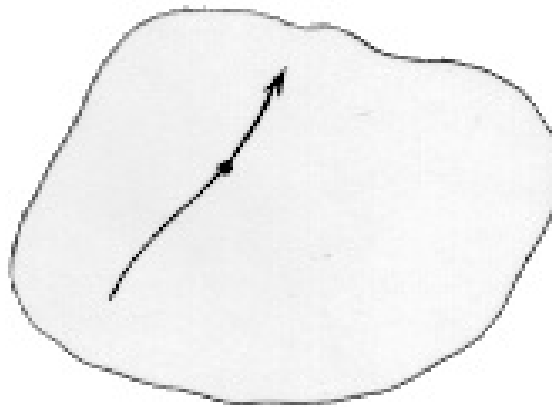


Eventi e linee di universo

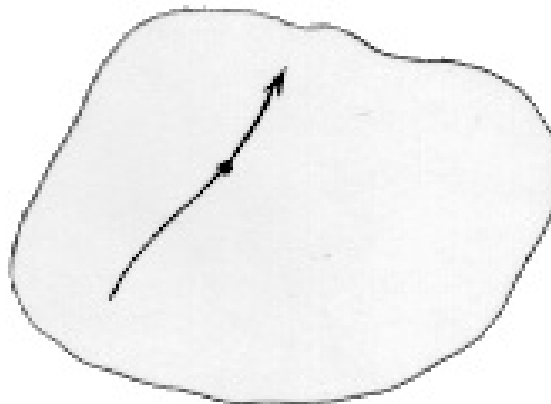


Evento: nozione primitiva. Un evento è ciò che accade in un tempo brevissimo in una zona piccolissima di spazio (à la Euclide:). Al limite un punto. È utile avere un diagramma. Un diagramma aiuta a riassumere le relazioni tra eventi.

Diagramma spaziotemporale

linea di universo: un insieme unidimensionale continuo di eventi che rappresenta la “storia” di un oggetto

spaziotempo \mathcal{M} : l'insieme di tutti i **possibili** eventi nell'universo.



rappresentazione matematica standard: \mathcal{M} è un continuo 4-dimensionale (varietà differenziabile localmente omeomorfa a \mathbb{R}^4)

Esempi

Esempi

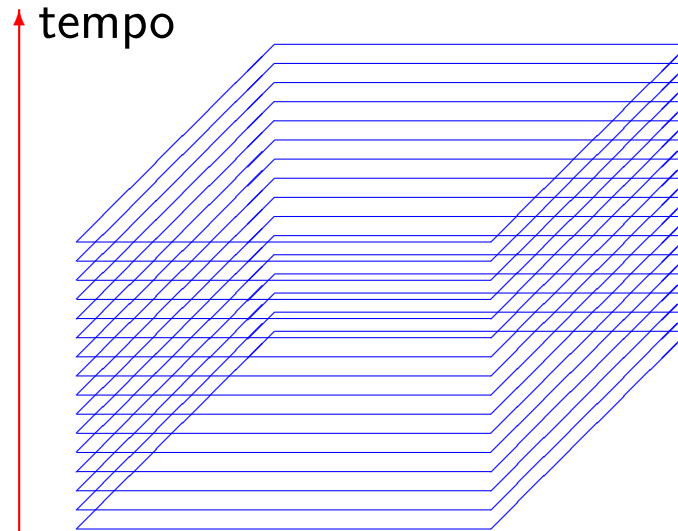
Esempi

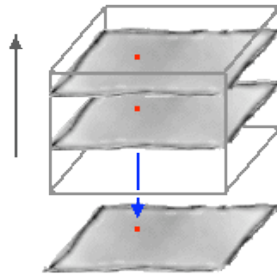
Esempi

Esempi

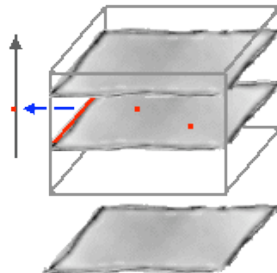
Esempi

Lo spaziotempo assoluto

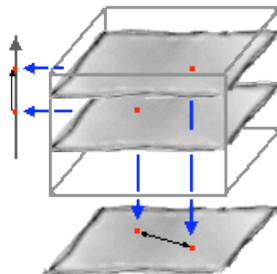




2 eventi nello stesso luogo (coincidenza nello spazio)



2 eventi allo stesso tempo (coincidenza temporale o simultaneità)



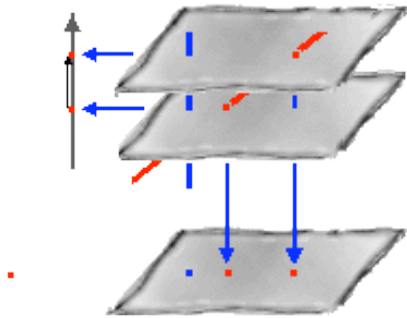
il tempo trascorso tra i 2 eventi

$$T(B) - T(A)$$

la distanza spaziale tra i due eventi

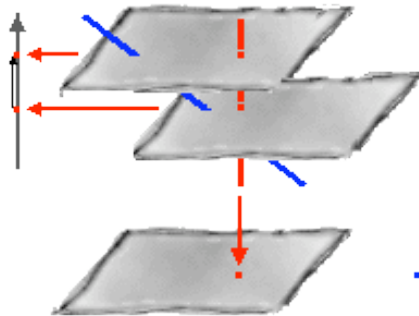
$$d(B, A)$$

Lo spaziotempo galileano



BLU è a riposo e **ROSSO** si muove con velocità uniforme

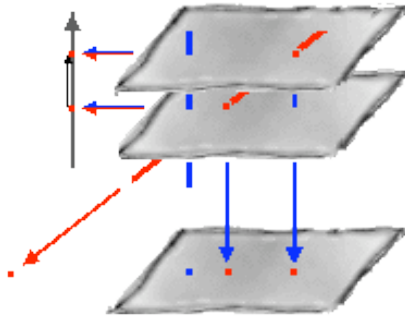
BLU determina che questi 2 eventi hanno una certa separazione spaziale



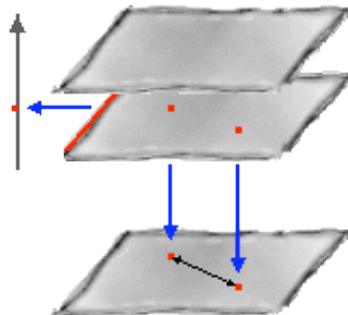
EQUIVALENTE:

ROSSO è a riposo e **BLU** si muove (nella direzione opposta)

ROSSO determina che gli stessi 2 eventi sono coincidenti nello spazio

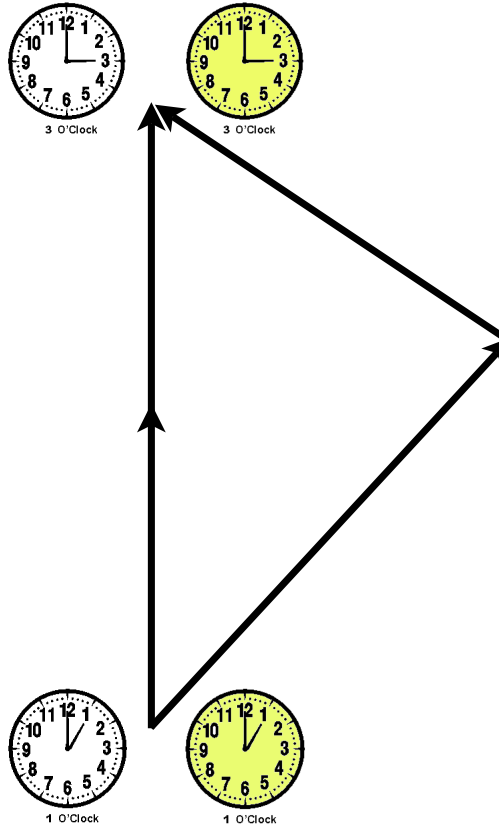


Tuttavia **BLU** e **ROSSO** determinano lo stesso tempo trascorso tra questi 2 eventi
Il tempo è assoluto



BLU e **ROSSO** determinano la stessa separazione spaziale tra 2 eventi simultanei
La distanza tra due eventi simultanei è assoluta

Il tempo trascorso non dipende dalla storia tra 2 eventi



h_{AB} : storia di un oggetto (orologio) dall'evento A all'evento B (ci sono tante possibili storie)

$t(h_{AB})$: tempo misurato dall'orologio che ha la storia h_{AB}

nello spazio tempo galileano:

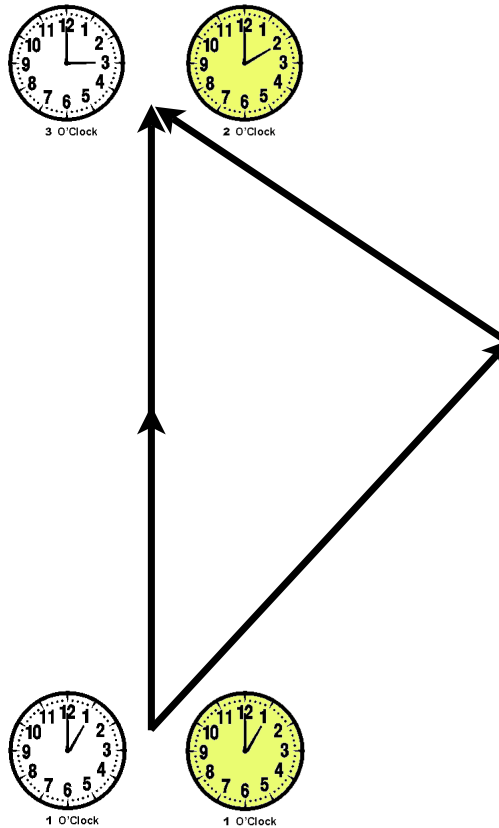
$t(h_{AB})$ non dipende dalla storia h_{AB} , ma solo da A e B

Quindi nello spazio tempo galileano:

$$\exists T : \mathcal{M} \rightarrow \mathbb{R} \quad \text{tale che} \quad t(h_{AB}) = T(B) - T(A)$$

LA SCOPERTA PIÙ IMPORTANTE DEL XX SECOLO

Il tempo trascorso **dipende** dalla storia tra 2 eventi



Demonstrating Relativity by Flying Atomic Clocks

At speeds encountered in everyday life, relativistic effects are very small. When Einstein published his work on relativity the clocks then available were not sufficiently accurate to observe the predicted effects on time. Instead, indirect evidence obtained from astronomy and particle physics was used to support the relativity theories.

Highly accurate atomic clocks, the first of which was built and operated at NPL in 1955, opened up the possibility of directly measuring relativistic effects. Atomic clocks enable time to be measured far more accurately than any other physical quantity. The original NPL clock, like many that followed it, maintained time by counting cycles of an atomic frequency transition present within the caesium atom. Atomic clocks have been developed that are sufficiently portable to be flown in an aircraft, and possess sufficiently good timekeeping properties that the relativistic effects may be observed.

In 1971 Keating and Hafele operating from the United States Naval Observatory in Washington DC, performed the most famous flying clock experiment. Four commercial caesium atomic clocks were flown around the world on commercial aircraft, firstly travelling from east to west, and then travelling from west to east. The results of the experiment did indeed confirm the relativistic predictions.

To commemorate the 25th anniversary of the Keating and Hafele experiment, NPL featured in a BBC Horizon programme that involved flying a single caesium atomic clock from London to Washington and then back again. The timekeeping properties of atomic clocks had improved very significantly over the 25 years since the original experiment, and as a result relativistic effects would be observable following much shorter clock trips.

Several relativistic effects need to be considered when performing a flying clock trip, including:

- The speed of the aircraft relative to an observer on the ground. This is a result of the special theory of relativity.
- The height and hence gravitational potential of the clock on the aircraft relative to an observer on the ground. This is a result of the general theory of relativity.

Before the start of the experiment, the travelling clock was compared directly against the UK's national timescale at NPL, to establish both its offset and rate. During the flights the height, speed and estimated position of the aircraft were regularly monitored. From these measurements the following predictions were made regarding the expected time gain of the travelling clock relative to NPL's reference timescale.

Results included:

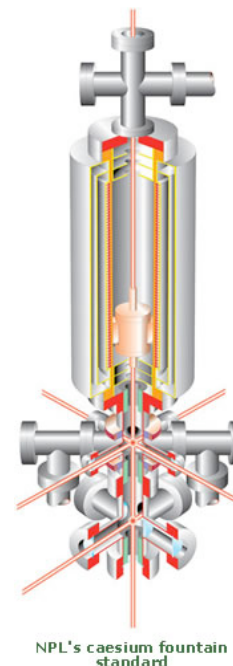
- The combined flight times of 14 hours and mean height in excess of 10 km resulted in a predicted clock gain of 53 ns. This followed the principle that a clock in a weaker gravitational field (higher altitude) will run faster.
- The effect of the aircraft's speed relative to the Earth's surface resulted in a predicted clock loss of 16.1 ns. This followed the principle that a moving clock runs slow.



Essen (right) and Parry with the original NPL atomic clock

On return to NPL the travelling clock was predicted to have gained 39.8 ns, including an additional geometric factor. This compared remarkably well with a measured gain of 39.0 ns. We estimated the uncertainty due to clock instabilities and noise to be around ± 2 ns. This short flying clock experiment therefore provided a clear demonstration of relativistic effects.

Research is continuing to develop new atomic clocks that are either more stable, such as NPL's caesium fountain standard, or are very significantly smaller than those used in these flying clock experiments. There is considerable potential for future improvements. Atomic clocks now operate continuously in space on the US Global Positioning System satellites. The observation of relativistic effects and their correction has become an important part of both the operation of satellite navigation systems and of international timekeeping.



NPL's caesium fountain standard

The UK's National Measurement Laboratory, Metromnia, 18 - Spring 2005

Quindi nel “nostro” spazio tempo

$$\exists T : \mathcal{M} \rightarrow \mathbb{R} \quad \text{tale che} \quad t(h_{AB}) = T(B) - T(A)$$

Qual è la struttura del “nostro” spazio tempo?

