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Building a Foundation for Cognitive Search

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Over a century ago, William James, the father of modern psychology, proposed that humans search through memory much the same way as they rummage through a house looking for a lost set of keys (James 1890). This recognition of commonalities between search in physical and information domains—including space, memory, and the Internet—has become increasingly salient as information resources expand and our capacity to search successfully for such information gains greater economic and personal importance.

Just as animals spend much of their time searching for resources, including territory, food, and mates, so too do humans—albeit our search is often conducted in different kinds of spaces. We search for items in visual scenes (e.g., a favorite brand on a crowded supermarket shelf or a weapon in a luggage X-ray image), for historical facts or shopping deals on Internet sites, for new friends or opportunities in a social network. We search our memories for past experiences and solutions to novel problems. In all these cases, just as in James's search for lost keys, the structures of resources and information in the world govern how we search and what we will find.

Search—the behavior of seeking resources or goals under conditions of uncertainty—is a common and crucial behavior for most organisms. It requires individuals to achieve an adaptive trade-off between exploration for new resources distributed in space or time and exploitation of those resources once they are found. Because this search problem is common to so many aspects of our lives, search behavior has been studied in a diverse range of scientific disciplines and paradigms: theoretical biologists study the characteristics of evolutionary search in high-dimensional spaces; behavioral ecologists analyze animals foraging for food; experimental psychologists investigate search in vision, memory, decision making, and problem solving; neuroscientists study the neural mechanisms of goal-directed behavior in humans and other animals; psychiatrists and clinical neuroscientists analyze aberrant volition such as drug-seeking behavior in addiction and attentional control in attention deficit

From "Cognitive Search: Evolution, Algorithms, and the Brain," edited by Peter M. Todd, Thomas T. Hills, and Trevor W. Robbins. 2012. Strüngmann Forum Report, vol. 9, J. Lupp, series ed. Cambridge, MA: MIT Press. ISBN 978-0-262-01809-8.

hyperactivity disorder (ADHD); computer scientists develop information-search algorithms for mining large-scale databases and for individual navigation of the World Wide Web; social psychologists investigate how people seek and choose mates and friends; and political scientists study how groups look for solutions to problems.

Search behavior is so ubiquitous that it is constantly being examined, reexamined, and redefined by many disciplines. At the same time, these disciplines often proceed in their investigations independently of one another and even without awareness of the parallels with research going on in other fields. This has put search at an interdisciplinary "blind spot" in the study of human and animal cognition. Furthermore, although the various fields that compose cognitive science have each furthered our understanding of cognition at various levels of analysis, the success of these endeavors has contributed to a modular view of the mind, comprising separate processes independently evolved to solve specific problems. Little attention has been paid to how the processes may share similar algorithms, neurocognitive control systems, or common ancestry.

Individual fields have, however, started to uncover a number of such commonalities among search processes. Recent molecular and comparative biological findings of neural mechanisms in multiple species that control the search for and evaluation of resources support a putative common ancestral precursor for many of the search behaviors in animal foraging. Computer scientists have extended the principles of foraging for food to the study of human "information foraging" in knowledge environments such as the World Wide Web. Characterizations from network science of large-scale mental spaces (such as lexicons) and social spaces (such as friendship networks) have provided structurally similar terrains for modeling search behavior in those domains. Cognitive neuroscience has explored how interactions between the prefrontal cortex and basal ganglia mediate response selection among a variety of goal-directed behaviors, including trade-offs between exploration and exploitation. Similar neuronal and molecular machinery may handle problems as diverse as spatial target search (involving the parietal cortex), retrieval from memory (hippocampus and prefrontal cortex), and abstract decision making (anterior cingulate, prefrontal cortex, and dopamine-dependent functions of the striatum). These diverse goal-directed processes are central to cognition and rely on the integration of search-related architectures. Findings such as these lead to the surprising conclusion that the same cognitive and neural processes may underlie much of human behavior comprising cognitive search—both in the external world and in internal memory (reviewed in Hills 2006).

The pressing need to integrate these insights further has led to the current book, which provides a cross-cutting perspective on the underlying commonalities of cognitive search in different search domains, as studied through different disciplinary lenses. This perspective was developed at the Ernst Strüngmann Forum on Cognitive Search: Evolution, Algorithms, and the Brain. This Forum convened 44 scientists to discuss what can be learned about cognitive search

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from the study of animal behavior, psychology, neurobiology, and computer science, who sought to identify the commonalities and distinctions among the findings on search in these fields. The chapters in this book capture the beginnings of the foundation that was constructed for a common intellectual ground between the varied disciplines studying search behavior and cognition. This new conceptual base also highlights important directions for future research, including investigations on the underlying neuromolecular and evolutionary origins of human goal-directed cognition and the applications that follow from seeing human behavior as grounded in different types of search.

Central Themes in Cognitive Search

This book is organized around four main themes central to search behavior:

1. its evolutionary origins, adaptive functions, and main characteristics as described from an ecological perspective;
2. its neural and neurochemical underpinnings in the brain;
3. its cognitive manifestations and mechanisms in domains commonly studied by psychologists;
4. its algorithmic application to high-dimensional spaces including evolutionary search over genotypes, social search in social networks, and information search on the World Wide Web.

These themes framed the discussion of the four corresponding working groups at the Forum, and are similarly reflected in the four sections of this volume. Each section comprises background chapters followed by a group-authored chapter that summarizes the discussions and debates that arose. Here we give an overview of the questions that drove each group's discussions.

Group 1: Evolution of Search, Adaptation, and Ecology

This working group focused on the biological origins of search and the ultimate adaptive functions it plays for different species, and was guided by the following questions:

- What adaptive problems has search evolved to solve (e.g., food, habitat, mates, social partners, information, specific memories)?
- What are the common features of those problems (e.g., patchy vs. uniform distribution, competition, degree of uncertainty)?
- What are the common features of the solutions (e.g., individual vs. group foraging, exploration vs. exploitation, local vs. global, parallel vs. serial)?
- What is the evolutionary history and fate of strategies (e.g., phylogeny, homology, exaptation)?

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Much of this group's discussion (see Hutchinson et al., this volume) centered around defining search behavior (and what is not search), and on creating typologies of different kinds of search defined by features such as the distribution of resources in space and time and whether or not the resources are ephemeral. The intent was to provide a wide range of examples of different kinds of search and where they occur, and to build an ecological basis for thinking about search in other domains. Social search, including the dual roles that individuals may have in terms of finding resources versus scrounging them from others, was another central topic.

Group 2: Search, Goals, and the Brain

Focusing on the conserved proximate mechanisms—brain structures, neural circuits, and neurochemical modulations—that underlie search behavior across multiple domains, this group was guided by the following questions:

- What are the shared molecular and neural processes that control spatial and nonspatial attention and search?
- How does the brain implement goal maintenance and switching, and exploration versus exploitation trade-offs?
- How is the neuromodulation of search processes (e.g., via the molecular signaling functionality of dopamine) controlled and conserved across species and behaviors?
- What can be learned from pathologies of goal-directed search such as obsessive-compulsive disorder, ADHD, and Parkinson's disease?

After discussing definitions of search and its connection to goal seeking, Winstanley et al. (this volume) worked to come up with a model of the neural mechanisms underlying goal-directed behavior that brings together much of what is currently known in the literature. This provided a useful jumping-off point for discussions with the other groups, particularly the psychologists in Group 3. Relatively less progress was made on the questions related to pathologies, which remains an important direction for further research.

Group 3: Mechanisms and Processes of Cognitive Search

This working group focused on the cognitive and memory mechanisms involved in search, as studied by psychology and cognitive science, and the possibility of a general cognitive search process. Discussions were guided by the following questions:

- What are the psychological components (e.g., exploration, sampling, evaluation, stopping rules) in common to various types of cognitive search (e.g., visual, memory, spatial), and how do these compare to the components of search in external environments?

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- Do the shared aspects of cognitive models of memory recall and recognition, visual search, and lexical retrieval point to a common underlying mental search process, and what methods (e.g., priming between search tasks) could be used to study this?
- What are appropriate ways to represent mental search spaces, and what do these representations presume about the underlying search processes?
- How is cognitive search directed and controlled (e.g., focus of attention, cue selection, feeling of knowing, inhibition of return)?

Pachur et al. (this volume) centered on search tasks that have been traditionally studied in laboratory experiments, including search through memory of paired-associate lists, visual search in simple two-dimensional arrays of images, and the search for information or cues to be used in making decisions. Group members agreed that more emphasis needs to be put on real-world tasks, such as searching for memories of routes to known locations in one's environment or for objects in a natural visual scene.

Group 4: Search Environments, Representation, and Encoding

This working group focused on how people search through high-dimensional environments (beyond two or three dimensions), such as social networks or collections of information, and on comparisons with search processes in evolution and computer science. Organizing questions included:

- How are different search domains structured and represented to searchers (e.g., patches of resources, topological distributions in physical, mental, and social environments)?
- Where do these search space structures come from, and how are they formed (e.g., evolution, ontogeny, network growth)?
- What are the similarities and differences between mechanisms and behaviors for search in high-dimensional (e.g., information) versus low-dimensional (e.g., physical) spaces?
- How does the structure and dimensionality of the environment impact the search process? Are different strategies appropriate in predictable ways across memory search, World Wide Web search, and social network search?
- How can we facilitate individual and group search in different environments (e.g., in the semantic web or social networks)?

Schooler et al. (this volume) considered ways that search has been implemented in computer science, where search is a central concept for developing algorithms that find solutions to problems or information sought by users. Social scientists reported related studies in which people search their social networks for others who may have parts of solutions that they need to solve problems

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cooperatively. The theory of neutral networks from genetics was discussed as a way for agents to search along "ridges" in a high-dimensional space so that they can avoid getting stuck in local maxima. Semantic space models relating concepts in memory or on the World Wide Web were also considered as prime targets for developing better methods for search.

Synergy and Future Directions

Throughout the Forum, issues arose that cut across the different groups, leading to even wider interdisciplinary conversations. For example, biologists and psychologists in Groups 1 and 3 explored the many commonalities between the basic principles underlying animal search for resources and those governing human cognition. Just as animals often search spatial patches, like berries on separate bushes, so humans also search patchy memory representations, hunting for useful clusters of information in their own minds and then exploiting what they find. To sustain their intake rate, foraging animals have evolved rules that guide them to leave a patch when their rate of finding things falls below that which they could achieve if they look elsewhere; the psychologists in Group 3 debated evidence that people behave similarly when searching in memory or a visual scene. Computer scientists in Group 4 argued that information search on the World Wide Web follows similar principles: users give up on websites when their "information scent" falls below the level indicating further profitable exploration in that direction. The brain architecture underlying such goal-directed searching behavior and the seeking of memories to guide voluntary action toward those goals was also the main focus of neuroscientists in Group 2.

Open questions raised at the Forum demonstrate that we are just at the beginning of understanding the intertwined evolutionary, psychological, and neurological bases of the great range of search behaviors of humans and other animals. The most pressing and promising avenues for research include:

- further elucidating the underlying similarities and differences of search in different domains (e.g., Web search, memory search, visual search, mate search, search for food);
- specifying the neural and cognitive mechanisms governing search across different domains;
- exploring the phylogeny of search and how one type of search could evolve into another;
- studying individual differences in search behavior, their genetic bases, and the possible adaptive nature of mixed strategies;
- determining the usefulness of considering some clinical conditions as aberrations of search, leading to too much exploration (e.g., ADHD) or too much focus (e.g., obsessive-compulsive disorder), and possibly

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sharing neuromodulatory mechanisms similar to those that control search in other species (e.g., dopamine);

- seeking new treatments for goal-directed pathologies (e.g., drug addiction, Parkinson's disease, ADHD) based on knowledge of the brain mechanisms of search;
- building tools that structure the increasingly overwhelming information environment to work with people's search mechanisms and help them successfully find satisfactory results.

Further interdisciplinary cross-fertilization and scientific inquiry will increase our knowledge of the foundations of cognitive search, which will in turn find use in a variety of new applications. These include clinical treatments and "brain training" to improve strategic search and focus; greater vigilance and control of attention in airport baggage checking, medical image screening and diagnosis, and intelligence analysis; enhanced use of the wisdom of crowds in social problem solving; and better decision making through insights into the evolutionary origins of our abilities to think rationally about finding and using resources. With a greater understanding of how various forms of search are related to each other, we will enhance our search for all that we seek.

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