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# Identifying quantum chaos using rigorous statistics and random matrix theory

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Simulating chaotic systems is difficult, due to randomness from divergent sensitivity to system parameters, and the same holds for quantum chaos—often understood as dynamics in quantum systems that exhibit classical chaos in a large-system limit. Yet in quantum technologies, quantum chaos also arises in systems which do not possess any straightforward classical limit. For example, quantum computing algorithms such as digital quantum simulations only become interesting in large-system regimes which *cannot* be simulated classically: the dynamical randomness in quantum chaotic systems makes them good candidates for computationally complex quantum simulations [1]. We therefore need to be able to characterise quantum chaos independent of a classical reference system.

Essentially, a system is quantum chaotic if its unitary dynamics follow the predictions of *random matrix theory* (RMT): that is, if it samples from a universal RMT unitary matrix ensemble, as some parameter is varied. While this understanding is not new, it is difficult to quantify, and most previous analysis has relied on direct analytics, inconclusive methods like qualitative visual comparisons [2,3]. Recently, we introduced a new, quantitative and objective technique based on statistically rigorous comparison of a unitary with RMT predictions, at the full distribution level, using chi-squared tests [4]. Here, we describe the general technique, and illustrate its performance in the context of recently demonstrated digital quantum simulation performance thresholds arising from an onset of quantum chaos. We use it to objectively characterise RMT correspondence through quantitative comparisons with standard chi-squared confidence regions, and demonstrate the technique's versatility by analysing eigenvector and level-spacing statistics, individual eigenvectors, mixed phase-space regions, chaos-to-chaos transitions, and characterisation of small-system quantum chaos.

[1] Arute et al. *Nature* **574**, 505 (2019)
[2] Heyl, Hauke and Zoller. *Sci. Adv.* **5**, 4 (2019).
[2] Sieberer, et al. *npj Quantum Inf.* **5**, 78 (2019).
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