Sex in Fungi

Molecular Determination and Evolutionary Implications
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Sexual reproduction is ubiquitous in nature, from organisms as diverse as fungi to plants and animals. As the engine that drives reassortment of genes to generate diversity, sex accelerates adaptation in the ever-changing environment and provides that more progeny avoid the relentless accumulation of deleterious mutations. In these ways, it plays a central role in the origin and success of species. As such, the molecular bases by which sexual identity and reproduction are defined and controlled have captured the interests of biologists for more than a century. These topics and interests have been pursued in a variety of organisms, with significant and wide-ranging contributions coming from explorations in the fungal kingdom. The insights that have come from investigating sexual reproduction in the major groups within the kingdom, including members of the Ascomycetes, Basidiomycetes, Chytridiomycetes, and Zygomycetes, are the subject of this book.

More than 40 years ago, John Raper published a thin text entitled *Genetics of Sexuality in Higher Fungi* (Ronald Press, New York, NY, 1966), which encapsulated much of what was known at that time on this topic in the basidiomycete fungi. While fascinating, the complex genetics of the system represented a puzzle and a challenge. How could it be that model mushroom species possessed literally thousands of mating types, or sexes, rather than the more pedestrian two sexes common in plants and animals and even many other fungi? The understanding came via molecular biology approaches whose advent and application were decades hence (1970s and 1980s). In parallel, advances in other fungal systems, notably the budding yeast *Saccharomyces cerevisiae*, provided further illuminating insights into the molecular details of cell-type specification, mating-type switching, pheromone perception and signaling, and cellular and nuclear fusion. This wealth of detailed molecular information on the wiring of a mating system provided a paradigm that guided research into the mechanisms of mating in all of the other fungi described in this book. With the advent of genomic approaches in
the past 10 years, a window was opened on the entire genomes of many additional fungi, enabling kingdom-wide models of sex determination and sexual cycle evolution to be realized. The tremendous impact of comparative genomics on the analysis of mating is evident in many of the chapters in this book.

Here we have assembled chapters from a contingent of experts in the field to take stock of just how far knowledge of these fascinating biological systems and processes has progressed from 1966 to today. This includes chapters on the evolution and function of the mating-type locus, the specialized region of the genome that governs the establishment of cell type and orchestrates the sexual cycle in fungi. The species described in these chapters represent both the euascomycete and the hemiascomycete lineages of the prominent Ascomycetes phylum of fungi, as well as representatives of the Basidiomycetes, including the wood-rotting model fungus *Schizophyllum commune* that was the focus of John Raper’s life work and his original text.

We have included representative chapters on both model and pathogenic fungi, given that many pathogenic fungi appear to have cryptic sexual cycles that may influence virulence or their evolution. Additionally, a section that looks forward to what we hope to learn in other fungal lineages is encapsulated in four chapters. Finally, the book concludes with a selection of chapters on the implications of sex, and studies of experimental evolution, to round out the discussions in a broader evolutionary context.

It is our hope and intent that the presentations throughout this book are not simply descriptions of the mating type loci, or a parts list of what fungi require for sexual reproduction. Rather, we hope this to be an exposé of the biological and molecular nature of sexual reproduction in an entire kingdom of life, one that is particularly amenable to genetic, molecular, and genomic analysis and that serves as a central paradigm to understand how sexual cycles function in, as well as drive, evolution. The biological principles that have emerged are profound and serve as general paradigms for how cell identity is established and maintained, how cells sense and respond to extracellular cues, the role of genetic rearrangements in generating changes in cell identity and fate, and how genomic regions governing sexual identity are organized and evolved.

We intend this new volume, *Sex in Fungi: Molecular Determination and Evolutionary Implications*, not only to encompass the current state of knowledge and to serve as a resource to guide the next several decades of study on these systems and organisms, but also to pay homage to those who made this effort possible. First, this text is dedicated in appreciation to John and Cardy Raper; to John for his insight in writing a text published in 1966 that is still cited to this day, and which foretold much of what was subsequently discovered on the molecular basis for transitions in mating behavior between out-crossing heterothallic systems and inbreeding homothallic organisms; and to Cardy, for carrying on with the molecular analysis of the *S. commune* mating type loci for several decades in her own laboratory at the University of Vermont after John. John and Cardy inspired a multitude of investigators, including many of the authors of the chapters in this book, and without them the field would certainly not be where it is today.

We also dedicate this text to Ira Herskowitz, who served as a champion for *Saccharomyces cerevisiae* as a premier model system and whose indefatigable efforts resulted in a molecular understanding of mating-type determination and mating-type switching. His elegant and powerful reductionist approaches, applying phage logic to a eukaryotic yeast, made possible the transition from complex genetics to textbook-clear models, establishing this yeast as a paradigm for all of biology. Again, Ira’s intellectual leadership and his encouragement of other inves-
tigators, and of investigations with other fungi, helped inspire and drive the field to the current state documented in this book.

We are indebted to these three individuals for seeing sooner and farther than others, for sharing their vision with us, and for making this text both possible and worthwhile.

It has been our pleasure to serve as the co-editors, and also as authors, for this text and we invite you, the readers, to share your experiences with us. Moreover, we hope that this text inspires some of you to join us in this endeavor and to make it possible and necessary for the next text on this topic to be written.

In closing, we thank our families, our laboratory members, numerous readers, and our editor at ASM Press, Greg Payne, without whose efforts, forbearance, patience, and tolerance this book could not have been realized.

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It is a poignant and sobering realization that a book entitled *Sex in Fungi* will be published without a chapter from Ira Herskowitz. Although the book is poorer for lacking his chapter, we can celebrate Ira’s many other contributions to this volume, contributions so deep and pervasive that they probably outweigh those of any other single scientist. In the numerous citations of his work, the many authors of this volume whose careers he helped guide, the influence of his writing and diagrammatic style, and finally, the scientific work itself, Ira’s influence pervades this volume and continues to shape our research. Ira convinced us all that when he studied sex in fungi he was really studying fundamental problems in cell and molecular biology. Through his engaging personality, his accessible speaking style, and his many influential reviews and research articles, he provoked even the most narrowly focused biologist to think about fungal sex. Ira’s work, and his influence on others, have thrust fungal mating into the pages of all major college textbooks in biology.

But it is the creative use of genetics as an exploratory tool that is Herskowitz’s greatest legacy. Many scientists, from beginning students to accomplished professors, have tried to carry out “Ira-type” experiments—simple genetic studies designed to solve an outstanding biological problem in a new field. And some have succeeded, guided not only by the Herskowitz example, but often by the man himself. When it came to discussing a biological problem, Ira was generous with his time and seemingly tireless. Many biologists credit a discussion with him for pushing (or more often enticing) them to delve into new experimental realms or to develop a new way of conceptualizing old problems.

Ira’s first papers were published in 1970, while a graduate student with Ethan Signer at MIT. He solved an important problem in gene regulation of bacteriophage λ: how a single regulatory protein turns on a whole battery of phage genes. Setting the style for much of his future work, Herskowitz attacked the problem using solely genetics, showing that the activator protein, called Q, must work at