Characterizing a non-equilibrium phase transition on a quantum computer

Quantum systems subject to driving and dissipation display distinctive non-equilibrium phenomena relevant to condensed matter, quantum optics, metrology and quantum error correction. An example is the emergence of phase transitions with uniquely quantum properties, which opposes the intuition that dissipation generally leads to classical behaviour. The quantum and non-equilibrium nature of such systems makes them hard to study with existing tools, such as those from equilibrium statistical mechanics, and represents a challenge for numerical simulations. Quantum computers, however, are well suited to simulating such systems, especially as hardware developments enable the controlled application of dissipative operations in a pristine quantum environment. Here we demonstrate a large-scale accurate quantum simulation of a non-equilibrium phase transition using a trapped-ion quantum computer. We simulate a quantum extension of the classical contact process that has been proposed as a description for driven gases of Rydberg atoms and has stimulated numerous attempts to determine the impact of quantum effects on the classical directed-percolation universality class. We use techniques such as qubit reuse and error avoidance based on real-time conditional logic to implement large instances of the model with 73 sites and up to 72 circuit layers and quantitatively determine the model’s critical properties. Our work demonstrates that today’s quantum computers are able to perform useful simulations of open quantum system dynamics and non-equilibrium phase transitions.

A remarkable feature of nature is that complicated systems governed by completely different microscopic rules, such as water and kitchen magnets, can behave essentially identically on large length and time scales when changing between two phases of matter, as long as they share a few basic properties such as symmetry and topology. This universal behaviour near phase transitions makes it possible to predict many behaviours of complex materials by studying simple models. Physicists have made great progress in understanding phase transitions, especially in equilibrium, by computing the properties of simplified models and validating the calculations with experiments. However,
In this work, we study a dissipative quantum circuit model that generalizes a canonical classical model, the contact process, known to exhibit a non-equilibrium phase transition in the directed-percolation (DP) universality class. We are motivated in part by related continuous-time models and quantum cellular automata models relevant to Rydberg atom quantum simulators, for which a combination of field-theoretic and numerical analyses have been interpreted as a possible deviation from classical DP scaling. In large part due to the classical difficulty of obtaining precise results for sufficiently large system sizes and evolution times, a definitive answer to this question remains elusive. We note that even if the universal scaling properties of a phase transition in a quantum model turn out to be classical, verifying such behaviour may be classically intractable.

We use a trapped-ion quantum computer to experimentally probe the non-equilibrium phase transition in the dissipative circuit model (we also characterized the transition using classical tensor network methods). Using the mid-circuit measurement and reset capabilities available on Quantumum’s HI series quantum computer, we are able to study this model for large times and system sizes (72 layers of two-qubit gates acting on a 73-site lattice). The high gate fidelities, together with error-avoidance techniques enabled by real-time (circuit-level) conditional logic, allow us to verify power-law growth of observables near the critical point. Our classical and quantum simulations suggest that classical DP universality is robust to the introduction of quantum fluctuations, at least for the model, observables and initial states considered in this work. Although evidence has been put forward that quantum fluctuations may affect the critical exponents of a continuous-time version of this model (due to a breaking of ‘rapidity-reversal’ symmetry), our classical simulation results suggest that this is not the case for our discrete-time model (Supplementary Information).

A driven-dissipative quantum circuit

In this work, we study a quantum circuit that we call the one-dimensional (1D) Floquet quantum contact process (FQCP; Fig. 1a–c). In each time step, the 1D FQCP circuit executes a layer of probabilistic resets (sets each qubit to $|0\rangle$ with probability $p$) followed by four alternating layers of controlled-rotation gates: $C_{\text{RX}}(\theta) = e^{-\frac{i}{2} \sigma_y \sin(\theta)} \sigma_z \sigma_y$, where $\sigma^x$, $\sigma^y$, $\sigma^z$ are Pauli matrices and $\theta$ is a gate angle parameter.

The FQCP is a quantum circuit arising from the contact process, a simple model for disease spreading by contact between infected individuals (other quantum generalizations can be found in refs. 6, 7). In the 1D FQCP, each site in a 1D chain of qubits is labelled ‘active’ ($|1\rangle$) or ‘inactive’ ($|0\rangle$). In the circuit, there is a competition between a unitary driving process and a non-unitary dissipative process. The driving (set by $\theta$) caused by the two-qubit gates enables active sites to spread to inactive neighbours through the process $|0\rangle \rightarrow \cos(\theta/2) |0\rangle + e^{i\phi} \sin(\theta/2) |1\rangle$, where $\phi \in [0, \pi/2]$ is a phase (Fig. 1). For generic choices of $\theta, \phi$, such processes thermalize subsystems to the infinite-temperature maximally mixed state $\rho \propto I$. We note that at $\theta = \pi$, the model maps bitstrings in the computational basis to other bitstrings without generating entanglement; at this special point, our model is therefore classical, efficiently simulable and guaranteed to have DP critical exponents (Fig. 1 and Supplementary Information). The dissipation (set by $p$) caused by the probabilistic reset channels drives the entire system to the product state $\rho = \sum_{0 \to 0} |0\rangle \langle 0|$, called the absorbing state, which the system can reach but not exit. In chains of length $L$, the competition of unitary spreading and spontaneous decay separates two regimes: an inactive regime at high decay rate $p$.

Thermal equilibrium is an idealization that often does not hold; many features of the world around us—from geological formations, to the spread of disease, to the flocking of birds—arise due to processes that are fundamentally non-equilibrium in nature. Non-equilibrium systems also exhibit universal behaviour at phase transitions, but with a richer and generally less-well-understood phenomenology than their equilibrium counterparts. The experimental realization of many platforms for simulating quantum dynamics has brought a particularly poorly understood question to the forefront in recent years: can microscopic quantum features of non-equilibrium systems persist at macroscopic scales and affect universal properties of the dynamics?

Quantum computers may be helpful in addressing this question for two reasons. First, classically simulating open quantum systems can be more difficult than simulating unitary dynamics often requiring empirically larger memory or simulation time. Although dissipation can sometimes limit the growth of entanglement, it can also lead to non-trivially entangled steady states (for example, in quantum error correction and dissipative state engineering). Second, because energy conservation does not play a role in many non-equilibrium processes, universal features may be captured by discrete quantum circuits without the large overhead of continuous-time Hamiltonian simulation techniques.

Fig. 1 | A driven-dissipative quantum circuit. a. The 1D FQCP evolving an initial state with a single active seed at spatial position $r = 0$ ($|1\rangle$ is active; $|0\rangle$ is inactive). The greyed-out gates and channels act as identity and do not need to be applied. b. The two-qubit gates and quantum channels used in the model. The two key processes in the model: quantum branching/coagulation of active sites produced by the controlled-rotation gates and decay of active sites produced by the probabilistic resets. Active sites ($|1\rangle$) are shown as yellow circles and inactive sites ($|0\rangle$) as dark blue circles. c. Sample trajectories at the classical point ($\theta = \pi$) of the model for $p = 0.2 < p_c = 0.3943 < p_c$ and $p = 0.6 > p_c$. The trajectory-averaged active site density at $\theta = 3\pi/4$ for $p = 0.1 < p < 0.3 < p_c$ and $p = 0.5 > p_c$, obtained from experiments executed on the HI-1 quantum computer. Numerical estimates of $p_c$ are discussed in Supplementary Information.
where the active sites decay exponentially in time, and an active regime
where the spreading processes produce a finite density of active sites
that survives to late times $\log t \sim L$. As $L \to \infty$, these regimes become
sharply distinct phases separated by a critical decay rate $\epsilon_c$ at which
the active site density grows super-diffusively, forming a self-similar
fractal active cluster.

To probe the transition, we scan $p$ for fixed $\theta$ and time-evolve an
initial state $\rho_0$ that has a single active ‘seed’ at position $r = 0$ in a
chain of $-L \leq r \leq L$ sites, for $t$ time steps and system size $L = 2t$ (Fig. 1a).
Denoting the operator that indicates an active site at position $r$ by
$n_r = |1\rangle \langle 1|$, and $E_r(\cdot)$ as $t$ steps of evolution, we examine the active site
density $\langle n(r,t) \rangle = \text{tr}(E_r(\rho_0)n_r)$ and the total number of active sites
$\langle N(t) \rangle = \sum_1^L \langle n(r,t) \rangle$.

Generically, it is postulated that models with absorbing states
and no other explicit symmetries undergo non-equilibrium phase
transitions in the DP universality class. At the critical point $p = p_c$ of
a DP transition, observables asymptotically scale as power laws: for
example, $\langle N(t) \rangle \sim t^\theta$, where the universal exponent $\Theta$ has been
determined numerically ($\Theta = 0.313686(8)$ in 1D (refs. 5,19)). Likewise, in 1D,
the active site density profile at late times and $p = p_c$ obeys an asymp-
totic scaling form $\langle n(r,t) \rangle \sim e^{-t^\theta f(r/t^z)}$, where $f(x)$ is a universal scaling
function and $z = 1.580745(10)$ (refs. 5,19).

**Implementation on a trapped-ion quantum computer**

We implement the FQCP model on Quantinuum’s H1-1 trapped-ion
quantum processor (Fig. 2d). Using recently developed qubit-reuse
and quantum tensor network techniques involving mid-circuit measure-
ment and resets (Fig. 2a), we perform up to $t = 18$ steps of time evolution
using $t + 2 = 20$ qubits, a substantial savings over the $4t + 1 = 73$ qubits.
needed without qubit reuse. High-fidelity and low-crosstalk mid-circuit resets are particularly crucial for this study as the FQCP’s probabilistic reset channels would have required hundreds of additional ancilla qubits to implement without mid-circuit resets.

For the single-active-seed initial state, the averaged dynamics is reflection symmetric about \( r = 0 \), so that \( (n(r,t)) = (n(-r,t)) \). Exploiting this fact, we only implement the operations causally connected to qubits measured at \( r \geq 0 \), \( t > 0 \) (Fig. 2a), which reduces the number of required qubits from \( 4t + 1 \) to \( 3t + 1 \). Qubit reuse further reduces the qubit requirements to \( t + 2 \).

We use an error-avoidance technique that allows us to significantly reduce the effects of two-qubit errors in our circuits. During each experiment, we maintain a real-time log of qubits known to be currently in the \( |0\rangle \) state—prior mid-circuit resets—and use that log to conditionally avoid the application of any two-qubit gate for which the control qubit is known to be in \( |0\rangle \), thereby avoiding errors accompanying gates that do not induce any dynamics (Fig. 2b,c).

Results

We experimentally perform dynamic simulations of the FQCP model for times \( t = 2, 4, ..., 18 \) on both sides of the phase transition and near the critical point. From extensive numerical simulations using matrix product operator techniques\(^{13-15}\) (Supplementary Information), we find evidence of a DP phase transition for both classical \( (\theta = \pi, p_\text{c} = 0.394) \) and quantum \( (\theta = 3\pi/4, p_\text{c} = 0.3) \) instances of the model. Informed by these classical numerics, we perform experiments on the quantum version of the model, choosing \( \theta = 3\pi/4 \) and targeting (1) the active phase \( (p < 0.1) \), (2) the critical regime \( (p = 0.3) \) and (3) the inactive phase \( (p = 0.5) \). We emphasize that although our experiments are not in the quantum advantage regime because they involve only 20 qubits that can be classically simulated, the dynamics of the FQCP model is challenging to compute classically in practice, requiring large-scale matrix product operator simulations at times late enough to see clear signatures of criticality.

The spreading of active sites as a function of space \( r \) and time \( t \) measured in our three sets of experiments is shown in the heatmaps of Fig. 1e. From these heatmaps, we can qualitatively observe the expected physical behaviour: in the active phase \( (p < p_\text{c}) \), the cluster seeded from the single active site grows ballistically in size, forming a clear cone shape; at the critical point \( (p = p_\text{c}) \), the cluster also grows, but sub-ballistically; and in the inactive phase \( (p > p_\text{c}) \), the cluster shrinks as the quantum state is pulled into the inactive absorbing state.

The total number of active sites measured experimentally, compared to noise-less simulations, is shown in Fig. 3a. These plots clearly show how two-qubit gate errors seed new active sites, which leads to a late-time ballistic \( (\sim t) \) propagation of errors for \( p = p_\text{c} \). Despite the gate errors, our data at \( p = 0.1, 0.5 \) are quantitatively accurate to late times.

After zero-noise extrapolation (ZNE), the \( p = 0.3 \) data are quantitatively accurate up to \( t = 12 \), up to which time they show good agreement with DP critical scaling \( (\sim t^\theta) \).

A scaling collapse of the experimental data at the critical point is shown in Fig. 3c, with \( y = (n(r,t)) t^{\Omega(z)} \) plotted versus \( x = r t^{1/z} \) and with \( \Omega, z \) set to the known DP values. Even for the limited \( t \) available, we are able to see a reasonable collapse of the data to a universal curve \( y = f(x) \). The largest deviations from the collapse are seen in the \( t \geq 12 \) experimental data, which show clear deviations from the early-time data, consistent with a change in scaling behaviour due to two-qubit gate errors.

Discussion

We have demonstrated that near-term quantum computers are capable of studying interesting non-equilibrium dissipative quantum phenomena, by examining the phase transition of a quantum circuit generalization of the contact process. The tools we used to make this quantum simulation experimentally feasible—such as qubit reuse and error avoidance using real-time conditional logic—are generally applicable and will be helpful primitives for future studies.

Both tensor-network numerics and direct simulation on a quantum computer indicate that our model exhibits critical scaling at the phase transition consistent with DP. In a related continuous-time model\(^{16-18}\), numerical simulations\(^{15} \) suggested that quantum fluctuations break ‘rapidity-reversal’ symmetry, causing the quantum model to not obey DP scaling. In future work, it would be useful to verify and better understand the origin of this apparent difference between the continuous-time model and the discrete-time model considered in this work. Such a study would greatly benefit from the development of additional tools for simulating open quantum systems, as existing tools\(^{12-42} \) are currently underdeveloped compared to closed-system simulation methods.

In general, open quantum systems, which can have entropy-increasing and entropy-decreasing processes, provide a rich platform for realizing interesting dynamics and steady-state physics and, in practice, are difficult to simulate classically. One promising future direction would be to study open system dynamics in higher spatial dimensions on a quantum computer, because classical simulations of such dynamics are particularly challenging. It would also be important to explore types of non-equilibrium phase transition other than the one considered in this work, particularly those that are robust to hardware errors (in our case, the DP transition is sensitive to bit flips caused by gate errors). One could also investigate the non-equilibrium behaviour of quantum circuits with classical feedback mechanisms\(^{13-42} \)—for example, similar to those employed in quantum error correction—and see if such dynamics can give rise to interesting physics or error-robust critical phenomena.
Online content
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Data availability
The data produced by the Quantinuum devices for this work are available online in Supplementary Information. Additional classical simulation results are available upon reasonable request.

Code availability
The code used to generate data for this work is available upon reasonable request.

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E.C., M.F.-F., D.H., A.C.P. and S.G. conceived the experiment. T.M.G., J.A.G., K.G., D.G., A. Hall, A. Hankin, M.M., T.M., B.N. and R.S. executed the experiment on the Quantinuum quantum computer. E.C. analysed the experimental data. E.C. and Z.C. performed numerical simulations. E.C., M.F.-F., Z.C., A.C.P., D.H. and S.G. wrote the paper and supplement. All authors edited the paper.

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