

# National Geographic Festival of Science

“Causation”

Rome April 2018

“There’s no time like the Present”

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# Three part story

- Time: the facts
- Causality in the physical world
- The future of time



# 1. Time: The Facts

- What can we **prove** about time?
- “Prove” = predict and test with repeatable experiments
- Here are three surprising facts about time:

# Time: 3 surprising facts

1. “The Present” = everything that’s happening now – ie simultaneously ?

But...

there is no “The Present” that is the same for everyone

Two events that happen at the same time for one person are not simultaneous for another person if they are moving relative to each other (Special Relativity)



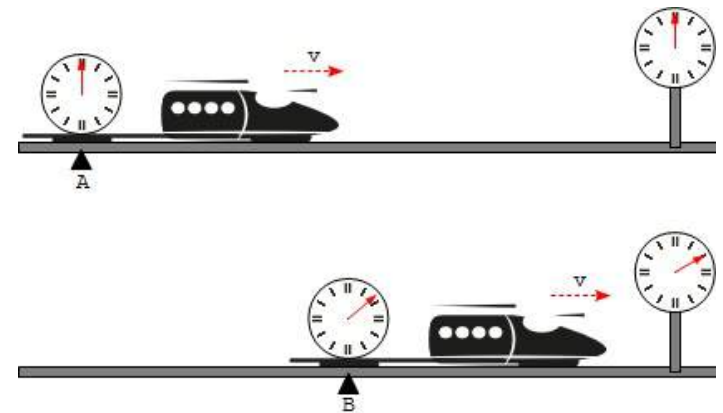
# Time: 3 surprising facts

2. “Clocks” measure the passing of time. Two identical clocks will run at the same rate and keep the same time ?

No, this is false:

there is no fixed rate of time passing

A clock that is moving with respect to a clock that is stationary will run more slowly (Special Relativity)



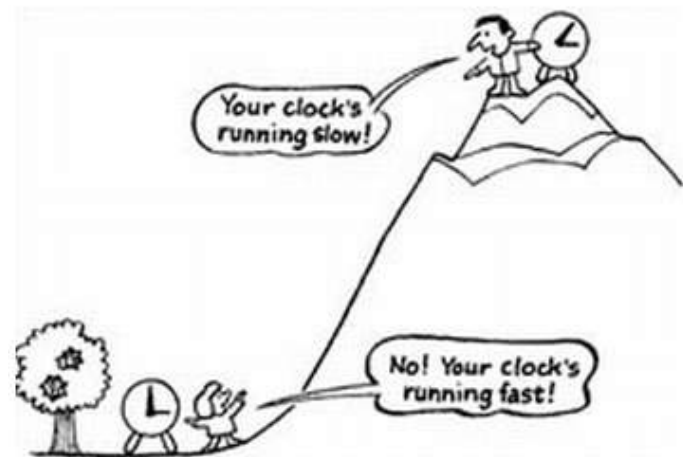
# Time: 3 surprising facts

3. But two identical, stationary clocks in different places will run at the same rate?

No:

gravity slows time down

A clock that is in a region of stronger gravity will run more slowly than one in a region of weaker gravity (General Relativity)



# Facts about time: some surprising consequences

Because of these facts about time we can travel into the future\*

[Crouches down then stands again]

Q: How far into your future did I just travel?

A:  $10^{-7}$  nanoseconds

I would have to crouch down for a billion years in order to travel one second into your futures 😊

Just because these numbers are small and you don't see or feel them doesn't mean that they are not real !

\* This “experiment” ignores the affects of accelerations



# Other facts about time

You can also do experiments on humans and our perception of time:

- Children learn about time as they grow
- We have a chemical clock in our brain running on ~25 hour cycles
- We also have a “second hand” in our brain and can estimate short intervals
- We cannot distinguish events less than  $1/10^{\text{th}}$  second apart – our “present” is smeared
- It also takes us up to two seconds to integrate visual input, affecting our perception of when events occur

But these are consequences of how we are made physically rather than fundamental facts about time itself



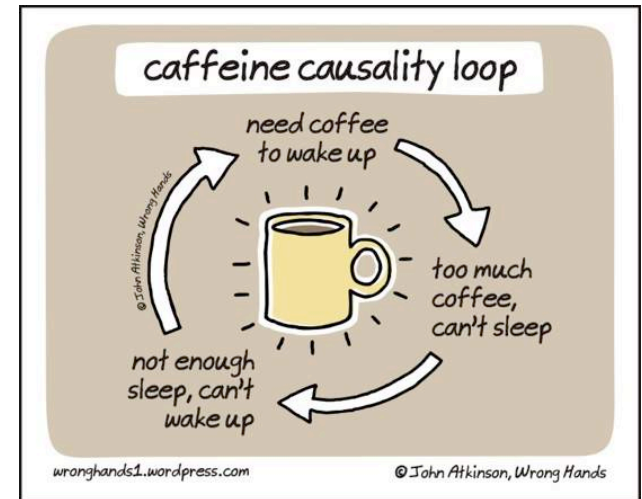
## 2. So what about Causality?

What does “causality” mean?

Naively:

if one event B happens as a consequence of another event A, then A “causes” B.

Event A has to happen before event B

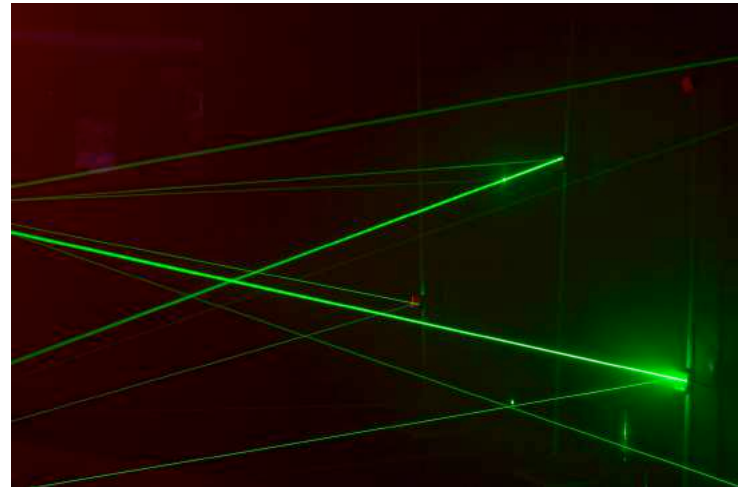


# Causality in the real (physical) world

But if there is no absolute “now” for any event (it depends on the observer), then how can we know if one event happens before another?

More precise (and consistent!) definition of “A happens before B”:

Event A happens “before” event B if it is possible for a message to travel from A to B at less than or equal to the speed of light



# Causality in Physics

A lightning summary:

- The universe is entirely made from fundamental particles and their interactions, described by relativistic quantum (field) theory
- “Causing” is described by interaction terms in the equations
- A field  $\phi$  at a space-time point (event) A affects a field  $\chi$  at B if and only if the interaction (correlation function)  $\langle \phi(A) \chi(B) \rangle$  is non-zero
- The theory has this property:  $\langle \phi(A) \chi(B) \rangle = 0$  if  $(A-B)^2 < 0$
- ie A can cause B only if there is an interaction term and a message can be sent from A to B at a speed less than or equal to the speed of light

**Conclusion: causality is a fundamental feature built into physics theories**

# Causality in Physics II

Additional complication: quantum theory is **probabilistic**

Event A can cause a range of events B, described by a (well-defined) distribution of probabilities

It is **not** that one of the possible outcomes B has happened (with some probability) before we look to see (like rolling a dice before looking)

The possible outcomes B do not have a real but unseen existence until the act of observation selects one!

# Digression: unitarity

Can you create something out of nothing, or make something disappear (ie create nothing out of something) ?

Not in physics: due to conservation of probability

The probability of something happening (including nothing changing!) is always equal to one

This is called “unitarity” and is a fundamental requirement, like causality – more later

# 3. The Future of Time

There is a lot we don't know:

- Our current best Theory of Everything (the Standard Model) works beautifully but looks ugly →
- We don't yet know what 96% of the matter in the universe is (dark matter/energy)
- We don't have a theory which combines general relativity with quantum mechanics

# The Standard Model

$$\mathcal{L}_{SM} = \mathcal{L}_{Dirac} + \mathcal{L}_{mass} + \mathcal{L}_{gauge} + \mathcal{L}_{Higgs} \quad (1)$$

Here,

$$\mathcal{L}_{Dirac} = \psi_L^\dagger \partial_t \psi_L + \psi_L^\dagger \partial_x \psi_L + \psi_L^\dagger \partial_y \psi_L + \psi_L^\dagger \partial_z \psi_L + \psi_L^\dagger \partial_t \psi_L + \psi_L^\dagger \partial_x \psi_L + \psi_L^\dagger \partial_y \psi_L + \psi_L^\dagger \partial_z \psi_L \quad (2)$$

$$\mathcal{L}_{mass} = -\psi ( \lambda_1 \psi_L^\dagger \psi_R^\dagger + \lambda_2 \psi_L^\dagger \psi_R^\dagger + \lambda_3 \psi_L^\dagger \psi_R^\dagger + h.c. ) - M_W^2 W_\mu^+ W^{-\mu} - \frac{M_Z^2}{2 \cos^2 \theta_W} Z_\mu Z^\mu \quad (3)$$

$$\mathcal{L}_{gauge} = -\frac{1}{4} (G_{\mu\nu}^a)^2 - \frac{1}{2} W_{\mu\nu}^+ W^{-\mu\nu} - \frac{1}{4} Z_{\mu\nu} Z^{\mu\nu} - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \mathcal{L}_{WZA} \quad (4)$$

where

$$\begin{aligned} G_{\mu\nu}^a &= \partial_\mu A_\nu^a - \partial_\nu A_\mu^a - g_s f^{abc} A_\mu^b A_\nu^c \\ W_{\mu\nu}^{\pm} &= \partial_\mu W_\nu^{\pm} - \partial_\nu W_\mu^{\pm} \\ Z_{\mu\nu} &= \partial_\mu Z_\nu - \partial_\nu Z_\mu \\ F_{\mu\nu} &= \partial_\mu A_\nu - \partial_\nu A_\mu \end{aligned} \quad (5)$$

and

$$\begin{aligned} \mathcal{L}_{WZA} &= i g_2 \cos \theta_W \left[ (W_\mu^+ W_\nu^- - W_\nu^+ W_\mu^-) \partial^\mu Z^\nu + W_\mu^+ W^{-\mu\nu} Z^\nu - W_\mu^- W^{+\mu\nu} Z^\nu \right] \\ &+ i g_2 \left[ (W_\mu^+ W_\nu^- - W_\nu^+ W_\mu^-) \partial^\mu A^\nu + W_\mu^+ W^{-\mu\nu} A^\nu - W_\mu^- W^{+\mu\nu} A^\nu \right] \\ &+ g_2^2 \cos^2 \theta_W (W_\mu^+ W_\nu^- Z^\mu Z^\nu - W_\mu^+ W^{-\mu\nu} Z_\nu Z^\mu) \\ &+ g_2^2 (W_\mu^+ W_\nu^- A^\mu A^\nu - W_\mu^+ W^{-\mu\nu} A_\nu A^\mu) \\ &+ g_2 g' \cos \theta_W [W_\mu^+ W_\nu^- (Z^\mu A^\nu + Z^\nu A^\mu) - 2W_\mu^+ W^{-\mu\nu} Z_\nu A^\mu] \\ &+ \frac{1}{2} g_2^2 (W_\mu^+ W_\nu^-) (W^{+\mu\nu} W^{-\nu\mu} - W^{+\mu\nu} W^{-\mu\nu}) \end{aligned} \quad (6)$$

and

$$\mathcal{L}_{Higgs} = -\partial_\mu A_\nu^\dagger \partial^\mu A^\nu - g_2 (W_\mu^+ J_{W^+}^\mu + W_\mu^- J_{W^-}^\mu + Z_\mu J_Z^\mu) - e A_\mu J_A^\mu \quad (7)$$

where

$$\begin{aligned} J_{(0)}^\mu &= \psi_L^\dagger \gamma^\mu \psi_L + \psi_R^\dagger \gamma^\mu \psi_R \\ J_{W^+}^\mu &= \frac{1}{\sqrt{2}} (\psi_L^\dagger \gamma^\mu \psi_L + \psi_R^\dagger \gamma^\mu \psi_R) \\ J_{W^-}^\mu &= (J_{W^+}^\mu)^\dagger \\ J_Z^\mu &= \frac{1}{\cos \theta_W} \left[ \frac{1}{2} \psi_L^\dagger \gamma^\mu \psi_L + \left( -\frac{1}{2} + \sin^2 \theta_W \right) \psi_L^\dagger \gamma^\mu \psi_L + (\sin^2 \theta_W) \psi_R^\dagger \gamma^\mu \psi_R \right] \\ &+ \left( \frac{1}{2} - \frac{2}{3} \sin^2 \theta_W \right) \psi_L^\dagger \gamma^\mu \psi_L + \left( -\frac{2}{3} \sin^2 \theta_W \right) \psi_R^\dagger \gamma^\mu \psi_R \\ &+ \left( -\frac{1}{2} + \frac{1}{3} \sin^2 \theta_W \right) \psi_L^\dagger \gamma^\mu \psi_L + \left( \frac{1}{3} \sin^2 \theta_W \right) \psi_R^\dagger \gamma^\mu \psi_R \\ J_A^\mu &= (-1) \psi_L^\dagger \gamma^\mu \psi_L + \left( \frac{2}{3} \right) \psi_R^\dagger \gamma^\mu \psi_R + \left( -\frac{1}{3} \right) \psi_R^\dagger \gamma^\mu \psi_R \end{aligned} \quad (8)$$

It's not pretty.....

but it works

<http://nuclear.ucdavis.edu/~tgutierr/files/stmL1.html>

# What is the biggest Unknown?

A: Marrying gravity and quantum theory

General relativity: gravity is just curved spacetime

Quantum theory: matter/energy are fuzzy

So it should be easy: “quantum gravity” = “fuzzy spacetime” !

But.... after 100+ years of trying we haven't found this theory yet



# What's our best theory of quantum gravity?

(Super) string/M theory: the fundamental objects are not point-like particles but extended objects – strings or membranes

This looks like it might solve some of the big problems with quantum gravity – eg what happens at small scales

No exposition here (!) but will talk about some interesting applications to **current physics**

# What we know: the Standard Model

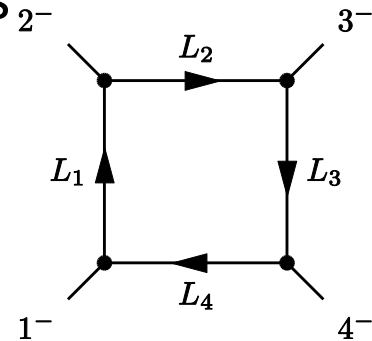
The Standard Model: everything is made from fundamental particles

Force particles (gluons, W,Z bosons, photon) and matter particles (quarks, leptons Higgs bosons)

These interact in a well-defined and tested way

The interactions are described by “scattering amplitudes”<sup>2-</sup>

The standard calculations use “Feynman diagrams” :



# New ideas from string theory

Calculations in the Standard Model, using Feynman diagrams, quickly become very difficult and lead to complicated answers – like this:

Result of a brute force calculation:

$$k_1 \cdot k_4 \epsilon_2 \cdot k_1 \epsilon_1 \cdot \epsilon_3 \epsilon_4 \cdot \epsilon_5$$

$$k_1 \cdot k_4 \epsilon_2 \cdot k_1 \epsilon_1 \cdot \epsilon_3 \epsilon_4 \cdot \epsilon_5$$

\* Example from Zvi Bern, UCLA

# New Ideas from String Theory

Current theories use spacetime “points” – time/place where events occur

This gives complicated results – but all the terms in the formula add up to much more simple expressions like

$$g^{n-2} \frac{\langle 13 \rangle^4}{\langle 12 \rangle \langle 23 \rangle \dots \langle n1 \rangle}$$

# Is spacetime the right language?

How to explain why complicated formulae can be written in simple ways ?

Idea: use a **new geometry** → twistor space

In the new geometry, the simple formulae reflect simple ideas - eg **particles form a straight line in twistor space**

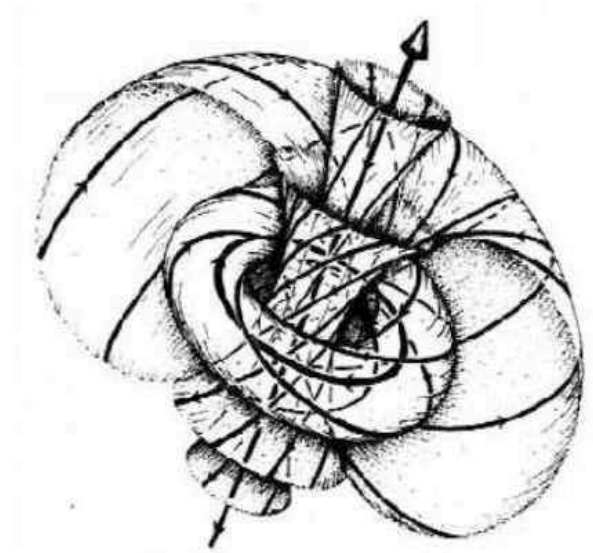


FIGURE 1: A time-slice ( $t=0$ ) of a Robinson congruence.

From *On the Origins of Twistor Theory*, Roger Penrose  
<http://users.ox.ac.uk/~tweb/00001/#07>

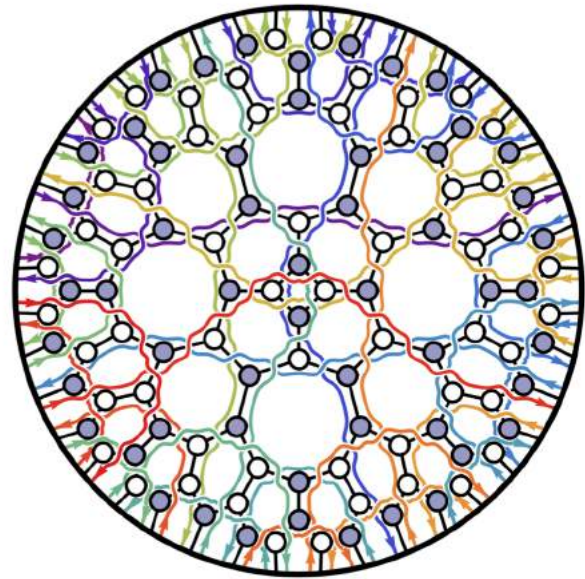
# Recent results I

Last few years – this has led to a beautiful new geometry:

Closer look at scattering amplitudes using twistors rather than space time

“On-shell” diagrams replace old Feynman diagrams

All particles are moving at the speed of light



N. Arkani-Hamed, J. Bourjaily, F. Cachazo, A. Goncharov, A. Postnikov and J. Trnka arXiv: hep-th/1212.5605

# Recent results I

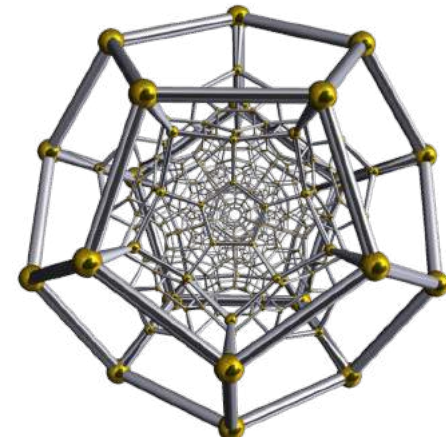
Outcome: amplitudes are higher dimensional crystals called

## Amplituhedra

These are related to higher dimensional polyhedra like this 4-d dodecaplex:



(this is made from 120 dodecahedra, joined 3 at a time at each edge)



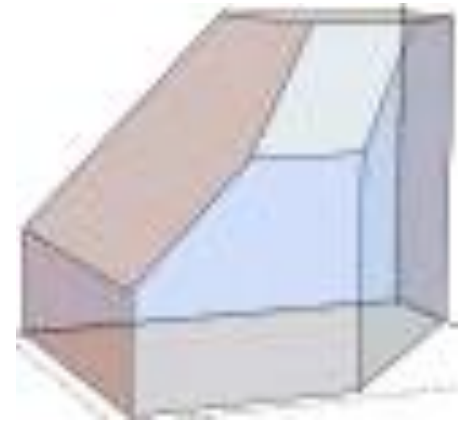
Unitarity and locality/**causality** appear as **derived quantities**

[https://commons.wikimedia.org/wiki/File:Schlegel\\_wireframe\\_120-cell.png](https://commons.wikimedia.org/wiki/File:Schlegel_wireframe_120-cell.png)

# Recent results II

Recent work\*: this crystal geometry can be “pulled back” into the space of momenta to reveal corresponding structures –

## The Associahedron



6 scalar particle associahedron

New feature:

Color-kinematics duality (“BCJ”)

Possible new geometry for non-gravitational forces

Work in progress.....

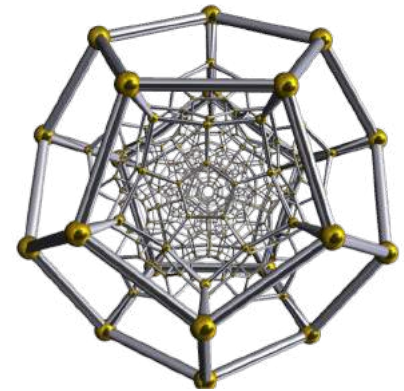
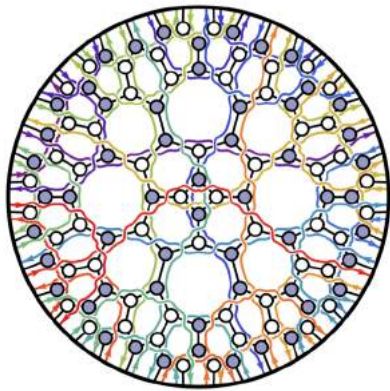
\*N. Arkani-Hamed, Y. Bai, S. He and G. Yan, arXiv: hep-th/1711.09102



# What is this telling us about causality?

- Maybe space and time are not the best language for understanding physical reality – **twistors** (~ light rays) might be better
- What happens to time for a light ray? Clocks slow to a halt as you approach the speed of light. For a light ray **Everything is Now** - until something happens, then a New Now starts
- In recent developments in physics, the fundamental objects are geometric/combinatoric, and essential features like causality are **emergent properties**
- Maybe there really is no time like the present - we should stop worrying about time and causality and think more about **higher dimensional crystal geometry** 😊

*If you're facing big challenges ahead, summon the healing white light of Fluorite by sitting quietly with the stone [crystal] and giving it an intention. Follow your breath, inhaling peace and clarity while exhaling confusion and chaos. Let your breathing slow to a natural pace and inhale the peaceful vibes of the universe, exhaling turmoil and letting it all go with each breathe. Rinse and repeat until you feel a deep relaxation that helps clear the fog of your mind. With a clear head, fully experience all the intricate details of our beautiful world\*.*



\* <https://www.energy muse.com/fluorite-meaning>