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INVITED
PAPER

Taking the Human Out of the Loop: A Review of Bayesian Optimization

The paper introduces the reader to Bayesian optimization, highlighting its methodical aspects and showcasing its applications.

By BOBAK SHAHRIARI, KEVIN SWERSKY, ZIYU WANG, RYAN P. ADAMS, AND NANDO DE FREITAS

ABSTRACT | Big Data applications are typically associated with systems involving large numbers of users, massive complex software systems, and large-scale heterogeneous computing and storage architectures. The construction of such systems involves many distributed design choices. The end products (e.g., recommendation systems, medical analysis tools, real-time game engines, speech recognizers) thus involve many tunable configuration parameters. These parameters are often specified and hard-coded into the software by various developers or teams. If optimized jointly, these parameters can result in significant improvements. Bayesian optimization is a powerful tool for the joint optimization of design choices that is gaining great popularity in recent years. It promises greater automation so as to increase both product quality and human productivity. This review paper introduces Bayesian optimization, highlights some of its methodological aspects, and showcases a wide range of applications.

KEYWORDS | Decision making, design of experiments, optimization, response surface methodology, statistical learning

1. INTRODUCTION
Design problems are pervasive in scientific and industrial endeavours: scientists design experiments to gain insights

into physical and social phenomena, engineers design machines to execute tasks more efficiently, pharmaceutical researchers design new drugs to fight disease, companies design websites to enhance user experience and increase advertising revenue, geologists design exploration strategies to harness natural resources, environmentalists design sensor networks to monitor ecological systems, and developers design software to drive computers and electronic devices. All these design problems are fraught with choices, choices that are often complex and high dimensional, with interactions that make them difficult for individuals to reason about.

For example, many organizations routinely use the popular mixed integer programming solver IBM ILOG CPLEX[®] for scheduling and planning. This solver has 76 free parameters, which the designers must tune manually—an overwhelming number to deal with by hand. This search space is too vast for anyone to effectively navigate.

More generally, consider teams in large companies that develop software libraries for other teams to use. These libraries have hundreds or thousands of free choices and parameters that interact in complex ways. In fact, the level of complexity is often so high that it becomes impossible to find domain experts capable of tuning these libraries to generate a new product.

As a second example, consider massive online games involving the following three parties: content providers, users, and the analytics company that sits between them. The analytics company must develop procedures to automatically design game variants across millions of users; the objective is to enhance user experience and maximize the content provider's revenue.

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Taking the Human Out of the Loop: A Review of Bayesian Optimization

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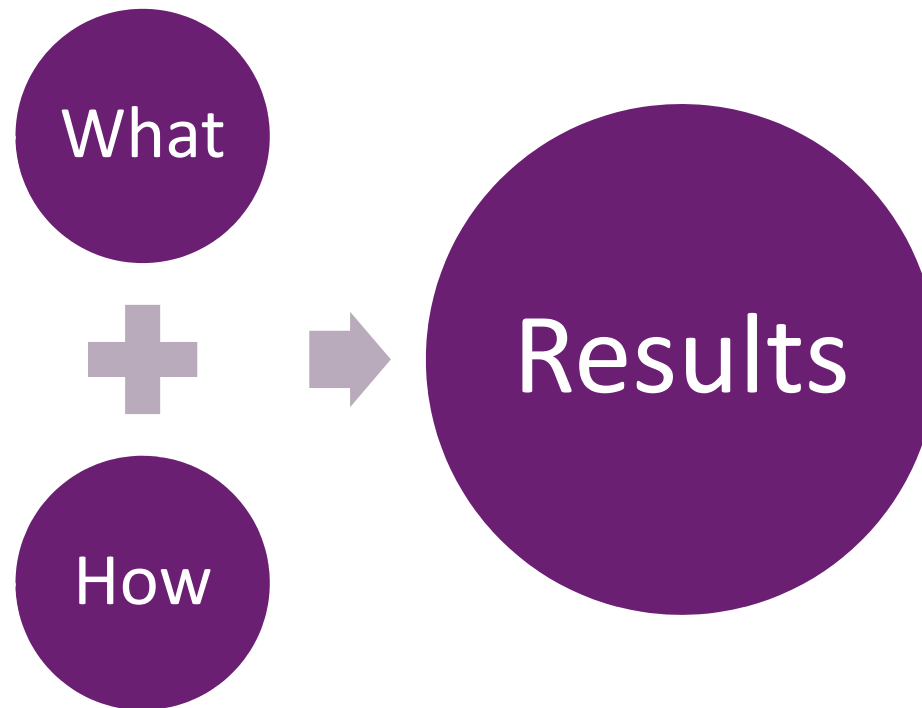
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Approach and Results



Discussion and Conclusion

Discussion

- ▶ What your results mean
- ▶ Why it makes a difference

Conclusion

- ▶ Broader implications
- ▶ Areas for further study

SECTION IX. CONCLUDING REMARKS

In this paper, we have introduced Bayesian optimization from a modeling perspective. Beginning with the beta-Bernoulli and linear models, and extending them to nonparametric models, we recover a wide range of approaches to Bayesian optimization that have been introduced in the literature. There has been a great deal of work that has focused heavily on designing acquisition functions; however, we have taken the perspective that the importance of this plays a secondary role to the choice of the underlying surrogate model.

In addition to outlining different modeling choices, we have considered many of the design decisions that are used to build Bayesian optimization systems. We further highlighted relevant theory as well as practical considerations that are used when applying these techniques to real-world problems. We provided a history of Bayesian optimization and related fields and surveyed some of the many successful applications of these methods. We finally discussed extensions of the basic framework to new problem domains, which often require new kinds of surrogate models.

Although the underpinnings of Bayesian optimization are quite old, the field itself is undergoing a resurgence, aided by new problems, models, theory, and software implementations. In this paper, we have attempted to summarize the current state of Bayesian optimization methods; however, it is clear that the field itself has only scratched the surface and that there will surely be many new problems, discoveries, and insights in the future.

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Author Biography and Photo



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Biography

Klaus Mcdonald-Maier (Senior Member, IEEE) is currently the Head of the Embedded and Intelligent Systems Laboratory, University of Essex, Colchester, U.K. He is also the Chief Scientist with UltraSoC Technologies Ltd., the CEO of Metrarc Ltd., and a Visiting Professor with the University of Kent. His current research interests include embedded systems and system-on-chip design, security, development support and technology, parallel and energy-efficient architectures, computer vision, data analytics, and the application of soft computing and image processing techniques for real-world problems. He is a member of VDE and a Fellow of the IET. *(Based on document published on 28 January 2020).*

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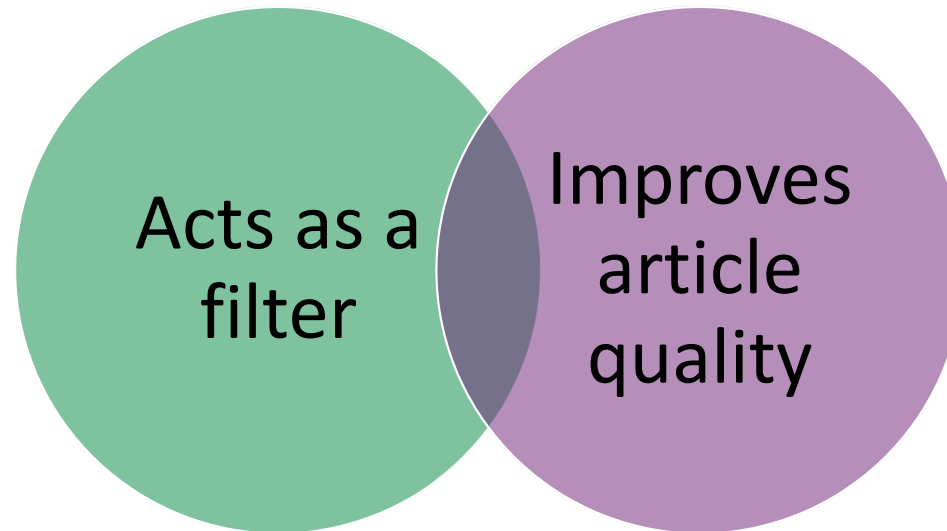
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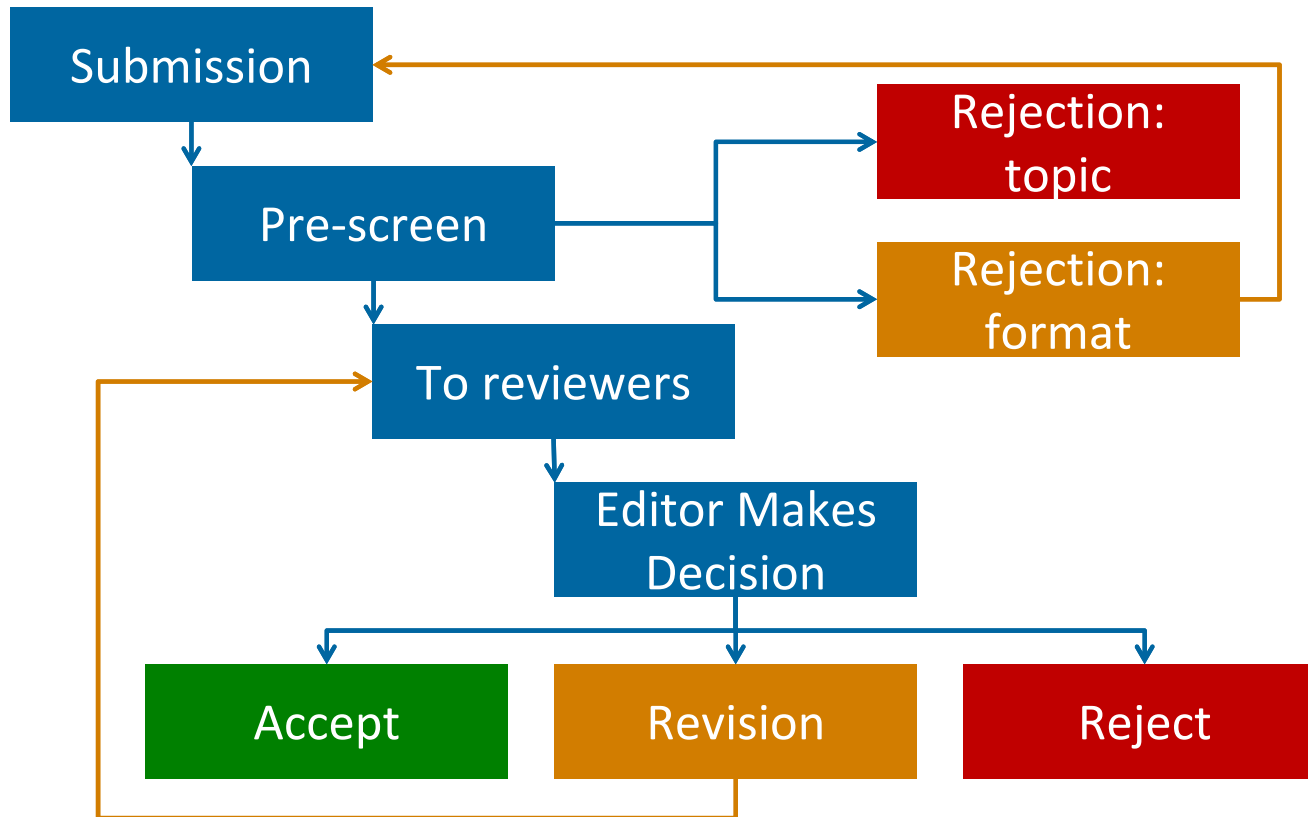


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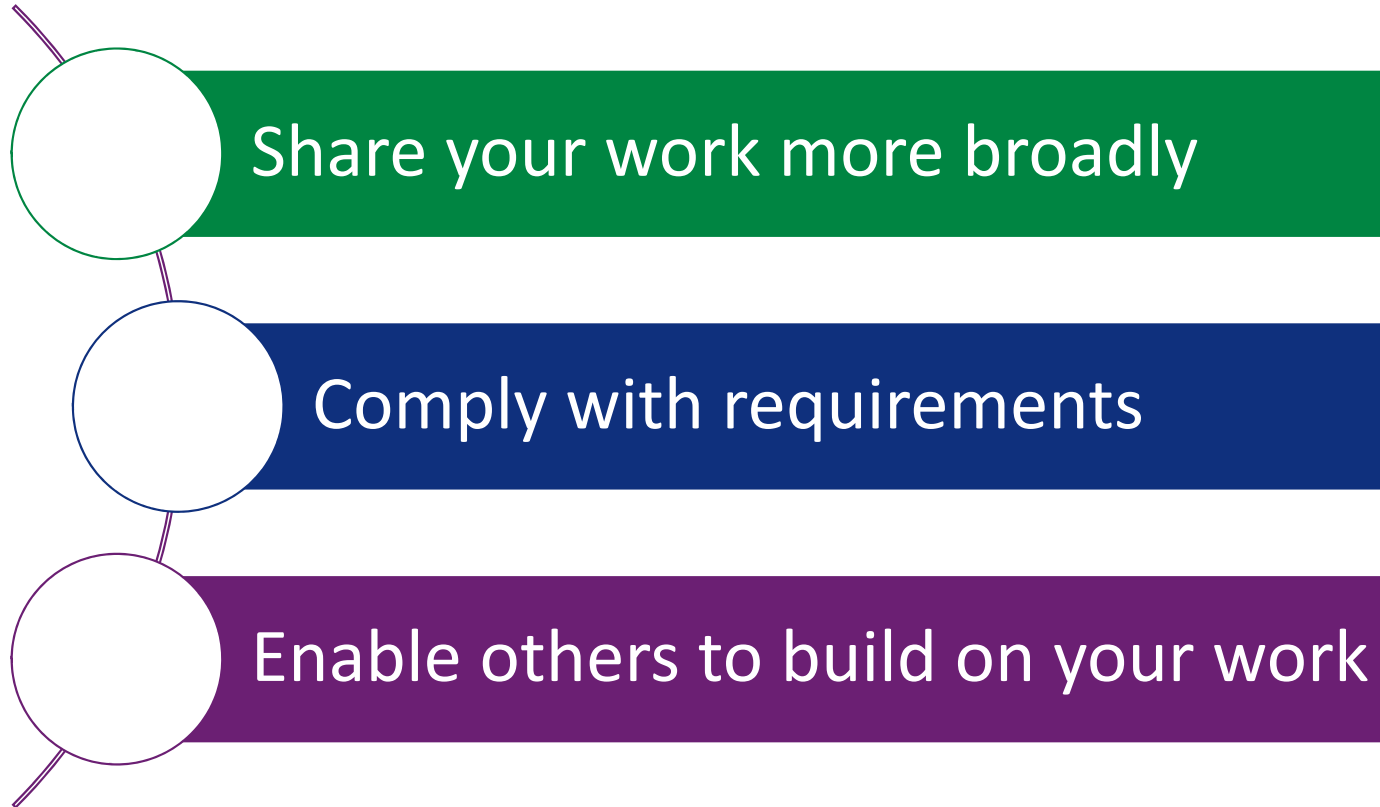
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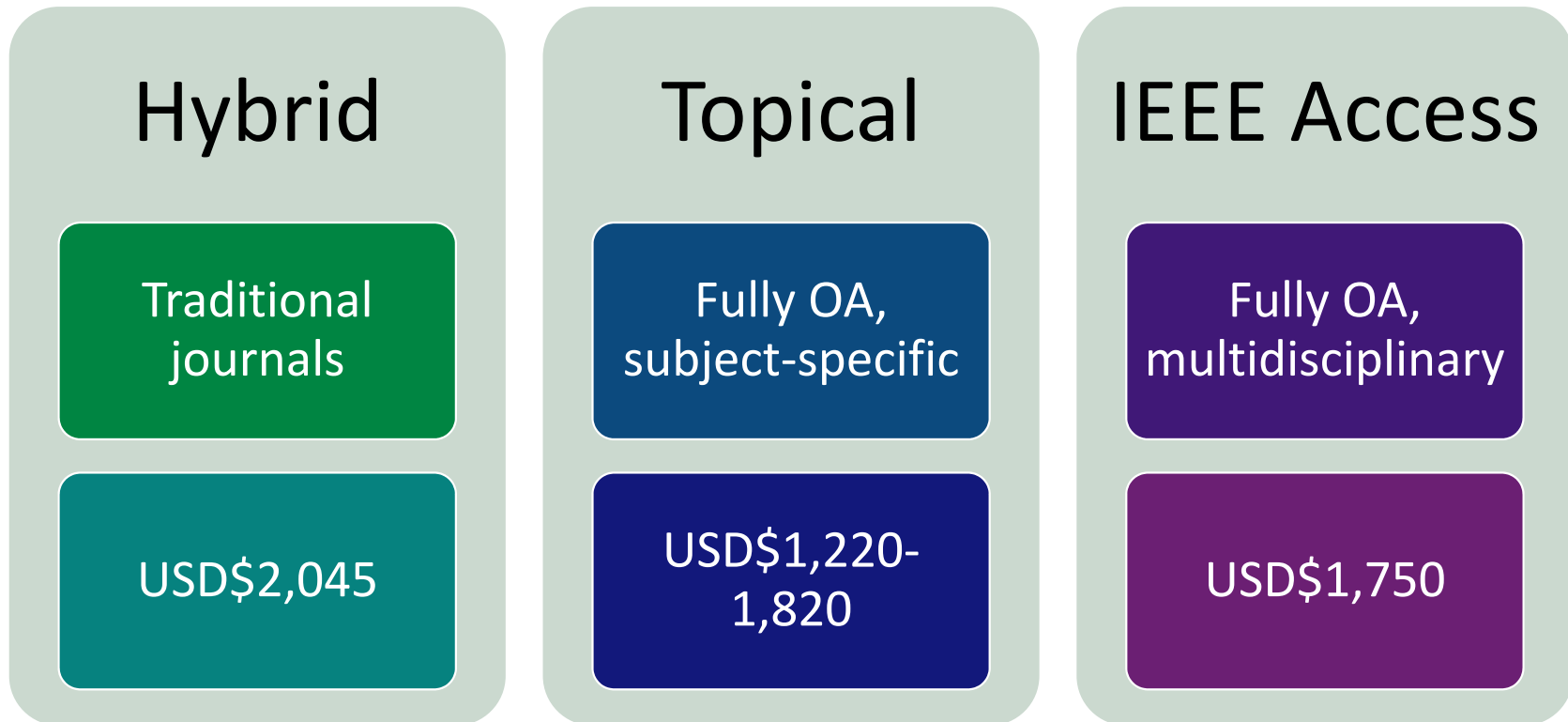
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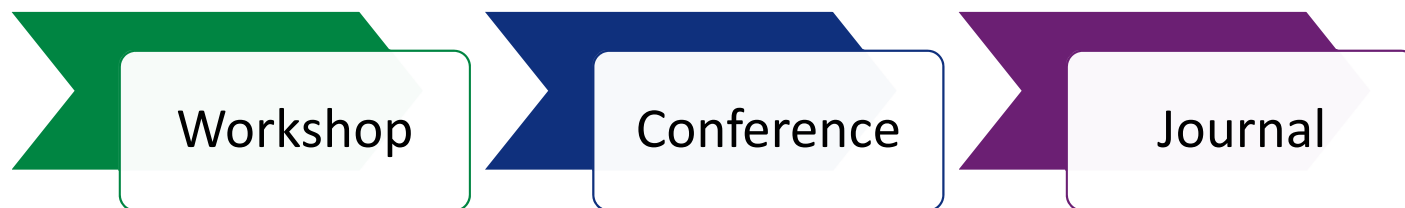
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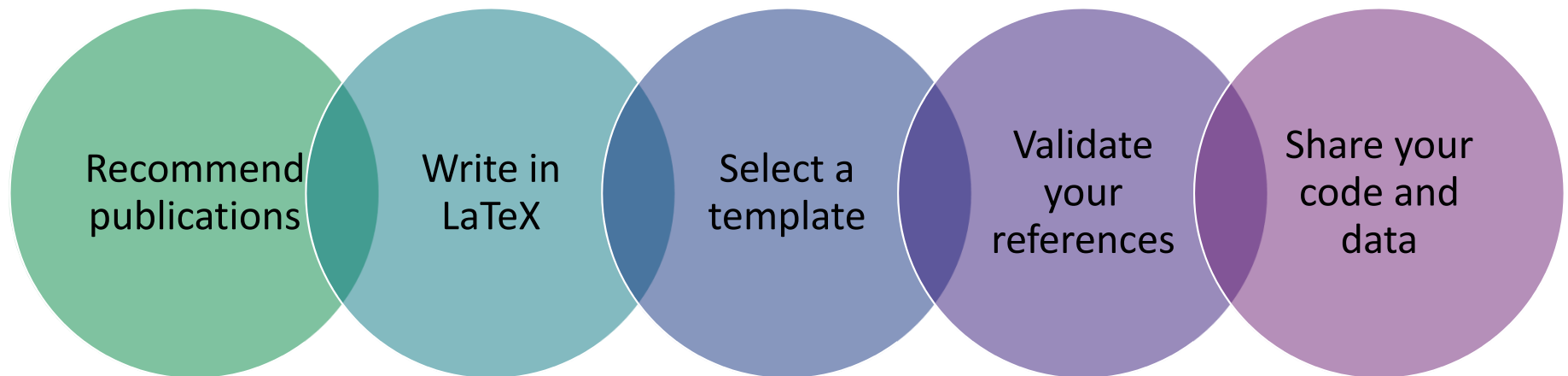
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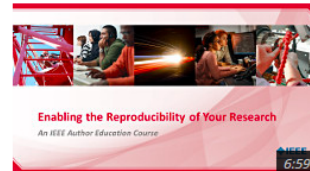
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