Scientific report

Search and Exploration

Convenor and Workshop Director

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University Pierre and Marie Curie, 4 Place Jussieu, Paris, France

Timeslot

from 3^{d} of June 2013 to 7th of June 2013

Venue

Cargese Institute for Scientific Studies, Corsica, France

Summary

Search processes play a fundamental role in physical, chemical and biological systems, and operations research. Examples are diffusion-limited encounters of molecules involved in a chemical reaction; search for a global minimum in a complex energy landscape; proteins searching for their specific target sites on DNA; dwell times in mechano-chemical cycles of molecular motors; animal foraging; automated searches of registers in databases, or search engines exploring the Internet and naval vessels hunting a submarine. Our exploratory workshop has been organised at the premises of the Institute of Scientific Studies in Cargese, Corsica, France, with the aim to bring together young researchers just starting to work in this field and the leading experienced scientists, in order to discuss recent theoretical and experimental progress in studies of search processes and to advance the synergies between the communities working in condensed matter and statistical physics, quantitative biology, and mathematics. This workshop attracted 40 participants overall, including 31 invited speakers (both early stage and experienced scientists), as well as a reasonable number of PhD students and postdoctoral researchers.

Keywords

Search, swarming, evasion and pursuit, first passage times, optimization and stochastic optimization, molecular motors, efficiency, detection probability

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Scientific content

Search processes are ubiquitous in many physical, chemical, and biological systems, and operations research. Examples include diffusion-limited encounters of molecules involved in chemical reactions; the dynamical or stochastic search for a global minimum in a complex energy landscape, relevant to systems such as glasses, protein (folding), and others; proteins searching for their specific target sites on DNA in gene regulation; transition rates of mechano-chemical cycles of molecular motors; animal foraging; survival at the edge of extinction due to low availability of energetic resources; automated search of registers in high-capacity databases, search engines (e.g., "crawlers") that explore the internet, naval vessels in pursuit of a submarine and even pizza delivery in a jammed traffic system of a medium-size town. In this way, the subject is interesting, challenging and inherently multidisciplinary, and has very recently become an important scientific area of investigation.

The search for a desired target may depend on a variety of conditions. Targets may be sparse, hidden, difficult to detect even when found. The targets may be mobile or immobile, they may try to avoid searchers, and there may be one target or many. They may have a finite life-time and vanish before they are detected. Searchers may search "blindly", detecting the target only upon encounter, or may perceive distant targets and adjust their motion accordingly. They may have no memory of previously visited areas, or they may avoid such areas. The searchers may act individually or in swarms, optimizing their search efficiency by exchanging information. Finally, the "efficiency" of a search may be judged by a variety of measures, including the time to reach a target or targets, the number of encounters of searchers and targets per unit time, or the exploration range of

space per unit time. In general, for each specific situation different search strategies may be appropriate. The quest for optimal strategies has motivated a great deal of work in the past and currently represents one of the most rapidly growing fields of research.

Although the applications are diverse, the underlying physical mechanisms are often the same. Moreover, the inherent complexity of the problem, the abundance of ideas and methods found in this interdisciplinary, innovative field of research is studied in many areas of physics. In particular, the concepts and methods of statistical mechanics are particularly useful to the study of random search. On the one hand, it centers on how to find the global or local maxima of search efficiency functions with incomplete information. This is, naturally, related to the long tradition in physics of using different conceptual and mathematical tools to optimize relevant quantities, e.g., energy, entropy, and action. Such ideas and approaches are very important to solve computationally complex problems involving optimizations in very high dimensional energy landscapes, e.g., in protein folding. On the other hand, random search can also be studied from the perspectives of diffusion and transport properties, stochastic processes, Levy walks and flights, complex systems and fractal geometry. Some important questions in random search, especially in the case of discrete landscapes, are also associated with graph theory, random lattices, and complex networks.

The highly innovative character of the subject stems from a cross-fertilization of approaches, ideas and fruitful synergies between condensed matter and statistical physics, quantitative biology and mathematics. In particular, analyzing the data gathered by biologists on the trajectories of lizards, fish, or birds searching for food, one introduces random search strategies, based either on Levy-type or on intermittent random motion, (in which slow search phases alternate with fast relocations), which explore most of the available space within a minimal time, with minimal oversampling and having the best chances of success. As one important outcome, one may introduce more efficient computer algorithms for the search for global minima in non-convex (multiple extrema) energy landscapes by simulated annealing it appears that a random search with Levy-type jump-length distributions allows for a faster cooling scheme, and hence, for a considerable reduction of computer time, than standard algorithms (Boltzmann machine) based on a nearest-neighbor exploration. An observation that in reality a protein finds a specific binding site on a DNA 10^3 times faster than it is predicted by conventional chemical kinetics, prompted a very deep understanding of the role of non-specific parts of the DNA. Being inert with respect to the reaction, they act as very efficient antennae reducing the overall search time, essentially in the same way as cell bound glycoproteins, extending in the extracellular medium, enhance the efficiency of chemoreception by capturing the ligands and facilitating their transport to the cell bound receptors. Indeed, finding the target in a finite amount of time is of fundamental importance for many biological processes in the cell, in particular for protein diffusion along DNA. In vivo biological cells are characterized by a high degree of molecular crowding and under some conditions, by an inhomogeneous environment, affecting not only the way proteins and biological molecular motors carrying them move, but perhaps even the internal functioning of the molecular motor and its efficiency. For this, the stochastic aspects of thermodynamics of such systems are of particular interest for the experimental-

ists, due to the recent advance in the technologies of manipulating systems at nano and micro scales.

The aim of our workshop was to bring together leading scientists working in this field to exploit and to advance the synergies between the communities working in condensed matter and statistical physics, quantitative biology and mathematics. We have exchanged recent theoretical and experimental advances in the understanding of various search processes ranging from the ones taking place in living cells up to the search of animals for food. Also, some recent work pointed towards the existence of relations between some (intermittent) search strategies and Brownian motors, an aspect that we had further explored.

The workshop has been attended by 40 researchers with a wide participation from across Europe, USA and Israel. Some participating groups have had already either well-established or incipient collaborations. Our post-workshop aim is to enlarge the scale of existing collaborations.

The workshop has been attended by post-graduate and post-doctoral researchers, providing them a good opportunity to present their work and giving an ample time for exchanging ideas and discussions with the leaders in the field, which might turn to be very helpful in their further carrier.

The workshop scientific program has been centred along the following topics:

- search in inhomogeneous environments

- perception-limited search strategies

- anomalous diffusion

- fluctuation theorems for anomalous diffusion

- search in biological and biophysical systems

- single particle tracking techniques and interpretation of data

- applications of random search strategies in computer science, chemistry and physics

- search and molecular motors

- analysis of different agent-based search strategies and their efficiency

- first passage times in complex systems

- pursuit and swarming vs evasive and deceptive avoidance strategies

- chemotaxis and infotaxis

The workshop was organized in five to nine daily presentations of 30 minutes each (see the attached program), some of which were reserved for young researchers.

Special emphasis was given to informal discussions and working group meetings and, to this purpose, the schedule of the workshop was structured in order to have an ample free time periods during the lunch break.

Assessment of the results

We judge that this meeting was very fruitful and successful. The presentations covered a wide spectrum of topics in the area of search and exploration in physical, biological and chemical systems. Concerning the quality of presentation and of the scientific work, the overwhelming majority of the contributions were well beyond the "average". Therefore, the participants could gain a comprehensive overview of the state-of-the-art in the field as well as learn about the new developments both on theoretical and experimental sides.

Everyone participated enthusiastically during the lectures and also in informal working discussions. We have found that most of the participants were positive concerning the free allocated time for such discussions. As a matter of fact, after the conclusion of the workshop we received very positive and enthusiastic evaluations from most of the participants. Many of them referred to this workshop as "very interesting and pleasant", as "with a very good balanced topics". Moreover, during the workshop it was mentioned that open problems could be solved as a result from the interaction between participants, and that new collaborations were initiated.

Projecting the responses of the participants, we expect that a few research articles will be published as a direct outcome of this meeting.

Lastly, we would like to mention that the success of this workshop has motivated other colleagues to organize future workshops on this subject.

Remarks on the budget

The funding sources supporting the organisation of this workshop were:

- The European Science Foundation (ESF) through the research networking programme "Exploring the Physics of Small Devices".

- The EU IRSES programme FP7-PEOPLE-2010-IRSES 269139 DCP-PhysBio "Dynamics and Cooperative Phenomena in Complex Physical and Biological Media", in association with the Laboratory J-V Poncelet, CNRS and the Independent University of Moscow.

- The Institute of Physics (UK), which sent its representative to the workshop (Mrs Alex Haywood).

- The Office of Naval Research (ONR) Global via the Collaborative Science Program.

Economic support was obtained from

ESF	**5000 EUR**
ONR	**7600 EUR**
IOP	**500 EUR**
EU IRSES	**4200 EUR**

The grant from ESF has been used to support the stay (overall 2932.08 euros for the hotels and 776.23 euros for meals - lunches and coffee breaks) and some modest part of travel expenses (overall 840 euros) of 7 early carrier and 1 senior EU participants and one senior participant from the United States, and also to cover some of the logistic expenses (administrative costs, overall 450 euros). The detailed account is presented in the bill furnished by the Institut of Scientific Studies in Cargese.

The names of the researchers from the EU are:

Dr. Elena AGLIARI (Parma, Italy)
Dr. Jaehyung JEON (Tampere, Finland)
Dr. Andrea PARMEGGIANI (Monpellier, France)
Dr. Alberto ROSSO (Orsay, France)
Dr. Grgory SCHEHR (Orsay, France)
Dr. Mahsa VAHABI (Palaiseau, France)
Mr. Juan DUQUE (Madrid, Spain)
Prof. Pascal VIOT (Paris, France)

The senior participant from US was:

Prof. Dan SCHWARTZ (Boulder, USA)

The Convenor

Gleb Oshanin

Appendix A: Program of the meeting

The programme of the workshop

Program of the Workshop with the titles of the talks

Monday, June 3
9.15 - 9.30. Opening
Chair : **Gleb Oshanin**
9.30 - 10.00. **Katja Lindenberg** (San Diego, USA), *Evanescent wandering traps: Can a target survive?*
10.00 - 10.30. **Enrique Abad** (Merida, Spain), *Dead man walking: the physics of evanescent random walkers*
10.30 - 11.00. Coffee break
11.00 - 11.30 **Carlos Mejia-Monasterio** (Madrid, Spain / Helsinki, Finland), *Minimal-dissipation transitions in small systems*
11.30 - 12.00. **Lene Oddershede** (Copenhagen, Denmark), *DNA supercoiling enhances cooperativity and efficiency of an epigenetic switch*

	Monday	Tuesday	Wednesday	Thursday	Friday
09.15-09.30	*Opening*				
09.30-10.00	**Lindenberg**	**Redner**	**Eliazar**	**Krapf**	**Viot**
10.00 - 10.30	**Abad**	**Lomholt**	**Metzler**	**Parmeggiani**	**Esposito**
10.30 - 11.00	*Coffee Break*	*Coffee Break*	*Coffee Break*	*Coffee Break*	*Coffee Break*
11.00 - 11.30	**Mejia**	**Jardat**	**Talbot**	**Jeon**	**Bancaud**
11.30 - 12.00	**Oddershede**	**Agliari**	**Schehr**	**Grebenkov**	**Vahabi**
12.00 - 15.00	*Lunch*	*Lunch*	*Lunch*	*Lunch*	*Lunch*
15.00 - 15.30	**Newby**	**Rosso**	**Angelani**	*Excursion*	*Departure*
15.30 - 16.00	**Schwartz**	**Imparato**	**Campos**		
16.00 - 16.30	**Rupprecht**	*Coffee Break*	*Coffee Break*		
16.30 - 17.00		**Guerin**	**Godec**		
17.00 - 17.30		**Mattos**	**Palyulin**		
19.30			*Dinner*		

12.00 - 15.00 Lunch at the Institute

Chair : **Olivier Benichou**

15.00 - 15.30. **Jay Newby** (Ohio, USA / Oxford, UK), *Uniform asymptotic approximation of diffusion to a small target*

15.30 - 16.00. **Daniel Schwartz** (Boulder, USA),*Intermittent Molecular Trajectories at Interfaces: Desorption-Mediated Diffusion and Intermolecular Associations*

16.00 - 16.30. **Jean-Francois Rupprecht** (Paris, France), *Exact escape times and optimality of surface-mediated diffusion in spherical geometries*

Tuesday, June 4

Chair : **Ralf Metzler**

9.30 - 10.00. **Sidney Redner** (Boston, USA), *Survival of the Lamb*

10.00 - 10.30. **Michael Lomholt** (Odense, Denmark), *The search strategy of the restriction enzyme EcoRV*

10.30 - 11.00 Coffee break

11.00 - 11.30. **Marie Jardat**(Paris, France), *Diffusion in disordered media from numerical simulations*

11.30 - 12.00. **Elena Agliari** (Parma, Italy), *Absorption and collisions on branched structures*

12.00 - 15.00. Lunch at the Institute

Chair : **Katja Lindenberg**

15.00 - 15.30. **Alberto Rosso** (Orsay, France), *Current statistics in wires with anomalous disorder landscape*

15.30 - 16.00. **Alberto Imparato** (Aarhus, Denmark), *Efficiency at Maximum Power of Molecular Machines*

16.00 - 16.30. Coffee break

16.30 - 17.00. **Thomas Guerin** (Paris, France), *Non-Markovian Polymer Reaction Kinetics*

17.00 - 17.30. **Thiago Mattos** (Stuttgart, Germany), *Trajectory-to-trajectory fluctuations in first passage phenomena in bounded domains*

Wednesday, June 5
Chair : **Raphael Voturiez**

9.30 - 10.00. **Iddo Eliazar** (Holon, Israel), *Benford's Law: A Poisson Perspective*

10.00 - 10.30. **Ralf Metzler** (Potsdam, Germany), *Anomalous diffusion and ergodicity in crowded systems*

10.30 - 11.00. Coffee break

11.00 - 11.30. **Julian Talbot** (Paris, France), *Effect of fluid structure on first passage times in confined environments*

11.30 - 12.00. **Gregory Schehr** (Orsay, France), *Asymmetric Levy flights in the presence of absorbing boundaries*

12.00. Lunch at the Institute

Chair : **Carlos Mejia-Monasterio**

15.00 - 15.30. **Luca Angelani** (Rome, Italy), *Escaping from chasers*

15.30 - 16.00. **Daniel Campos** (Barcelona, Spain), *Search efficiency and perception: predictions and experiences*

16.00 - 16.30. Coffee break

16.30 - 17.00. **Aljaz Godec** (Potsdam, Germany / Ljubljana, Slovenia), *Levy walks reloaded*

17.00 - 17.30. **Vladimir Palyulin** (Potsdam, Germany), *Search in the gradient: Levy vs Brown*

19.30. Conference dinner

Thursday, June 6 Chair : **Iddo Eliazar**

9.30 - 10.00. **Diego Krapf** (Boulder, USA), *Fractional Brownian motion on the surface of mammalian cells enhances endocytic reactions*

10.00 - 10.30. **Andrea Parmeggiani**(Montpellier, France), *Exclusion processes on networks as models for cytoskeletal transport*

10.30 - 11.00. Coffee break

11.00 - 11.30. **Jae-Hyung Jeon** (Tampere, Finland), *Anomalous diffusions induced by polymer network*

11.30 - 12.00. **Denis Grebenkov** (Palaiseau, France), *Evidence of Hydrodynamic and Subdiffusive Motion*

12.00. Lunch at the Institute

14.00. Conference excursion

Friday, June 7
Chair : **Sid Redner**

9.30 - 10.00. **Pascal Viot** (Paris, France), *Blockage in concurrent and countercurrent flows: exact results for non-Markovian models*
10.00 - 10.30. **Massimiliano Esposito** (Luxembourg), *Stochastic Thermodynamics and Information Processing*
10.30 - 11.00. Coffee break
11.00 - 11.30. **Aurelien Bancaud** (Toulouse, France), *Structure and Dynamics of yeast chromosome XII studied by single particle imaging: relevance of the blob picture in vivo*
11.30 - 12.00. **Mahsa Vahabi** (Palaiseau, France), *Area coverage of radial Levy flights with periodic boundary conditions*
12.00. Lunch at the Institute

Appendix B: List of participants

Below we list the names of established and young scientists who have made oral presentations at the workshop:
1. Katja Lindenberg (San Diego, USA)
2. Michael Lomholt (Odense, Denmark)
3. Sid Redner (Boston, USA)
4. Marie Jardat (Paris, France)
5. Carlos Mejia-Monasterio (Madrid, Spain / Helsinki, Finland)
6. Andrea Parmeggiani (Montpellier, France)
7. Gregory Schehr (Paris, France)
8. Lene Oddershede (Copenhagen, Denmark)
9. Pascal Viot (Paris, France)
10. Thiago Mattos (Stuttgart, Germany)
11. Massimiliano Esposito (Luxembourg)
12. Elena Agliari (Parma, Italy)
13. Enrique Abad (Badajos, Spain)
14. Jean-Francois Rupprecht (Paris, France)
15. Thomas Guerin (Paris, France)
16. Daniel Campos (Barcelona, Spain)
17. Jay Newby (Oxford, UK / Ohio, USA)
18. Aurelien Bancaud (Toulouse, France)
19. Luca Angelani (Roma, Italy)
20. Denis Grebenkov (Paris, France)
21. Julian Talbot (Paris, France)
22. Alberto Imparato (Aarhus, Denmark)
23. Daniel K Schwartz (Boulder, USA)
24. Aljaz Godec (Potsdam, Germany / Ljubljana, Slovenia)
25. Diego Krapf (Fort Collins, USA)
26. Alberto Rosso (Paris, France)
27. Jae-Hyung Jeon (Tampere, Finland)
28. Mahsa Vahabi (Paris, France)

29. Ralf Metzler (Potsdam, Germany)
30. Iddo Eliazar (HIT, Israel)
31. Vladimir Palyulin (Potsdam, Germany)

Several younger researchers have participated in the workshop and made poster presentations:
1. Oleg Vasilyev (Stuttgart, Germany)
2. Pierre Illien (Paris, France)
3. Adam Law (Stuttgart, Germany)
4. Vicenc Mendez (Barcelona, Spain)
5. Artem Aerov (Stuttgart, Germany)