Quantum error mitigation by layerwise Richardson extrapolation

Vincent Russo[1], **Andrea Mari**[2]*

1. *Unitary Fund, San Francisco, USA*

2. *University of Camerino, Camerino, Italy*

** Presenting author*

Abstract: We introduce a new error mitigation technique for noisy quantum computers. Noise acting on different layers of a circuit is amplified with different scale factors and the results are extrapolated to the zero-noise limit.

A widely used method for mitigating errors in noisy quantum computers is zero-noise extrapolation [1-3] and, in particular, Richardson extrapolation [1]. This is a technique in which the overall effect of noise on the estimation of quantum expectation values is captured by a single parameter that, after being scaled to larger values, is eventually polynomially extrapolated to the zero-noise limit.

We generalize this approach by introducing layerwise Richardson extrapolation (LRE) [4], an error mitigation protocol in which the noise of different individual layers (or larger chunks of the circuit) is amplified and the associated expectation values are linearly combined to estimate the zero-noise limit (see Figure 1).

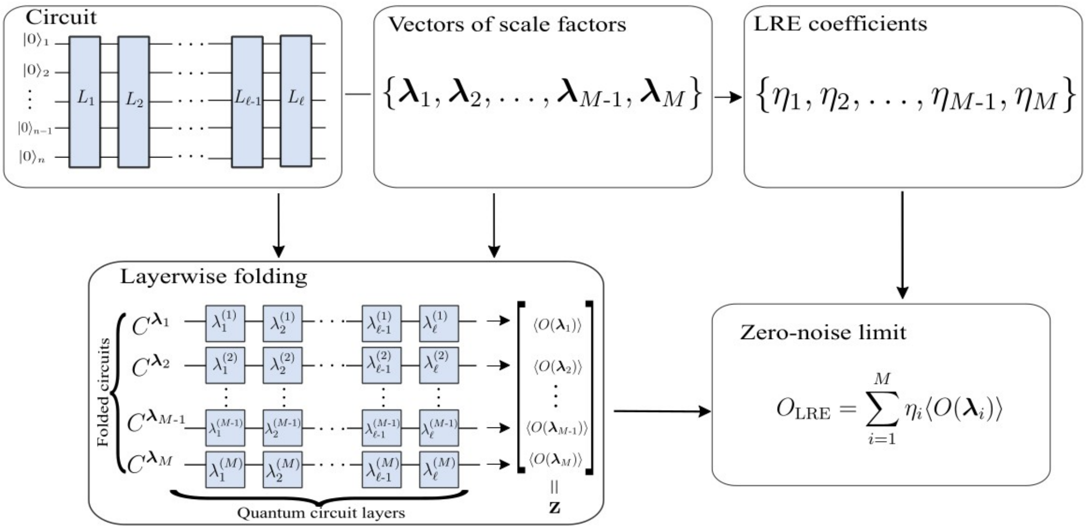

Fig. 1 Scematic representation of the LRE error mitigation technique. As input, we consider an n-qubit quantum circuit consisting of ℓ layers or, equivalently, ℓ circuit chunks. Given the parameter ℓ and the extrapolation order d, we generate M linearly independent vectors of scale factors. From this, we perform layerwise folding on the input circuit generating M different circuits, one for each vector of scale factors. Each generated circuit is almost identical to the input one, except for a few layers that are folded to amplify their noise sensitivity. For each circuit we estimate the respective expectation value $\langle O \rangle$ on a noisy quantum computer. By taking a linear combination of the noise-scaled expectation values, we obtain the error-mitigated result.

The coefficients $\{\eta_i\}$ of the linear combination are analytically obtained from the mathematical theory of multivariate Lagrange interpolation. LRE leverages the flexible configurational space of layerwise unitary folding, allowing for a more nuanced mitigation of errors by treating the noise level of each layer of the quantum circuit as an independent variable.

We provide numerical simulations demonstrating scenarios where LRE achieves superior performance compared to traditional (single-variable) Richardson extrapolation.

References

[1] K. Temme, S. Bravyi, and J. M. Gambetta, "Error mitigation for short-depth quantum circuits," PRL 119, 180509 (2017).
[2] Y. Li and S. C. Benjamin, "Efficient variational quantum simulator incorporating active error minimization," PRX 7, 021050 (2017).
[3] S. Endo, S. C. Benjamin, and Y. Li, "Practical quantum error mitigation for near-future applications," PRX 8, 031027 (2018).
[4] V. Russo, A. Mari, "Quantum error mitigation by layerwise Richardson extrapolation," PRA 110, 062420 (2024).