Computation and holography

Daniel Harlow

MIT

August 10, 2020

Computation and Holography

- The last twenty years have seen substantial theoretical exploration of a deep connection between quantum gravity in asymptotically anti-de Sitter space and strongly-interacting many-body quantum physics: the AdS/CFT correspondence.

Computation and Holography

- The last twenty years have seen substantial theoretical exploration of a deep connection between quantum gravity in asymptotically anti-de Sitter space and strongly-interacting many-body quantum physics: the AdS/CFT correspondence.
- The first ten of those years was dominated by attempts to use classical gravity to provide new insights into many-body physics, but more recently we have transitioned to using many-body physics to teach us about quantum gravity.

Computation and Holography

- The last twenty years have seen substantial theoretical exploration of a deep connection between quantum gravity in asymptotically anti-de Sitter space and strongly-interacting many-body quantum physics: the AdS/CFT correspondence.
- The first ten of those years was dominated by attempts to use classical gravity to provide new insights into many-body physics, but more recently we have transitioned to using many-body physics to teach us about quantum gravity.
- This latter approach however has been limited by the fact that many-body quantum systems are difficult to study analytically: for the most part we have relied on general principles rather than detailed computations.

Computation and Holography

- The last twenty years have seen substantial theoretical exploration of a deep connection between quantum gravity in asymptotically anti-de Sitter space and strongly-interacting many-body quantum physics: the AdS/CFT correspondence.
- The first ten of those years was dominated by attempts to use classical gravity to provide new insights into many-body physics, but more recently we have transitioned to using many-body physics to teach us about quantum gravity.
- This latter approach however has been limited by the fact that many-body quantum systems are difficult to study analytically: for the most part we have relied on general principles rather than detailed computations.
- This is where quantum computation is relevant: theoretically it has already proven very useful in organizing our thinking, and the practice will hopefully eventually enable many concrete calculations.

Quantum simulation of holographic systems

The most obvious use of quantum computers in holography is to simulate the real-time dynamics of the boundary CFT.

Quantum simulation of holographic systems

The most obvious use of quantum computers in holography is to simulate the real-time dynamics of the boundary CFT.

- Confirm expected features of the correspondence ("check the algebra").

Quantum simulation of holographic systems

The most obvious use of quantum computers in holography is to simulate the real-time dynamics of the boundary CFT.

- Confirm expected features of the correspondence ("check the algebra").
- Discover new phenomena which are inaccessible on pencil/paper.

Quantum simulation of holographic systems

The most obvious use of quantum computers in holography is to simulate the real-time dynamics of the boundary CFT.

- Confirm expected features of the correspondence ("check the algebra").
- Discover new phenomena which are inaccessible on pencil/paper.
- Test quantum hardware using gravitational phenomena which are surprising from the boundary point of view: they wouldn't happen unless you are doing things right.

Quantum simulation of holographic systems

The most obvious use of quantum computers in holography is to simulate the real-time dynamics of the boundary CFT.

- Confirm expected features of the correspondence ("check the algebra").
- Discover new phenomena which are inaccessible on pencil/paper.
- Test quantum hardware using gravitational phenomena which are surprising from the boundary point of view: they wouldn't happen unless you are doing things right.

Already some very simple trial runs have been done, with more on the way soon. Swingle/Bentsen/Schleier-Smith/Hayden 2016, Landsman et. al., Nature 2019, Brown et. al., 1911.06314

Quantum simulation of holographic systems

The most obvious use of quantum computers in holography is to simulate the real-time dynamics of the boundary CFT.

- Confirm expected features of the correspondence (“check the algebra”).
- Discover new phenomena which are inaccessible on pencil/paper.
- Test quantum hardware using gravitational phenomena which are surprising from the boundary point of view: they wouldn’t happen unless you are doing things right.

Already some very simple trial runs have been done, with more on the way soon. Swingle/Bentsen/Schleier-Smith/Hayden 2016, Landsman et. al., Nature 2019, Brown et. al., 1911.06314

On the other hand, a full simulation of a boundary system which is dual to quasi-realistic gravity is likely decades away; in particular it will likely be *harder* than simulating QCD (more fields, more symmetries to preserve).

Holography and quantum cryptography

It has been understood in the six years that the AdS/CFT correspondence is an example of a *quantum error correcting code*, leading to many new discoveries:

Holography and quantum cryptography

It has been understood in the six years that the AdS/CFT correspondence is an example of a *quantum error correcting code*, leading to many new discoveries:

- **Entanglement wedge reconstruction:** A precise characterization of which bulk regions can be accessed from which boundary regions, showing that at least in some cases the black hole interior is accessible.

Holography and quantum cryptography

It has been understood in the six years that the AdS/CFT correspondence is an example of a *quantum error correcting code*, leading to many new discoveries:

- **Entanglement wedge reconstruction:** A precise characterization of which bulk regions can be accessed from which boundary regions, showing that at least in some cases the black hole interior is accessible.
- **No global symmetries:** A new argument confirming the old conjecture that quantum gravity does not allow global symmetries, with possible implications for particle physics.

Holography and quantum cryptography

It has been understood in the six years that the AdS/CFT correspondence is an example of a *quantum error correcting code*, leading to many new discoveries:

- **Entanglement wedge reconstruction:** A precise characterization of which bulk regions can be accessed from which boundary regions, showing that at least in some cases the black hole interior is accessible.
- **No global symmetries:** A new argument confirming the old conjecture that quantum gravity does not allow global symmetries, with possible implications for particle physics.
- **Black hole information problem:** Clarifying how information can be recovered from the Hawking radiation of an evaporating black hole.

Holography and quantum cryptography

It has been understood in the six years that the AdS/CFT correspondence is an example of a *quantum error correcting code*, leading to many new discoveries:

- **Entanglement wedge reconstruction:** A precise characterization of which bulk regions can be accessed from which boundary regions, showing that at least in some cases the black hole interior is accessible.
- **No global symmetries:** A new argument confirming the old conjecture that quantum gravity does not allow global symmetries, with possible implications for particle physics.
- **Black hole information problem:** Clarifying how information can be recovered from the Hawking radiation of an evaporating black hole.
- **New Codes:** The codes provided by AdS/CFT often come close to saturating theoretical bounds on the performance of quantum codes. It seems AdS/CFT may be a tool for discovering better quantum cryptography?

Holography and Quantum Complexity

Also making an appearance in recent work on black holes and holography is quantum complexity theory, which is the study of what kinds of tasks can be performed efficiently on a quantum computer.

Holography and Quantum Complexity

Also making an appearance in recent work on black holes and holography is quantum complexity theory, which is the study of what kinds of tasks can be performed efficiently on a quantum computer.

- General arguments show that black holes reveal some information about how they were formed once they are more than halfway evaporated, but standard complexity assumptions imply that extracting this information is exponentially hard. Harlow/Hayden, 2013

Holography and Quantum Complexity

Also making an appearance in recent work on black holes and holography is quantum complexity theory, which is the study of what kinds of tasks can be performed efficiently on a quantum computer.

- General arguments show that black holes reveal some information about how they were formed once they are more than halfway evaporated, but standard complexity assumptions imply that extracting this information is exponentially hard. Harlow/Hayden, 2013
- This exponential difficult was recently geometrized via the notion of a "python's lunch", which gives a new graphical way to think about complexity theory. Brown/Gharibyan/Penington/Susskind, 2019

Holography and Quantum Complexity

Also making an appearance in recent work on black holes and holography is quantum complexity theory, which is the study of what kinds of tasks can be performed efficiently on a quantum computer.

- General arguments show that black holes reveal some information about how they were formed once they are more than halfway evaporated, but standard complexity assumptions imply that extracting this information is exponentially hard. Harlow/Hayden, 2013
- This exponential difficult was recently geometrized via the notion of a "python's lunch", which gives a new graphical way to think about complexity theory. Brown/Gharibyan/Penington/Susskind, 2019
- A related geometrization has been attempted via the various "complexity = something" proposals of Brown/Roberts/Susskind/Swingle/Zhao, 2015.

Holography and Quantum Complexity

Also making an appearance in recent work on black holes and holography is quantum complexity theory, which is the study of what kinds of tasks can be performed efficiently on a quantum computer.

- General arguments show that black holes reveal some information about how they were formed once they are more than halfway evaporated, but standard complexity assumptions imply that extracting this information is exponentially hard. Harlow/Hayden, 2013
- This exponential difficult was recently geometrized via the notion of a "python's lunch", which gives a new graphical way to think about complexity theory. Brown/Gharibyan/Penington/Susskind, 2019
- A related geometrization has been attempted via the various "complexity = something" proposals of Brown/Roberts/Susskind/Swingle/Zhao, 2015.
- Complexity seems to be an important element of the recent progress on the black hole information problem, where a major issue is why the radiation looks thermal unless one looks very closely (i.e. one does something complex).

Each of the three approaches I mentioned is in some sense just beginning. This is clearly the case for the "experimental" program, but even for the theoretical questions there are many remaining issues:

Each of the three approaches I mentioned is in some sense just beginning. This is clearly the case for the "experimental" program, but even for the theoretical questions there are many remaining issues:

- How do we think about locality at distances which are small compared to the AdS radius?

Each of the three approaches I mentioned is in some sense just beginning. This is clearly the case for the "experimental" program, but even for the theoretical questions there are many remaining issues:

- How do we think about locality at distances which are small compared to the AdS radius?
- How do we think about the interior of black holes in generic microstates?

Each of the three approaches I mentioned is in some sense just beginning. This is clearly the case for the "experimental" program, but even for the theoretical questions there are many remaining issues:

- How do we think about locality at distances which are small compared to the AdS radius?
- How do we think about the interior of black holes in generic microstates?
- How complex is the AdS/CFT dictionary for general bulk observables?

Each of the three approaches I mentioned is in some sense just beginning. This is clearly the case for the "experimental" program, but even for the theoretical questions there are many remaining issues:

- How do we think about locality at distances which are small compared to the AdS radius?
- How do we think about the interior of black holes in generic microstates?
- How complex is the AdS/CFT dictionary for general bulk observables?
- How do we move beyond AdS to more realistic cosmologies?

Each of the three approaches I mentioned is in some sense just beginning. This is clearly the case for the "experimental" program, but even for the theoretical questions there are many remaining issues:

- How do we think about locality at distances which are small compared to the AdS radius?
- How do we think about the interior of black holes in generic microstates?
- How complex is the AdS/CFT dictionary for general bulk observables?
- How do we move beyond AdS to more realistic cosmologies?

I am optimistic that the solutions of these problems will involve quite a bit of back and forth with the theory, and hopefully the practice, of quantum computation, with plenty of benefit to all involved!