

Our Universe

The universe contains 4 fundamental forces. In our day to day life, we only observe two of these forces:

1. Electromagnetism: The force which produces electricity (e.g electrons and their flow around circuits).
2. Gravity: The force which makes us fall to the ground and keeps the earth revolving around the sun.

An open problem in modern physics is to combine electromagnetism and gravity into a singular mathematical theory. Recent developments have shown that these two forces are related via a process known as the *Double Copy*.

The Double Copy: An Overview

The Double Copy is a *duality* (an invertible relationship between two theories) between classical electromagnetism (electricity and magnetism without the presence of Quantum Mechanics) and Einstein's theory of General Relativity, our most complete theory of gravity.

The Double Copy works by taking the mathematical description of phenomena in electromagnetism (such as an electron), and multiplying it (along with various replacement rules to swap out special numbers in electromagnetism for special numbers in gravity) with itself to produce a (corresponding) solution in gravity.

Figure (1) schematically illustrates the process of taking the Double Copy of an electron to a special type of black hole known as the *Schwarzschild solution*.

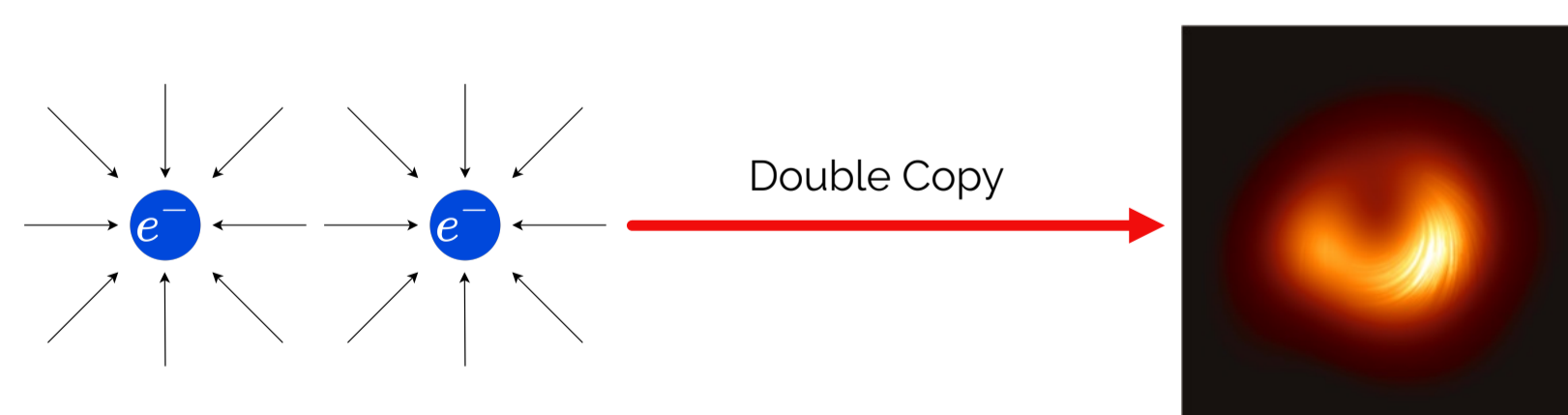


Figure 1. An electron being doubled copied into a black hole [1].

Biadjoint Scalar Theory: The Blueprint for the Natural World

It turns out that both General Relativity and Electromagnetism are both related to a theory known as *Biadjoint Scalar theory*. The fascinating thing about the Biadjoint Scalar theory is that it is not a physical theory of nature, but yet hardcodes into itself some of the information needed to describe every phenomenon we appreciate in our day-to-day lives on earth [2, 3].

The General Relationship

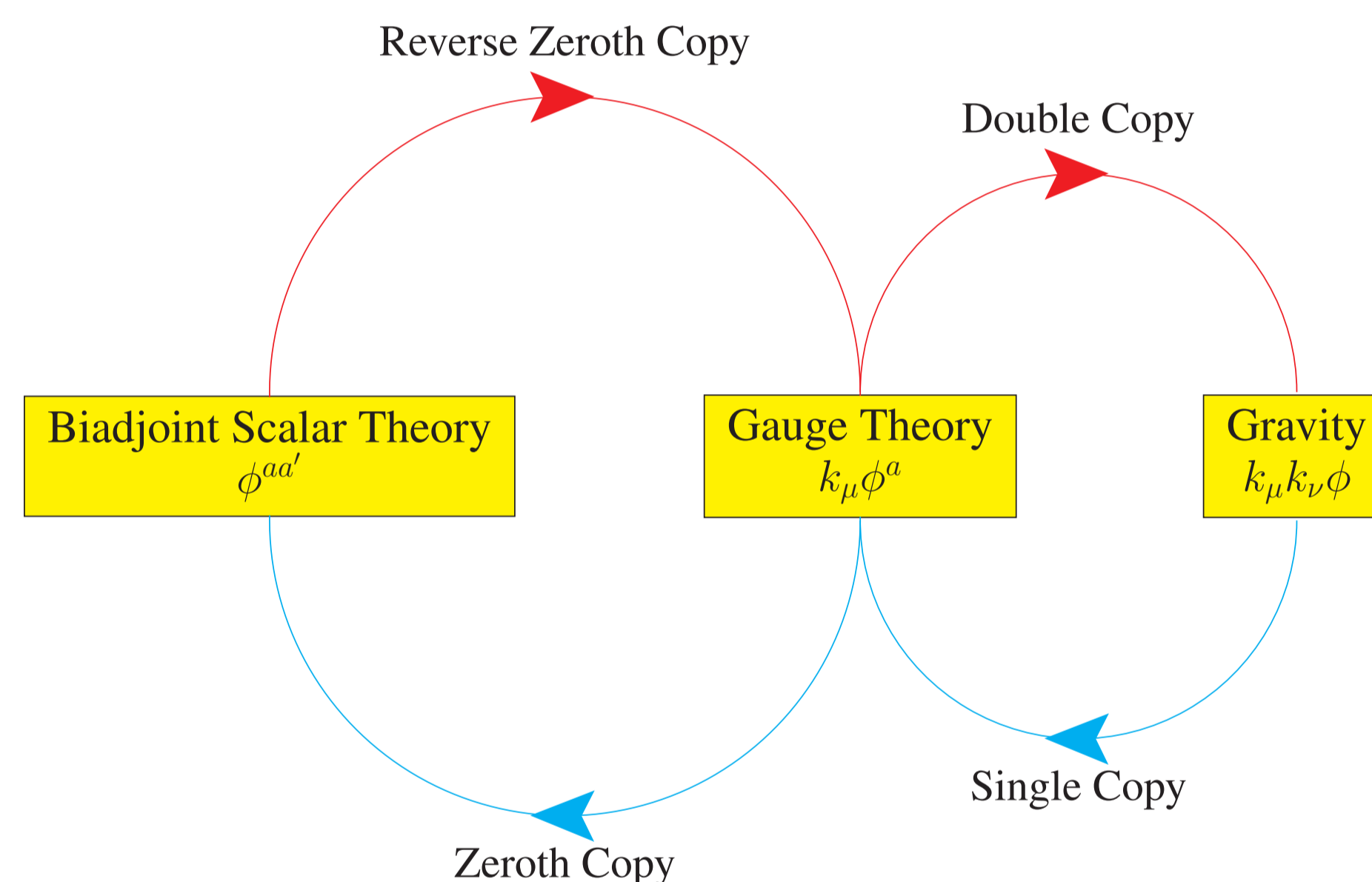


Figure 2. The Double Copy relationship.

An intricate set of processes are required to connect all 3 of these theories (as seen in Figure (2)). Firstly, the *Single Copy* is the inverse process of the Double copy; it takes an object in gravity and processes it into a phenomenon in Electromagnetism (also known as a *Gauge Theory*).

Moreover, the process which takes us from Electromagnetism to Biadjoint Scalar theory is known as *Zeroth Copy*, with its inverse being the *Inverse Zeroth Copy*.

Similar to the Double Copy, the Zeroth Copy involves replacing special numbers belonging to electromagnetism numbers with numbers corresponding to Biadjoint Scalar theory.

Using Maths to Connect the World

To relate these dualities to mathematics, we again refer to Figure (2). For Biadjoint Scalar theory, we denote the theory with a quantity $\phi^{aa'}$. The indices a and a' and referred to as *gauge indices*. Simply, the presence of a singular gauge index assigns a compass at each point in space; whose needle points in a certain direction. In the case of Biadjoint Scalar theory, every point in space has two associated compasses.

Applying the Inverse Zeroth Copy on Biadjoint Scalar Theory to obtain Electromagnetism, removes one of the gauge indexes (a') off $\phi^{aa'}$, and replaces it with an object known as a *Kerr-Schild vector* (k_μ). k_μ has a value for each direction in space (where μ labels the different values for each direction).

In addition, the Double Copy removes the final gauge index off ϕ^a (a) and replaces it with an additional Kerr-Schild vector (k_ν) to give a corresponding object in gravity. In order to perform the inverse operations to ultimately take gravity phenomena into Biadjoint Scalar Theory, one would simply have to follow the above procedure backwards

The Double Copy: Beyond Day to Day Life

In generality, the Double Copy works for gauge theories other than Electromagnetism, known as *non-abelian* gauge theories. Non-abelian gauge theories play an integral role in the mathematics of the other two fundamental forces of nature (strong and weak nuclear forces). These two forces play a significant role in the mechanics of particle physics.

We can also apply the Double Copy to theories that incorporate Quantum Mechanics into themselves. The next big step for the Double Copy is to see whether it can be used to unite all 4 fundamental forces of nature into one mathematical theory. It is the job of myself and other theoretical physicists to see if this can be realized.

References

- [1] Kazunori Akiyama. First m87 event horizon telescope results. VII. polarization of the ring. page 48.
- [2] Chris D. White. The double copy: gravity from gluons. 59(2):109–125.
- [3] Chris D. White. Exact solutions for the biadjoint scalar field. 763:365–369.