UMEÅ UNIVERSITET

ADAPTATION DURING THE EARLY EVOLUTION OF MULTICELLULARITY

Mathematical models reveal the impact of unicellular history, environmental stress, and life cycles

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Akademisk avhandling

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Adaptation during the early evolution of multicellularity: mathematical models reveal the impact of unicellular history, environmental stress, and life cycles

Abstract
Multicellular organisms, such as plants and animals, have independently evolved several times over the last hundreds of millions of years. The evolution of multicellularity has significantly shaped modern ecosystems, yet its origins remain largely unknown. Due to the ancient history and the small size scale of early multicellular organisms, few intact fossils have been preserved. To uncover the origins of large and complex life, researchers have turned to alternative methods such as empirical studies and theoretical frameworks. These approaches have provided novel insights in the early steps of multicellular evolution; however, few studies have considered the role of adaptation in these novel life cycles. This thesis addresses the gap in our knowledge by employing mathematical modeling and computer simulations to study adaptation in novel multicellular life cycles. The first paper investigates the effects of unicellular reproduction modes on the spread of growth rate mutations. It demonstrates that unicellular history significantly influences the adaptation rate, with budding cells exhibiting greater sensitivity to the spatial distribution of mutations. In Paper II, the role of multicellular reproduction mode for the adaptation of altruistic and selfish mutations is explored. Specifically, the study examines how adaptation is affected when the filaments are exposed to a size-based selective pressure. It reveals that while the adaptation of altruistic mutations is favored by large offspring, the spread of selfish mutations depends on both offspring size and selection strength. Paper III investigates the evolution of life cycle regulation when fragmentation is based on internal information. The model demonstrates that using a single source of information leads to significant variations in the types of life cycles that emerge. This suggests that to evolve regulated life cycles, additional mechanisms beyond internal information may be necessary, such as cell communication. Most multicellular organisms have specialized cells performing various tasks. In Paper IV, the evolutionary paths leading to differentiated multicellularity are investigated when a unicellular population is exposed to an abiotic (non-evolving) selective pressure. The model reveals that while many conditions may induce differentiation and multicellularity, continued adaptation to the stress eventually leads to reversion. This occurs because as cells adapt to the stress, the costs associated with specialization may no longer be justified. One potential strategy to prevent reversion could involve considering co-evolving selective pressures. Lastly, paper V delves into organisms composed by multiple uni- and multicellular species. Utilizing this framework reveals that the species composition influences both the ease of partnership establishment and its stability. Additionally, the mode of reproduction can endow organisms with a memory of prior partnerships, enhancing their adaptability in forming new ones. This ability opens up novel evolutionary pathways. In summary, this thesis offers new insights into how the life cycle structures of simple multicellular organisms impact mutation accumulation and trait acquisition. The adaptability of organisms plays a pivotal role in fostering higher complexity and paving the way for further evolution. Enhancing our understanding in this domain will continue to illuminate the origins of complex life and elucidate the evolutionary factors underlying the rich diversity of multicellular organisms we encounter today.

Keywords
Multicellularity, evolution, adaptation, life cycles, mutations, unicellular history, information, selective pressures, fragmentation, computational simulations, mathematical modeling

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