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End-to-End Optimal Detector Design with Mutual Information Surrogates

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We introduce a novel approach for end-to-end black-box optimization of high energy physics (HEP) detectors using local deep learning (DL) surrogates. These surrogates approximate a scalar objective function that encapsulates the complex interplay of particle-matter interactions and physics analysis goals. In addition to a standard reconstruction-based metric commonly used in the field, we investigate the information-theoretic metric of mutual information. Unlike traditional methods, mutual information is inherently task-agnostic, offering a broader optimization paradigm that is less constrained by predefined targets.

We demonstrate the effectiveness of our method in a realistic physics analysis scenario: optimizing the thicknesses of calorimeter detector layers based on simulated particle interactions. The surrogate model learns to approximate objective gradients, enabling efficient optimization with respect to energy resolution.

Our findings reveal three key insights: (1) end-to-end black-box optimization using local surrogates is a practical and compelling approach for detector design, providing direct optimization of detector parameters in alignment with physics analysis goals; (2) mutual information-based optimization yields design choices that closely match those from state-of-the-art physics-informed methods, indicating that these approaches operate near optimality and reinforcing their reliability in HEP detector design; and (3) information-theoretic methods provide a powerful, generalizable framework for optimizing scientific instruments. By reframing the optimization process through an information-theoretic lens rather than domain-specific heuristics, mutual information enables the exploration of new avenues for discovery beyond conventional approaches.

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