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Carpooling to solve the cosmological simulation bottleneck

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To exploit the power of next-generation large-scale structure surveys, ensembles of numerical simulations are necessary to give accurate theoretical predictions of the statistics of observables. High-fidelity simulations come at a towering computational cost. Therefore, approximate but fast simulations, *surrogates*, are widely used to gain speed at the price of introducing model error. We propose a general method that exploits the correlation between simulations and surrogates to compute fast, reduced-variance statistics of large-scale structure observables *without model error* at the cost of only a few simulations. We call this approach Convergence Acceleration by Regression and Pooling (CARPool). In numerical experiments with intentionally minimal tuning, we apply CARPool to a handful of GADGET-III N-body simulations paired with surrogates computed using COmoving Lagrangian Acceleration (COLA). We find ~ 100-fold variance reduction even in the non-linear regime, up to $k_{\rm max} \approx 1.2\ h{\rm Mpc}^{-1}$ for the matter power spectrum. CARPool realises similar improvements for the matter bispectrum. In the nearly linear regime CARPool attains far larger sample variance reductions. By comparing to the 15,000 simulations from the *Quijote* suite, we verify that the CARPool estimates are unbiased, as guaranteed by construction, even though the surrogate misses the simulation truth by up to 60% at high k. Furthermore, even with a fully configuration-space statistic like the non-linear matter density probability density function, CARPool achieves unbiased variance reduction factors of up to ~ 10, without any further tuning. Conversely, CARPool can be used to remove model error from ensembles of fast surrogates by combining them with a few high-accuracy simulations.

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