What is time?
Answers from modern physics

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FQXi Foundation,
“The physics of what happens”
This is a fish

Mariana trench: 8150m deep
This is a fish

Mariana trench: 8150m deep

Its universe is a 10km cube of water...
This is a fish

Mariana trench: 8150m deep

Its universe is a 10km cube of water...

What would he think if we'd tell him about stars?
This is a fish

Its universe is a 10km cube of water...

What would he think if we'd tell him about stars?

Mariana trench: 8150m deep

Remember the fish: keep your mind open!
what am I going to talk about?
I'll give an intuition of the strangest and counterintuitive aspects of time.
WHAT is time?
“What is time? If no one asks me, I know, but as soon as I try to explain it, I don't know.”

S. Augustine of Ippona (Confessions)
“What is time? If no one asks me, I know, but as soon as I try to explain it, I don't know.”

S. Augustine of Ippona (Confessions)

Can we do better than than?
“What is time? If no one asks me, I know, but as soon as I try to explain it, I don't know.”

S. Augustine of Ippona (Confessions)

Can we do better than than? Not much!
WHAT is time?

“What is time? If no one asks me, I know, but as soon as I try to explain it, I don't know.”

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Can we do better than than? Not much!

It seems impossible to define time without using temporal concepts (“before”, “after”, etc.) ➔ circular definition!
What is time? If no one asks me, I know, but as soon as I try to explain it, I don't know.

S. Augustine of Hippo (Confessions)

Can we do better than than? Not much!

It seems impossible to define time without using temporal concepts ("before", "after", etc.) → circular definition!

But "time" is one of the most used nouns in all languages (in English it is in the top 10)!

... are there any doubts we're talking of things we don't know?!?
WHAT is time?

In physics?
In physics?

“Time is what is measured by a clock”

... but what is a clock?!
WHAT is time?

In physics?

"Time is what is measured by a clock"
... but what is a clock?!

... or a "coordinate"

something that measures the distance between events
WHAT is time?

In physics?

“Time is what is measured by a clock”

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... but what is an event?!
In physics?

“Time is what is measured by a clock”

... but what is a clock?!

... or a “coordinate”

something that measures the distance between events

... but what is an event?!

the two main meanings of time in physics
other meanings?

Table 2.1: Times.

<table>
<thead>
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<th>Time notion</th>
<th>Property</th>
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<td>Special relativistic time</td>
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<td>Cosmological time</td>
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<tr>
<td>Proper time</td>
<td>temporally global</td>
<td>world line proper time</td>
<td>$m^\infty$</td>
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<td>Clock time</td>
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<tr>
<td>Parameter time</td>
<td>one dimensional</td>
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<td>$L^\infty$</td>
</tr>
<tr>
<td>No-time</td>
<td>none</td>
<td>quantum gravity</td>
<td>none</td>
</tr>
</tbody>
</table>

[Rovelli, “quantum gravity”]
use our intuition? FAIL!!
use our intuition? FAIL!!

- Time “flows”
use our intuition? FAIL!!

- Time “flows” \[\Rightarrow\] NO!
use our intuition? FAIL!!

- Time “flows”  🔄 NO!

Something flows with respect to something else. The river flows with respect to the clock, my heart beats with respect to the river.
use our intuition? FAIL!!

Time “flows” → NO!

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Time flows with respect to ...? .. and at what “speed”? One second per second?!?!
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Some philosophers: Leibni(t)z, McTaggart, Barbour

time doesn’t “exist”
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Time doesn't "exist"

(perhaps too drastic...)
use our intuition? FAIL!!

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theses: time doesn't “exist”

(time is relational)

(perhaps too drastic...)
use our intuition? FAIL!!

- the present “exists”, the past and the future don't

(past, present and future have different essence)
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Why NOT?!
Relativity of simultaneity

Two events SIMULTANEOUS for me:

“the lamp is switched on”

“a glass falls”
Relativity of simultaneity

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“the lamp is switched on”

“a glass falls”

do we all agree that they are simultaneous?
Two events SIMULTANEOUS for me:

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“a glass falls”

do we all agree that they are simultaneous? → NO!
Two events SIMULTANEOUS for me:

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“a glass falls”

do we all agree that they are simultaneous? → NO!

For an observer MOVING with respect to me, one happens BEFORE, the other AFTER: for him they are not simultaneous!! (evident only at high speeds)
Relativity of simultaneity

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“a glass falls”

“the lamp is switched on”

do we all agree that they are simultaneous? → NO!

For an observer MOVING with respect to me, one happens BEFORE, the other AFTER: for him they are not simultaneous!! (evident only at high speeds)

→ relativity of simultaneity
All events simultaneous to now are the “present”.

the present depends on the motion!
All events simultaneous to now are the “present”.

Alice's present on the train is different from Bob's present at the station (important difference only for high speeds)
Relativity of simultaneity

All events simultaneous to now are the “\textit{present}”. The present depends on the motion!

Alice's present on the train is \textbf{different} from Bob's present at the station (important difference only for high speeds)

For Alice the glass falls and the lamp is switched on at the same time, for Bob they don't!
All events simultaneous to now are the “present”. The present depends on the motion!

Alice's present on the train is **different** from Bob's present at the station (important difference only for high speeds)

For Alice the glass falls and the lamp is switched on at the same time, for Bob they don't!

If past-present-future had different essence, who would win? Should Alice's present “exist”? Or should Bob's?
If past-present-future had different essence, who would win? Should Alice's present “exist”? Or should Bob's?

All events simultaneous to now are the “present”. The present depends on the motion!

It's like saying that “right” and “left” have different essence! (whose right?!)

For Alice the glass falls and the lamp is switched on at the same time, for Bob they don't!

If past-present-future had different essence, who would win? Should Alice's present “exist”? Or should Bob's?
Relativita' della simultaneita'

The present depends on motion!!

If past-present-future have different essence, A and B would disagree on what “exists” and what doesn't.

Relativity forces us to give the same “degree of existence” to past-present-future!!
The present depends on motion!!

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Physicists speak about “block universe”: one has to consider space-time as a single “block”, I can't divide space from time (considering space at a certain time)
if past-present-future have different essence,
A e B would disagree on what “exists” and what doesn't.

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Physicists speak about “block universe”: one has to consider space-time as a single “block”, I can't divide space from time (considering space at a certain time)

Relativity=division of spacetime into space and time is relative (to the observer)

Time is a coordinate (as space)
Relativity forces us to give the same “degree of existence” to past-present-future!!
Relativity forces us to give the same “degree of existence” to past-present-future!!

“For us who believe in physics, the difference between past, present and future is just an illusion, however persistent”

Albert Einstein
Relativity forces us to give the same “degree of existence” to past-present-future!!

“For us who believe in physics, the difference between past, present and future is just an illusion, however persistent”

Albert Einstein, writing to console the widow of his dear friend Michele Besso (or to console himself?)

(May 21, 1955)
Past-present-future have the same degree of existence...

but what does it mean to say that time “exists”? 
Philosophy question: if I block all change and movement, time would still exist?
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Newton: “Absolute, true and mathematical time, of itself, and from its own nature flows equably without regard to anything external”

Time “exists” even if nothing happens
"absolute" vs. "relative" time

Philosophy question: if I block all change and movement, time would still exist?

Newton: “Absolute, true and mathematical time, of itself, and from its own nature flows equably without regard to anything external”

Time “exists” even if nothing happens

Aristotle, Lucrezio, Leibni(t)z: time is only relational: a change of something with respect to something else

Time doesn't “exist” if nothing happens
Philosophy question: if I block all change and movement, time would still exist?

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Who's right?
Philosophy question: if I block all change and movement, time would still exist?

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Time “exists” even if nothing happens

Aristotle, Lucrezio, Leibni(t)z: time is only relational: a change of something with respect to something else

Time doesn't “exist” if nothing happens

None, but in part, both!
Newton: “Absolute, true and mathematical time, of itself, and from its own nature flows equably without regard to anything external”

Time “exists” even if nothing happens but it's not **absolute**!
Newton: “Absolute, true and mathematical time, of itself, and from its own nature flows equably without regard to anything external”

Time “exists” even if nothing happens but it's not absolute!

Aristotle, Lucrezio, Leibni(t)z: time is only relational: a change of something with respect to something else

Time is relational: I can only localize an event with respect to another.
If past and future “exist”,

Can I travel in time?
If past and future “exist”,

Can I travel in time?

- To the future (without return)?
If past and future “exist”,

Can I travel in time?

• To the future (without return)?
  Yes! (almost trivial)
Can I travel in time?

- To the future (without return)?
  Yes! (almost trivial)

- To the past?
If past and future “exist”,

Can I travel in time?

• To the future (without return)?
  Yes! (almost trivial)

• To the past?
  Yes! (maybe!)
  ...only theoretically!
Question 1:

time travel to the future (without return)?
Time travel to the future (no return)
Time travel to the future (no return)

What?

I arrive to tomorrow before you... I.e. I arrive to your tomorrow in a few of (my) seconds. When we meet again, for me a few seconds went by, for you 24h.
Time travel to the future (no return)

How?!?
Simple!  

Relativistic time dilation
Time depends from the state of motion (why it's called relativity)
Simple! Relativistic time dilation

Time depends from the state of motion (why it's called relativity)

Time in systems that move (with respect to us) is slower than ours
Simple! → Relativistic time dilation

Time depends from the state of motion (why it's called relativity)

Time in systems that move (with respect to us) is slower than ours

Is it sufficient to move, to travel in time?
Time depends from the state of motion (why it's called relativity)

Time in systems that move (with respect to us) is slower than ours

Is it sufficient to move, to travel in time?

Yes!
Twin paradox!
Twin paradox!

Alice

Bruna

Bruna

Alice
then why don't we ever see this?!?
….then why don't we ever see this?!?

Because we'd need to move at relativistic speeds \( \sim c \)!!!

...or do precise measurements
(small effect at slow speeds)
....then why don't we ever see this?!?

Because we'd need to move at relativistic speeds ~c!!!!

...or do precise measurements (small effect at slow speeds)

Hafele–Keating (1971): traveled to the future by 40 ns by traveling around the world in an airplane (~1000Km/h)
....then why don't we ever see this?!?

Because we'd need to move at relativistic speeds ~c!!!!

...or do precise measurements (small effect at slow speeds)

Hafele–Keating (1971): traveled to the future by 40 ns by traveling around the world in an airplane (~1000Km/h)

Atomic clocks

Hostess
How fast do I have to travel to go to your tomorrow in half your time?
(with respect to a stationary you?)
How fast do I have to travel to go to your tomorrow in half your time?
(with respect to a stationary you?)

700 billion Km/h!!!
(200.000 Km/s)
Light moves very fast!

Galileo tried to measure it unsuccessfully.

How far should he have sent the other person for a time delay of about a second?
Relativistic time dilation: through movement. Other mechanism? **Gravity**
Relativistic time dilation: through movement. Other mechanism? **Gravity**

Time in systems in a larger gravitational (than ours) field flows slower (than ours)
Relativistic time dilation: through movement. Other mechanism? **Gravity**

Time in systems in a larger gravitational (than ours) field flows slower (than ours)

1h water planet = 7 years on earth.
Relativistic time dilation: through movement. Other mechanism? **Gravity**

... but a person at sea level ages slower (more gravity) than a person on the top of a mountain?
Relativistic time dilation: through movement. Other mechanism? **Gravity**

... but a person at sea level ages slower (more gravity) than a person on the top of a mountain? Yes!
Relativistic time dilation: through movement. Other mechanism? **Gravity**

... but a person at sea level ages slower (more gravity) than a person on the top of a mountain?

One second for our head = 1.00000000000000001 second for our feet!

**Yes!**
Relativistic time dilation: through movement. Other mechanism? Gravity

... but a person at sea level ages slower (more gravity) than a person on the top of a mountain?

One second for our head = 1.00000000000000001 second for our feet!

16 zeros!!! The effect is almost negligible.

This strange “time dilation”...

...should we care about it?!?!
This strange “time dilation”...

...should we care about it?!?

without relativity, gps wouldn't work!!
Satellites are fast and are in a weaker gravitational field: they lose 40 microsec per day
40 microseconds =
40 millionths of a second

Negligible!?
40 microseconds = 40 millionths of a second

Negligible!?  

NO!  
a microsecond = 300 m (GPS signals travel at light speed).

Without relativity GPS would lose 1Km per day
Question 2:

Time travel to the past?
• To the past?
  Yes! (maybe!)
    ...only theoretically!
• To the past?

Yes! (maybe!)

...only theoretically!

What?

General relativity predicts time travel to the past
What?
General relativity predicts time travel to the past

...BUT!

- To the past?
  Yes! (maybe!)
  ...only theoretically!
To the past?

Yes! (maybe!)

...only theoretically!

What?

General relativity predicts time travel to the past

...BUT!

1. GR could be wrong? → Hawking
• To the past?

Yes! (maybe!)
...only theoretically!

What?
General relativity predicts time travel to the past

...BUT!

1. GR could be wrong? → Hawking

2. Even if it's right, building a time machine would be impossible in practice
General relativity predicts time travel to the past

...BUT!

1. GR could be wrong? → Hawking

2. Even if it's right, building a time machine would be impossible in practice (black holes rotating at relativistic speeds!)
General relativity predicts time travel to the past

Kurt Gödel's discovery, the greatest mathematical logician of history, and great friend of Einstein

This discovery was Einstein's 70th birthday present

[Palle Yourgrau, a world without time]
Goedel: “general relativity predicts time travel”

Einstein's reply?
Goedel: “general relativity predicts time travel”

Einstein's reply?

Uff!!!
Goedel: “general relativity predicts time travel”

Einstein's reply?

[Uff!!!]

[A. Einstein, in P.A. Schilpp “Albert Einstein Philosopher-Scientist”, pg. 687]

- this is a problem for the theory (time travel paradoxes)
- Perhaps physics prevents it?
Gödel's universe: a universe that “rotates on itself”.

Visualization of the Gödel universe
http://iopscience.iop.org/1367-2630/15/1/013063/article
Gödel's universe: a universe that “rotates on itself”.

Ours?
Gödel's universe: a universe that “rotates on itself”.

Ours?

Ours doesn't...
So... we can't use Goedel's trajectories to travel in time
back to time travel

Temporal paradoxes
Two types are known:
1. Grandfather paradox
2. Monna Lisa paradox
1. Grandfather paradox

I go to the past and kill my grandfather before he meets my grandmother

..then I can't be born, so I can't kill my grandfather.
1. Grandfather paradox

I go to the past and kill my grandfather before he meets my grandmother

..then I can't be born, so I can't kill my grandfather.

logical contradiction I need to avoid that!!!
Solutions:
Solutions:

1. Time travel is impossible:

\[ \text{general relativity} + \text{quantum mechanics} = \text{no time travel} \]
Solutions:

1. Time travel is impossible:

   general relativity + quantum mechanics = no time travel

   (unknown mechanism!)

   Hawking chronology protection conjecture
Solutions:

1. Time travel is impossible:
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   (unknown mechanism!)
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2. Only paradoxes are impossible
Solutions:

1. Time travel is impossible:
   general relativity + quantum mechanics = no time travel
   (unknown mechanism!)
   Hawking chronology
   protection conjecture

2. Only paradoxes are impossible
   boundary conditions -> no paradox
   Novikov principle
   (with Kip Thorne)
Solutions:

1. Time travel is impossible:

   - General relativity + quantum mechanics
   - Hawking chronology protection conjecture
   - (unknown mechanism)

2. Only paradoxes are impossible

   - Novikov principle
   - Boundary conditions
   - (with Kip Thorne)
2. Monna Lisa paradox

I take a photo of Monna Lisa to Leonardo who paints the picture copying my photo.
2. Monna Lisa paradox

I take a photo of Monna Lisa to Leonardo who paints the picture copying my photo

who painted the picture? Leonardo took it from me, I took it from him!
2. Monna Lisa paradox

I take a photo of Monna Lisa to Leonardo who paints the picture copying my photo who painted the picture? Leonardo took it from me, I took it from him!

No logical contradiction!
2. Monna Lisa paradox

I take a photo of Monna Lisa to Leonardo who paints the picture copying my photo who painted the picture? Leonardo took it from me, I took it from him!

No logical contradiction!
Avoiding these paradoxes is then much more difficult!

known solutions require QM
Relativity forces us to give the same “degree of existence” to past-present-future!!!!
Relativity forces us to give the same “degree of existence” to past-present-future!!!!

Relativity allows for time travel (theoretically)
Already relativity has drastic consequences on our explanation of time...
Already relativity has drastic consequences on our explanation of time...

... what happens if we introduce also quantum mechanics?!
Relativity + quantum mechanics

Already relativity has drastic consequences on our explanation of time...

What happens if we introduce also quantum mechanics?!

The two theories that govern the world
...another wrong intuition...

- The universe evolves
The universe evolves

...another wrong intuition...

NO!
...another wrong intuition...

- The universe evolves → NO! (we're not sure)
...another wrong intuition...

- The universe evolves ➡️ NO! (we're not sure)

Wheeler-De Witt equation: joins relativity and quantum mechanics

\[ \hat{H} |\Psi\rangle = 0 \]
The universe evolves\textcolor{red}{} \Rightarrow \textcolor{red}{\textit{NO! (we're not sure)}}

Wheeler-De Witt equation: joins relativity and quantum mechanics
\[ \hat{H} |\Psi\rangle = 0 \]
what does it mean?
...another wrong intuition...

• The universe evolves \[\rightarrow\] NO!  (we're not sure)

Wheeler-De Witt equation: joins relativity and quantum mechanics
\[\hat{H}|\Psi\rangle = 0\]
what does it mean?

The state of the universe is stationary
...another wrong intuition...

The universe evolves  ➔  NO! (we're not sure)

Wheeler-De Witt equation: joins relativity and quantum mechanics
\[ \hat{H} |\Psi\rangle = 0 \]

what does it mean?

The state of the universe is stationary

...but!!!
...another wrong intuition...

The universe evolves $\rightarrow$ NO! (we're not sure)

Wheeler-De Witt equation: joins relativity and quantum mechanics

$\hat{H}|\Psi\rangle = 0$

what does it mean?

The state of the universe is stationary

...but!!!

“Problem of time” in modern physics

(many proposed solutions: it tells us that quantum general relativity is still unknown)
One after another, the characteristic features of time have proved to be approximations, mistakes determined by our perspective, just like the flatness of the Earth or the revolving of the sun. The growth of our knowledge has led to a slow disintegration of our notion of time. What we call “time” is a complex collection of structures, of layers. Under increasing scrutiny, in ever greater depth, time has lost layers one after another, piece by piece.

(Carlo Rovelli)
these ideas make you wonder.....

Are physicists all crazy?
Are physicists all crazy? or have they lost touch with reality?
these ideas make you wonder.....

Are physicists all crazy? or have they lost touch with reality?

NO!!!!
these ideas make you wonder.....

Are physicists all crazy? or have they lost touch with reality?

NO!!!!

The truth is that

it's necessary to abandon the limitations of our senses and our common sense to understand reality!!!
Are physicists all crazy? or have they lost touch with reality?

NO!!!!

The truth is that it's necessary to abandon the limitations of our senses and our common sense to understand reality!!!

(e.g. Plato!)
Are physicists all crazy? or have they lost touch with reality?

NO!!!!

The truth is that it's necessary to abandon the limitations of our senses and our common sense to understand reality!!!

(True scientists know this: they study for years to eliminate their prejudices against reality.)

(e.g. Plato!)
Physicists are *not* crazy

it's physics that is very strange...

REMEMBER THE FISH:
Don't be fish: tackle modern physics with *open minds*
I close my eyes to see

("Je ferme les yeux pour voir.")
Paul Gauguin
I close my eyes to see
("Je ferme les yeux pour voir.")
Paul Gauguin

It's impossible to “see” the results from relativity and quantum mechanics

You have to use the eyes of the mind, helping yourself with mathematical formalism: the language of physics

\[ H(t)|\psi(t)\rangle = i\hbar \frac{\partial}{\partial t}|\psi(t)\rangle \]

\[ R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = 8\pi G T_{\mu\nu} \]
time = “what's shown on a clock”, “a coordinate”
What did I say?

- \( \text{time} = \text{"what's shown on a clock"}, \text{"a coordinate"} \)

- Time \text{“flows”} \rightarrow \text{NO!}
What did I say?

- Time "flows" → NO!
- The present "exists", the past and future don't → NO!

Past-present-future have the same essence (block universe)
What did I say?

- time = “what's shown on a clock”, “a coordinate”
- Time “flows” NO!
- The present “exists”, the past and future don't NO!

Past-present-future have the same essence (block universe)

- Time travel Yes (only theoretically)

relativity
What did I say?

- time = “what's shown on a clock”, “a coordinate”
- Time “flows” → NO!
- The present “exists”, the past and future don't → NO!

Past-present-future have the same essence (block universe)

- Time travel → Yes (only theoretically)

- The universe evolves → NO (?)

relativity

relativity+quantum mechanics
What did I say?

- time= “what's shown on a clock”, “a coordinate”
- Time “flows” → NO!
- The present “exists”, the past and future don't → NO!
- Past-present-future have the same essence (block universe)
- Time travel → Yes (only theoretically)
- The universe evolves → NO (?)
- The language of science
Paul Davies
I misteri del tempo.
Mondadori

Carlo Rovelli
L'ordine del tempo
Adelphi

Palle Yourgrau,
Un mondo senza tempo.

Mauro Dorato
Che cos'e' il tempo?
Carocci (2013)

Pedro Ferreira
The perfect theory

Technical literature:
C. Rovelli, "Quantum Gravity",
Sec 2.4.4: “Meanings of time”.

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