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Characterizing the Stability of NISQ Devices

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Questions we will cover

Agenda

Part I:

- Why the need for a new metric? (Motivating Moment Based Distance)
- What is the definition of MBD?
- Is MBD any good vs other methods? (Benchmarking against TVD)
- How good is the practical approximation? (since the MBD is an infinite series)

Part II:

- What basic criteria should quantum devices meet to support digital computation? (The DiVincenzo criteria)
- How should we define the reliabity profile for a Quantum Computer?
- The concept of temporal stability
- The concept of spatial stability

Part I: What's the need for a new metric?

Motivating Moment Based Distance

- A metric for reproducibility should be simple yet mathematically robust.
- Contemporary research often use Fidelity and Kullback–Leibler divergence as distribution distance measures. However, neither Fidelity nor Kullback–Leibler divergence satisfy the **triangle inequality** and hence do not qualify as a *true distance metric*.
- Another measure commonly in use is the Total Variation Distance (TVD). While it is a true distance metric, it ignores **higher order effects** (such as kurtosis and skew).
- Such distance measures could be **misleading** when used for benchmarking.

Part I: What is the definition?

Moment Based Distance (MBD)

Given two histograms f and g of a random variable X:

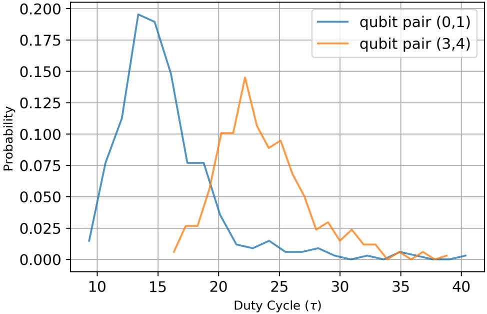
$$MBD = d(f,g) = \sum_{m=0}^{\infty} S_m(f,g) \tag{1}$$

$$S_m(f,g) = \frac{1}{(m)!} \int_a^b \left| \left(\frac{x}{\gamma}\right)^m (f(x) - g(x)) \right| dx \tag{2}$$

$$\gamma = \max(|a|, |b|) \tag{3}$$

Part I: Sample case for histogram comparison

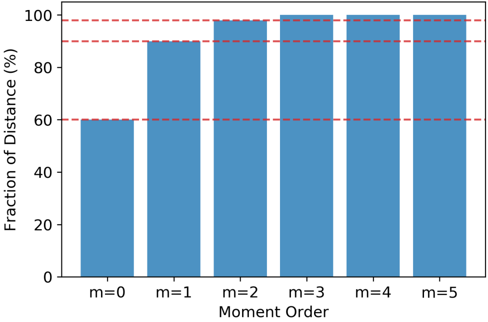
Please ignore details as we have not covered the concepts yet



- Experimental histograms of the duty cycle τ for qubit pairs that are observed to be furthest (spatially) in the sense of the moment-based distance. The data history spans from March 2019 to March 2020.

Part I: Can we get a feel for the formula?

Illustrative example

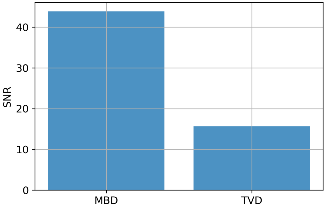


- We compare two normal distributions:
- $\mathcal{N}_1(\mu_0, \sigma_0)$
- $\mathcal{N}_2(2\mu_0, 2\sigma_0)$
- Plot shows how MBD converges (in other words, how the approximations improve and stabilize quickly.)

Contribution to moment based distance (d) from increasing moment orders.

Part I: Is MBD any good vs other methods?

Benchmarking against TVD



- Distance metric from different methodologies are not comparable. One can however compare robustness (using SNR).
- We generated 2 timeseries, by sampling 2 different distributions, and calculate the MBD and TVD between these timeseries
- We repeat this 400 times to generate a **distribution of the TVD and MBD distances**.

MBD could have more statistical power as indicated by a higher SNR.

Part I: How good is the approximation?

Remember MBD is an infinite series

Distribution	d_4	d_{20}	Error(%)
$N(\mu, \sigma)$	0.00000	0.00000	NA
$N(\mu + \Delta, \sigma)$	2.70868	2.70876	-0.00289
$N(\mu, 2\sigma)$	0.83252	0.83253	-0.00104
$N(\mu, 4\sigma)$	1.47301	1.47304	-0.00180
$N(2\mu, \sigma)$	2.93489	2.93520	-0.01033
$N(\mu, 1.5\sigma)$	0.49215	0.49216	-0.00091
$N(1.01\mu, \sigma)$	0.11739	0.11740	-0.00079
$SkewedNormal(\mu, 2\sigma)$	0.80887	0.80888	-0.00140
$Gumbel(\mu, 2\sigma)$	0.95131	0.95134	-0.00246

Part II: What basic criteria should quantum devices meet to support digital computation?

The DiVincenzo criteria

- Host a scalable array of well-defined and addressable quantum physical systems
- Support initialization of the quantum state of these physical systems to a well-defined fiducial state
- Realize a universal set of gate operations
- Maintain the coherence of the quantum state much longer than the duration of any individual gate
- Support addressable measurements of each quantum physical system

SOURCE: arXiv: 2008.09612

Part II: How can we define the reliabity profile for a Quantum Computer?

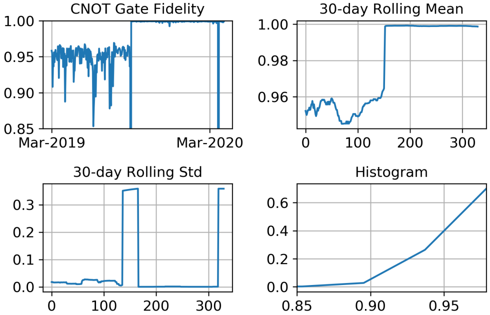
Device metrics using DiVincenzo criteria

Device Metric (Symbol)	*Description*
Register Capacity (n)	The maximal amount of information that may be stored in the register.
Initialization Fidelity (F_{I})	The accuracy with which the register state is prepared as the fidelity state.
Gate Fidelity (F_{G})	The accuracy with which a gate operation prepares the expected output.
Duty Cycle (τ)	The ratio of the gate duration to coherence time.
Addressability (F_{A})	The ability to address qubits individually.

SOURCE: arXiv: 2008.09612

Part II: Let's look at a sample dataset

CNOT Gate Fidelity data between 0 and 1 for IBM Yorktown



- The plots show (in clockwise order):
  (a) time-series,
  (b) the 30-day rolling mean,
  (c) the histogram,
  (d) the 30-day rolling standard deviation.

The publicly-available data provided by IBM is processed 'as-is' and we defer efforts to validate the experimental data collection process itself.

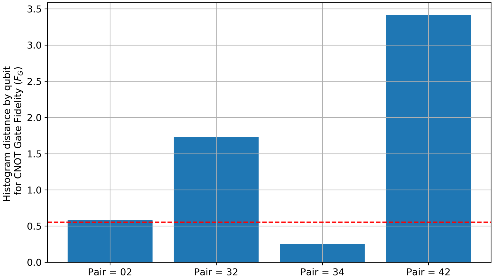
Part II: The concept of temporal stability

Using CNOT Gate Fidelity (referenced to March 2019 data)

- Data from Mar-2019 serves as the reference distribution.
- Subsequent points measure the distance between the reference distribution and the distribution observed in a specific month.
- The sharp improvement in gate fidelity around September 2019 corresponded to changes in hardware.

Part II: The concept of spatial stability

Using CNOT Gate Fidelity referenced to (0,1) between Mar19 - Mar20



- Plot of the moment-based distance d_4 with respect to the physical layout.
- Distance fluctuates spatially as well.

Concluding thoughts:

- How to decide the stability threshold?
- How should the threshold depend on the application?
- What is the best way to decide the reference distribution?
- How to generalize the MBD for multi-variate cases?