A la recherche de temps perdu... in quantum gravity

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Quantum Gravity is a shorthand for "Unity of Physics"

"Quantum Gravity" names the most serious "disjunction" in fundamental physics: our best theory of gravity is classical yet matter is quantum mechanical.

What road shall we take in seeking Unity? What will guide us?

Look for observational evidence: Signs that our current best theories are not doing well when it comes to explaining what we observe.

We can look **outwards** to Cosmology (more on this at the end).

In this talk I will suggest that we can also look **inwards**, to intimate experience for guidance. I am going to suggest that we have evidence that points in a particular direction of research in quantum gravity that is up close and personal: **our experience of the passage of time.**

The passage of time: is something lacking from GR?

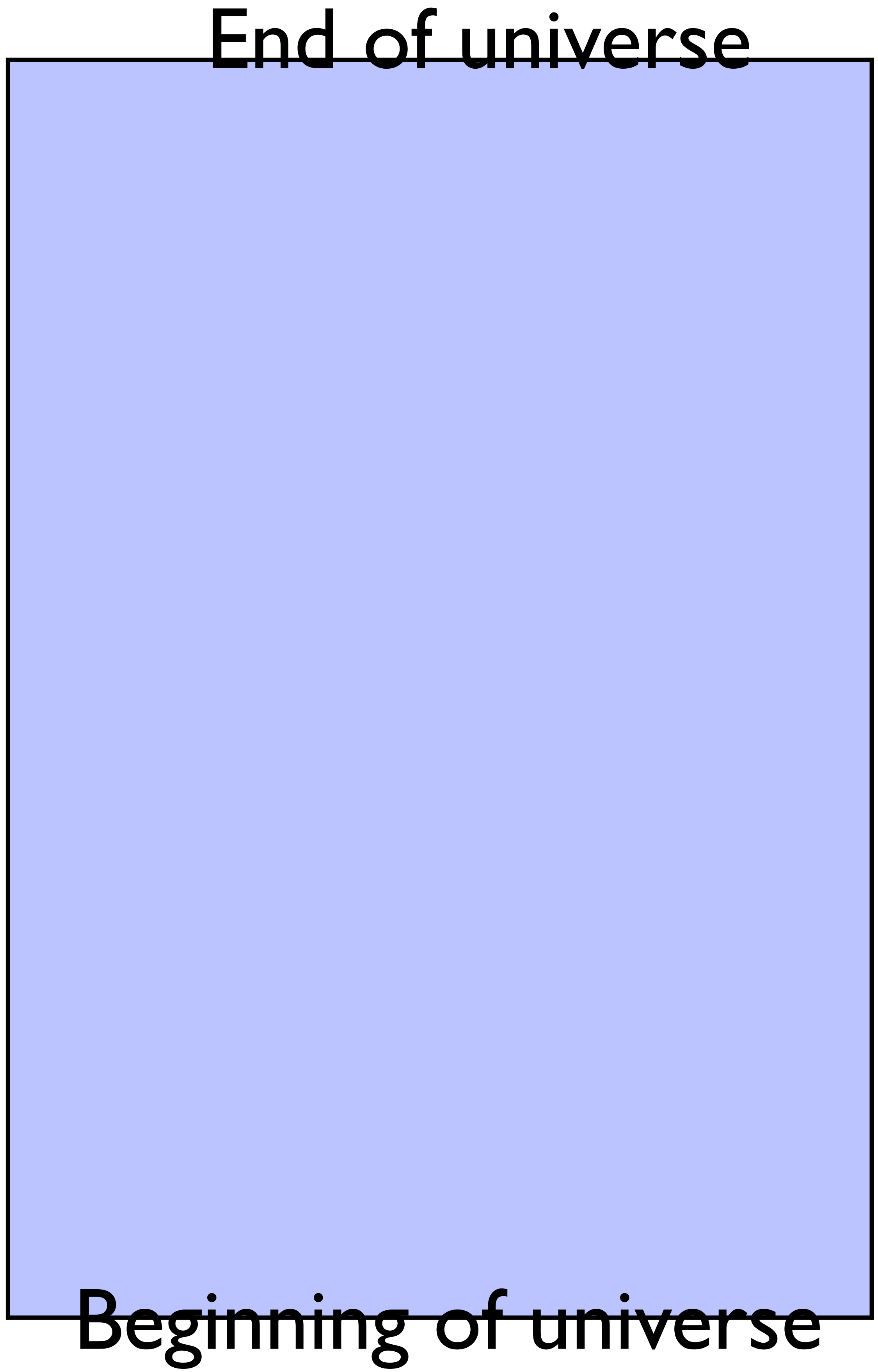
Is there something essential about our experience of the passage of time that cannot be accounted for within General Relativity?

There's no consensus on this! Scientists disagree and I believe there is no way to resolve the disagreement at our current stage of understanding of nature.

I'm going to argue instead that taking the view that GR does **not** do justice to our experience could be a fruitful heuristic in working towards a deeper theory of spacetime.

"Relativity theory does not imply that the future already exists: a counterexample" Rafael D. Sorkin gr-qc/0703098

In GR: the physical world is a 4 dimensional Block



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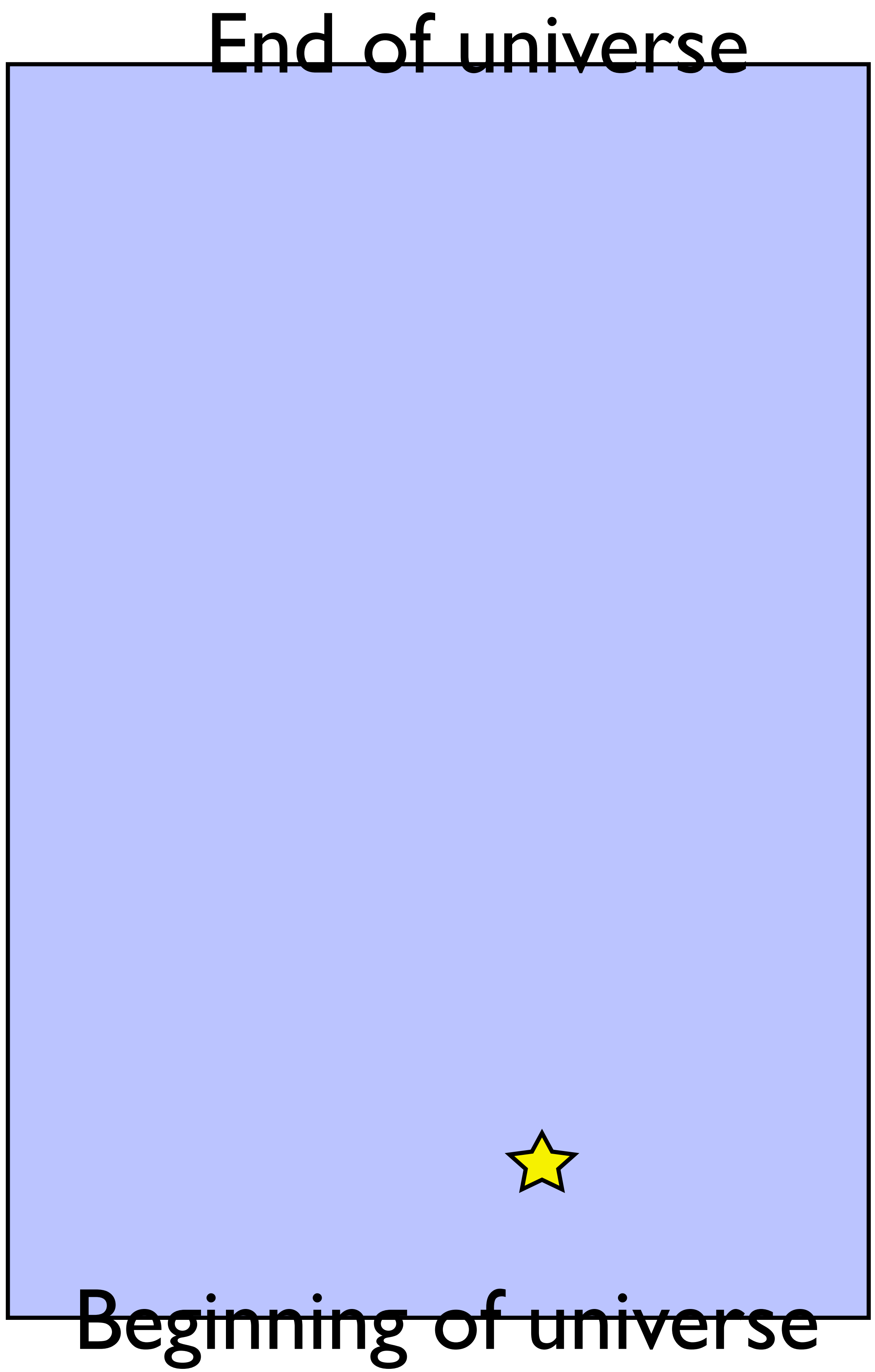

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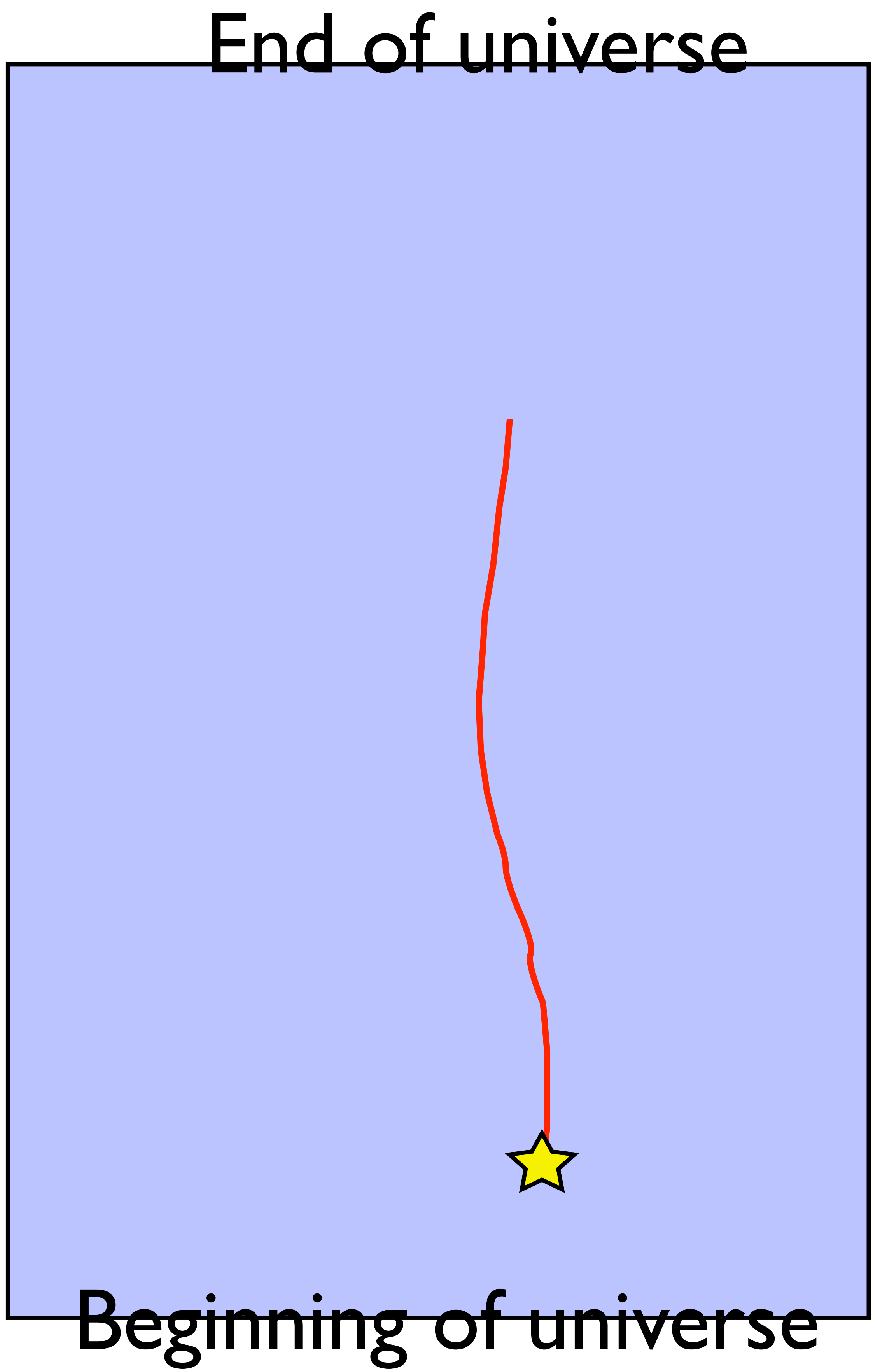

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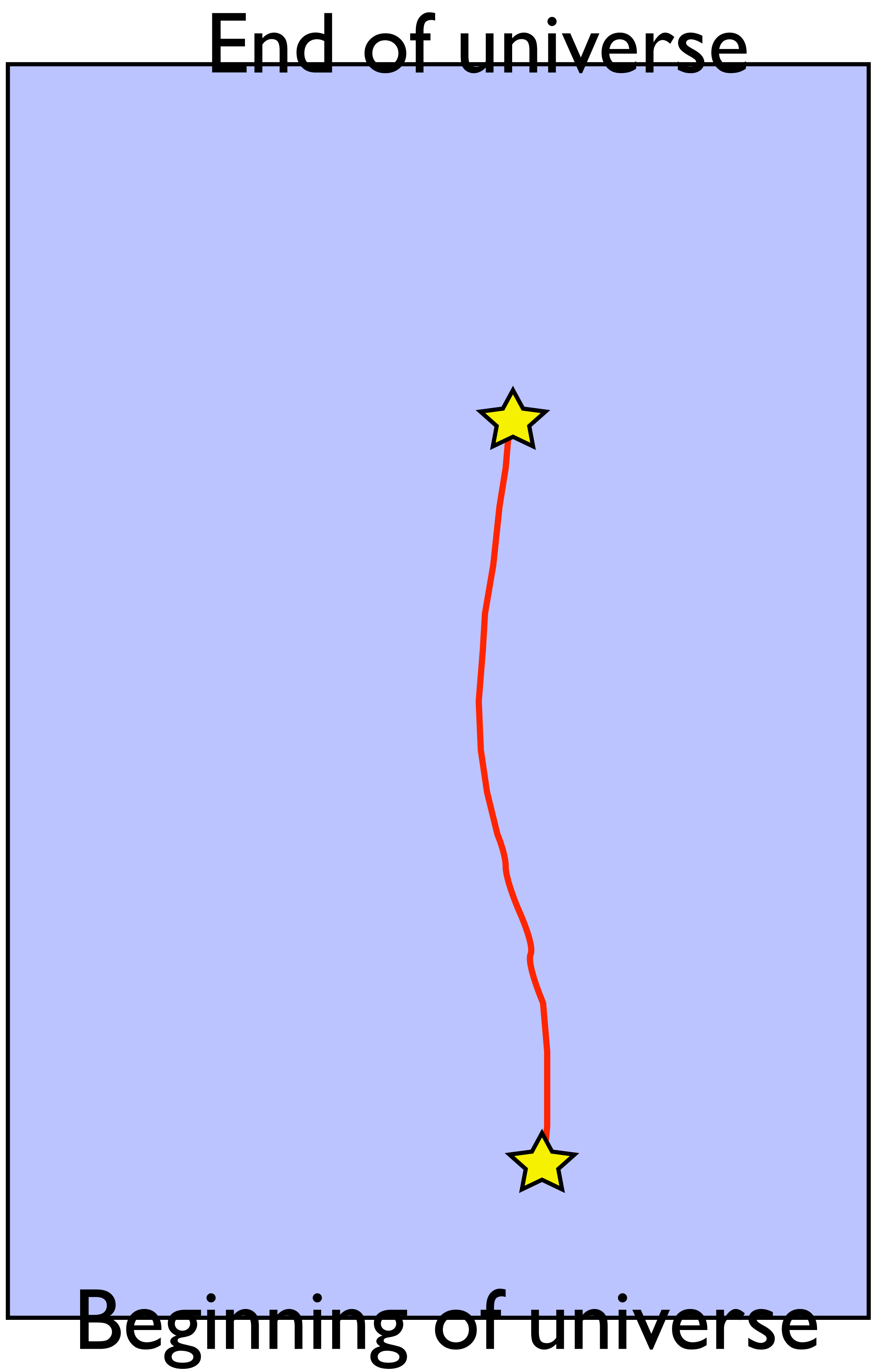

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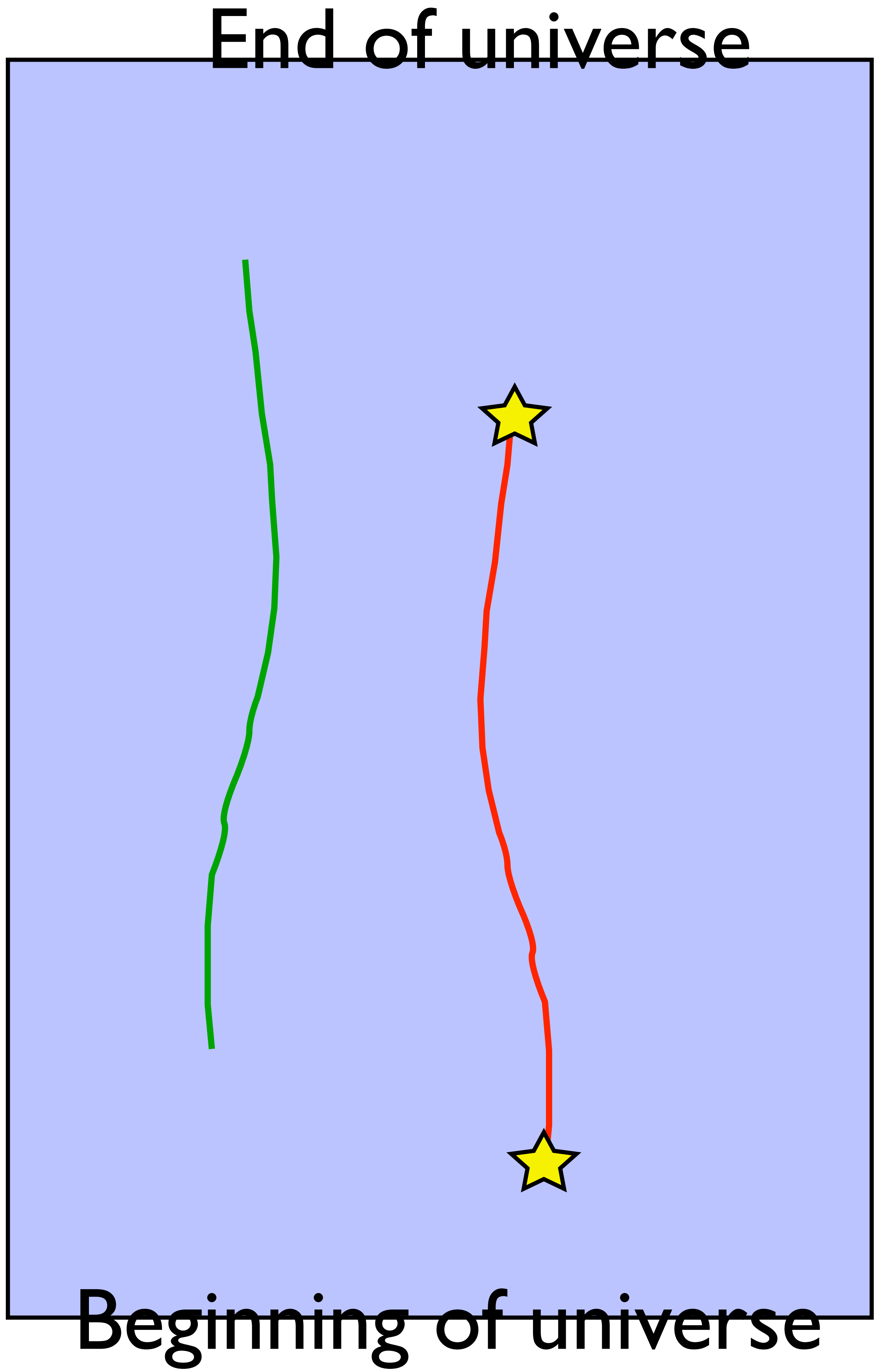

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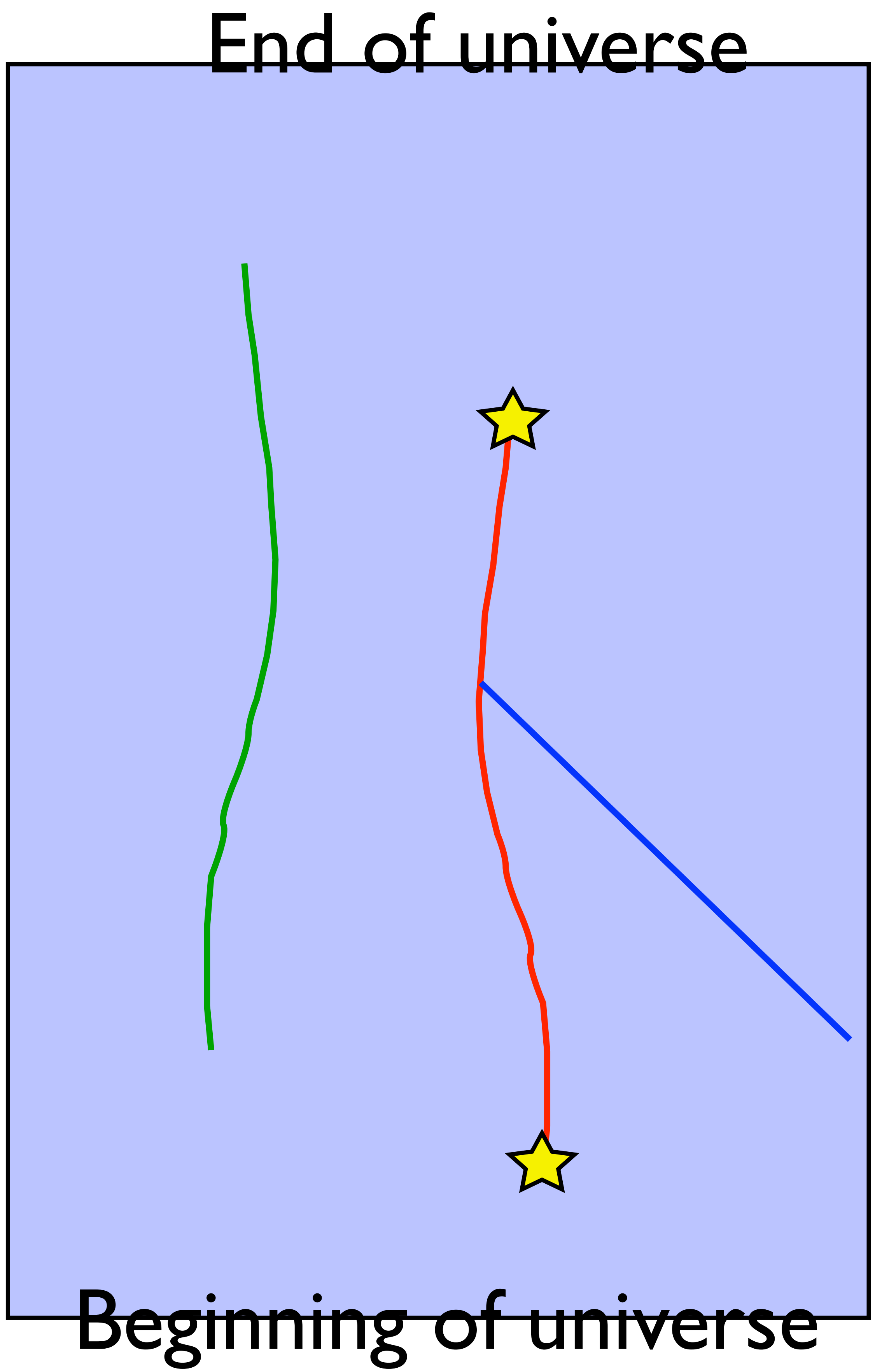

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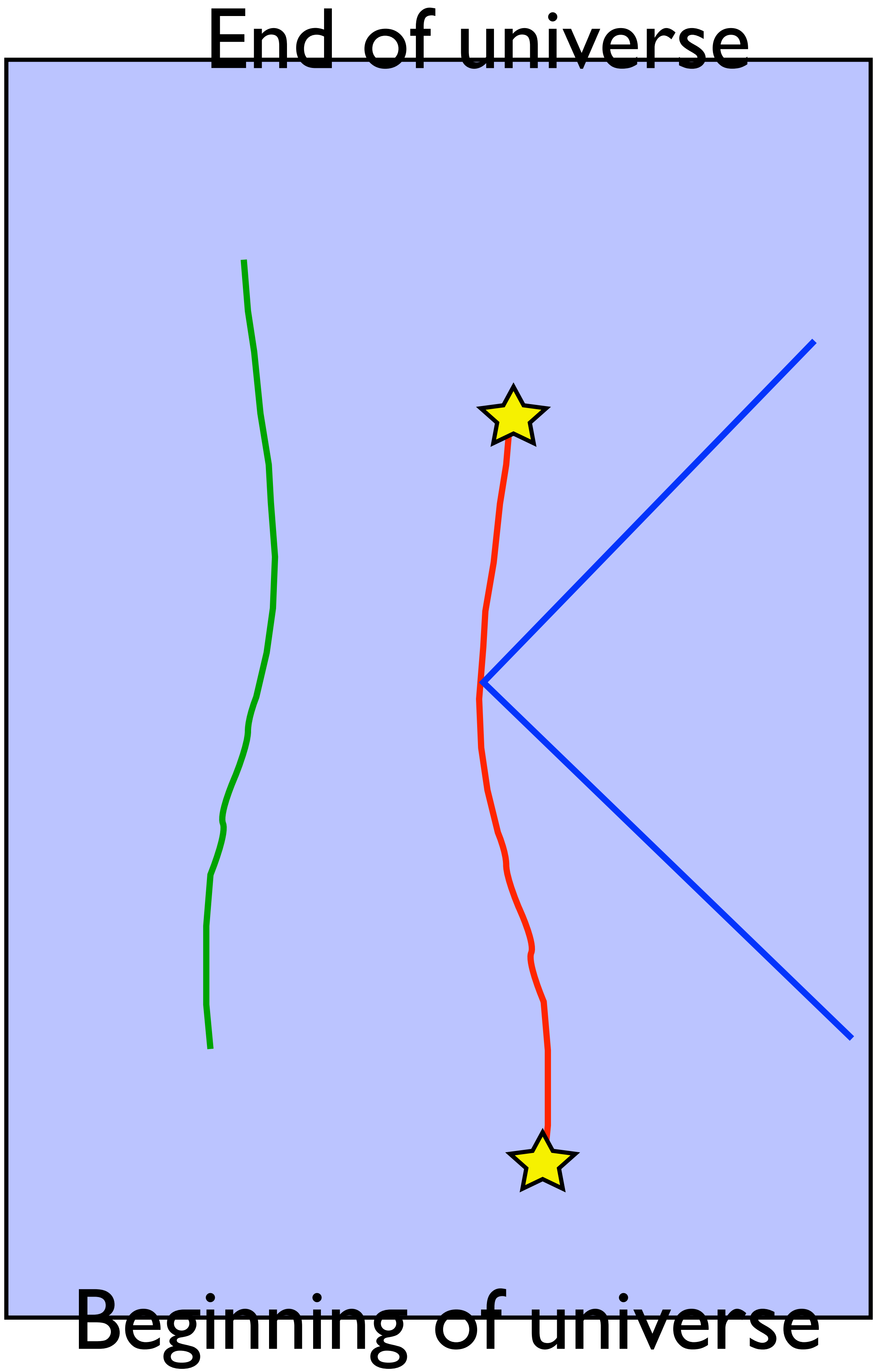

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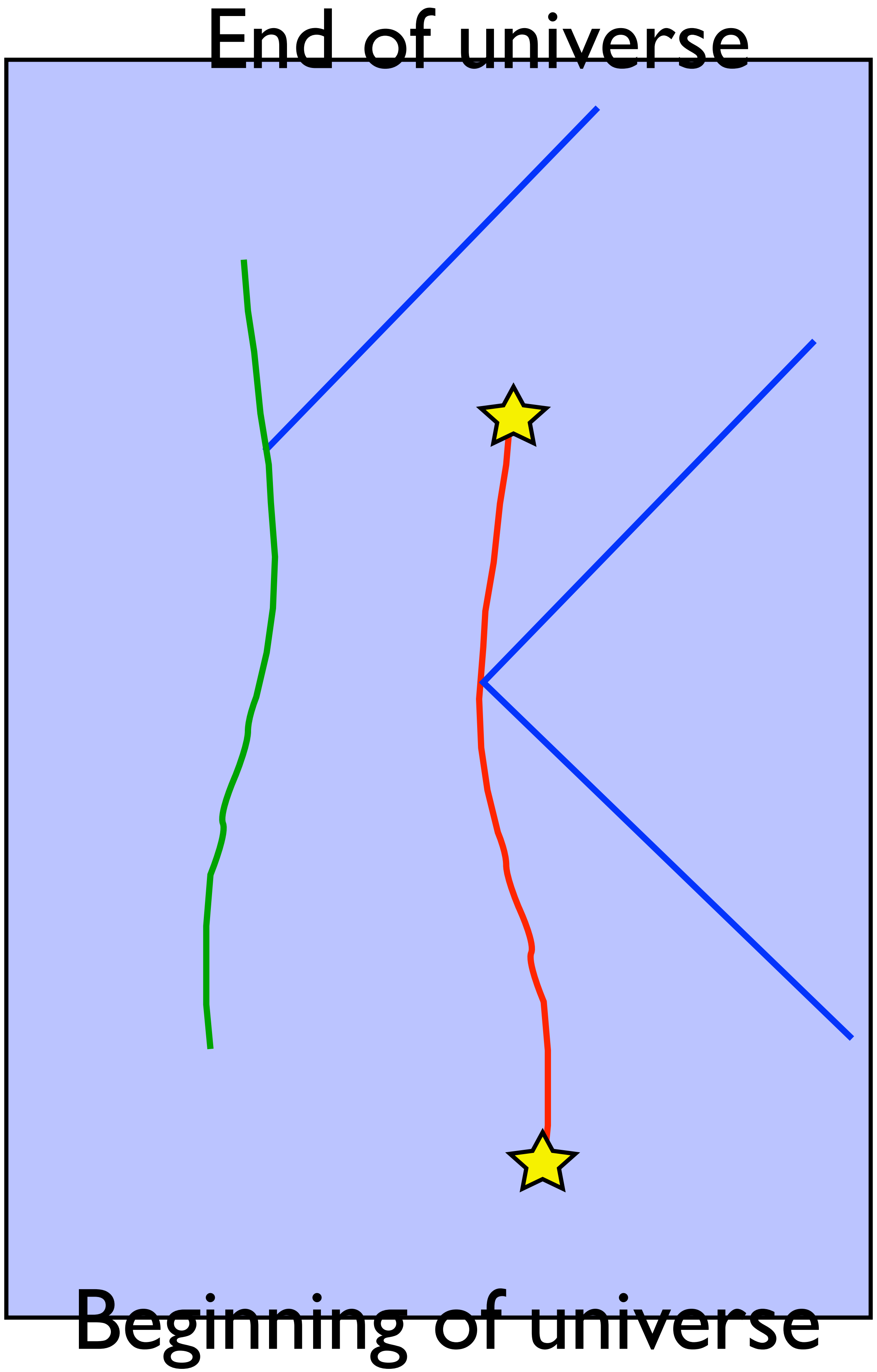

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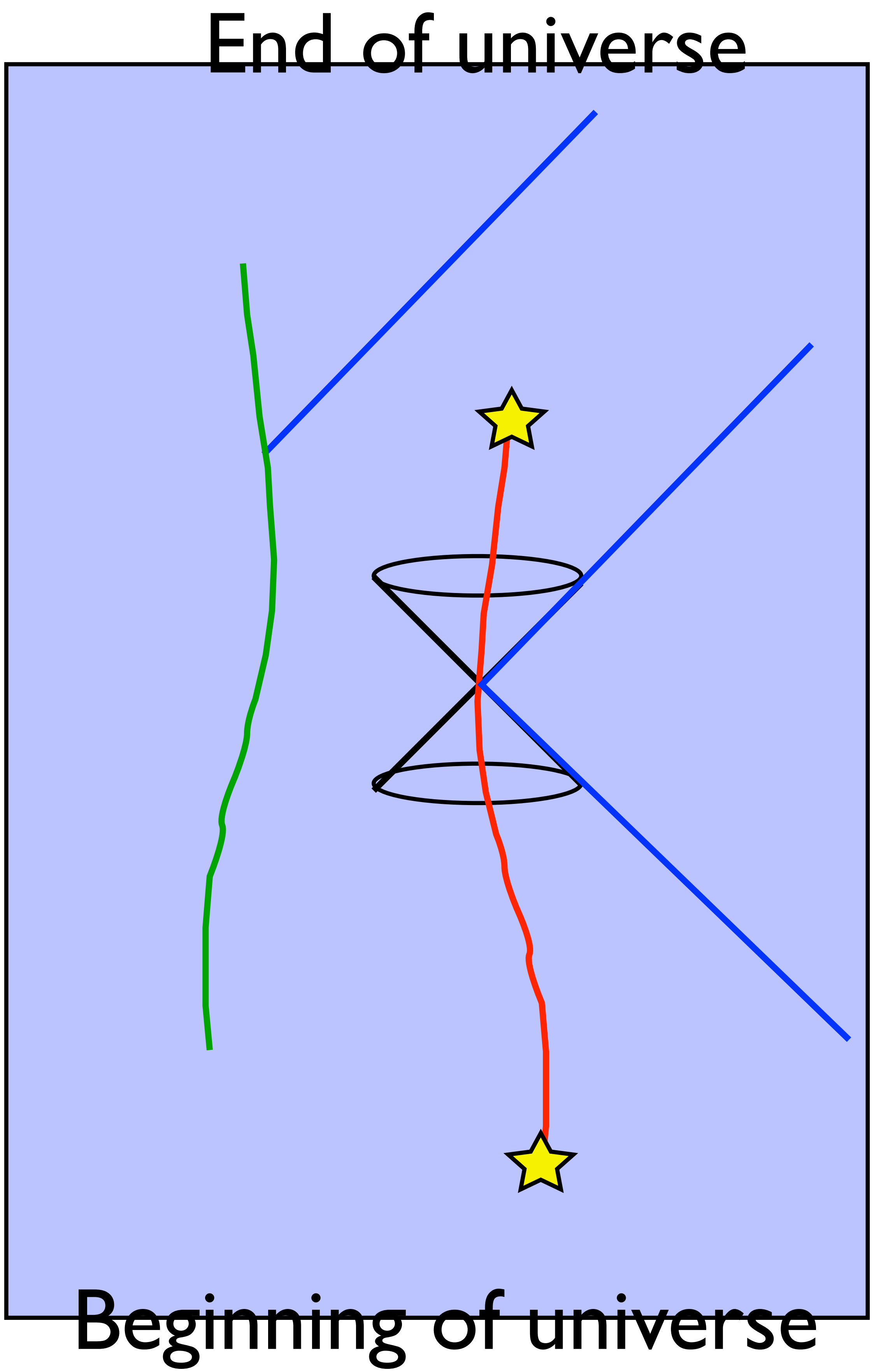
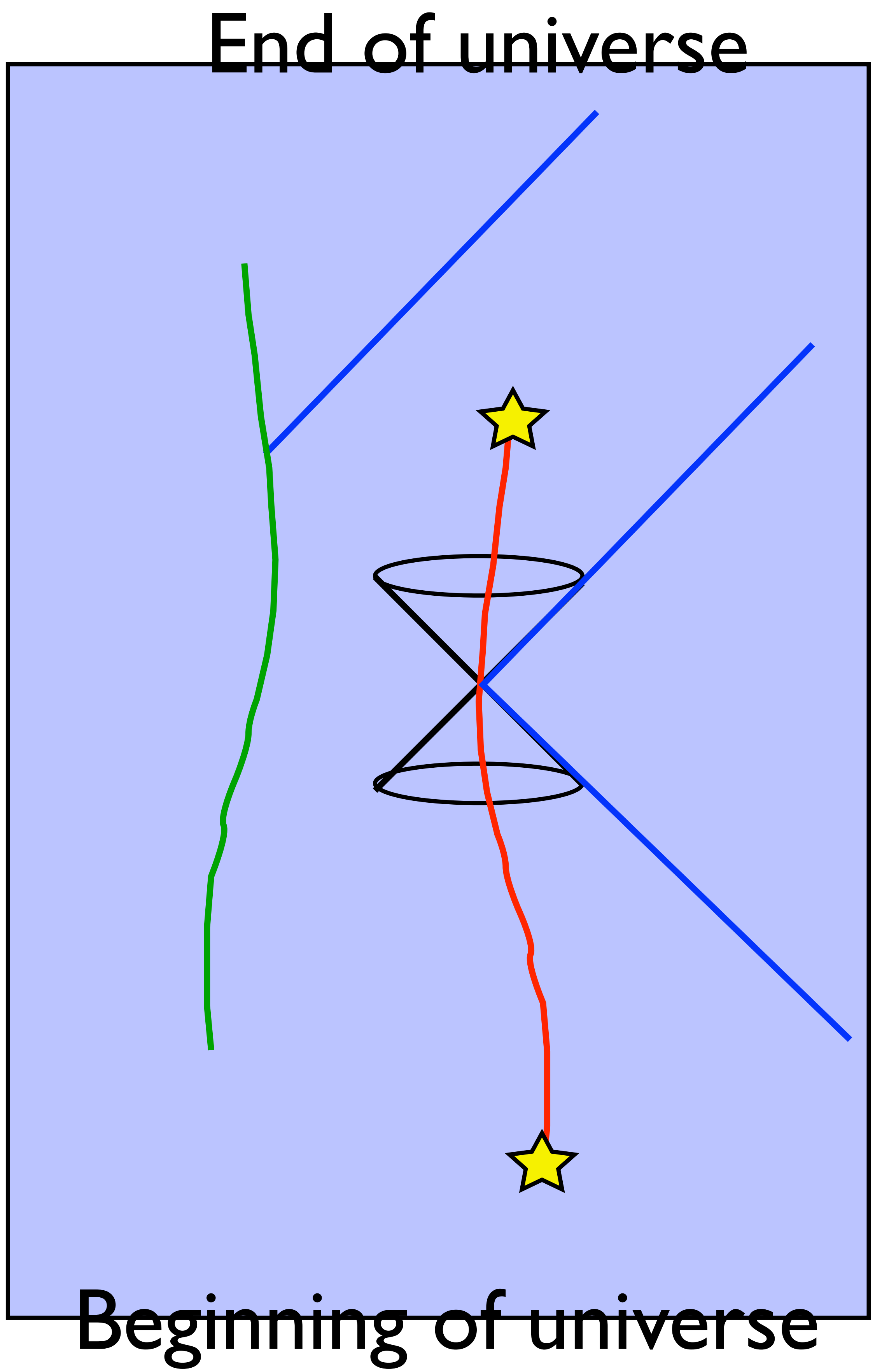


In GR: the physical world is a 4 dimensional Block

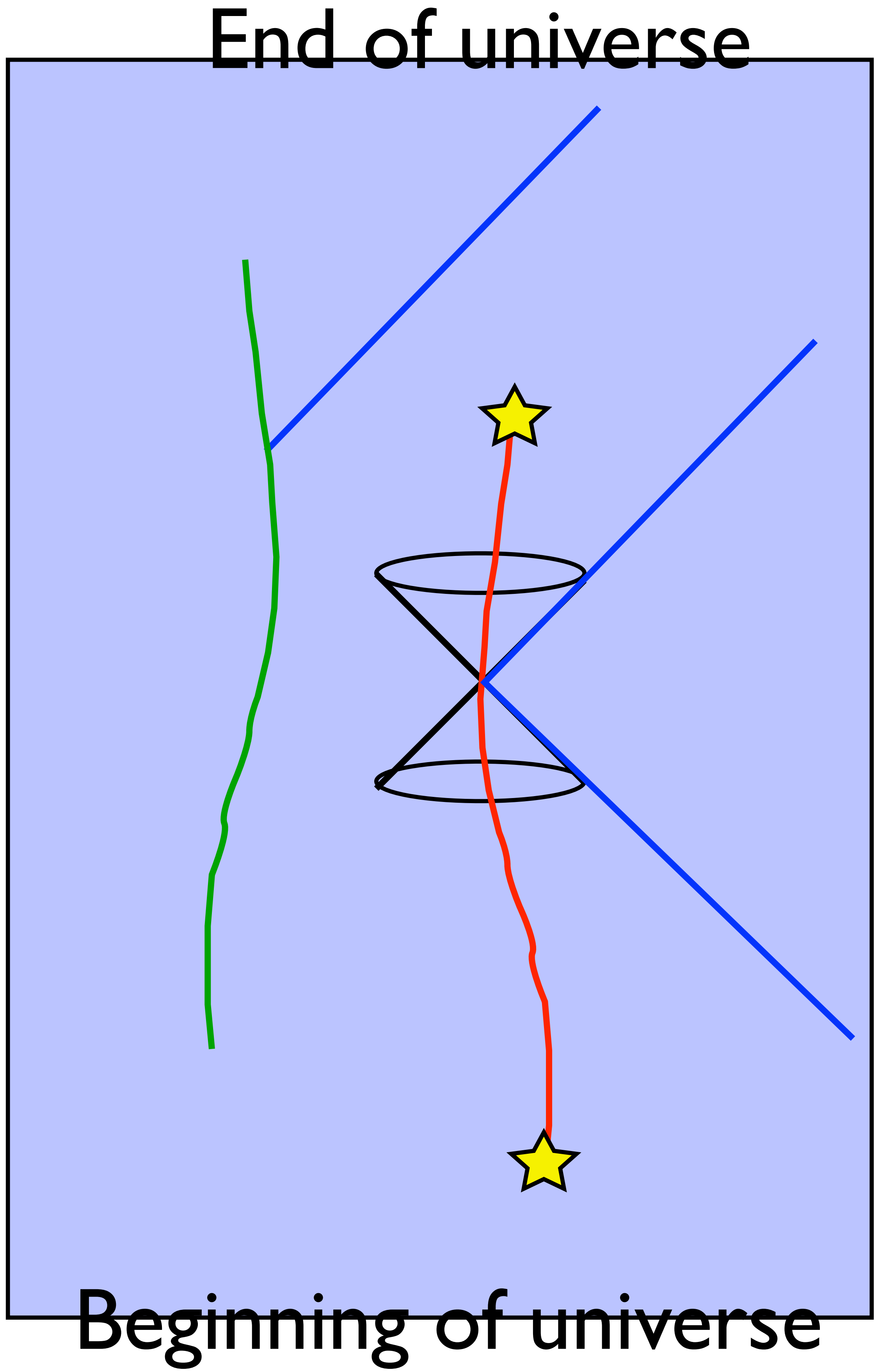
Spacetime itself obeys physical law



In GR: the physical world is a 4 dimensional Block

Spacetime itself obeys physical law

Nature has a spacetime character



Where is time in the Block?

Physical time is proper time along each timelike worldline. But where is the Now in the Block? There is no **global** Now because of General Covariance: any time function on spacetime is just a coordinate and has no physical significance.
A physical, global time does not exist in GR.

This has led many physicists to believe that a physical passage of time is incompatible with relativity. The Block simply exists, past, present and future "all at once" and our experience of the passage of time must be an illusion: Le Temps, c'est Perdu!

Others disagree.

I will show you that in a new conception of spacetime in which it is fundamentally **discrete or atomic**, there are new possibilities for dynamical laws which open the door to the recovery of the passage of time in physics.

Spacetime Discreteness

Most workers expect that in quantum gravity spacetime will not be described by a smooth manifold at the Planck scale and some kind of short distance cutoff will come into play. Spacetime discreteness is the simplest idea that realises this expectation: one spacetime atom per Planck volume of spacetime.

Note, the discreteness being proposed is **spacetime** discreteness not **spatial** discreteness:

10^{240} **Spacetime atoms** in the observable universe!

What structure can bind these atoms together so that they can form a Lorentzian geometry?

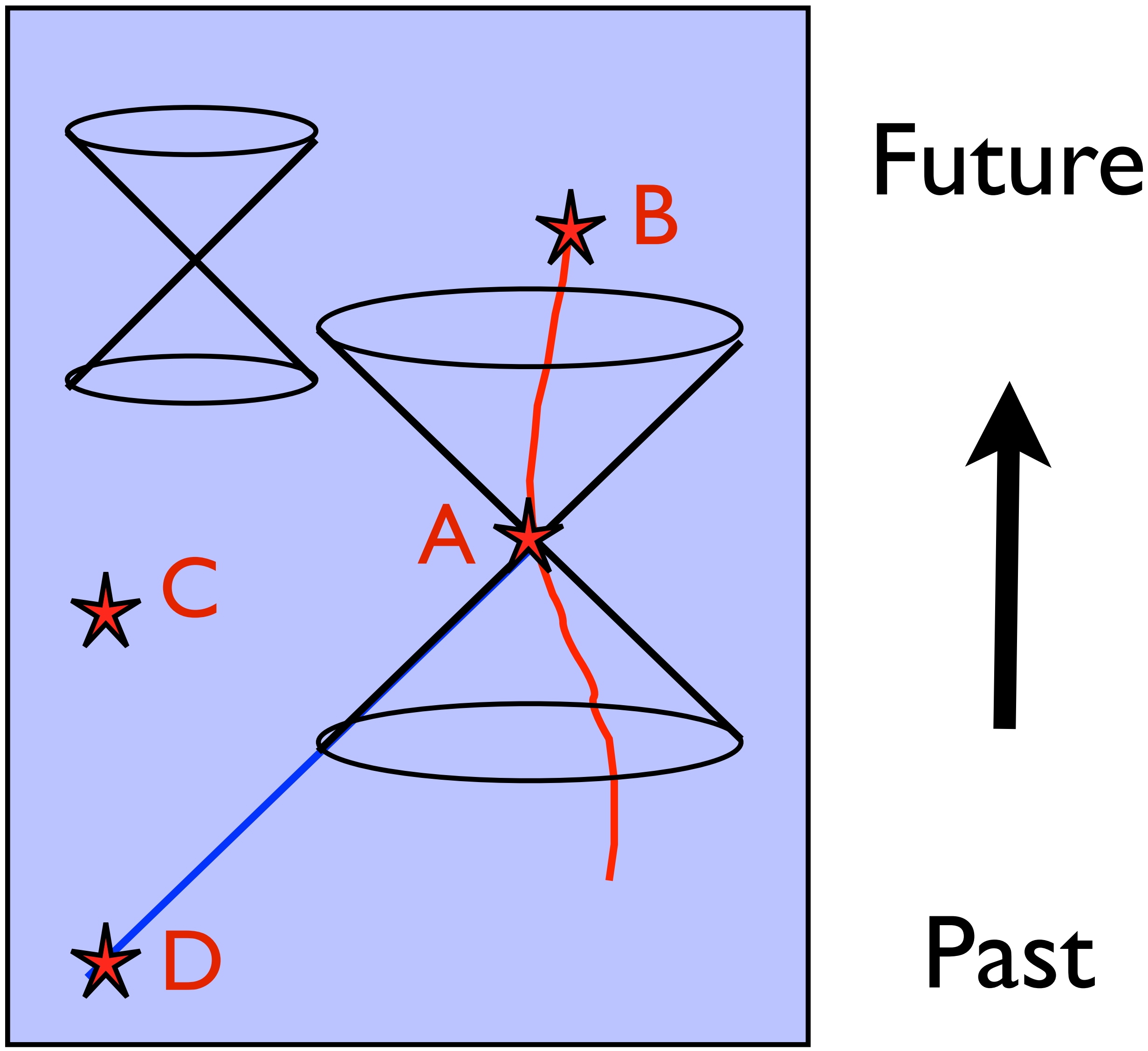
Theorem (Penrose, Kronheimer, Hawking, Malament): causal order plus spacetime volume tells you the whole Lorentzian geometry.

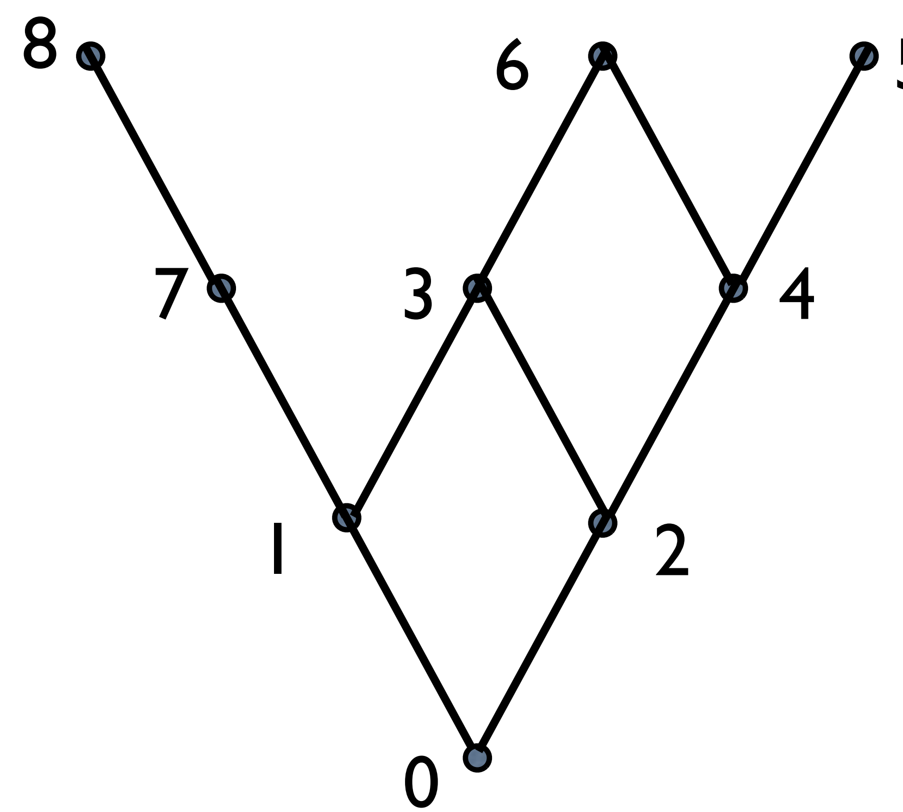
Discrete causal order = causal set

Spacetime in GR has a causal order. That causal order is fundamental to understanding GR (e.g. black holes)

Hypothesis: Underlying continuum spacetime is a **discrete partial order or causal set**

Sorkin





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Growth models for discrete spacetime (Rideout&Sorkin)

- A random process of continual births of new spacetime atoms.
- The two runs shown above are different representations of the same physics. They have the same probability. The only thing physical about the birth order is the order relation of the causal set that results.

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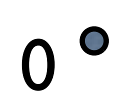

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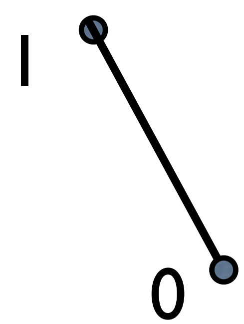

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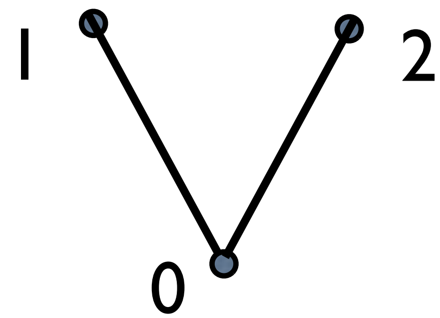

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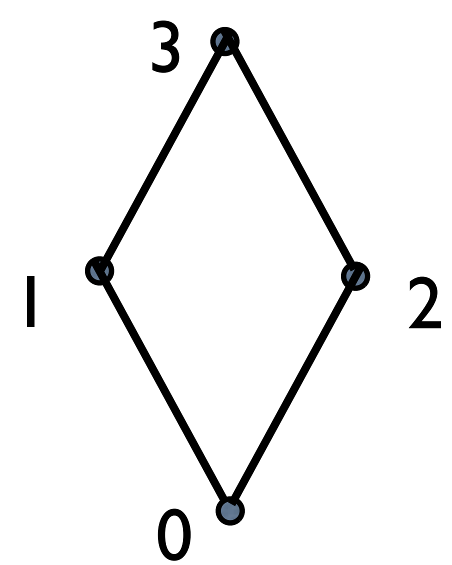

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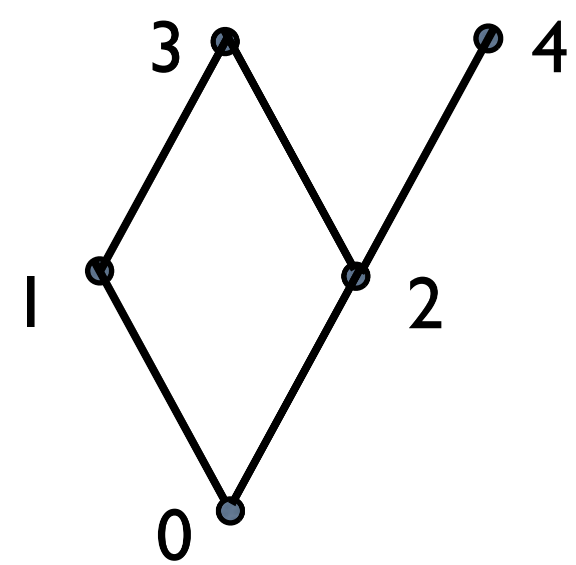

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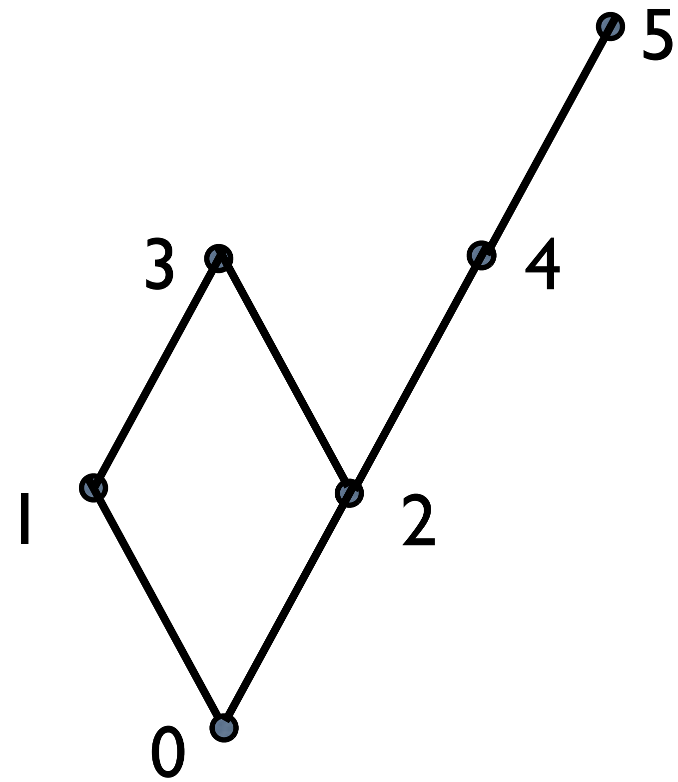

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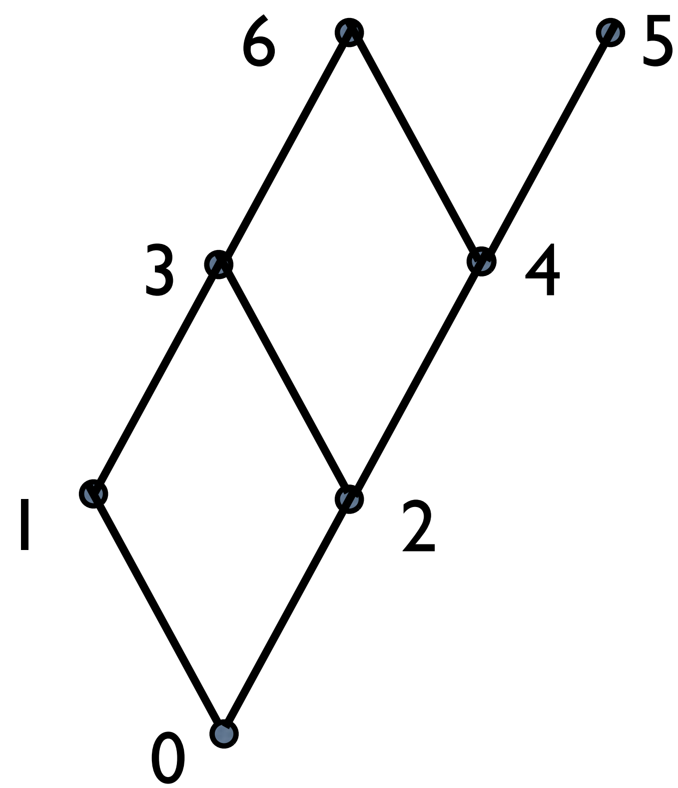

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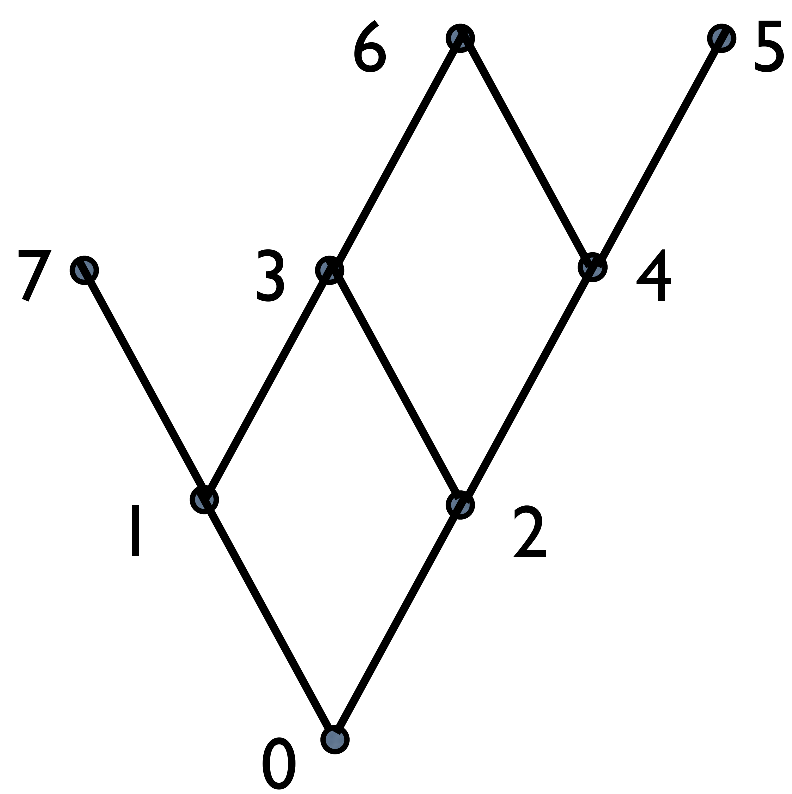

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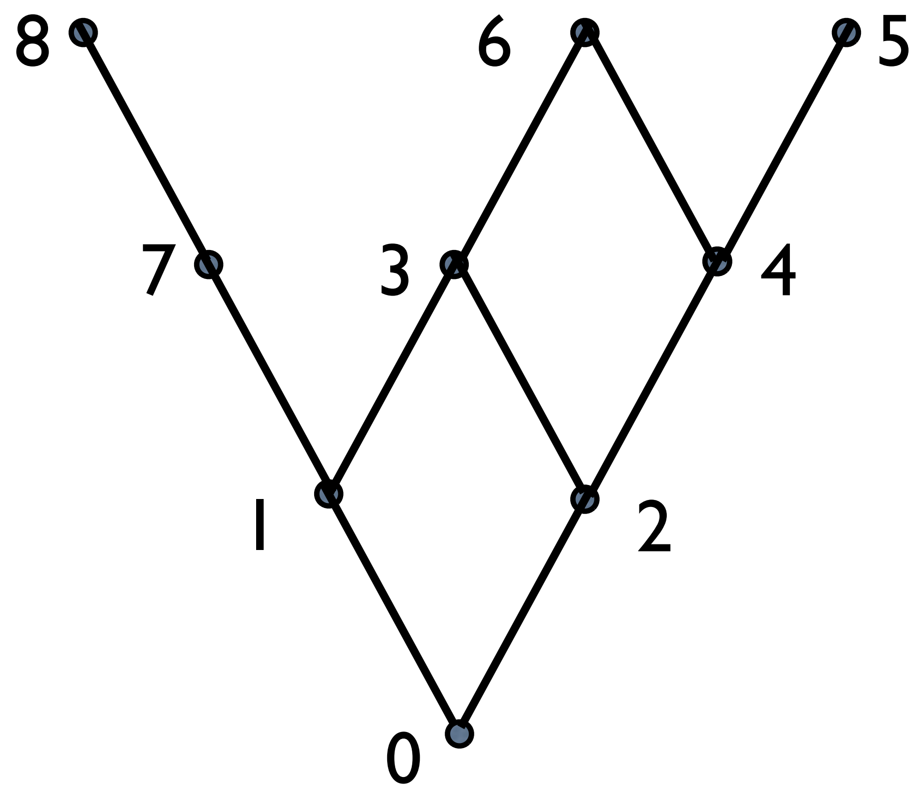

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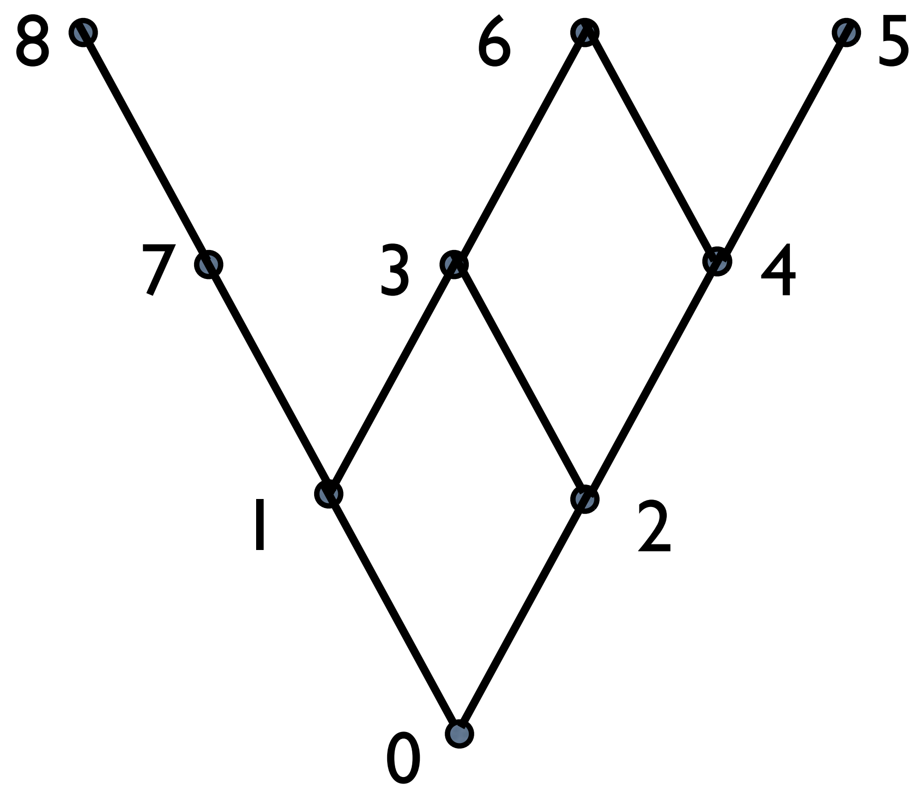

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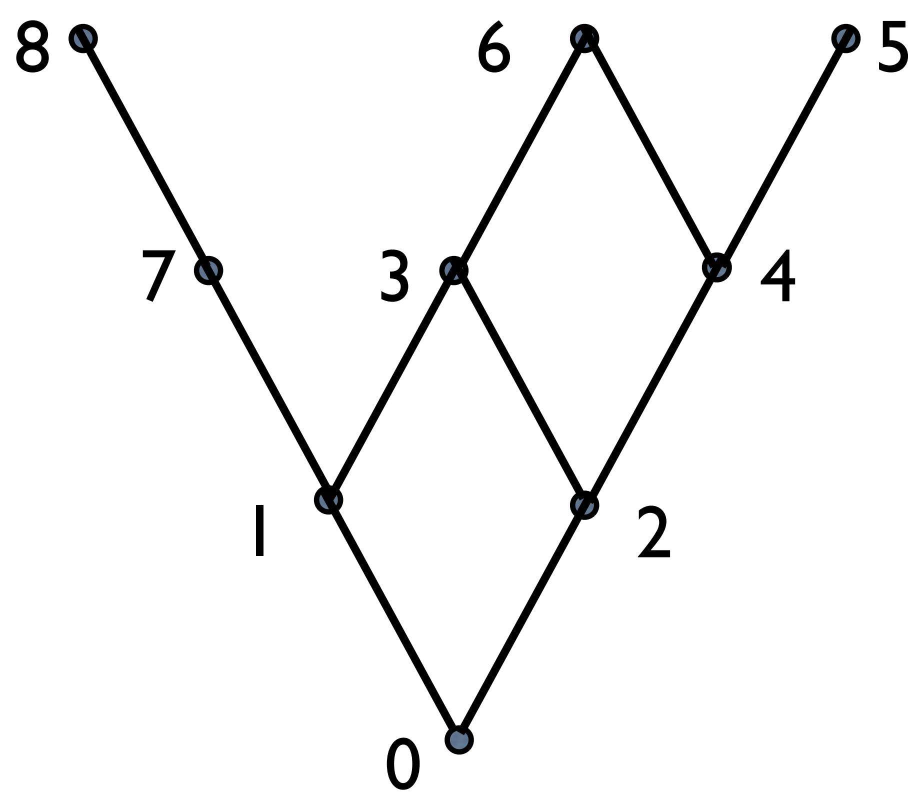

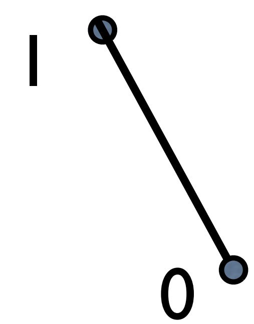

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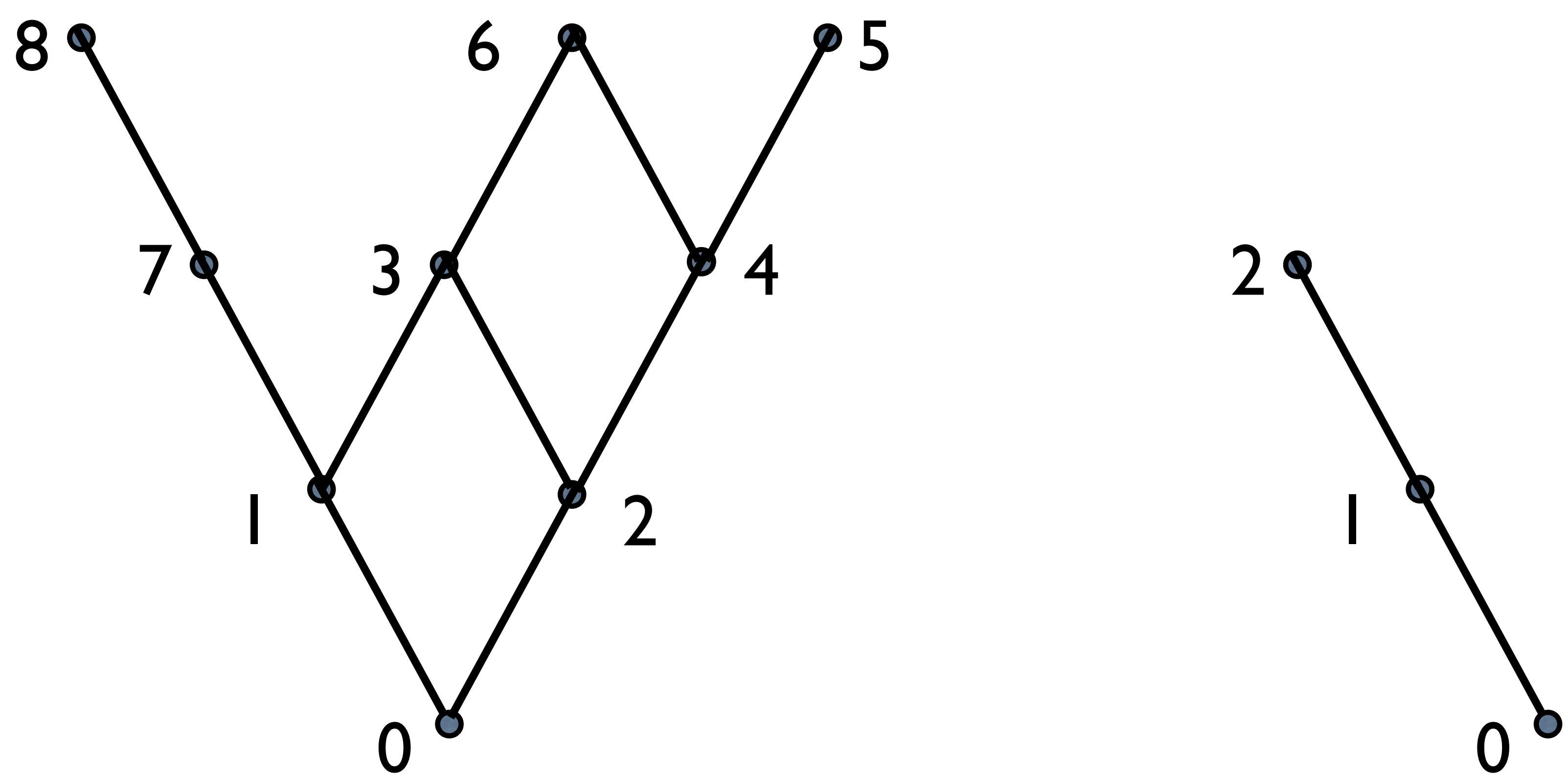

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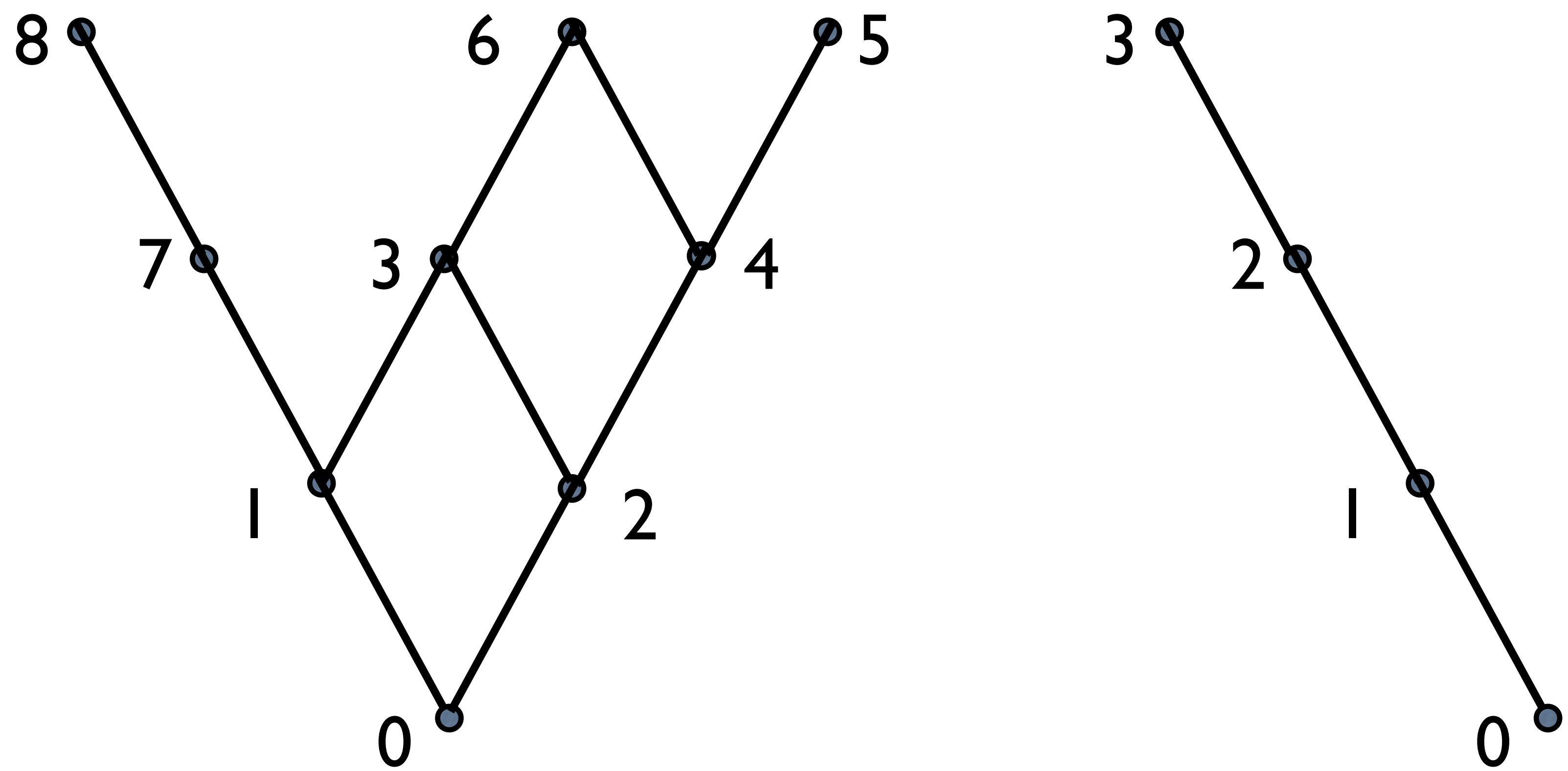

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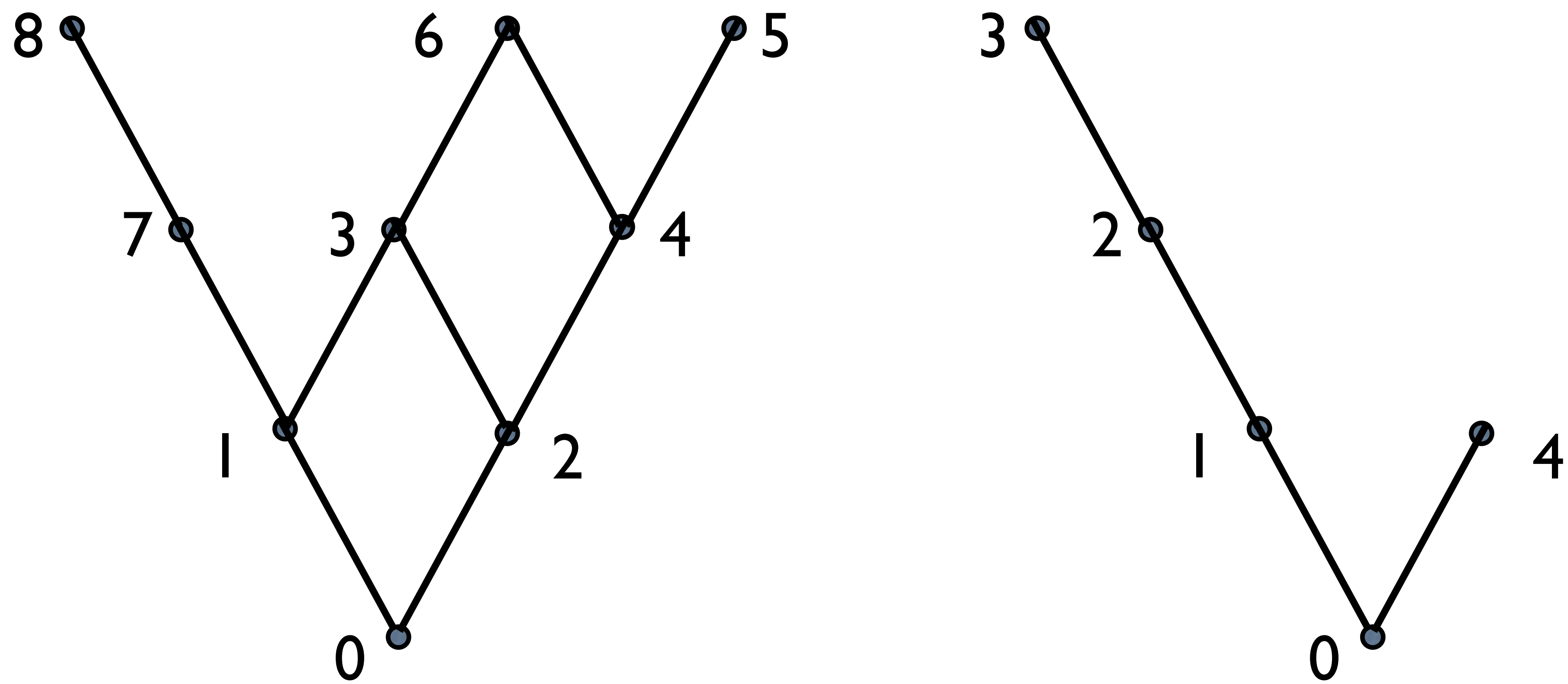

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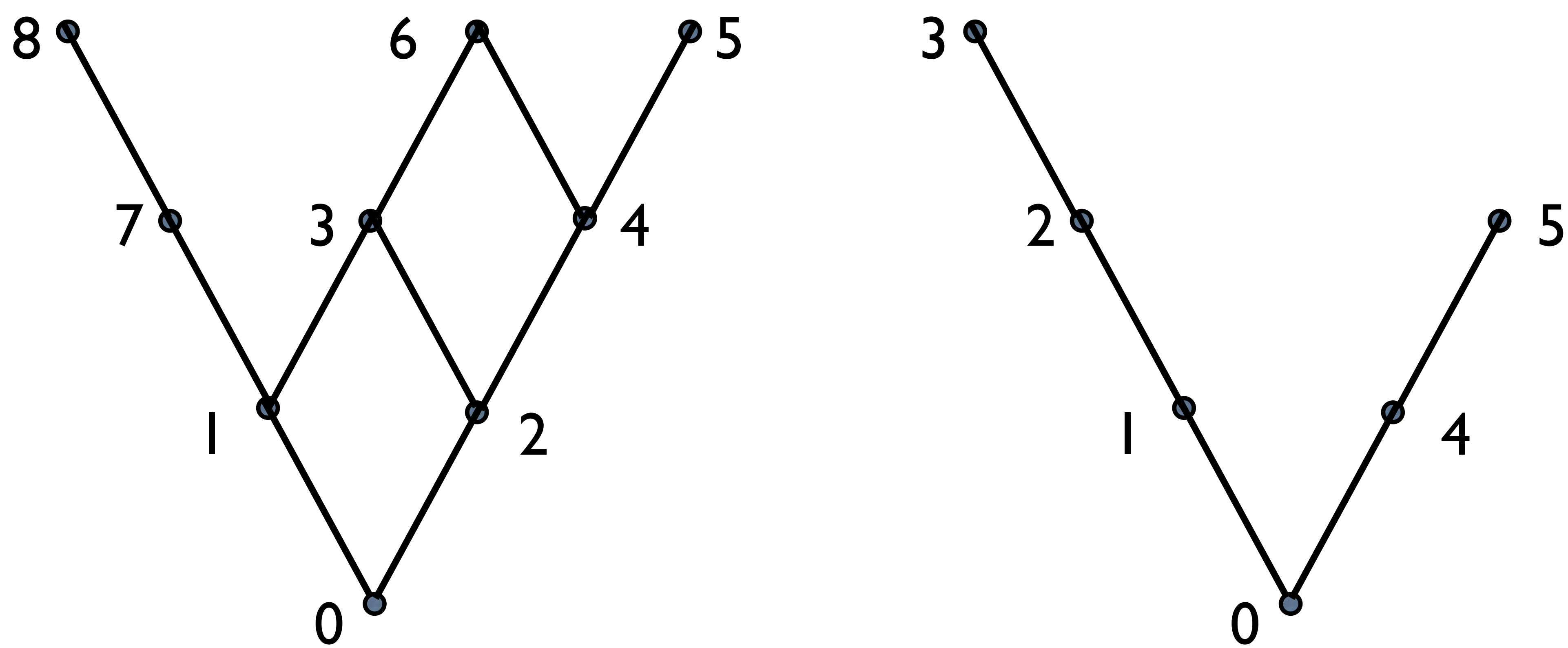

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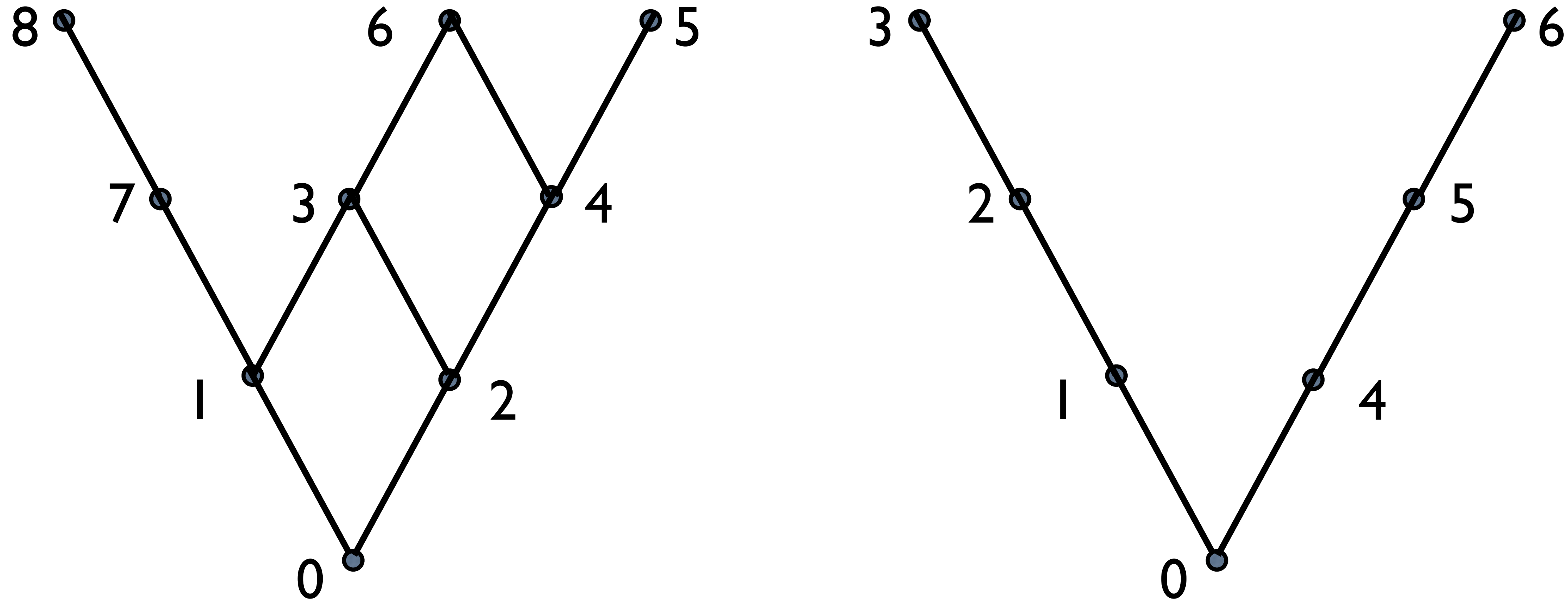

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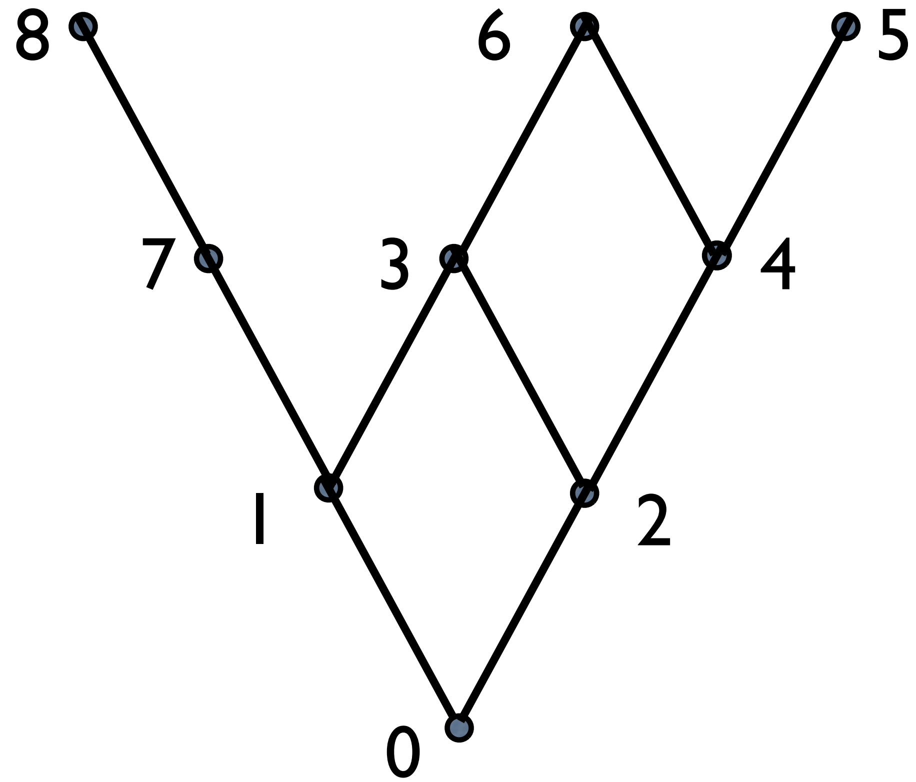

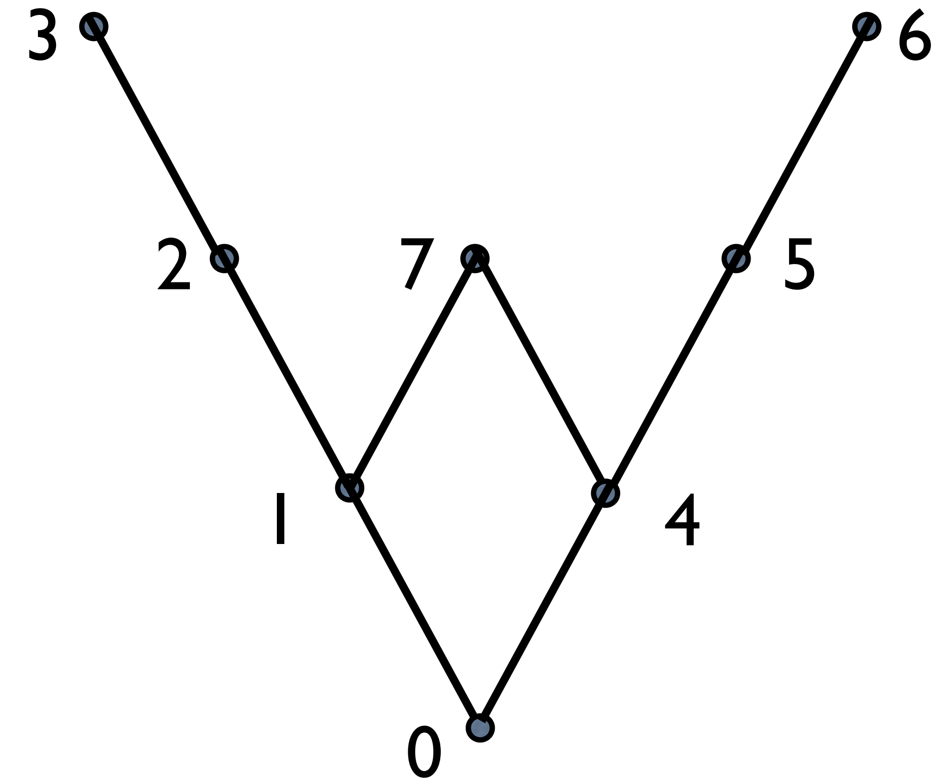

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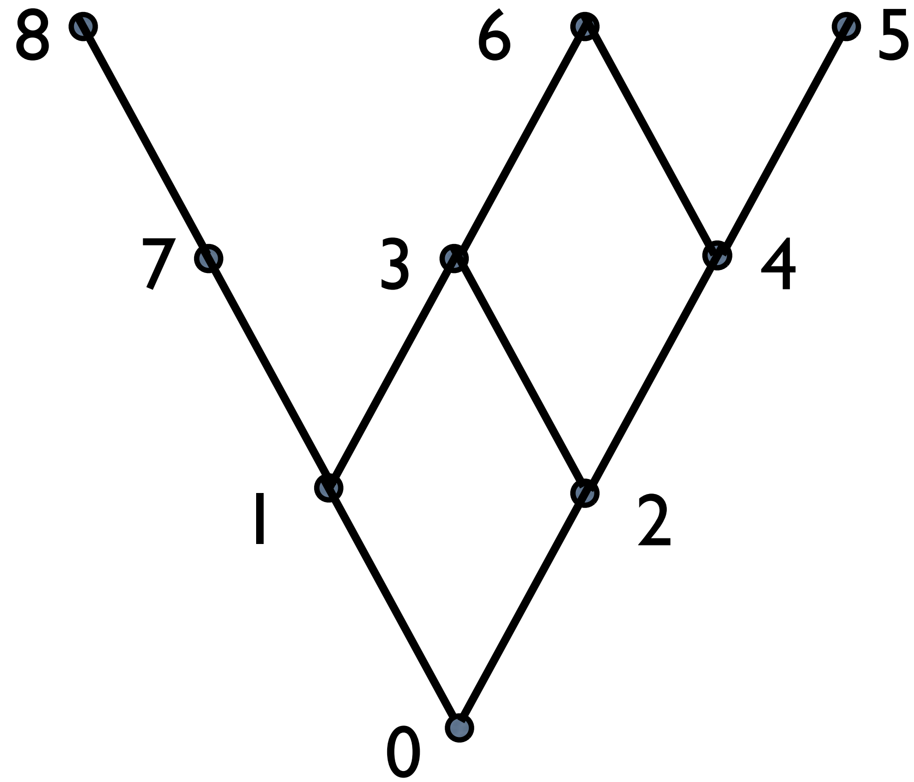

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The Present is the Birth Process **Sorkin**

- Sequential Growth models embody the notion of "becoming": the birth process is physical.
- Spacetime grows. It comes into being. It becomes.
- The physical order in which spacetime atoms are born **is** their order in the resulting causal set, a **partial** order
- "Becoming" and lack of a global time peacefully co-exist in these models.
- It is the discreteness of causal set theory which allows to make sense of a "growing block" view of the physical world.
- The "present" is **not** any particular collection of spacetime atoms.
- The birth of new spacetime atoms **is** the passage of time

How can something so "everyday" as our experience of time be a quantum gravity effect?

Let me give you an example from history where an every day observation was pointing to new physics, had people only paid attention to it

The Parable of the Sceptical Newtonian

General Relativity (GR) is our best theory of gravity. It replaced the Newtonian theory of Universal Gravitation because it accounts better for our observations of planetary motion in the solar system and, by now, for many other astrophysical and cosmological observations.

But, even **before** those observations accumulated, there was one observation that was being made, every day by every human being on earth, that pointed away from Newtonian gravity and towards GR. Even though the everyday regime is very far from the one where full GR effects are relevant.

I invite you now to make that observation.....

The Absence of Experience of a force of "Weight"

We do **not** feel a force pulling us down. We feel forces pushing up on us e.g. the chair and floor.

However, in Newtonian gravity there **must** be a force acting down on us: we call it weight. We learn to interpret the feeling of the upward force as the appropriate experience of the force of weight down on us. Hence the term "weightlessness" to describe the experience of astronauts in the space shuttle.

In General Relativity, there **is no force of weight** acting on us. It does not exist. Neither on us here on earth, nor on astronauts in space. In GR, the only forces acting on you are the ones you feel: no wonder you don't feel a force acting down on you: **there is no such physical force**.

There is only a force up on you (the pressure of the chair and floor) and you are, in fact, **accelerating upwards** at 9.8 metres per second, as Newton's second law requires.

An opportunity going begging for over 200 years!

This lack of force of weight was one of the key ingredients that Einstein needed to develop General Relativity. Now, consider the following conversation.

17th Century Scientist: There is a physical force of weight on you -- look at celestial mechanics, etc. The Newtonian theory perfectly accounts for all that data
17th Century Sceptic: But I don't experience this gravitational force of weight whereas I do experience other forces of comparable magnitude.
Scientist : The force of weight is physical. So your sense-experience of no force must be an illusion. Neurology, psychology, the way the mind and body work to produce sense-experience must be responsible for this illusion.
Sceptic: Maybe. But maybe this is telling us to look for a theory in which there is no force of weight.

Note I: The lack of sense-experience of a force of weight did not contradict Newtonian gravity, it was **not even a fact** within it. The 17th Century Scientist held an unassailable position!
Note II: The lack of sense-experience of a force of weight is evidence from a regime far from that in which **full** GR is required (strong gravity).

We may be in a similar position regarding our experience of time

The following conversation might turn out to be analogous:

21st Century Scientist: There is no physical passage of time in General Relativity and GR perfectly accounts for all our data.
21st Century Sceptic: But I experience time passing.
Scientist : Your sense-experience of time passing must be an illusion. Neurology, psychology, the way the mind and body work to produce sense-experience must be responsible for this illusion.
Sceptic: Maybe. But maybe this is telling us to look for a theory in which there is a passage of time.

Summary

- It is possible that we already have a clue as to the fundamental nature of spacetime in quantum gravity: our experience of the passage of time.
- General Relativity and its lack of a global notion of time implies that the universe is a timeless Block.
- Spacetime atomicity provides new possibilities for dynamical laws for spacetime: laws of **growth** which are compatible with the lack of a global time.
- The order in which spacetime atoms are born is a **partial order**
- The birth of new spacetime atoms **is** the passage of time in these models.
- The challenge now is to make these models quantum and recover GR....

Inner Space, Outer Space

- If this is all too introspective, looking outwards to the cosmos also gives an indication that causal set theory is along the right lines

- In the late 1980s and early 1990s Rafael Sorkin used elements of causal set theory to predict that the Cosmological "Constant" Lambda is not constant but suffers quantum fluctuations whose magnitude at any epoch would be of the order the ambient matter density.

- If one assumes (as Sorkin did) that Lambda fluctuates about a target value of zero then one should observe the fluctuations themselves as Lambda in the cosmological evolution. Which prediction was verified: we **do** observe a Lambda which is of that order of magnitude today.

- Sorkin's model also predicts that Lambda will have fluctuated between positive and negative values many times during the age of the universe.

- The current growing tension between data and standard LambdaCDM cosmology would be resolved by a negative Lambda in the past:

Debulac et al (BOSS): $\rho_{de}(z = 2.34) = (-1.2 \pm 0.8)\, \rho_{de}(z = 0)$