

Single-Qubit Gates with Errors at the 10^{-7} Level

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We report the achievement of single-qubit gates with sub-part-per-million error rates, in a trapped-ion $^{43}\text{Ca}^+$ hyperfine clock qubit. We explore the speed and fidelity trade-off for gate times $4.4 \leq t_g \leq 35 \mu\text{s}$, and benchmark a minimum error per Clifford gate of $1.5(4) \times 10^{-7}$. Calibration errors are suppressed to $< 10^{-8}$, leaving qubit decoherence ($T_2 \approx 70 \text{ s}$), leakage, and measurement as the dominant error contributions. The ion is held above a microfabricated surface-electrode trap that incorporates a chip-integrated microwave resonator for electronic qubit control; the trap is operated at room temperature without magnetic shielding.

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High-fidelity quantum logic operations are essential for realizing fault-tolerant quantum computation [1], as lowering gate errors considerably reduces the number of physical qubits and their control circuitry required for error correction [2]. In this respect, trapped-ion qubits are one of the most promising approaches to quantum information processing, and have been used to demonstrate gate fidelities [3–16] and state preparation and measurement (SPAM) [16–19] well beyond error correction thresholds.

A major advantage of trapped ions is the existence of “atomic clock” transitions for encoding qubits. These are transitions that, in the presence of the correct static magnetic field, are insensitive to changes in magnetic field (to first order), enabling coherence times in excess of an hour [20]. The gigahertz frequency of hyperfine clock transitions also enables qubit state manipulation using low-cost electronic sources with exceptionally stable amplitude and phase (compared with laser sources).

Electronically controlled trapped ions have been used to perform the highest fidelity single- and two-qubit operations of any platform, with gate errors of $1.0(3) \times 10^{-6}$ and $3(1) \times 10^{-4}$, respectively [3,16]. Even though single-qubit gates typically have higher fidelities than their two-qubit counterparts, quantum algorithms often require many more single-qubit than multiqubit operations and are therefore more sensitive to single-qubit gate errors [21].

High-fidelity single-qubit operations also have many other uses both in quantum information and further afield: for protecting “idle” qubits through dynamical decoupling [22]; in composite pulse sequences for error compensation [23] or addressing individual qubits [3,4]; and in quantum sensing applications [24,25].

In this Letter, we demonstrate microwave-controlled single-qubit gates, using a trapped-ion clock qubit, with errors benchmarked at $1.5(4) \times 10^{-7}$. This result constitutes nearly an order of magnitude improvement in both fidelity and gate speed over the previous best result [16]; see Fig. 1(a). We describe the calibration and error characterization methods that led to this result, which are readily applicable to all types of physical qubits. We give a comprehensive breakdown of known sources of error; our model predicts a gate error of $1.7(1) \times 10^{-7}$. Given the technical nature of the dominant errors, we thereby chart a path to even higher fidelity operations.

Experiments are carried out on a segmented surface-electrode Paul trap, used to confine an ion $40 \mu\text{m}$ above the chip surface. An on-chip microwave (MW) resonator is used, together with the MW drive chain detailed in Sec. S1 of the Supplemental Material (SM) [32], to generate an MW field for driving quantum logic operations. Our qubit is defined by the hyperfine states $|1\rangle = |F=4, M=1\rangle$ and $|0\rangle = |F=3, M=1\rangle$ of the ground manifold $4^2S_{1/2}$ of $^{43}\text{Ca}^+$. These states form a clock qubit at our static magnetic field strength of 28.8 mT and are connected by a magnetic dipole transition with a frequency splitting of 3.123 GHz. Further details about the trap design and choice of qubit can be found in Ref. [46] (although it should be noted that the trap is operated at room temperature in the present work).

Gate errors are measured through randomized benchmarking (RB) [47,48]. The ion is randomly prepared in

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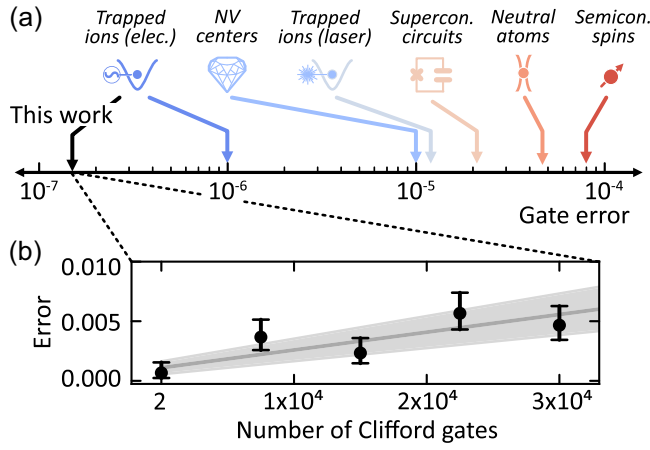


FIG. 1. Single-qubit gates: state of the art. (a) State-of-the-art single-qubit gates across different quantum computing platforms. From left to right: electronically driven trapped ions [16], nitrogen-vacancy (NV) centers [26], laser-driven trapped ions [27], superconducting circuits [28], neutral atoms [29,30], and semiconductor spin qubits [31]. (b) Single-qubit gate RB measurement carried out in this work. The average gate duration is 13 μ s; the fit yields an average Clifford gate error of $1.5(4) \times 10^{-7}$ and an average SPAM error of $1.1(5) \times 10^{-3}$, which is consistent with independent SPAM measurements.

either state $|0\rangle$ or $|1\rangle$ [16,49] before being subject to a pseudorandom series of Clifford gates. Each Clifford gate is decomposed into $\pm\pi/2$ pulses in the $\hat{\sigma}_x$ and $\hat{\sigma}_y$ bases, with an average of 2.2 pulses per Clifford. We then randomly shelve either $|0\rangle$ or $|1\rangle$ into the “dark” $3D_{5/2}$ manifold and measure the state of the ion using state-dependent fluorescence [50]. For each of the five different sequence lengths employed, we use 30 random gate sequences—with different sequences used for each gate time studied—and we repeat 100 shots of each sequence. The increase in error with sequence length yields an error of $1.5(4) \times 10^{-7}$ per Clifford gate for a gate duration of 13 μ s, as shown in Fig. 1(b). Results for a range of gate durations—between 4.4 and 35 μ s—are shown in Fig. 2. Further information regarding the implementation and analysis of the RB measurements can be found in Sec. S2 of SM.

By independently measuring or simulating all known sources of error, we predict a Clifford gate error of $1.7(1) \times 10^{-7}$ for a gate duration of 13 μ s. Table I summarizes the different error sources (see also Sec. S3 of SM). We find good agreement between the predicted and measured error, as shown in Fig. 2. The prediction begins to deviate from the measured error at shorter gate times, which indicates the existence of further error sources that we have not taken into account. We now discuss the different sources of error, giving specific values for the case of 13 μ s gates.

Pulses are generated by an arbitrary waveform generator (AWG) at ~ 100 MHz, and are then up-converted to MW

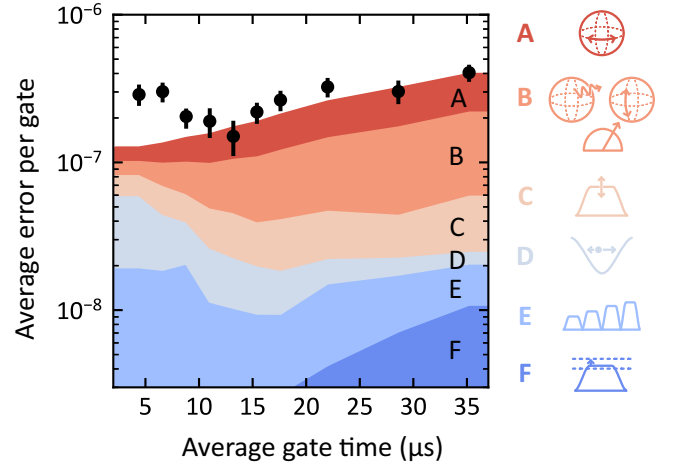


FIG. 2. Gate error contributions. The data points show RB measurements for different gate durations. Each point collates data from six different measurement runs carried out on six different days. Shaded areas show the contributions from known sources of error: A, decoherence; B, leakage, bit-flip, and time-dependent measurement errors; C, fast amplitude noise; D, harmonic motion; E, slow amplitude drift; F, amplitude resolution.

frequencies, amplified, and filtered, before being delivered to the on-chip resonator (see Sec. S1 of SM). The pulse amplitude is ramped up and down over 40 ns to reduce off-resonant excitation to other states in the $4S_{1/2}$ ground manifold. The error arising from the residual excitation to these states is estimated through simulation to be $< 1 \times 10^{-9}$ per gate. We use the minimum interpulse delay allowed by the AWG (40 ns) to minimize leakage, bit-flip,

TABLE I. Errors for a 13 μ s Clifford gate. These estimates of the different error contributions are either calculated from simulations or measured independently of the RB measurements. Estimated uncertainties are given in parentheses. The errors displayed in Fig. 2 use the same lettering. The ac Zeeman shift calibration error is not plotted in Fig. 2, as it is negligibly small for most gate times and can be readily reduced with our calibration procedure illustrated in Fig. 4.

Error source	Error ($/10^{-7}$)
A. Decoherence	0.64(7)
B. Leakage, bit-flip, and time-dependent measurement	0.62(7)
C. Fast amplitude noise	0.23(2)
D. Harmonic motion	0.13(2)
E. Slow amplitude drift	0.09(7)
ac Zeeman shift calibration	0.03(2)
F. Amplitude resolution	0.015
Excitation of spectator states	< 0.01
Interpulse Zeeman shift ramping	< 0.01
Non-rotating-wave dynamics	< 0.001
Expected total error per gate	1.7(1)
Measured total error per gate	1.5(4)

and time-dependent measurement errors due to unnecessary dead time.

To calibrate the gates, we fix the pulse duration, then determine the optimal MW amplitude and frequency to drive a $\pi/2$ rotation. For the amplitude calibration, we drive multiples of four $\pi/2$ pulses such that, in the ideal case, the qubit undergoes 2π rotations on the Bloch sphere as shown in Fig. 3(a). An offset in the amplitude will result in a net rotation of the qubit state at the end of the sequence, from which we can infer the optimal pulse amplitude. For efficiency, the number of $\pi/2$ pulses is increased exponentially until a statistically significant error signal has accrued; see Fig. 3(b). In practice, we end the sequence with an additional $\pi/2$ pulse, such that a measurement of $P_{|0\rangle} = |\langle\psi|0\rangle|^2$, where $|\psi\rangle$ is the qubit state at the end of the sequence, reveals an amplitude offset as a deviation from $P_{|0\rangle} = 1/2$. This makes the calibration linearly sensitive to small offsets in amplitude and indicates the sign of the offset.

We interleave this amplitude calibration with RB measurements, running it approximately every minute (the

calibration procedure takes a few seconds). The calibration rate was chosen to measure the “slow” drift in amplitude on a timescale of minutes—as shown in Fig. 3(c)—rather than to maximize the RB run-time, and could be run less frequently without compromising the gate error. We suspect that a dominant cause of amplitude drift is heating of the amplifier in the MW drive chain, given the correlation observed between its logged temperature and the calibrated pulse amplitude. These amplitude drifts were reduced by delivering a continuous MW drive, at the same amplitude and frequency used to drive gates, except during SPAM transfer pulses or RB sequences. This keeps the MW power dissipated in the drive chain constant, improving temperature stability once a thermal steady state is reached, as illustrated in the uncalibrated amplitude error after ~ 10 min of RB measurements in Fig. 3(c). Interleaved calibrations reduce the amplitude drift error from $\sim 1.4 \times 10^{-7}$ to $9(7) \times 10^{-9}$.

The effectiveness of the amplitude calibration is limited by the amplitude resolution of the AWG, and by “fast” amplitude fluctuations. The finite amplitude resolution of the AWG (15 bits) leads to a quantization of the pulse amplitude that, on average, translates to a gate error of $\sim 1.5 \times 10^{-9}$. We measure “fast” changes in amplitude between sequential shots of the experiment (i.e., on a ~ 100 ms timescale) using the same procedure as for the amplitude calibration. If the amplitude changes between sequential shots of the experiment, the net rotation induced by the pulse sequence will fluctuate, reducing the probability of recovering state $|0\rangle$ at the end of the sequence, as shown in Fig. 3(d). We would observe the same decay if the amplitude were changing throughout the sequence of pulses. To separate the changes in amplitude within a single sequence from shot-to-shot offsets, we repeat the same measurement but switch the phase of the $\pi/2$ pulses by 180° halfway through the sequence. We find that the error caused by drifts in amplitude during a sequence is $< 10^{-10}$ and is therefore negligible compared to shot-to-shot changes [$2.3(2) \times 10^{-8}$ error]. Further details can be found in Sec. S4 of SM.

The second calibration required is that of the MW frequency. The qubit is insensitive, to first-order, to dc Zeeman shifts, but remains sensitive to ac Zeeman shifts. These may be “ambient” shifts, such as those caused by the radio-frequency trapping field, or “MW-induced” shifts caused by the gate drive. Both types of ac Zeeman shift are calibrated before starting RB measurements. The “ambient” shift is calibrated through a Ramsey measurement, with uncertainty < 1 Hz. Miscalibration of this shift is not included in the error budget since the “MW-induced” shift calibration captures residual offsets in any “ambient” shifts.

The ac Zeeman shift induced by the MW pulses is calibrated by driving pairs of $\pi/2$ rotations around the $\pm X$ axes on the Bloch sphere, where the second pulse has a phase shift of 180° relative to the first, as shown in Fig. 4(a).

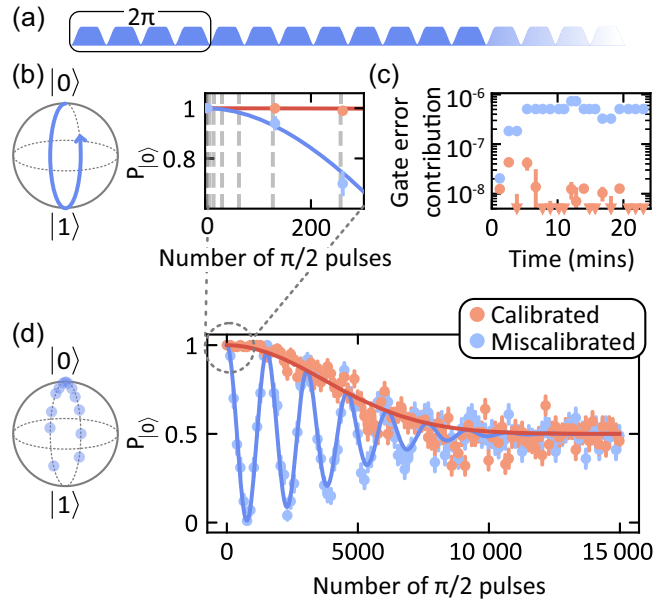
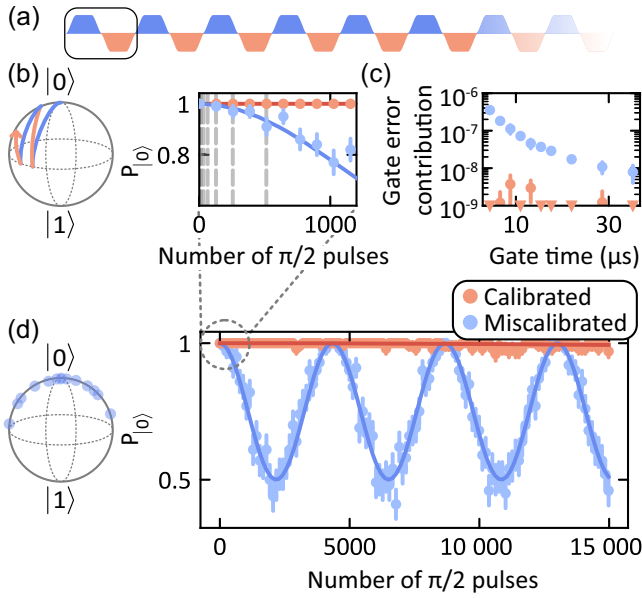
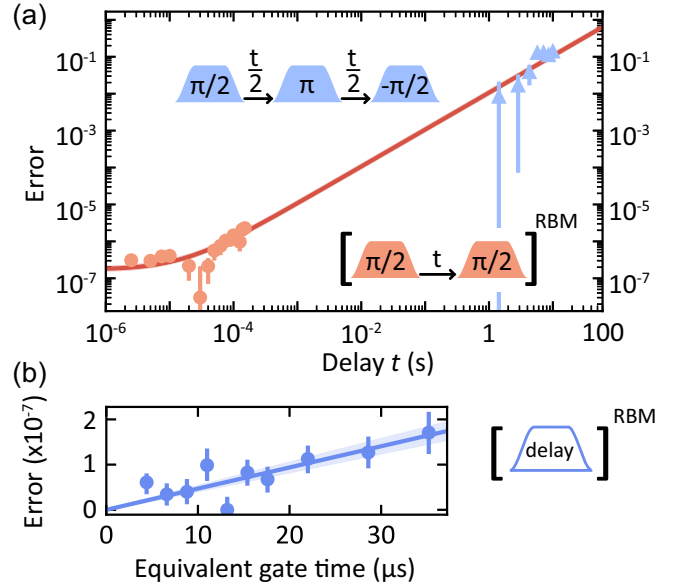


FIG. 3. Pulse amplitude calibration, drift, and fluctuations. (a) Changes in amplitude are measured by driving multiples of four $\pi/2$ pulses, such that ideally the ion is returned to state $|0\rangle$ at the end of the sequence. (b) The number of pulses is increased exponentially and, when the probability $P_{|0\rangle}$ of recovering the initial state is below a chosen threshold, the amplitude miscalibration is computed and compensated for. (c) Calibrations interleaved in the RB measurement process reveal the gate error that would arise from drifts (blue), and the reduced error obtained through repeated calibration (orange). (d) The accuracy of this calibration procedure is limited by shot-to-shot amplitude fluctuations. Amplitude changes between sequential shots of the experiment randomize the final state, reducing the reproducibility of measuring state $|0\rangle$ at the end of the sequence, so that $P_{|0\rangle} \rightarrow 0.5$ for long sequences.



If the MW drive has the correct frequency, the second pulse returns the ion to its starting state. If the MW drive is detuned with respect to the ac Zeeman-shifted qubit frequency, the pair of pulses will drive a net rotation about the Y axis; see Fig. 4(b). In practice, we append the sequence with a $\pi/2$ rotation around the Y axis, such that a measurement of $P_{|0\rangle} = |\langle\psi|0\rangle|^2$ reveals a detuning offset as a deviation from $P_{|0\rangle} = 1/2$. With the MW amplitude set so as to produce a mean gate duration of $13\ \mu\text{s}$, the ion experiences an ac Zeeman shift of $9(1)\ \text{Hz}$ that, if left uncorrected, would lead to a gate error of $6.0(7) \times 10^{-8}$; see Fig. 4(c).

Unlike the amplitude calibration, neither of these frequency calibrations is limited by “fast” changes in frequency or by the frequency resolution of the AWG (6 mHz). To verify the former, we take the same approach as with the amplitude calibration scheme, and drive 15 000 pairs of $\pi/2$ pulses, observing none of the consequences expected from frequency fluctuations [see Fig. 4(d)]. If the frequency were changing on either a shot-to-shot or a pulse-to-pulse timescale, we would observe a decay in the



probability of measuring $|0\rangle$ after many repetitions of $\pi/2$ pulse pairs. Frequency noise is therefore found to be a negligible source of error; we choose to calibrate the MW frequency such that the impact on gate error is $< 1 \times 10^{-9}$. There remains a varying detuning during the pulse ramp up and down and the interpulse delay—since the ac Zeeman shift is dependent on the MW amplitude—but the resulting error is $< 1 \times 10^{-9}$.

Finally, we will discuss gate errors that are unrelated to MW pulse calibrations. From Table I, we see that the dominant source of error is decoherence. This is measured in two ways: by interleaved randomized memory benchmarking at short timescales [51,52] and by spin-echo Ramsey measurement at long timescales [20,53–55], with both sets of results shown in Fig. 5(a). During interleaved randomized memory benchmarking, the delay between $\pi/2$ pulses in an RB sequence is increased and the subsequent increase in gate error provides a measure of a decoherence time constant, equal to $69(7)\ \text{s}$, that we denote by T_2^{**} . The absence of the MW-induced ac Zeeman shift during the delay is accounted for by adjusting the phase of the subsequent $\pi/2$ pulses in the sequence. Errors caused by

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leakage, bit-flip, and measurement are subtracted to isolate the effect of decoherence, using the independent measurement shown in Fig. 5(b). We determine the dominant source of decoherence to be phase noise in the MW drive chain [56,57] (further analysis can be found in Sec. S5 of SM).

Leakage, bit-flip, and time-dependent measurement errors constitute the second-largest source of error. These errors are measured using RB measurements, but with all MW pulses replaced with delays; see Fig. 5(b). The error increases with delay due to: “leakage,” population leaking out of the qubit subspace; “bit-flips,” population transfer between the two qubit states; or “time-dependent measurement errors,” an increase in the measurement error after a longer delay. We observed significant improvements in the first two error sources by reducing undesired laser and MW radiation; see Sec. S6 of SM for further details.

The remaining significant error source arises from the harmonic motion of the ion in its trapping potential, induced by motional heating during the gate sequence. This modulates the pulse amplitude since the ion is positioned on a MW amplitude gradient engineered for driving two-qubit gates [58]. During an RB experiment, the in-plane radial motional mode of the ion is dark-resonance cooled to 2.6(8) quanta before state preparation [59], but heats up at a rate of 0.37(5) quanta/ms. Through simulation (see Sec. S3 of SM), we estimate a gate error contribution due to this effect of $1.3(2) \times 10^{-8}$. The coupling to the other motional modes is much lower due to a significantly smaller MW field gradient in the axial and out-of-plane directions, making the error contribution from these modes negligible.

In conclusion, we have achieved a new state-of-the-art single-qubit gate error of $1.5(4) \times 10^{-7}$ and presented a breakdown of all known sources of error, which agrees well with the data over a wide range of gate speeds. Our fastest Clifford gate (4.4 μ s) has an error of $2.9(5) \times 10^{-7}$; this represents a 20 $\times$ speedup relative to the previous lowest-error gate [16]. Compared with our previous work [16], we have reduced the error by nearly an order of magnitude by better control of microwave amplitude and detuning with automated calibration procedures, and by reduced excitation of spectator transitions using pulse shaping and larger Zeeman splittings. Over the range of gate times studied, we determine the dominant contribution to the error to be decoherence, closely followed by leakage, bit-flip, and time-dependent measurement errors. The gate error could therefore be reduced further by improving the qubit coherence or by eliminating leakage out of the qubit states due to unwanted sources of radiation. Alternatively, the gate error could be reduced using state leakage detection techniques [60–62]. Calibrating the readout for different experimental sequence durations would allow us to separate the time-dependent measurement error from the gate error more unambiguously. Amplitude and frequency noise

of the MW pulses contribute an insignificant amount to the gate error, demonstrating the robustness of electronic control. With hardware improvements, one could implement longer gate sequences, enabling experiments to probe the non-Markovian nature of the different sources of error [63–66]. Note that these types of errors could cause the RB measurements used here (and in many other similar experiments) to underestimate the gate error [67,68]. For addressed single-qubit gates, multiple techniques exist to null the microwave field in nonaddressed zones [3,4,69,70], and even modest levels of cancellation can result in very low crosstalk through the use of composite pulses [3,71]. Alternatively, composite pulses can be used to drive different single qubit gates on n ions within the same zone or potential well, using a sequence of $\sim 3n/2$ pulses [4]. For composite pulse sequences, or applications such as protecting memory qubits by dynamical decoupling, the relevant error would be the error per physical $\pi/2$ pulse, which is $0.7(2) \times 10^{-7}$.

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M.C.S., A.D.L., M.F.G., and K.M. developed and maintained the experimental apparatus and acquired the data. M.C.S., A.D.L., and M.F.G. carried out the data analysis. M.C.S. wrote the manuscript with contributions from all authors. M.F.G. and D.M.L. supervised the work.

Data availability—The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

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