Gene Ontology enrichment analysis. We identified biological processes that were overrepresented and underrepresented in our set of genes relative to all genes in the *A. mellifera* Official Gene Set (Dataset S1).

Phylogenetic Tree Inference from EST Data. We used Bayesian inference to estimate the phylogenetic relationships among bee species from our set of 3,638 alignments (*SI Text*). The phylogenetic tree inferred from third nucleotide positions was identical in structure to trees inferred in published studies that included

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Data deposition: Transcriptome sequences reported in this paper are available at http://insectsociogenomics.illinois.edu/ and have been deposited in the NCBI Transcriptome Shotgun Assembly (TSA) database, http://www.ncbi.nlm.nih.gov/Genbank/TSA.html (for accession nos. see *SI Text*).

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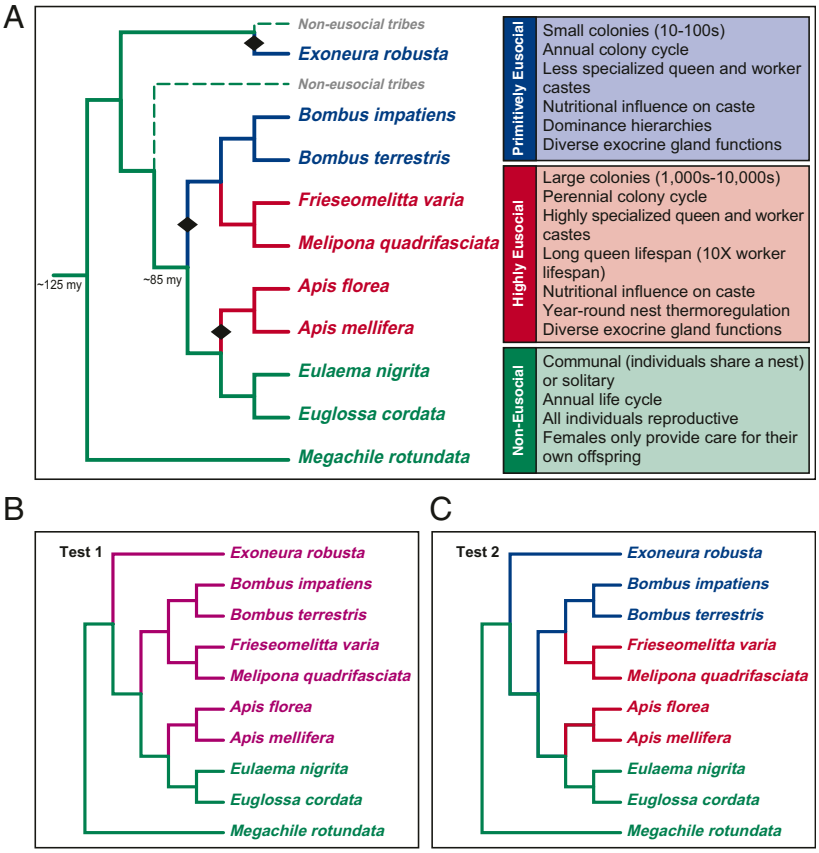

Fig. 1. Bee species and evolutionary models used to identify genes evolving rapidly in eusocial lineages. (*A*) Phylogeny of species in study based on previously published trees (9–11) and EST data (*SI Text*). Some analyses of EST data yielded an alternative topology; molecular evolutionary analyses performed with each topology gave highly similar results (*SI Text* and Table S2). Diamonds represent independent origins of eusociality. Reconstruction of eusocial origins based on phylogenies with greater taxon sampling (refs. 9–11 ; green dashed branches indicate position of non-eusocial lineages not included in the study). Lineages are color-coded by lifestyle: red, highly eusocial; blue, primitively eusocial; and green, non-eusocial. Boxes list key characteristics of each lifestyle (8, 13). (*B* and *C*) Representation of branch models of nonneutral evolution that were compared with null models by using likelihood ratio tests (LRTs). Lineages are color-coded as in *A*, except in test 1, where "All Eusocial" lineages are coded in purple. *B*, Test 1: $\omega_{\text{Eusocial}} \neq \omega_{\text{Non-eusocial}}$; *C*, Test 2: $\omega_{\text{Highly eusocial}} \neq \omega_{\text{Primitively eusocial}} \neq \omega_{\text{Non-eusocial}}$.

greater taxonomic sampling (9–11; Fig. S1). A single, different topology was obtained by inferring phylogeny from the other nucleotide positions and from amino acid sequences (Fig. S1). We therefore performed all of our molecular evolutionary analyses using both tree topologies. Overall, tree topology had little effect on the results of our molecular evolutionary analyses (Table S2), and the results reported here use the topology in Fig. 1.

Heterogeneous Patterns of Molecular Evolution Among Bee Lineages. We searched among the alignments for genes with accelerated rates of amino acid substitution in eusocial relative to non-eusocial lineages. We performed two tests (Fig. 1 *B* and *C*) that used likelihood ratio tests (LRTs) to compare models of neutral and nonneutral sequence evolution to search for genes in which the ratio of nonsynonymous to synonymous nucleotide substitutions (d_N/d_S, or ω) is higher in specified groups of eusocial lineages. Test 1 identified genes in which ω is higher in all eusocial lineages as a group relative to non-eusocial lineages and did not discriminate between the highly and primitively eusocial lineages. Test 2 did so discriminate and identified genes in which ω is highest in either all primitively or highly eusocial lineages as a group relative to all other lineages. These tests are not mutually exclusive; a gene may be evolving more rapidly in all eusocial relative to non-eusocial lineages, as well as evolving most rapidly in either the highly or primitively eusocial lineages.

Our tests of heterogeneous rates of protein evolution yielded a number of genes evolving differently between eusocial and non-eusocial lineages, and among eusocial lineages. For test 1, we found 212 out of 3,638 genes (6%) evolving significantly more rapidly in all eusocial lineages relative to non-eusocial lineages ("All Eusocial" gene list). For test 2, we found 173 genes (5%) evolving most rapidly in highly eusocial lineages ("Highly Eusocial" gene list) and 218 genes (6%) in primitively eusocial lineages ("Primitively Eusocial" gene list), relative to other lineages (false discovery rate adjusted $P < 0.05$ in all three cases; Dataset S2). Table 1 shows the most significant genes (based on *P* value) on each list. These results demonstrate that the pattern of genetic changes associated with eusocial evolution includes some common changes and some changes that are unique to the different eusocial lifestyles.

Evaluation of Biases in Data. We explored the results of our tests to search for potential biases related to nucleotide composition or EST sequence coverage (*SI Text*). We used Spearman's rank correlation to determine if the following characteristics of the sequence data were correlated with the *P* values from the LRTs: (*i*) average GC content at the third position; (*ii*) average overall GC content; (*iii*) *transition/transversion* ratio (kappa); and (*iv*) d_N tree length. The gappiness of an alignment could introduce potential biases in our results (17, 18), so we also looked for correlations between the *P* values from the LRTs and two metrics to assess coverage in our alignments: (*i*) gap percent (gapPCT), or the sum of the number of gaps in each sequence in an alignment divided by the sum of the total number of sites in all of the sequences in an alignment; and (*ii*) an alignment quality score (described in *SI Text*). Only a few of these characteristics of the data were significantly correlated ($P < 0.05$) with the *P* values of the LRTs, but all correlations were very weak (range of Spearman's rho = −0.1–0.06, for all tests; Dataset S2).

Biological Processes Evolving More Rapidly in Eusocial Relative to Non-Eusocial Bees. We performed Gene Ontology (GO) enrichment analyses based on orthology to *Drosophila melanogaster* to identify biological processes that were overrepresented on the All Eusocial, Highly Eusocial, and Primitively Eusocial gene lists. GO enrichment analysis accounts for the overrepresentation of cate-

Table 1. Genes evolving more rapidly in eusocial bee lineages

Gene	Function	*A. mellifera* gene	Rank	*P*	Relative ω*
Accelerated evolution in all eusocial lineages (test 1)					
girdin	Actin-binding protein; regulation of cell size	GB14448	4	0.00000	2.78
dihydrolipamide dehydrogenase 1	Enzyme; glycolysis	GB17626	8	0.00006	2.52
la autoantigen-like	Ribonucleoprotein; development	GB14277	11	0.00015	3.51
brahma	Chromatin remodeler; axonogenesis and oogenesis	GB30507	12	0.00015	4.25
syntaxin7	Membrane-bound protein; SNAP receptor activity	GB14433	15	0.00020	5.49
Accelerated evolution in primitively eusocial lineages (test 2)					
dopamine N acetyltransferase	Enzyme; dopamine signaling	GB18080	3	0.00000	24.5
no on or off transient A	mRNA binding protein; courtship song in *Drosophila*	GB18173	8	0.00000	5.74
signal recognition particle 14 kDa	mRNA binding	GB15372	9	0.00000	136.5
no on or off transient A	mRNA binding protein; courtship song in *Drosophila*	GB18173	10	0.00000	5.74
helicase 98B	Enzyme; immune response	GB14810	11	0.00000	4.62
β spectrin	Cytoskeletal protein; nervous system development	GB11407	12	0.00000	1.88
Accelerated evolution in highly eusocial lineages (test 2)					
phosphofructokinase	Enzyme; glycolysis	GB17113	3	0.00000	3.18
enolase	Enzyme; glycolysis	GB15039	4	0.00000	3.35
pelle	Serine/threonine kinase; immune response and axon targeting	GB16397	5	0.00000	2.80
nicotinate phosphoribosyltransferase	Enzyme; nicotinate metabolism	GB15603	24	0.00004	3.28
RhoGAP100F	GTPase; axonogenesis and signal transduction	GB15150	25	0.00005	2.39

Gene rank based on FDR-adjusted *P* values from LRTs. Evolutionary changes in the genes listed here do not appear to be strongly driven by any one lineage, and results do not seem to be affected by removal of any lineage from the analysis (*SI Text*).
*Relative ω is the fold difference compared with the non-eusocial ω. See Dataset S2 for full lists.

gories present in our set of 3,638 genes, but the underrepresentation of some categories in this set is one explanation for why these categories may not have been enriched in our gene lists (Dataset S1). "Gland development" and "cell surface receptor-linked signal transduction" were among the terms overrepresented exclusively in the All Eusocial gene list ($P < 0.05$, all GO results; Dataset S2 and Table S3).

Carbohydrate metabolism-related categories were enriched in both the All Eusocial and Highly Eusocial gene lists, suggesting that these genes are evolving both more rapidly in eusocial relative to non-eusocial lineages and also most rapidly in highly eusocial lineages (Fig. 2*A*). Fifteen of the 26 genes encoding glycolytic enzymes in our dataset showed evidence of accelerated evolution in one or both of these lists (Fig. 2*B*), including enzymes that play a key regulatory role (phosphofructokinase) or are involved in glycolytic flux (hexokinase, pyruvate kinase). Subsequent analyses (see *Robustness of Results*) revealed that 7 out of these 15 genes appear to be evolving most rapidly in honey bees (genus *Apis*; *SI Text*). Two of the most rapidly evolving genes on the Highly Eusocial gene list encode glycolytic proteins (Table 1).

Transcription-related categories were enriched in both the All Eusocial and Primitively Eusocial gene lists, but not in the Highly Eusocial gene list. This enrichment exclusively in the All Eusocial and Primitively Eusocial gene lists suggests a similar pattern to that seen with carbohydrate-metabolism related genes in the All Eusocial and Highly Eusocial gene lists, only here with an emphasis in primitively eusocial lineages.

Lifestyle- and Lineage-Specific Patterns of Molecular Evolution. Some biological processes were enriched exclusively in either the Highly Eusocial or Primitively Eusocial gene lists and were not enriched in the All Eusocial gene list (Dataset S2 and Table S3). For example, we detected a signature of accelerated evolution in brain-related functional categories in primitively eusocial bees, but not in highly eusocial bees.

We performed an additional series of "lineage-specific" tests to identify genes evolving more rapidly in any individual eusocial lineages relative to all other lineages in our study (*SI Text*). We were specifically interested in whether lineages with the same eusocial lifestyle showed similar biological processes undergoing accelerated evolution, but via changes in unique sets of genes. We did find evidence for this pattern in some lineages. For example, genes related to reproduction are rapidly evolving in both primitively eusocial lineages, Bombini and *Exoneura robusta*, relative to all other lineages, but the actual genes in Bombini and *E. robusta* are largely different (Dataset S2).

Robustness of Results. We performed an additional set of analyses to explore whether specific lineages may have contributed disproportionately to some of the results reported above. We performed "exclusion tests" in which we removed eusocial lineages from our alignments, one at a time, and reran tests 1 and 2 to look for genes for which one species may have driven the pattern of accelerated evolution that we had detected previously (*SI Text* and Fig. S2). Given that the removal of lineages can also affect statistical power to detect accelerated evolution in a gene (19), we consider this analysis to be useful for highlighting our strongest results, but we do not believe that this analysis is sufficient to invalidate the results obtained using the full set of species.

We created three new gene lists by removing the genes from the original All Eusocial, Highly Eusocial, and Primitively Eusocial gene lists whose significance appeared to have been driven by one eusocial lineage (*SI Text* and Dataset S3). GO enrichment analysis revealed that some of the trends identified in our analysis using all species (Fig. 2 and Dataset S2) were not robust to the removal of lineages (Table S3 and Dataset S3), including the enrichment of "gland development" in the All Eusocial gene list and the enrichment of transcription-related categories in the All Eusocial and Primitively Eusocial gene lists. Many biological processes were robust to the removal of lineages, including "cell surface receptor-linked signal transduction" in the All Eusocial gene list, carbohydrate metabolism-related categories in the All Eusocial and Highly Eusocial gene lists, and neuron differentiation-related categories in the Primitively Eusocial gene list.

We performed an additional analysis to determine whether artificial groupings of species would lead to the same enriched biological processes as our groupings of eusocial and non-eusocial

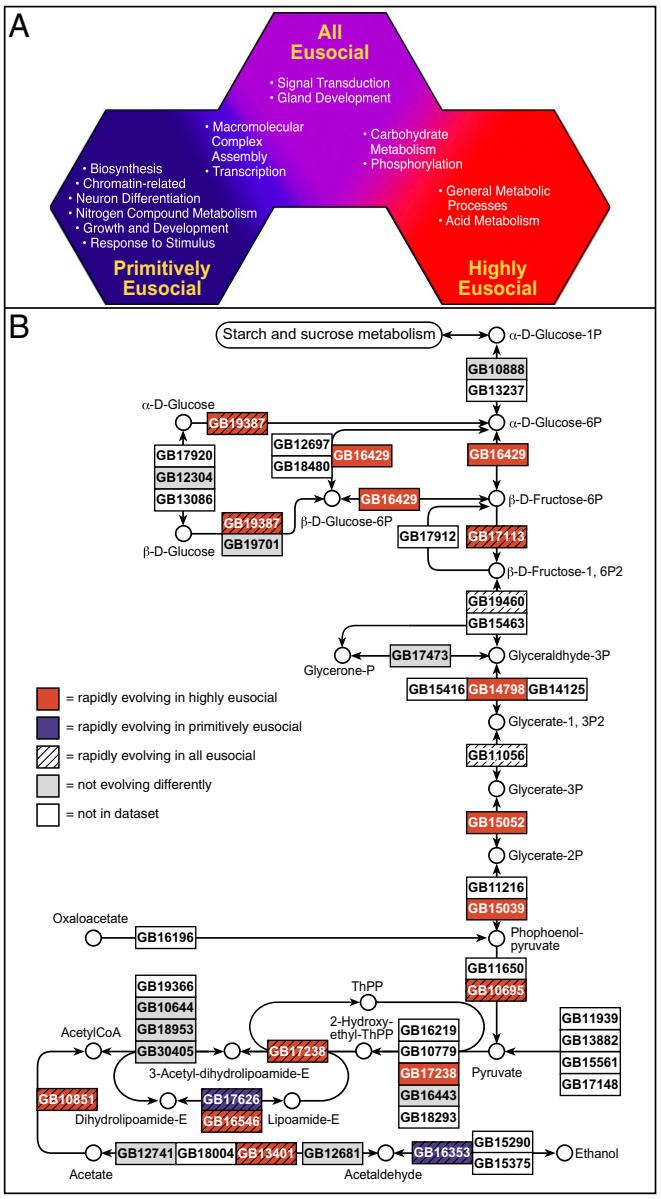

Fig. 2. Biological processes with evidence of accelerated evolution in eusocial lineages. (*A*) Overlap of rapidly evolving biological processes based on GO enrichment analysis of the All Eusocial, Highly Eusocial, and Primitively Eusocial gene lists. Individual GO categories were condensed into "meta-categories" based on related function (Table S3). (*B*) Rapidly evolving genes in the glycolysis pathway. *A. mellifera* genes mapped onto pathway based on orthology to *D. melanogaster* genes in KEGG (Kyoto Encyclopedia of Genes and Genomes, http://www.genome.jp/kegg/) glycolysis/gluconeogenesis pathway (dme00010). Genes likely evolving most rapidly in *Apis* are GB10695, GB10851, GB13401, GB16546, GB17113, GB17238, and GB19387.

lineages (*SI Text*). GO terms were enriched in the lists of significant genes derived from each artificial grouping (Dataset S3), but these terms were largely different from those obtained from our eusocial groupings. The finding of different enriched terms in this artificial grouping analysis provides additional support that our results truly relate to eusocial evolution.

Discussion

We identified several hundred genes with a molecular signature of accelerated evolution, including some with a signature in all eusocial lineages in our study and some with a signature that was specific to a certain type of eusocial lifestyle or specific to individual lineages. Together, these results demonstrate that convergent evolution can involve a mosaic pattern of molecular changes in both shared and lineage-specific sets of genes.

Genes involved in gland development, signal transduction, and carbohydrate metabolism were among the most rapidly evolving genes identified in this study. These findings provide a starting point for linking specific genetic changes to the evolution of eusociality in bees, which will be an important challenge for the future. Major steps in this endeavor include determining the consequences of the changes in amino acid sequence for protein function, learning how changes in protein function affect a particular biological process, and then understanding how evolutionary changes in a particular biological process might affect traits associated with eusociality (20). Below, we provide some speculation for the biological processes highlighted in our findings.

Genes associated with gland development appear to have been a strong target of selection during eusocial bee evolution. This is not surprising, because, relative to solitary insects, eusocial insects have remarkably diverse exocrine gland functions and produce many novel glandular secretions, including pheromones, brood food, and antimicrobial compounds (8, 13, 14). Chemical signaling is a vital mechanism used to coordinate the behavior and physiology of colony members, and it is possible that at least some of the protein-coding sequence changes identified here are related to the evolution of advanced systems of chemical communication found in social bees.

Another category of genes that appear to have been a strong target of selection during eusocial bee evolution is genes involved in signal transduction. Signal transduction has been implicated in the regulation of behavior across disparate taxa (21), and several genes on the All Eusocial gene list in this category have known roles in behavior and neuronal function, including *metabotropic GABA-B receptor subtype 1* (22). Our results provide further evidence that signal transduction may be a general target of selection during behavioral evolution.

Genes associated with carbohydrate metabolism appear to have been a particularly strong target of selection during eusocial bee evolution. Our finding of a shared pattern of accelerated evolution across all eusocial lineages in our study may reflect the fact that many eusocial bees rely more heavily on highly processed honeys in their diet than do non-eusocial species (8), although all bees use nectar as their carbohydrate source. In addition, several characteristics shared by all eusocial insects, including worker–queen caste determination and worker–worker division of labor, are influenced by nutrition (6). Transcriptomic analyses have implicated highly conserved molecular pathways associated with metabolism (6), especially insulin signaling (23–25), in both the evolution and function of these traits (6, 26). Our results are consistent with these findings and further suggest that coding sequence changes in carbohydrate metabolism-related genes may have been involved in the evolution of these novel eusocial traits in bees.

Additional changes in carbohydrate metabolism-related genes were also detected in the highly eusocial bee lineages, but not in primitively eusocial bee lineages. This result may be due to the evolution of unique metabolic demands in the highly eusocial lifestyle, such as year-round nest thermoregulation (8), extended lifespan in queens (10-fold longer than workers; refs. 13, 27), and greatly increased foraging activity (14). Nearly half of the genes in the glycolysis pathway that were enriched in the All Eusocial and/or Highly Eusocial gene lists were not robust solely to the removal of the *Apis* lineage from the analysis, suggesting that an abundance of changes in the glycolysis pathway may have occurred in this lineage.

We were initially surprised to detect a signature of accelerated evolution in brain-related GO categories in primitively eusocial bee lineages, but not in highly eusocial bee lineages. The Social

Brain Hypothesis, developed to explain primate brain evolution, posits that the cognitive demands of social life are a strong selective force in brain evolution (28). It might be assumed that these demands are greater in the larger and more complex colonies of the highly eusocial bees, and thus a stronger signature of rapid evolution in brain-related genes would be found in highly eusocial relative to primitively eusocial lineages (29). However, perhaps it is the primitively eusocial society members that face greater sociocognitive challenges, because social roles are more fluid and the balance between cooperation and competition is more dynamic in primitively eusocial colonies relative to the more structured, highly eusocial colonies (8, 13, 29).

One rapidly evolving gene in the Primitively Eusocial gene list, *dunce*, was originally identified as a *Drosophila* learning and memory mutant, and it has emerged as an important gene in the regulation of neural plasticity in both invertebrates and vertebrates (30). Recent studies implicate *dunce* and other genes in the cAMP pathway in social learning (31). Both the lineage-specific and robustness analyses suggest that, of the taxa studied here, *dunce* is evolving most rapidly in bumble bees. This finding of accelerated evolution in brain-related genes exclusively in primitively eusocial bees might eventually help us understand more about the evolution of behavioral differences that exist between primitively and highly eusocial species.

In addition to positive natural selection, nonadaptive phenomena such as relaxed constraint may contribute to the pattern of heterogeneous nucleotide substitution among sequences that we observed (16). Whether a gene is exposed to increased positive selection in eusocial lineages or to less purifying selection relative to non-eusocial lineages is a distinction that we cannot formally establish. In both cases, a difference in selective regime between the eusocial and non-eusocial lineages resulted in an increased rate of protein evolution in the eusocial lineages. Other issues have been raised regarding the reliability of the statistical methods we used for detecting adaptive molecular changes in individual genes (32–34). However, our focus on identifying biological processes represented by groups of genes, rather than individual genes, ameliorates these concerns. It is unlikely that so many genes in a single functional GO category, particularly those involved in basic "housekeeping" processes (e.g., carbohydrate metabolism), have been under relaxed constraint or exhibit consistent model departure stratified by sociality across lineages. The results we present motivate further investigation into differences in the functioning of these biological processes between eusocial and non-eusocial species and the functional effects of the specific genetic changes identified.

A key finding in this study is that convergent evolution of eusociality in bees involves both shared and lineage-specific sets of genes. The lineage-specific findings suggest that the multiple, independent evolutionary paths to eusociality may have each been shaped by different combinations of extrinsic and intrinsic factors, and perhaps also via different forces of selection. In the future, it may be possible to use molecular signatures of selection on different functional classes of genes to identify which forces of selection were important in eusocial evolution. Recent evidence suggests that reproductive protein evolution can be driven by sexual selection (7), but it is not yet known if there are similar connections between other selective forces and functional classes of genes.

Our finding of shared sets of rapidly evolving genes across three independent lineages that gave rise to eusociality in bees suggests that there might also be some common molecular roots for eusocial evolution, despite the incredible social diversity found among bees. Among the biological processes that appear to have been under selection across all eusocial lineages in our study, carbohydrate metabolism stands out. Insulin signaling, which is involved in carbohydrate metabolism, has been broadly implicated in the regulation of several eusocial traits, as mentioned above (6). It has been suggested that there is a "genetic toolkit" for eusociality, a set of highly conserved genes and molecular pathways that were co-opted for novel, social functions during eusocial evolution (26). Our results provide additional support for the possibility that genes related to carbohydrate metabolism are key components of this putative toolkit (6, 26). The existence of a genetic toolkit for eusociality can be rigorously tested because there are at least another eight independent gains of eusociality in the bees, ants, wasps, and termites (2). The insect societies provide rich material to explore how changes in DNA sequence are associated with the evolution of social life.

Materials and Methods

Bee Collection and Sequencing. Bees used for sequencing were free-flying or collected from nests. They were placed directly into liquid nitrogen for RNA preservation. Different ages, behavioral groups, and castes (when applicable) were used to maximize transcript diversity. RNA was extracted from brains and abdomens of 50+ females per species. Pooled mRNA (90% brain, 10% abdomen) was sequenced by 454 Life Science/Roche on the GS-FLX platform. Most transcripts in the genome are expressed in the brain (35); abdomen tissue was added to enhance transcript discovery for reproduction-related processes. Additional information about collections, RNA extractions, and sequencing is provided in *SI Text*.

EST and Alignment Assembly. EST reads were assembled by using Phrap to generate species-specific, nonredundant contigs and singletons. *A. mellifera* gene models were obtained from BeeBase (Official Honey Bee Gene Set; http://genomes.arc.georgetown.edu/drupal/beebase/). For each species, the assembled ESTs were matched to the *A. mellifera* gene models. Orthology was determined by using the reciprocal best BLAST hit. Gapped ortholog-reference-guided transcript assemblies (GOTAs) were created by concatenating the top reciprocal hits and trimming the overlaps. Multiple sequence alignments were then created by using MAFFT software (36). All alignments were manually inspected in Geneious (37), and ambiguous regions were masked from further analyses. Additional information about ortholog assignment and editing is provided in *SI Text*.

Phylogeny. Nucleotide sequences for 3,647 protein-coding EST gene fragments were aligned (36), edited manually (37), and modified to include fragments containing no gaps for any of the 10 taxa. Gene fragments of length >100 bp were concatenated, and the resulting inframe nucleotide alignment (n = 717 gene fragments; 69,461 bp total) was analyzed with Bayesian inference in MrBayes (v3.1.2 MPI (parallel) version for unix clusters) (38) under the substitution model GTR + I + G; amino acid translation analyses were run by using the JTT fixed-rate model. Fig. 1 shows the consensus of the Bayesian posterior distribution of phylogenetic trees from analysis of third codon positions (Fig. S1). The consensus trees based on all, first, and second position nucleotide sites and amino acid sequence are reported in Fig. S1.

Evolutionary Tests. We used the program *codeml* in the PAML package (39) to fit our alignment data to branch models of codon substitution by maximum likelihood to identify differences in ω within the tree. For each test, the likelihoods of two models of evolution (neutral and nonneutral) were compared by using an LRT. Any genes with one or more branches with $d_S > 2$ (n = 9) were considered to be saturated and were excluded from further analyses. To correct for multiple tests, we performed an FDR correction on nominal P values obtained from the LRTs.

GO Enrichment Analysis. For functional analyses, we used a preexisting list of *A. mellifera–D. melanogaster* orthologs (15). Orthologous fly sequences with annotation information were available for most (n = 3,451) genes in our dataset. Our GO analyses were performed by using the functional annotation tool on DAVID (40). Additional information about GO analysis is provided in *SI Text*.

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1. Maynard Smith J, Szathmary E (1995) *The Major Transitions in Evolution* (Oxford Univ. Press, New York).
2. Wilson EO, Hölldobler B (2005) Eusociality: Origin and consequences. *Proc Natl Acad Sci USA* 205:13367–13371.
3. Darwin C (1859) *On the Origin of Species* (Murray, London).
4. Queller DC (1992) A general model for kin selection. *Evolution* 46:376–380.
5. Nowak MA, Tarnita CE, Wilson EO (2010) The evolution of eusociality. *Nature* 466: 1057–1062.
6. Smith CR, Toth AL, Suarez AV, Robinson GE (2008) Genetic and genomic analyses of the division of labour in insect societies. *Nat Rev Genet* 9:735–748.
7. Wong A (2010) Testing the effects of mating system variation on rates of molecular evolution in primates. *Evolution* 64:2779–2785.
8. Michener CD (1974) *The Social Behavior of the Bees* (Harvard Univ. Press, Cambridge, MA).
9. Cameron SA, Mardulyn P (2001) Multiple molecular data sets suggest independent origins of highly eusocial behavior in bees (Hymenoptera:Apinae). *Syst Biol* 50: 194–214.
10. Schwarz MP, Richards MH, Danforth BN (2007) Changing paradigms in insect social evolution: Insights from halictine and allodapine bees. *Annu Rev Entomol* 52: 127–150.
11. Cardinal S, Straka J, Danforth BN (2010) Comprehensive phylogeny of apid bees reveals the evolutionary origins and antiquity of cleptoparasitism. *Proc Natl Acad Sci USA* 107:16207–16211.
12. Danforth BN, Sipes S, Fang J, Brady SG (2006) Recent and simultaneous origins of eusociality in halictid bees. *Proc Natl Acad Sci USA* 103:15118–15123.
13. Wilson EO (1971) *The Insect Societies* (Harvard Univ. Press, Cambridge, MA).
14. Roubik DW (1992) *Ecology and Natural History of Tropical Bees* (Cambridge Univ. Press, Cambridge, UK).
15. HBGSC (2006) Insights into social insects from the genome of the honeybee *Apis mellifera*. *Nature* 443:931–949.
16. Yang ZH, Bielawski JP (2000) Statistical methods for detecting molecular adaptation. *Trends Ecol Evol* 15:496–503.
17. Schneider A, et al. (2010) Estimates of positive Darwinian selection are inflated by errors in sequencing, annotation, and alignment. *Genome Biol Evol* 1:114–118.
18. Wong KM, Suchard MA, Huelsenbeck JP (2008) Alignment uncertainty and genomic analysis. *Science* 319:473–476.
19. Wong WSW, Yang Z, Goldman N, Nielsen R (2004) Accuracy and power of statistical methods for detecting adaptive evolution in protein coding sequences and for identifying positively selected sites. *Genetics* 168:1041–1051.
20. Dean AM, Thornton JW (2007) Mechanistic approaches to the study of evolution: the functional synthesis. *Nat Rev Genet* 8:675–688.
21. Ben-Shahar Y, Robichon A, Sokolowski MB, Robinson GE (2002) Influence of gene action across different time scales on behavior. *Science* 296:741–744.
22. Root CM, et al. (2008) A presynaptic gain control mechanism fine-tunes olfactory behavior. *Neuron* 59:311–321.
23. Ament SA, Corona M, Pollock HS, Robinson GE (2008) Insulin signaling is involved in the regulation of worker division of labor in honey bee colonies. *Proc Natl Acad Sci USA* 105:4226–4231.
24. Corona M, et al. (2007) Vitellogenin, juvenile hormone, insulin signaling, and queen honey bee longevity. *Proc Natl Acad Sci USA* 104:7128–7133.
25. Patel A, et al. (2007) The making of a queen: TOR pathway is a key player in diphenic caste development. *PLoS ONE* 2:e509.
26. Toth AL, Robinson GE (2009) Evo-devo and the evolution of social behavior: Brain gene expression analyses in social insects. *Cold Spring Harb Symp Quant Biol* 74: 419–426.
27. Finkel T, Holbrook N (2000) Oxidants, oxidative stress and the biology of ageing. *Nature* 405:239–247.
28. Dunbar RIM (2009) The social brain hypothesis and its implications for social evolution. *Ann Hum Biol* 36:562–572.
29. Gronenberg W, Riveros AJ (2009) *Organization of Insect Societies: From Genome to Sociocomplexity*, eds Gadau J, Fewell J (Harvard Univ. Press, Cambridge, MA), pp 377–401.
30. Silva A, et al. (1998) CREB and memory. *Annu Rev Neurosci* 21:127–148.
31. Sokolowski MB (2010) Social interactions in "simple" model systems. *Neuron* 65: 780–794.
32. Nozawa M, Suzuki Y, Nei M (2009) Reliabilities of identifying positive selection by the branch-site and the site-prediction methods. *Proc Natl Acad Sci USA* 106:6700–6705.
33. Suzuki Y, Nei M (2002) Simulation study of the reliability and robustness of the statistical methods for detecting positive selection at single amino acid sites. *Mol Biol Evol* 19:1865–1869.
34. Wolf JBW, Kunstner A, Nam K, Jakobsson M, Ellegren H (2009) Nonlinear dynamics of nonsynonymous (d(N)) and synonymous (d(S)) substitution rates affects inference of selection. *Genome Biol Evol* 1:308–319.
35. Lein ES, et al. (2007) Genome-wide atlas of gene expression in the adult mouse brain. *Nature* 445:168–176.
36. Katoh K, Misawa K, Kuma K, Miyata T (2002) MAFFT: A novel method for rapid multiple sequence alignment based on fast Fourier transform. *Nucleic Acids Res* 30: 3059–3066.
37. Drummond AJ, et al. (2010) Geneious v5.1. Available at http://www.geneious.com.
38. Ronquist F, Huelsenbeck JP (2001) MRBAYES: Bayesian inference of phylogenetic trees. *Bioinformatics* 19:1572–1574.
39. Yang ZH (2007) PAML 4: Phylogenetic analysis by maximum likelihood. *Mol Biol Evol* 24:1586–1591.
40. Huang DW, Sherman BT, Lempicki RA (2009) Systematic and integrative analysis of large gene lists using DAVID bioinformatics resources. *Nat Protoc* 4:44–57.