希望能在這個課程中，讓你感覺到物理思考的 **fun—樂趣**。

了解物理是一種有系統而且理性的思考方式
提供了我們面對自然世界，一個珍貴而不可或缺的觀點。

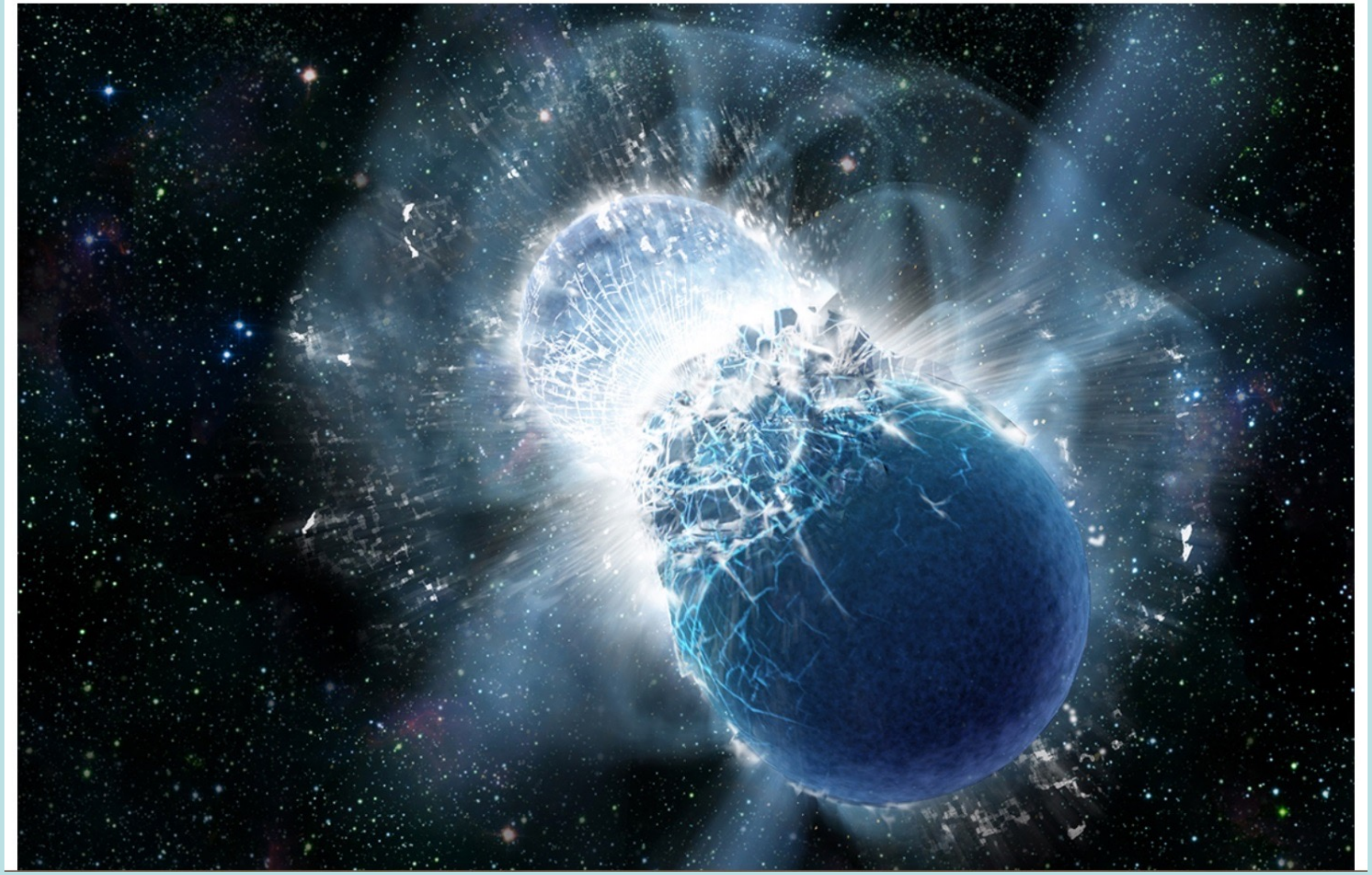
以這個觀點來了解自然，是充滿了 **fun 樂趣**。

It is an exciting time to be a physicist !

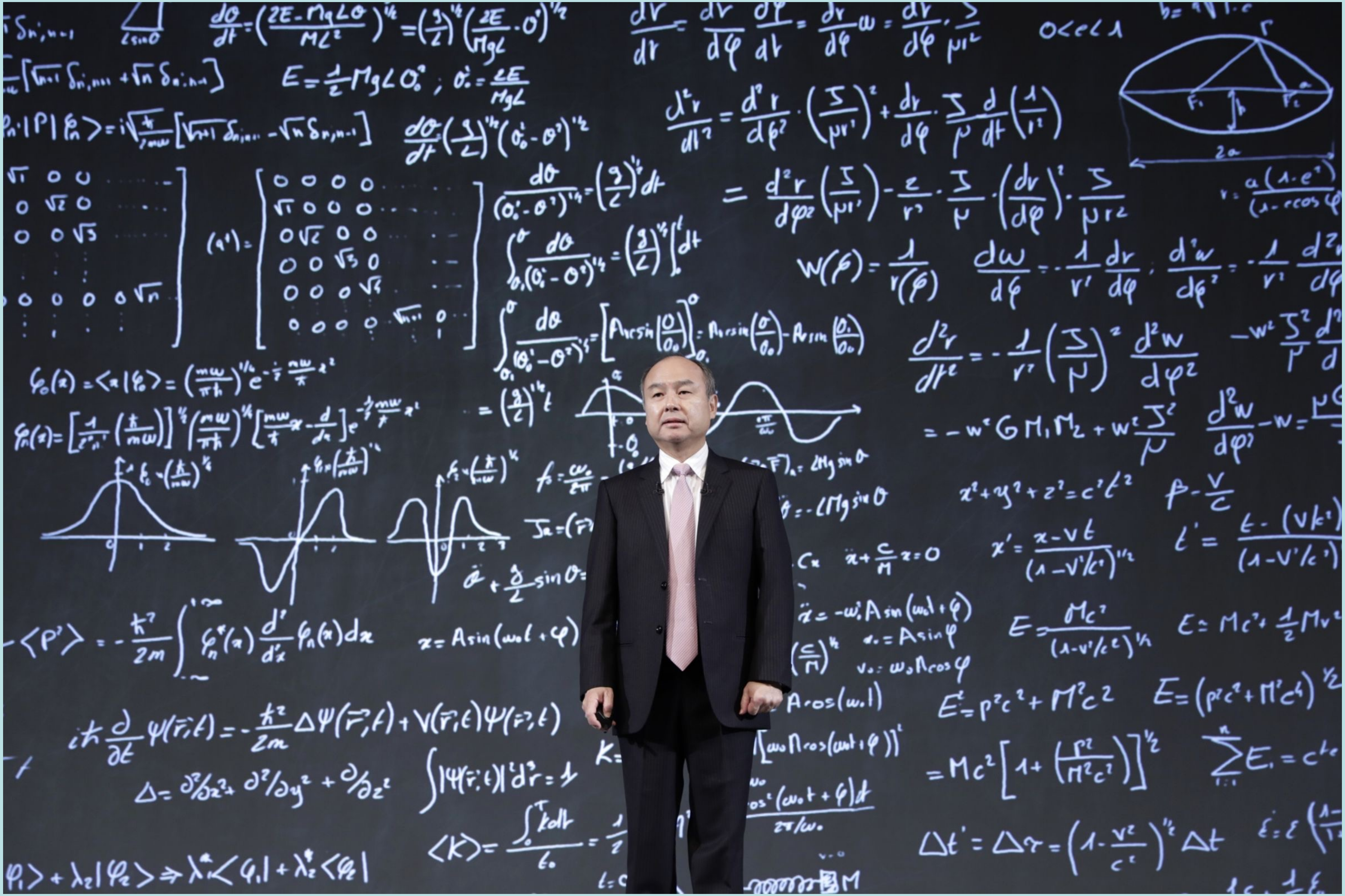
做物理、科學很令人興奮！

DAILY NEWS 23 August 2017, updated 23 August 2017

Exclusive: We may have detected a new kind of gravitational wave



物理是什麼？

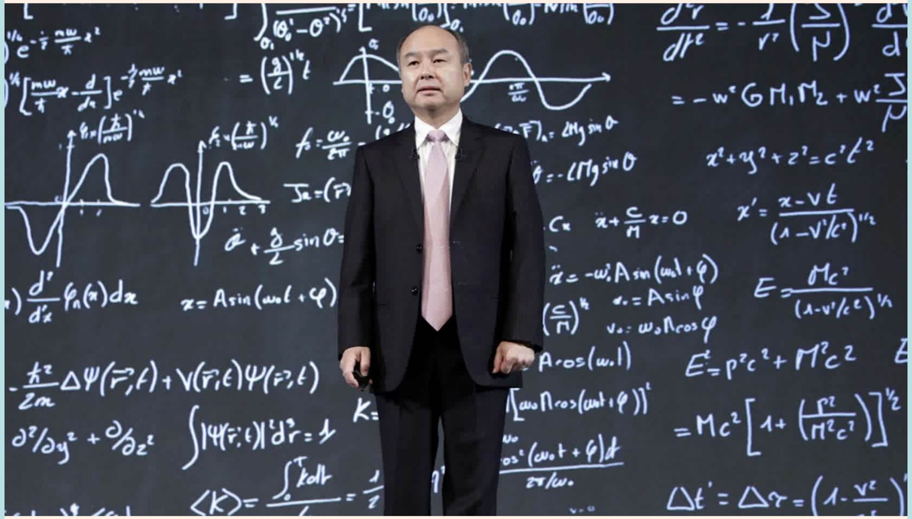


Home

SoftBank Group Corp + Add to myFT

SoftBank shareholders push for answers on ‘Nasdaq whale’ bets

Japanese group urged to reveal who is running unit at centre of large US equity options trades



Investors have unsuccessfully quizzed SoftBank for details on its new asset management unit since founder Masayoshi Son, pictured, disclosed it last month © Bloomberg

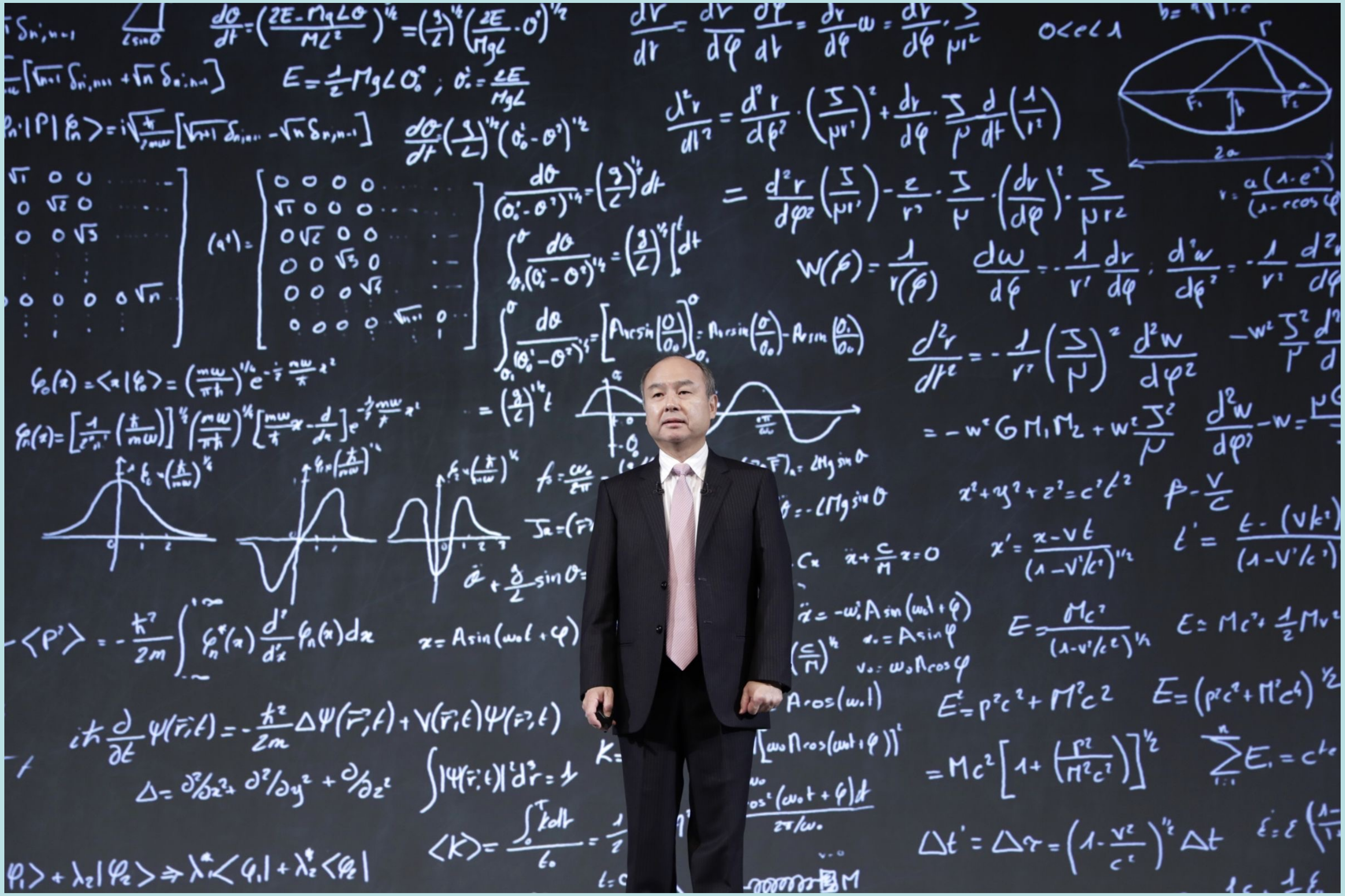
YESTERDAY by **Leo Lewis** and **Kana Inagaki** in Tokyo, and **Robert Smith** and **Katie Martin** in London

SoftBank shareholders are calling on the technology conglomerate to reveal who is running the unit at the centre of its large US equity options trades, with nerves over an unexplained strategic shift stoking a 10 per cent decline in its share price.

Investors have unsuccessfully quizzed SoftBank — famed for big bets on unlisted tech start-ups — for details on its new asset management unit since founder Masayoshi Son disclosed it last month, according to people briefed on the discussions.

日本軟體銀行孫正義

孫想讓人覺得軟銀很聰明，很尖端，用的就是一大堆的物理公式！



因此：物理 ＝ 聰明！

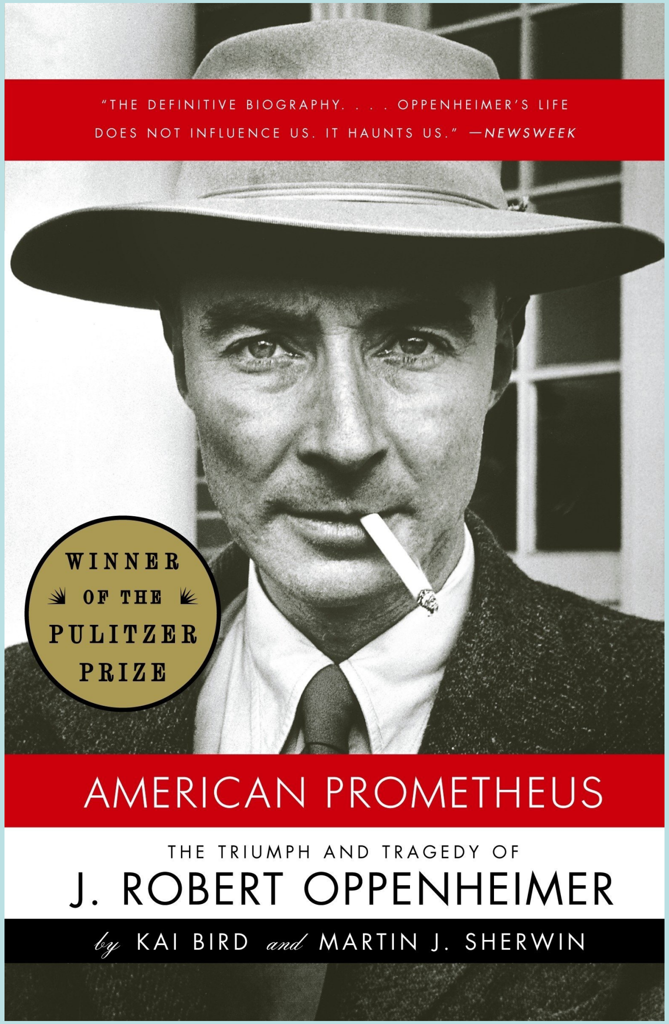
物理 ＝ 有錢！

物理是什麼？

史上最佳代言人

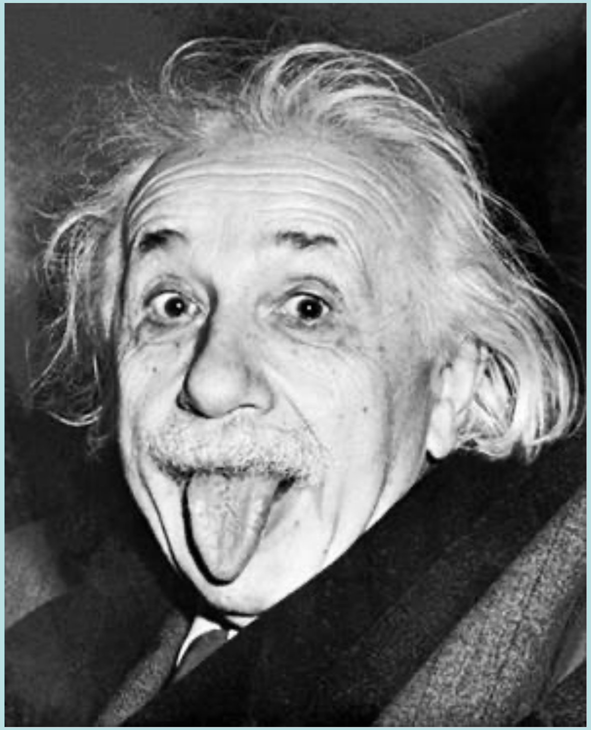
物理是什麼？

史上最佳代言人



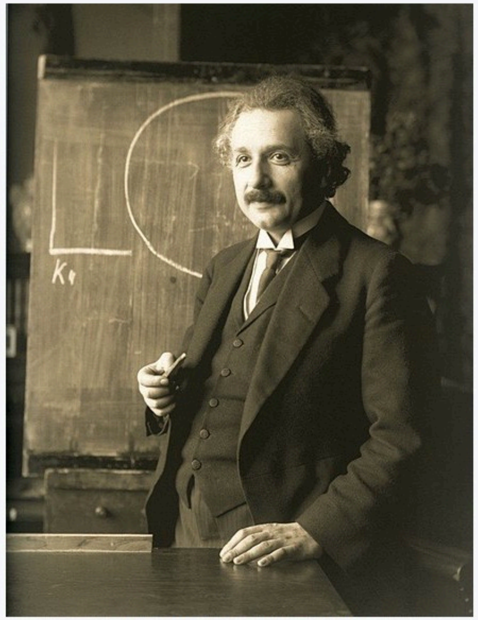

MARGOT ROBBIE CILLIAN MURPHY
BARBENHEIMER
THE WORLD FOREVER CHANGES

物理是什麼？



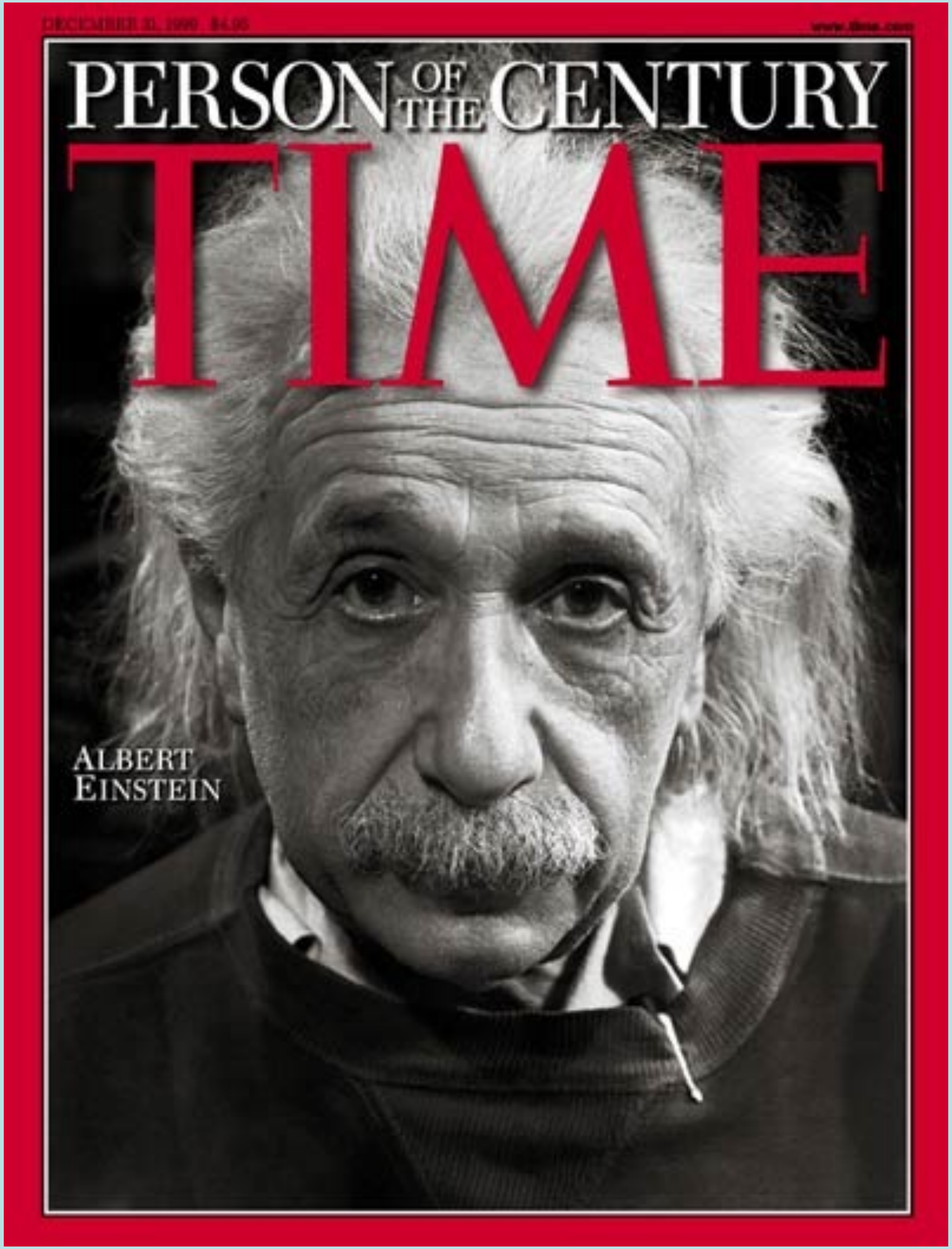
史上最佳代言人

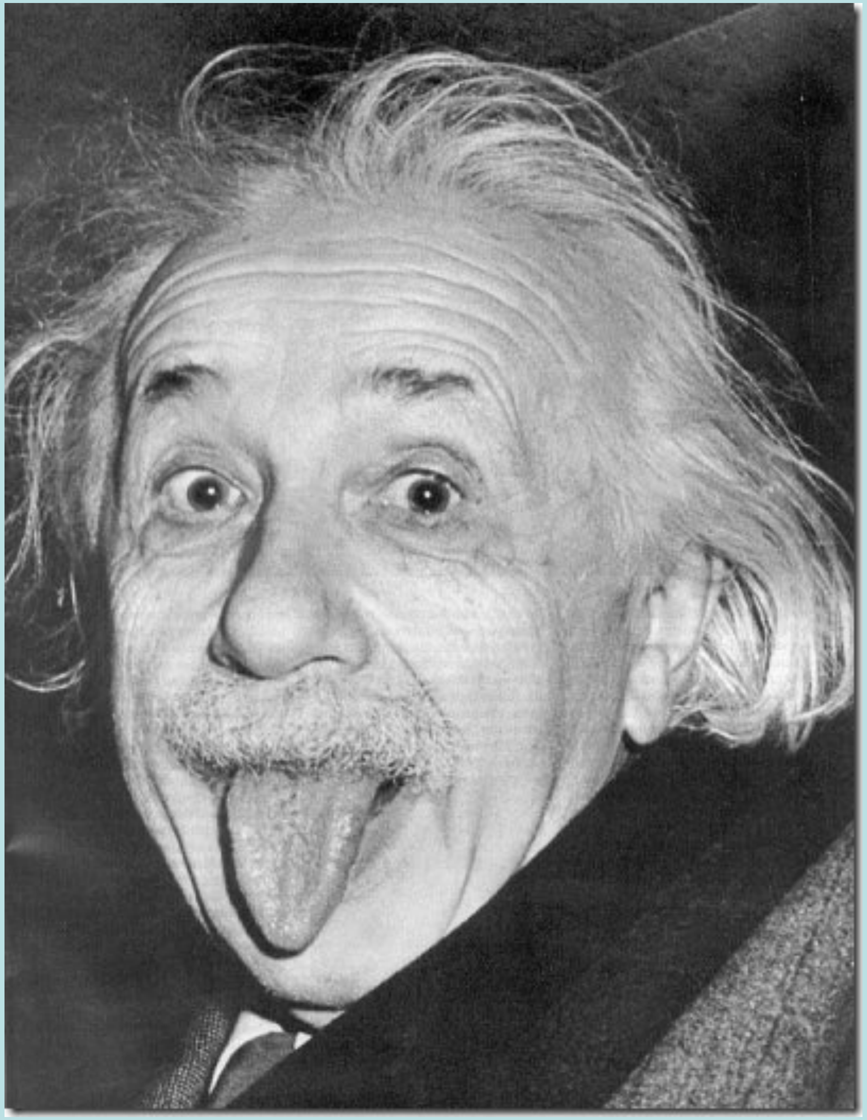
Albert Einstein

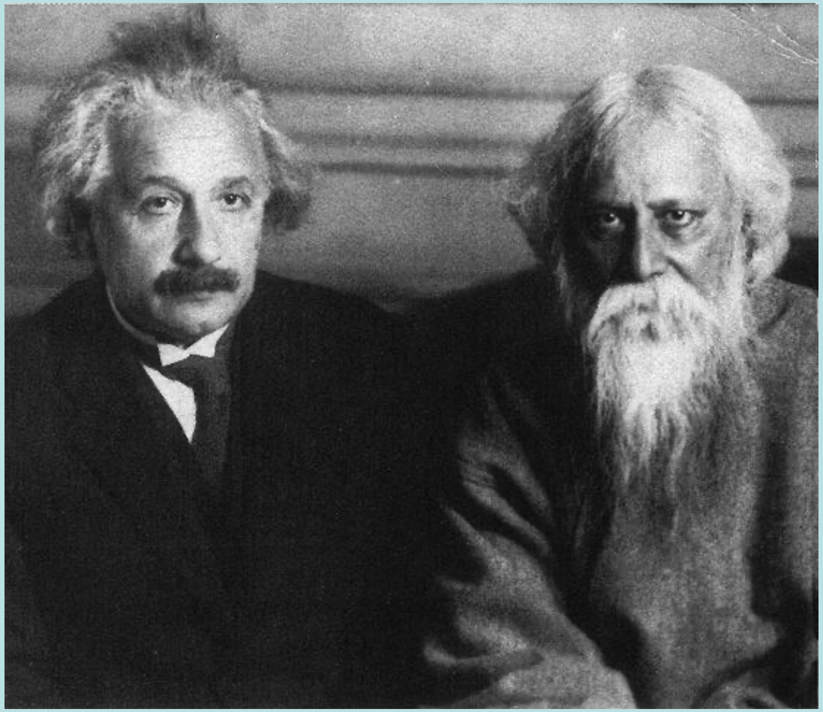


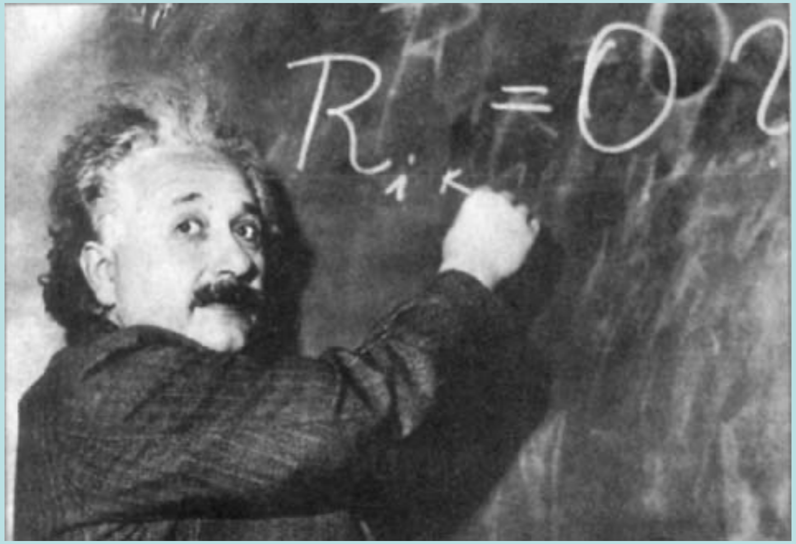
Albert Einstein in 1921

Born	14 March 1879 Ulm, Kingdom of Württemberg, German Empire
Died	18 April 1955 (aged 76) Princeton, New Jersey, US
Residence	Germany, Italy, Switzerland, Austria (present-day Czech Republic), Belgium, United States
Citizenship	Subject of the Kingdom of Württemberg during the German Empire (1879–1896)[note 1] Stateless (1896–1901) Citizen of Switzerland (1901–1955)

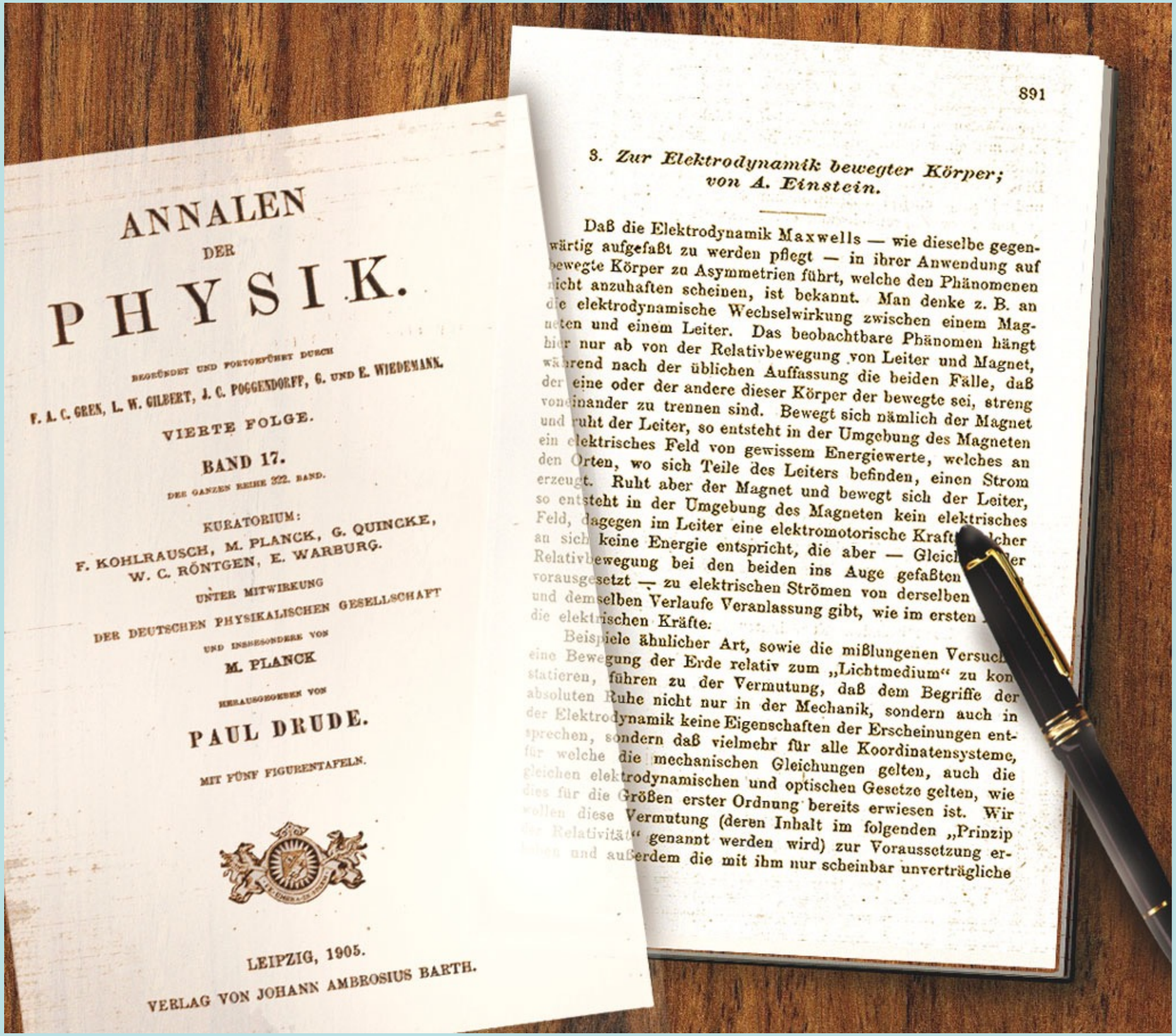

PERSON OF THE CENTURY
TIME
ALBERT EINSTEIN

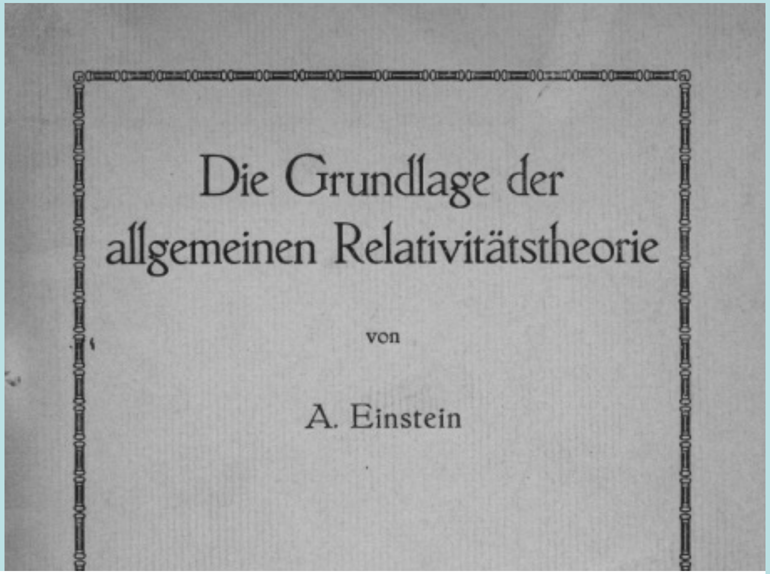





$R_{ik} = 0$

1905 Special Relativity 狹義相對論

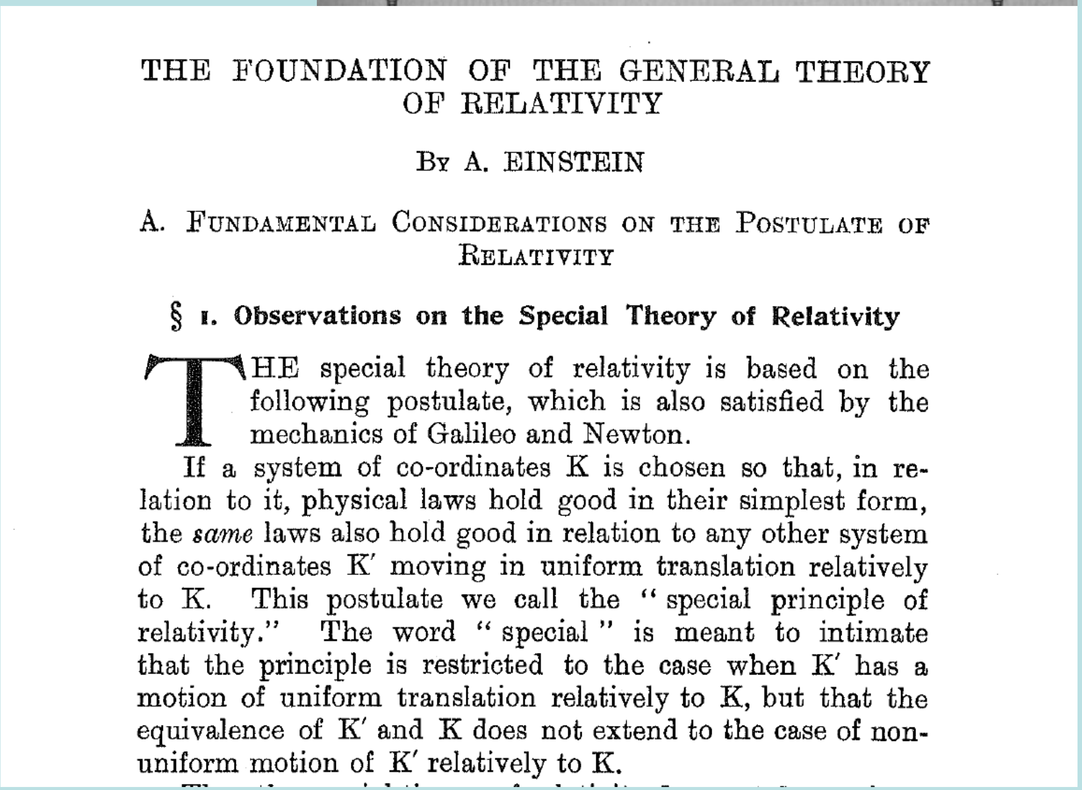




Die Grundlage der allgemeinen Relativitätstheorie

von

A. Einstein



THE FOUNDATION OF THE GENERAL THEORY OF RELATIVITY

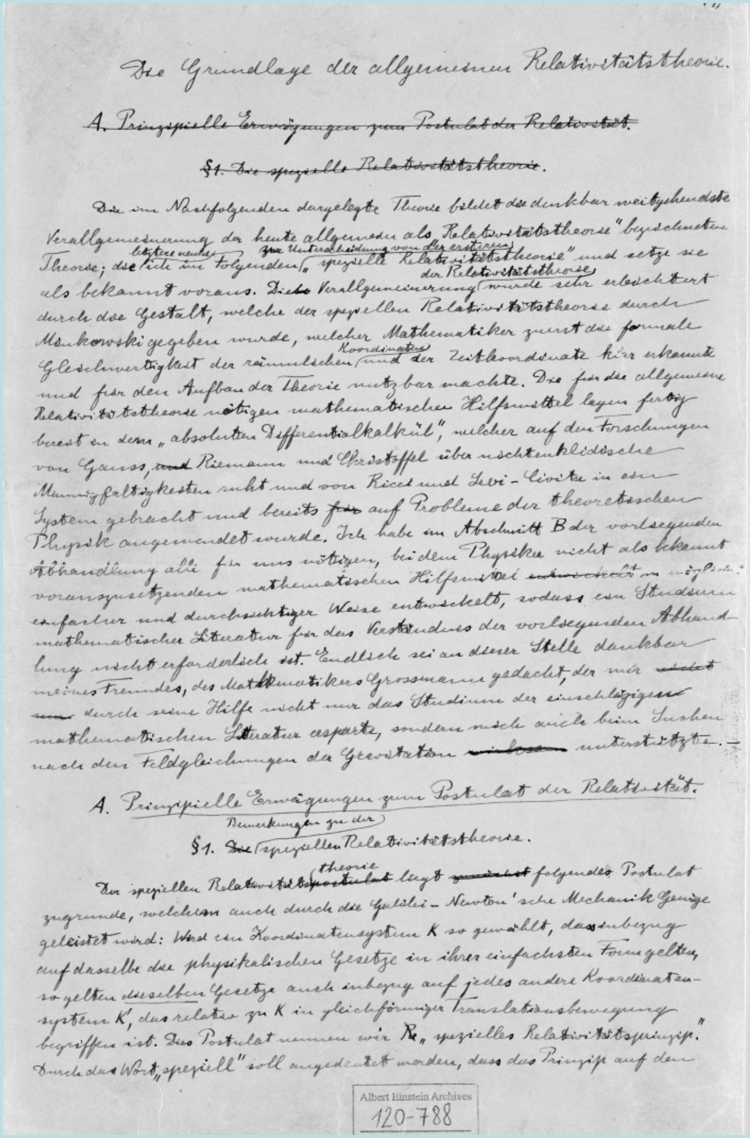
By A. EINSTEIN

A. Fundamental Considerations on the Postulate of Relativity

§ 1. Observations on the Special Theory of Relativity

THE special theory of relativity is based on the following postulate, which is also satisfied by the mechanics of Galileo and Newton.

If a system of co-ordinates K is chosen so that, in relation to it, physical laws hold good in their simplest form, the *same* laws also hold good in relation to any other system of co-ordinates K′ moving in uniform translation relatively to K. This postulate we call the "special principle of relativity." The word "special" is meant to intimate that the principle is restricted to the case when K′ has a motion of uniform translation relatively to K, but that the equivalence of K′ and K does not extend to the case of non-uniform motion of K′ relatively to K.



Die Grundlage der allgemeinen Relativitätstheorie.

~~A. Prinzipielle Erwägungen zum Postulat der Relativität.~~

~~§1. Die spezielle Relativitätstheorie.~~

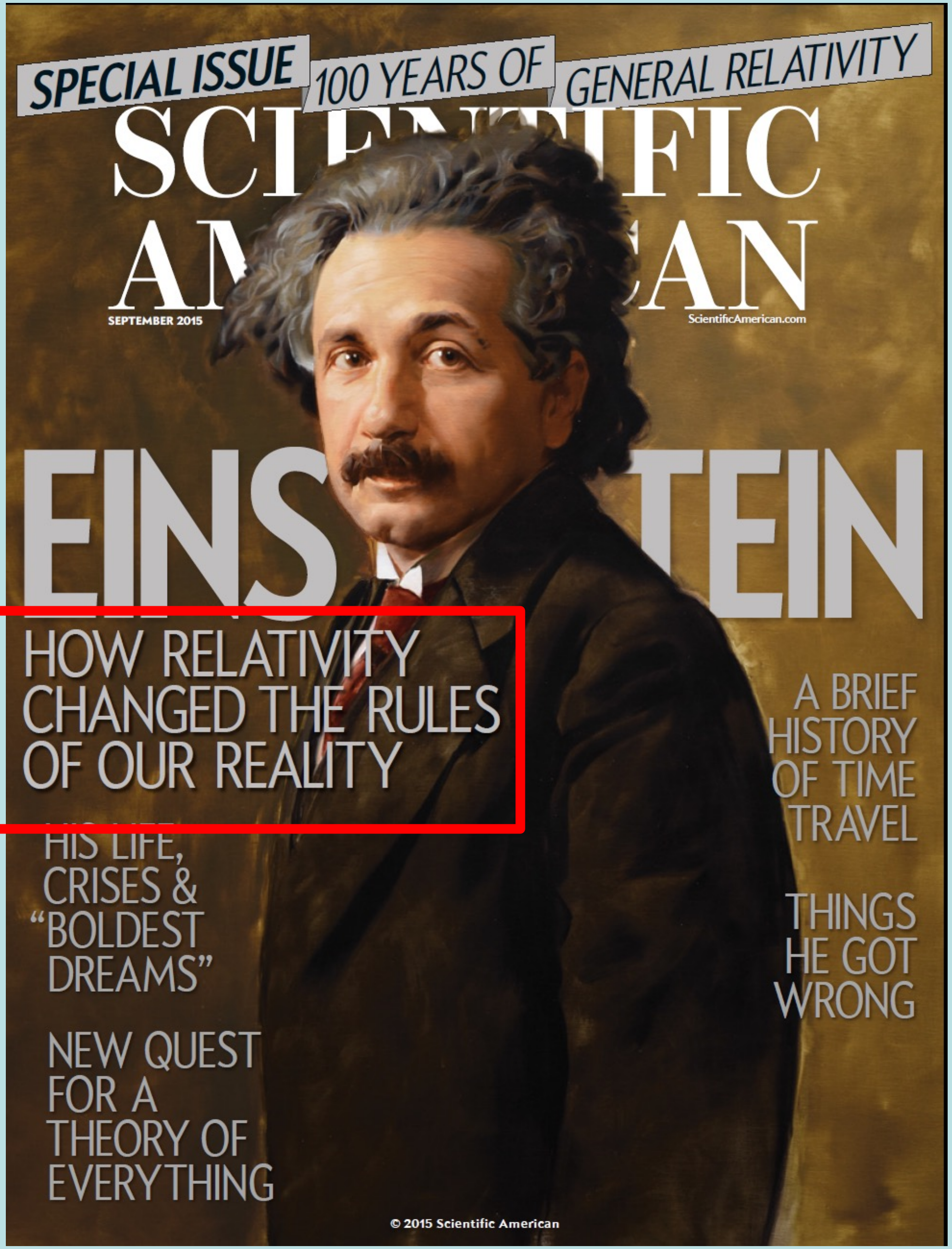
Die im Nachfolgenden dargelegte Theorie bildet die denkbar weitgehendste Verallgemeinerung der heute allgemein als „Relativitätstheorie" bezeichneten Theorie; die letztere nenne ich im Folgenden zur Unterscheidung von der ersteren „spezielle Relativitätstheorie" und setze sie als bekannt voraus. Die Verallgemeinerung der Relativitätstheorie wurde sehr erleichtert durch die Gestalt, welche der speziellen Relativitätstheorie durch Minkowski gegeben wurde, welcher Mathematiker zuerst die formale Gleichwertigkeit der räumlichen Koordinaten und der Zeitkoordinate klar erkannte und für den Aufbau der Theorie nutzbar machte. Die für die allgemeine Relativitätstheorie nötigen mathematischen Hilfsmittel lagen fertig bereit in dem „absoluten Differentialkalkül", welcher auf den Forschungen von Gauss, ~~und~~ Riemann und Christoffel über nichteuklidische Mannigfaltigkeiten ruht und von Ricci und Levi-Civita in ein System gebracht und bereits ~~für~~ auf Probleme der theoretischen Physik angewendet wurde. Ich habe im Abschnitt B der vorliegenden Abhandlung alle für uns nötigen, bei dem Physiker nicht als bekannt vorauszusetzenden mathematischen Hilfsmittel in möglichst einfacher und durchsichtiger Weise entwickelt, sodass ein Studium mathematischer Literatur für das Verständnis der vorliegenden Abhandlung nicht erforderlich ist. Endlich sei an dieser Stelle dankbar meines Freundes, des Mathematikers Grossmann gedacht, der mir durch seine Hilfe nicht nur das Studium der einschlägigen mathematischen Literatur ersparte, sondern mich auch beim Suchen nach den Feldgleichungen der Gravitation unterstützte. —

A. Prinzipielle Erwägungen zum Postulat der Relativität.

§1. ~~Die~~ Bemerkungen zu der speziellen Relativitätstheorie.

Der speziellen Relativitätstheorie liegt folgendes Postulat zugrunde, welchem auch durch die Galilei-Newton'sche Mechanik Genüge geleistet wird: Wird ein Koordinatensystem K so gewählt, dass inbezug auf dasselbe die physikalischen Gesetze in ihrer einfachsten Form gelten, so gelten dieselben Gesetze auch inbezug auf jedes andere Koordinatensystem K′, das relativ zu K in gleichförmiger Translationsbewegung begriffen ist. Dies Postulat nennen wir „spezielles Relativitätsprinzip." Durch das Wort „speziell" soll angedeutet werden, dass das Prinzip auf den

1916 General Relativity 廣義相對論



相對論改變了現實世界的基本規則！

愛因斯坦重建了現實！

許多我們自然以為是真實的，其實不一定是真實的。

感覺平凡的自然，原來如此奧妙！

重建現實竟如此簡單！只是你原來沒注意。

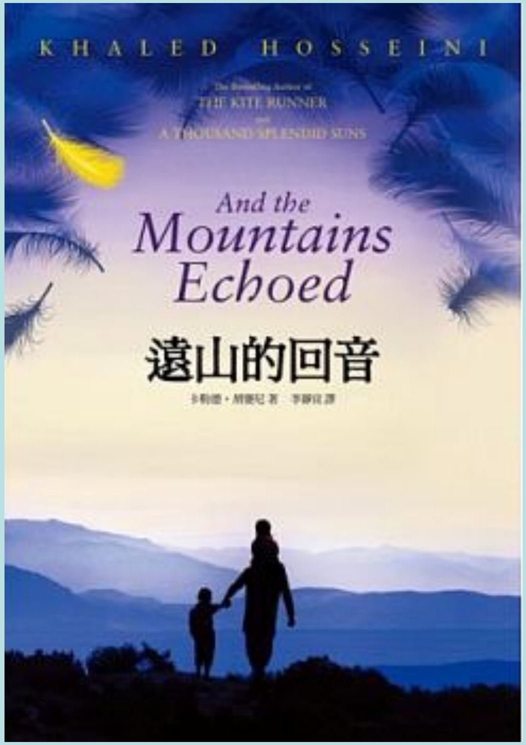
思考力的重訓！

別忘了，思考是你最厲害的功能！因此要多鍛鍊！

相對論的中心論述是植基於下列的事實：

自然界存在光，光傳播的速度非常快，但是有限的。

$c = 299{,}792{,}458\ \mathrm{m/s} \sim 3\times10^{8}\ \mathrm{m/s}$



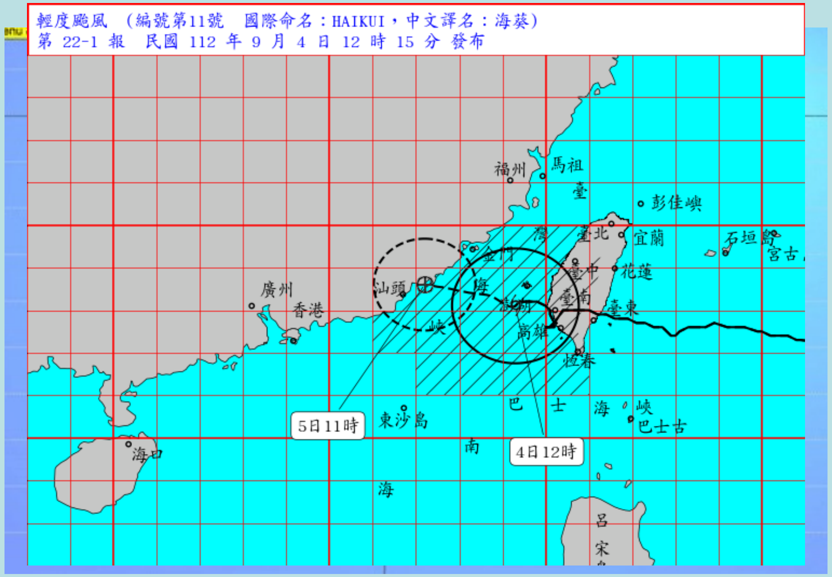
自然界存在光，光傳播的速度非常快，但是有限的。

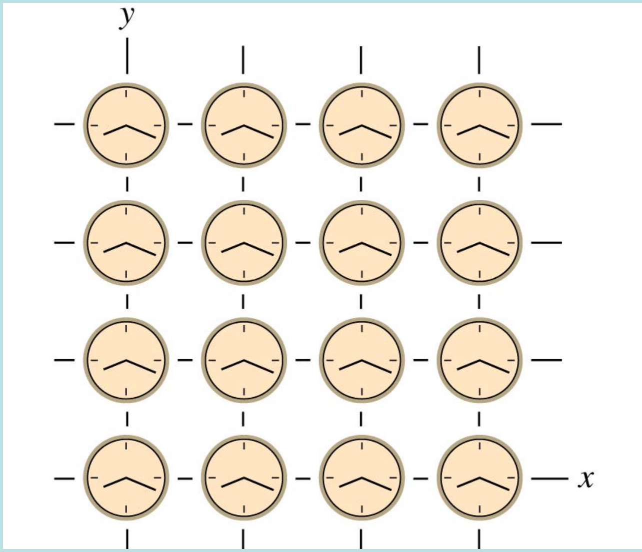
速度是運動快慢的度量，是位置的變化率！

$$變化率 = 單位時間的變化 = \frac{一段時間內的變化（位移）}{這段時間}$$

所以我們要會量位置座標、會量時間及時間差。

空間位置x與時間t是物理最基本的兩個量，而且比你想像複雜。





$$v = \frac{\Delta x}{\Delta t}$$

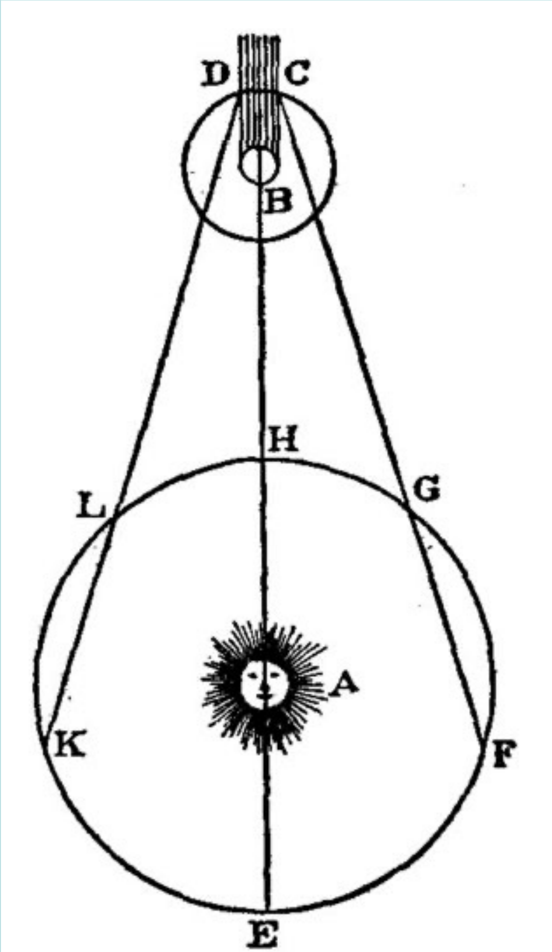
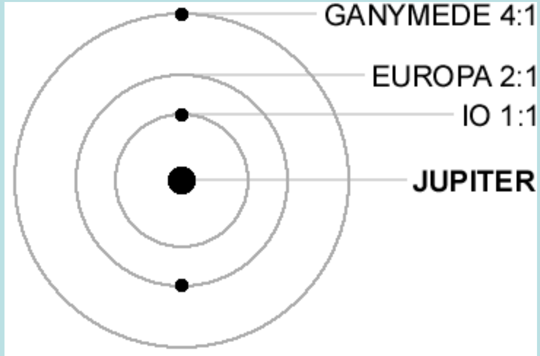


FIG. 70.

1676 Ole Rømer

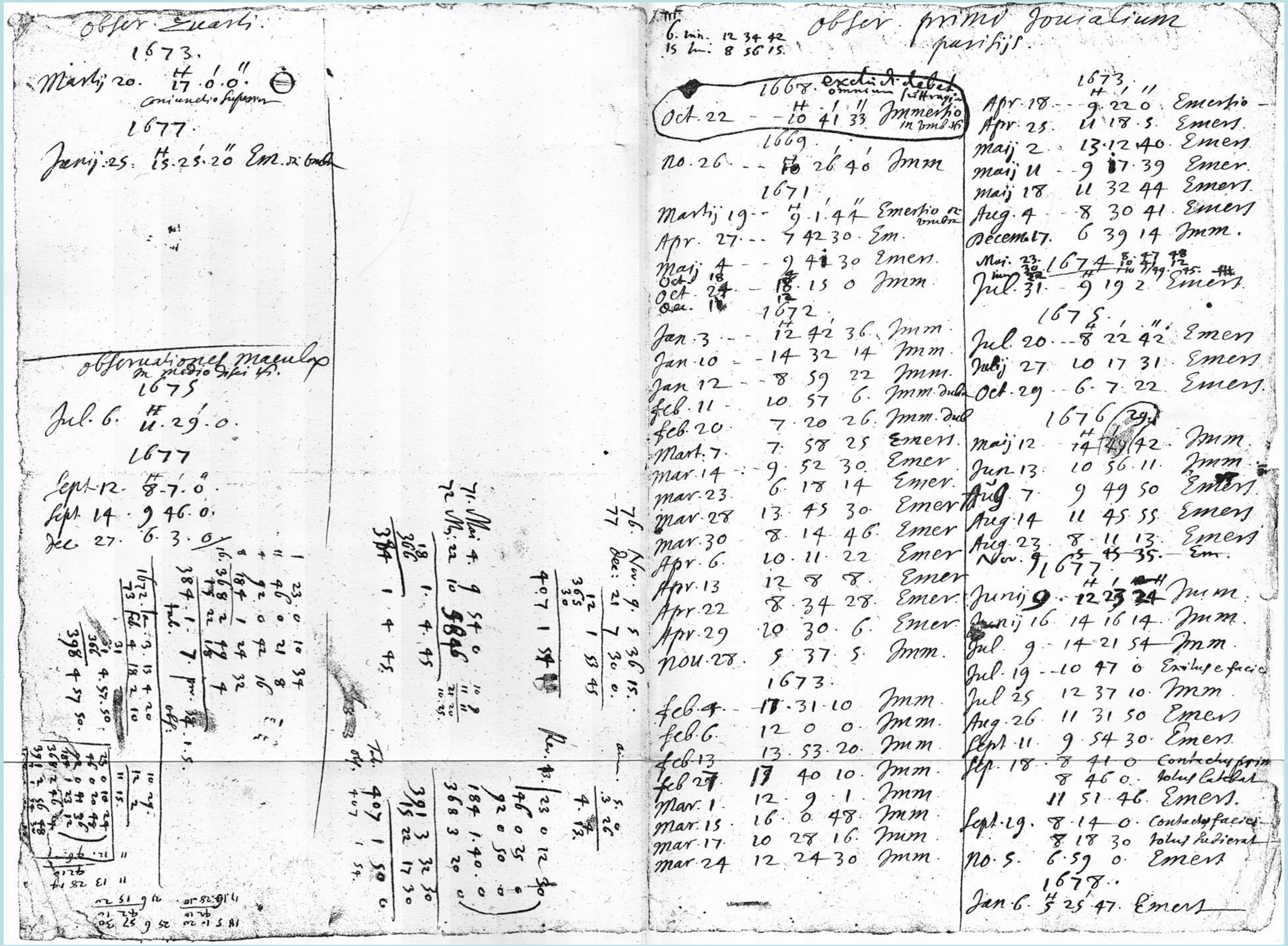


木星衛星IO繞木星的時間，是固定的~42h。

這也就是IO兩次離開木星影子遮蔽之間的間隔時間。但地球也在運動。

實際經過測量，在地球遠離木星圖中LK段時，此間隔會比週期稍長，

此差異，就是光要通過多走的距離上圖LK所需的時間。

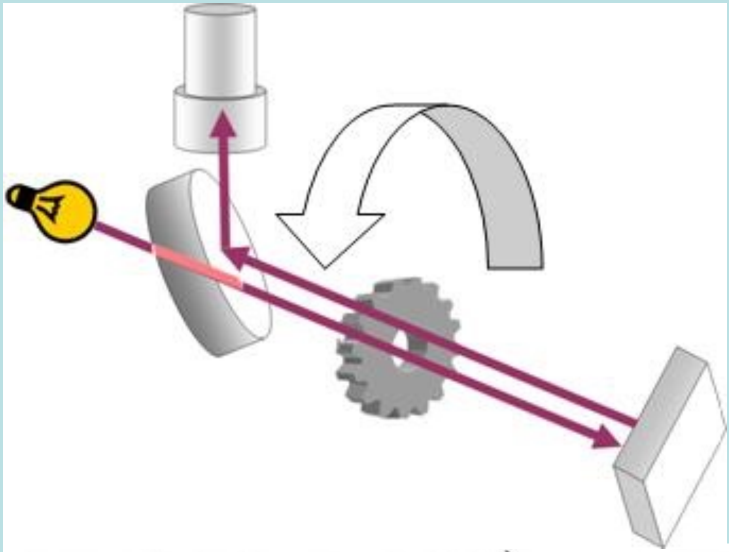


由數據，估計光通過地球繞日軌道直徑需要22m，

這樣得到的光速是~2.2×10^{8} m/s，約 小26%。

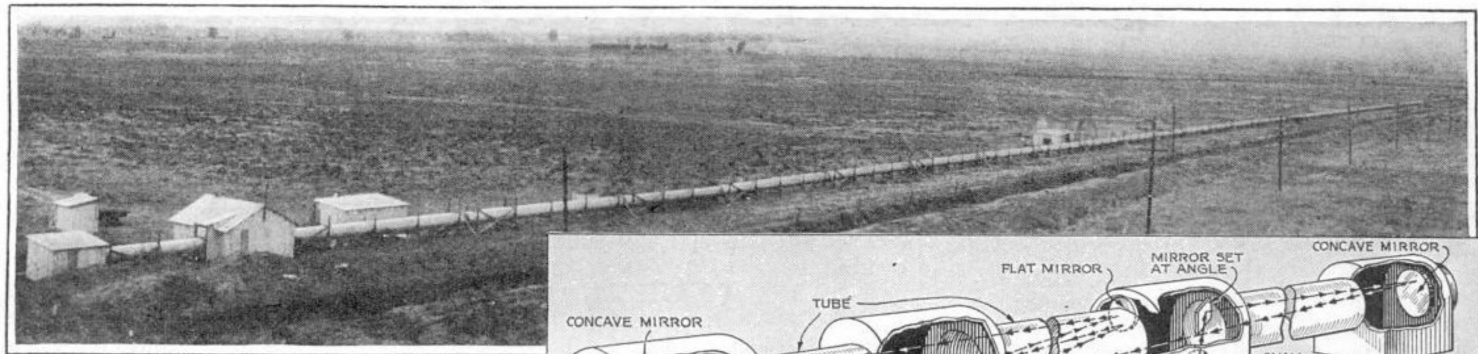
地面上的實驗

Fizeau–Foucault apparatus

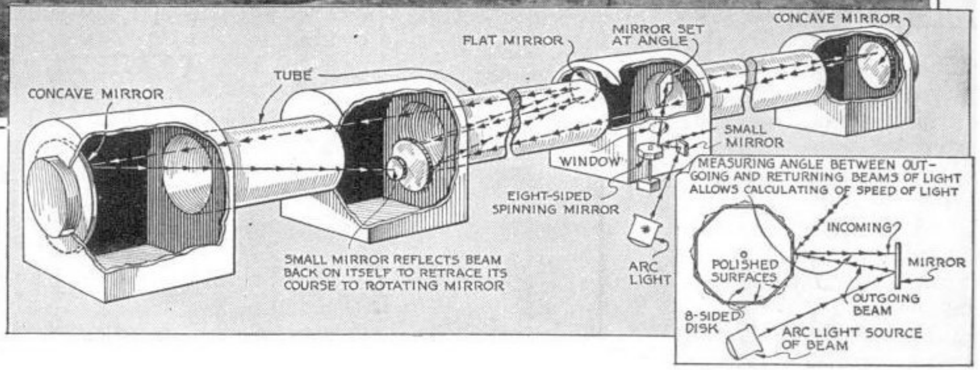


In 1848–49, Hippolyte Fizeau determined the speed of light between an intense light source and a mirror about 8 km distant. The light source was interrupted by a rotating cogwheel with 720 notches that could be rotated at a variable speed of up to hundreds of times a second.

Fizeau was able to calculate a value of $315000\ \mathrm{km/s}$ for the speed of light, about 5% too high.



A view of the mile-long vacuum tube, three feet in diameter, lying in a California valley. This is the main feature of the apparatus used by Dr. Michelson.



At right, the drawing shows the giant tube which Michelson is using, with the arrangement of mirrors which reflect the light ray up and down the tube until it has traveled ten miles. Inset shows how speed of light is calculated from the known angle.

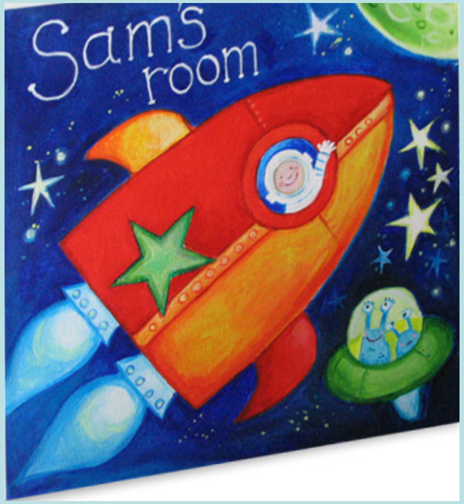
One of the last and most accurate time of flight measurements, Michelson, Pease and Pearson's 1930–35 experiment used a rotating mirror and a one-mile (1.6 km) long vacuum chamber which the light beam traversed 10 times. It achieved accuracy of ±11 km/s

自然界存在光，光的速度是有限的。

接下來就可以問這個相對論最核心的問題：

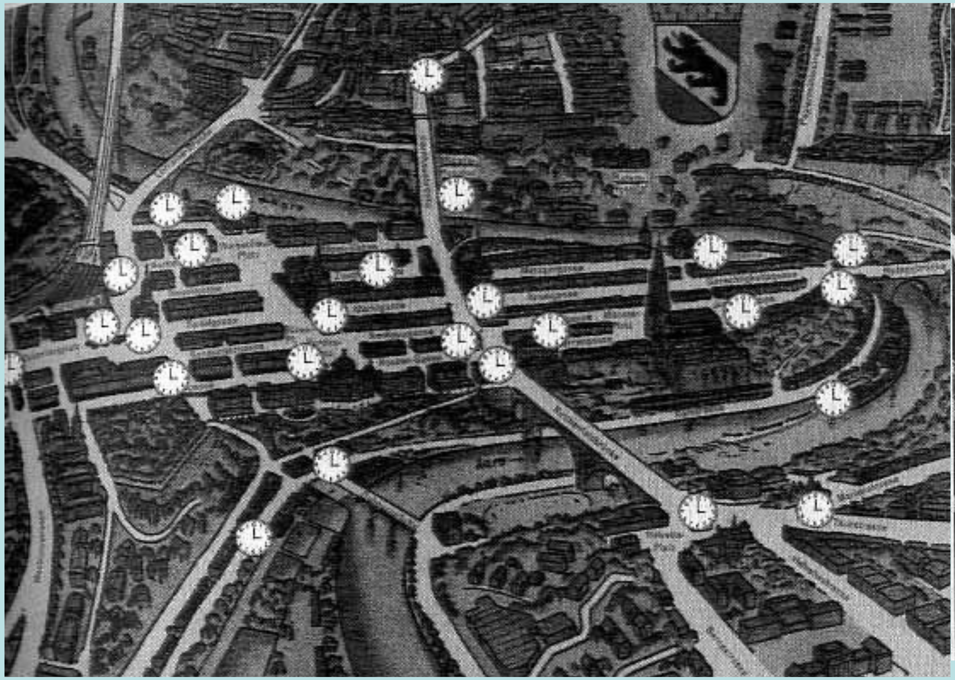
光的移動的速度，是否與觀察者的運動狀態有關？

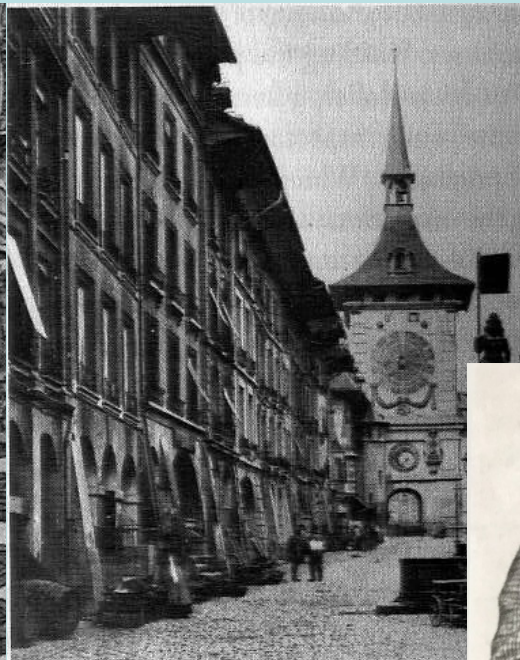
地球上量到的太陽光的光速，與火箭上量到的一樣嗎？



這個問題除了學術上的興趣之外，是有實際上的巨大影響

在Einstein的年代，二十世紀初，歐洲都市開始在市內建造一系列的鐘塔。





他在專利局的工作可能使他注意到同步這些鐘塔的問題。


azy Channel
PIXNET.NET
Yuki's Lazy Channel
HARUHII.PIXNET.NET


K-CAFE
EINSTEIN-HAUS
EINSTEIN
KAFFEE & RAUCHSALON
EINSTEIN
KAFFEE & RAUCHSALON
INTERNET
& coffee
Yuki's Lazy Channel
HARUHII.PIXNET.NET


12
Einstein in Bern (1902 – 1909)
Einstein lebte mit seiner Familie von Ende 1903 bis Mai 1905 an der Kramgasse 49, 2. Stock, wo er die revolutionäre Lichtquanten-Hypothese formulierte.
From late 1903 until May 1905, Einstein and his family lived at Kramgasse 49, 2nd story, where he developed his revolutionary light quantum hypothesis.
IN DIESEM HAVSE SCHVF
ALBERT EINSTEIN
IN DEN JAHREN 1903-1905
SEINE GRVNDLEGENDE
ABHANDLVNG VBER DIE
RELATIVITÄTSTHEORIE
Yuki's Lazy Channel
HARUHII.PIXNET.NET


Yuki's Lazy Channel
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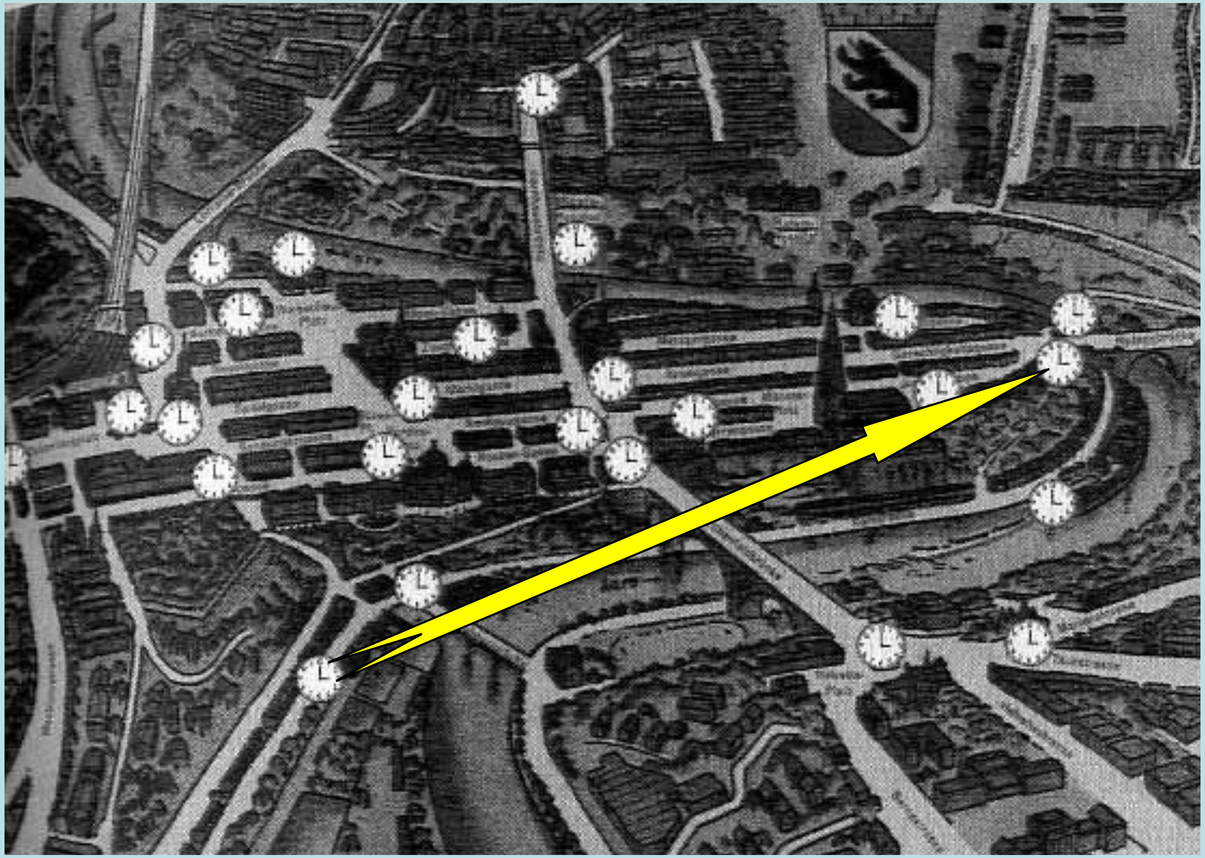
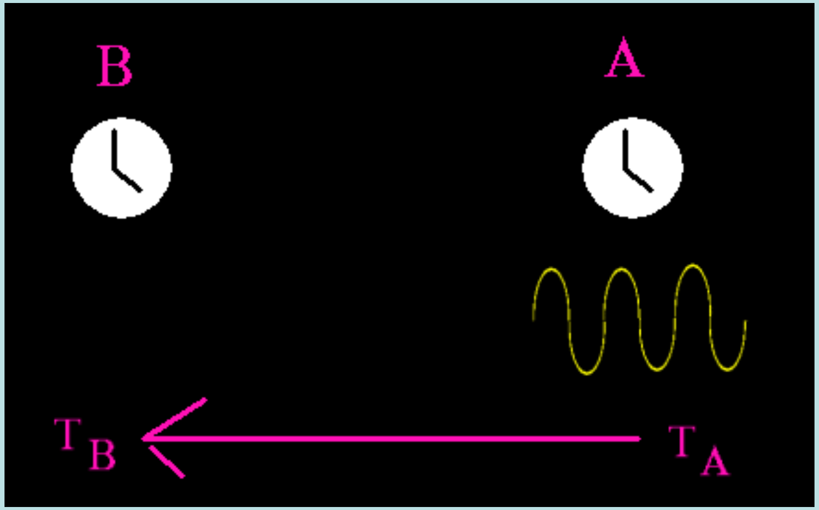
用光信號來將不同位置的計時器同步

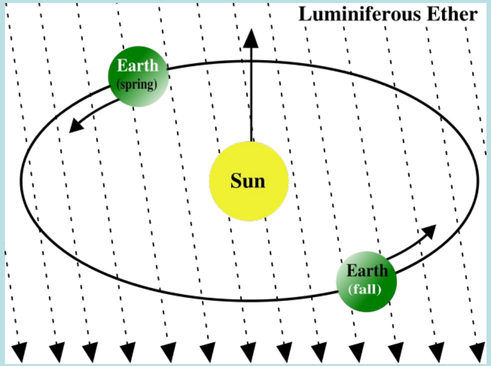


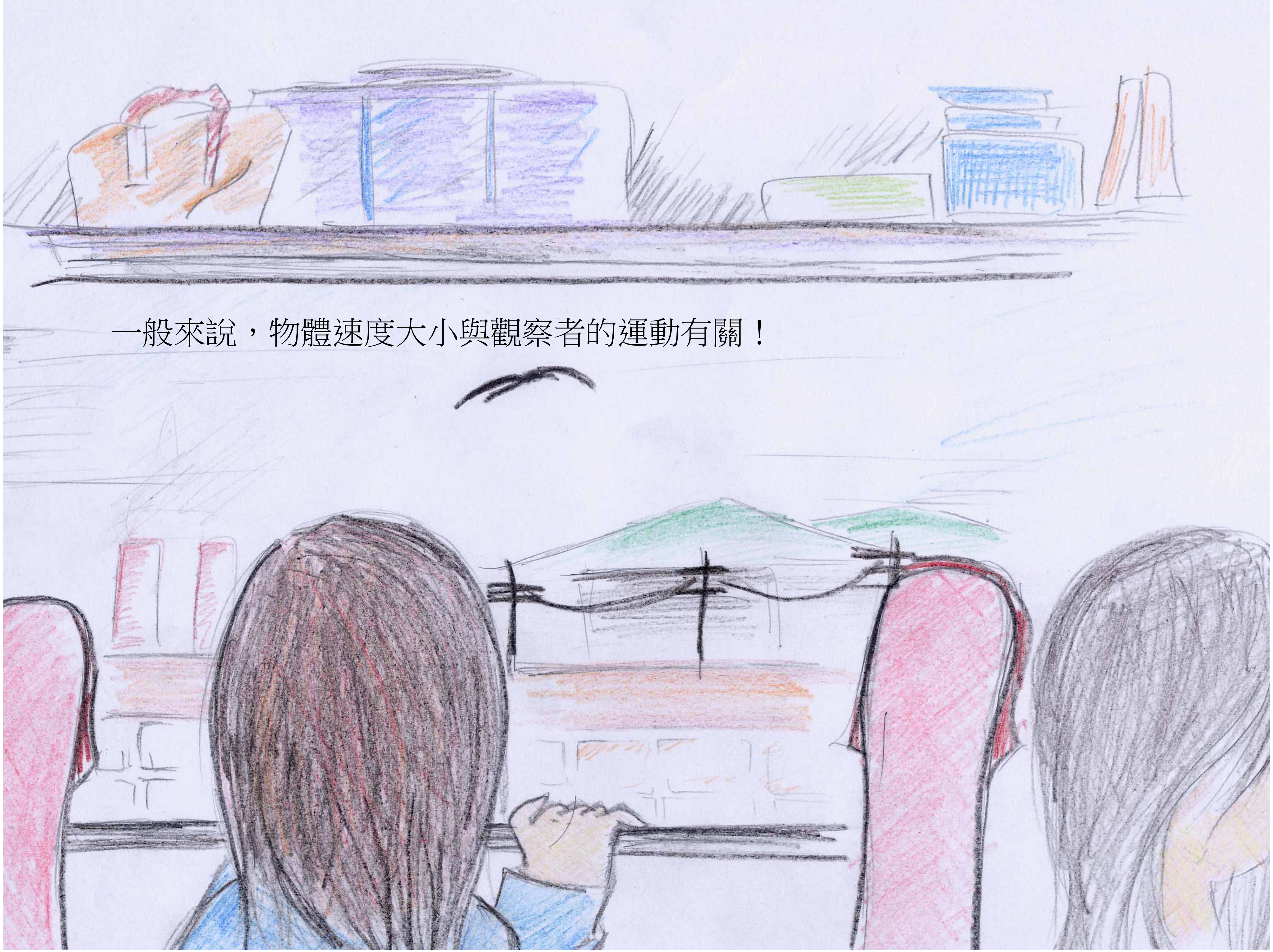
以光來同步不同位置的鐘！



$$T_B = T_A - \frac{AB}{c}$$

但如果光速不是一個定值，這個差異就必須被考慮進來。




一般來說，物體速度大小與觀察者的運動有關！

光是一種波。波一般相對於其介質有固定的波速！

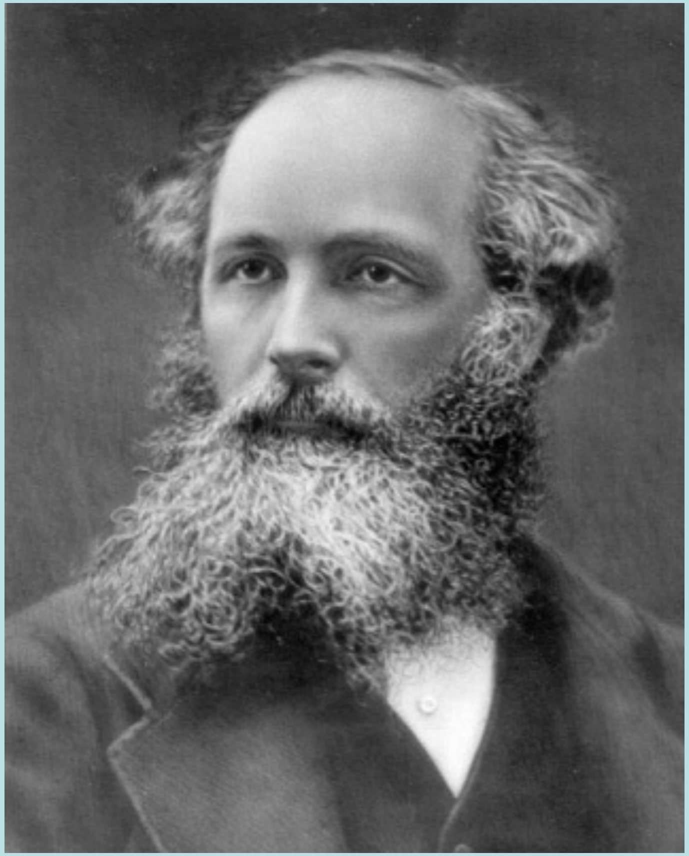
水波波速顯然與觀察者相對於介質的運動有關。

水波對不同速度船上的人看起來速度是不一樣！

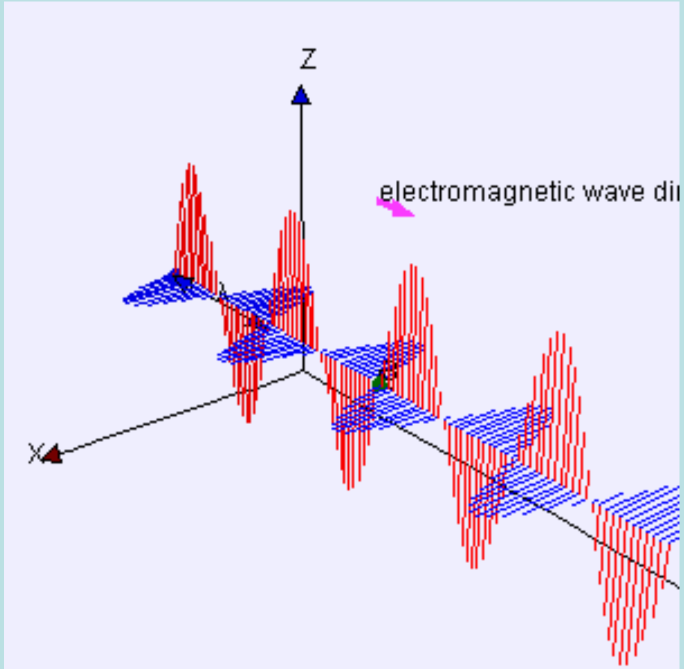
船若是以波速相對於水移動，水波甚至是靜止的！

但電磁波卻是非常少數在真空中傳播的一種波！它不需要介質。

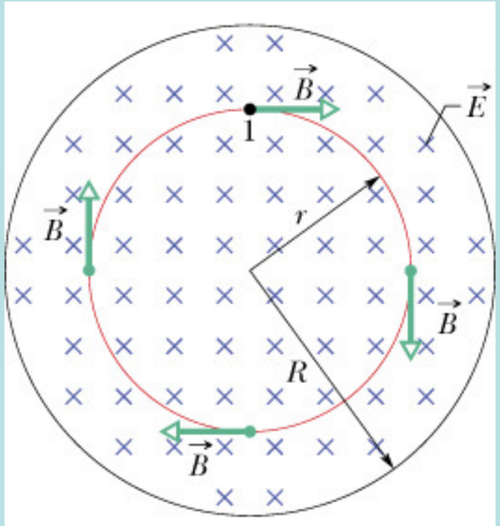
電磁波：電與磁的自動化！

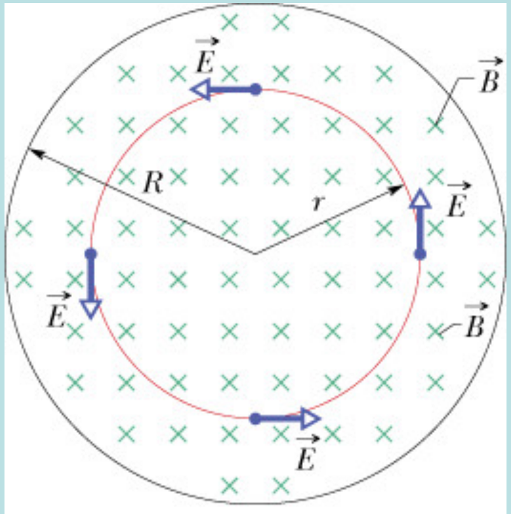


James Clerk Maxwell (1831–1879)



電磁波：電與磁的自動化！ 電磁感應





電場變化時會感應產生垂直的磁場！ 磁場變化時會感應產生垂直的電場！

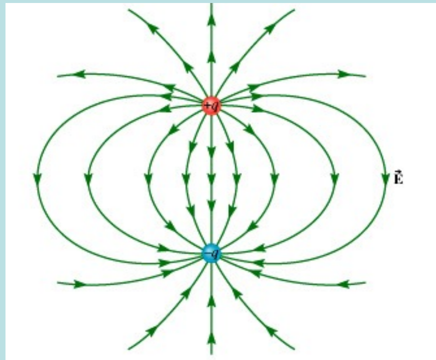
即使沒有電流與電荷，變化的電磁場也可以成為電磁場的來源！

$$\oint \vec{B} \cdot d\vec{l} = \mu_0 \varepsilon_0 \frac{d\Phi_E}{dt}$$

$$\oint \vec{E} \cdot d\vec{l} = -\frac{d\Phi_B}{dt}$$

設想如果在原點突然出現一個電偶極，

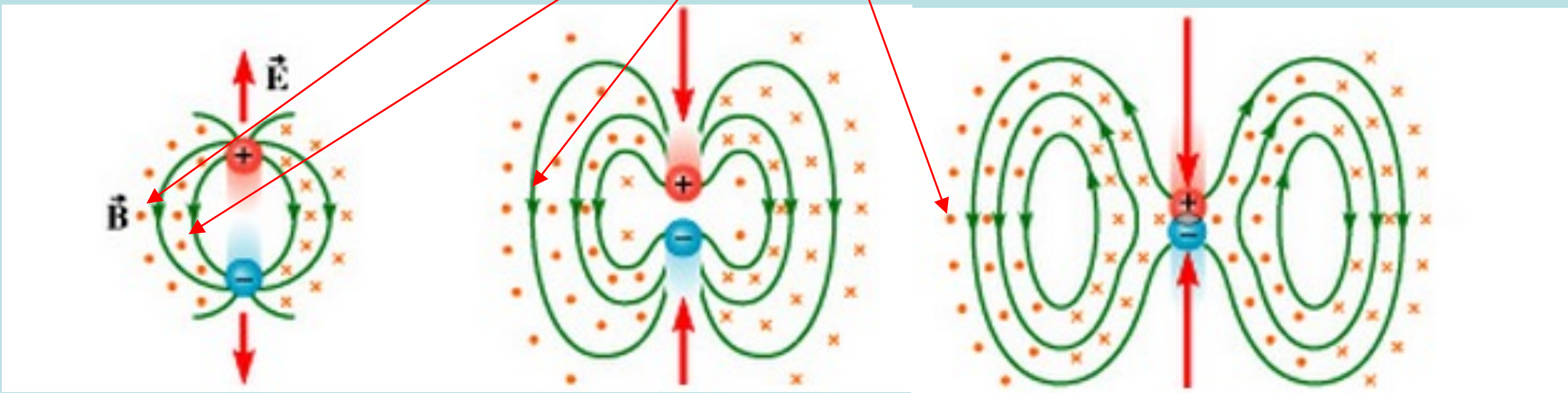
在近處應該會突然出現一電場，類似電偶極的靜電場：

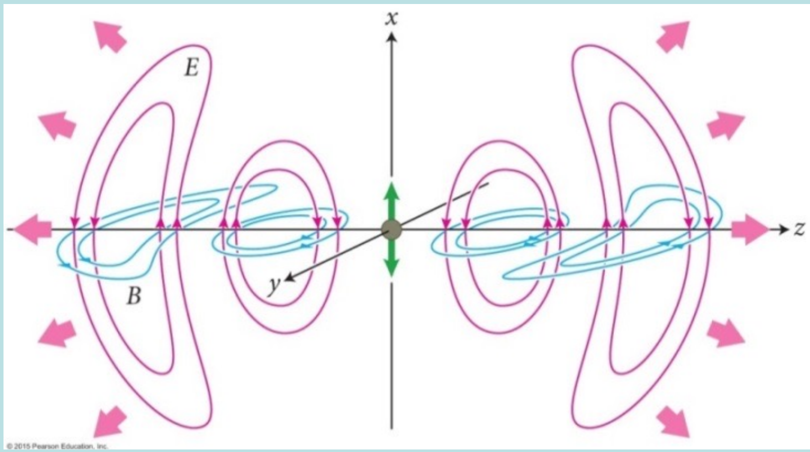


此突然的電場變化會產生垂直的感應磁場。

突然的磁場變化又在更遠處產生感應電場。

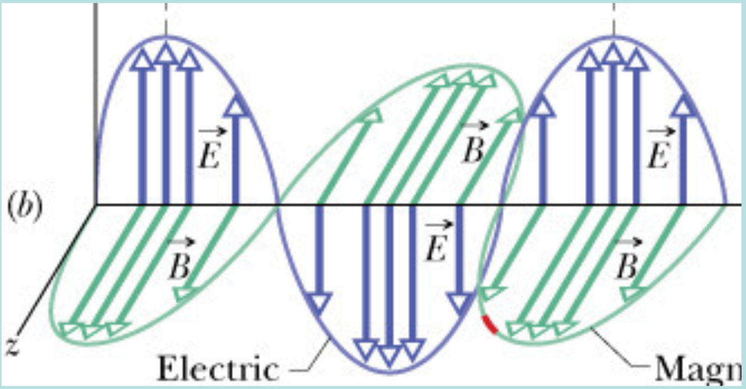
突然的電場變化又在更遠處產生感應磁場。





愛因斯坦很小時就在思考，那麼當一個人幾乎以光速移動，

他看到的光會變成怎樣？光不就凍結了嗎？

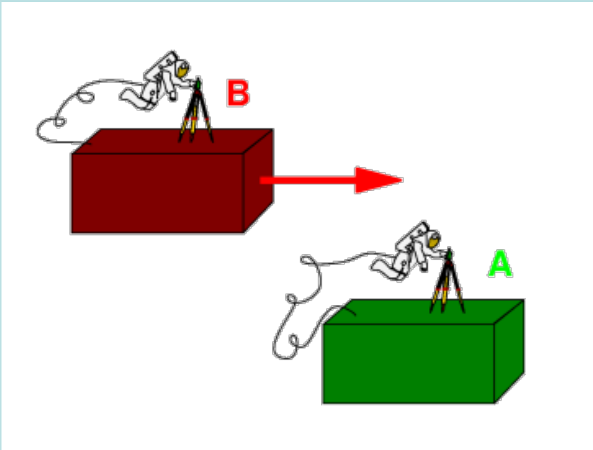


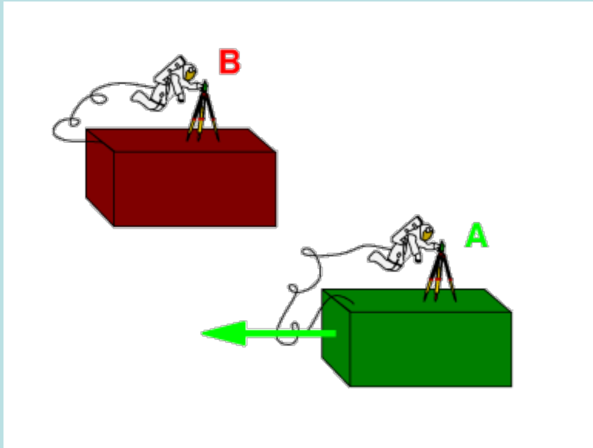
如果電磁波不需要介質，是在真空中傳播，那觀察者就沒有可以相對的對象！

在真空中，靜止的觀察者與幾乎以光速運動的觀察者，應該完全沒有分別。

想像一個靜止的觀察者A，一個運動的觀察者B ，

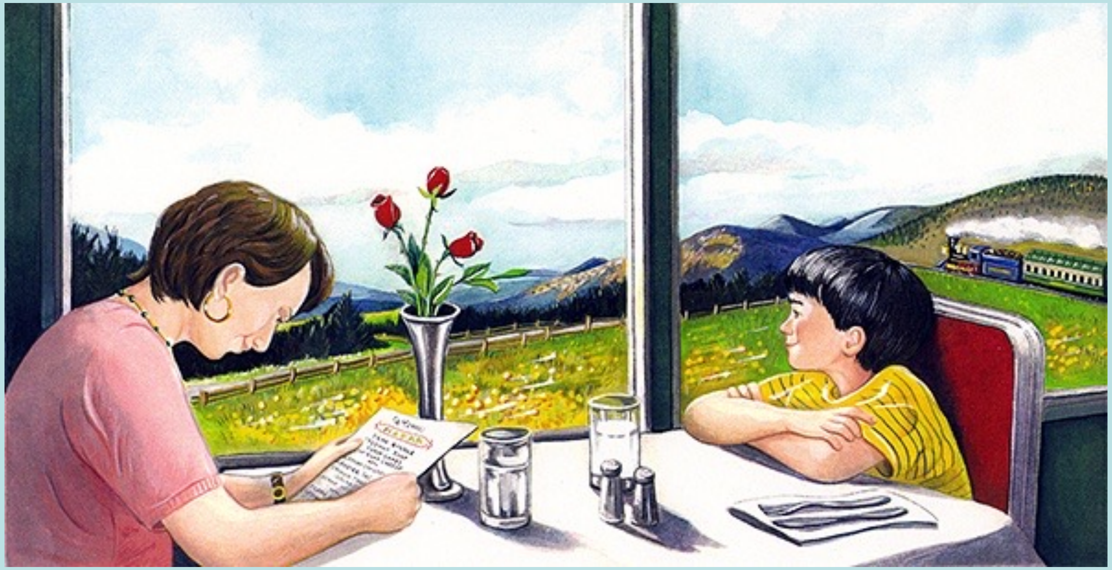
從運動的觀察者B的觀點，會以為自己是靜止的，而靜止者是在移動。





這個觀點並沒有錯，愛因斯坦認為運動是相對的，而不是絕對的。

在平穩移動的火車上，你會以為自己是靜止的，移動的是山。



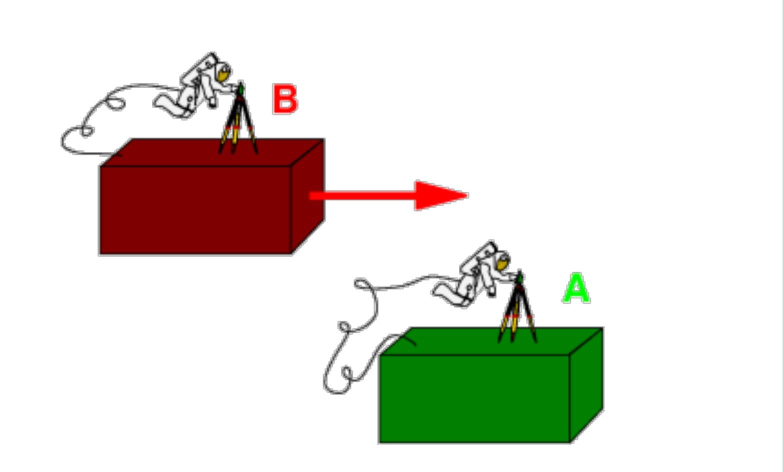
在遊輪中，你幾乎會以為自己是靜止的。

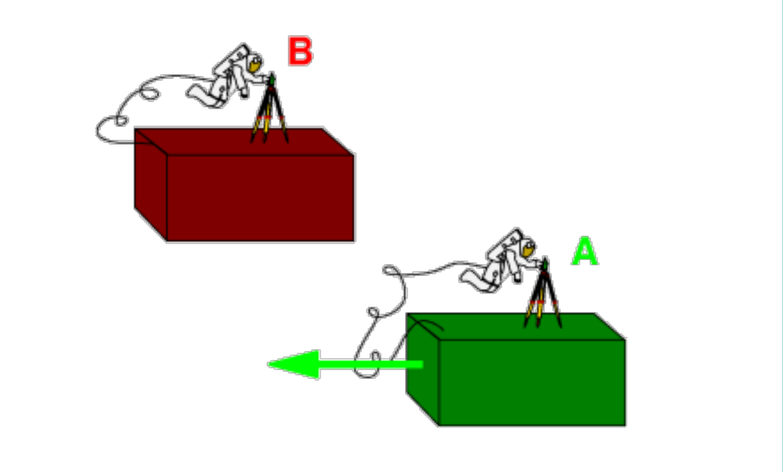
在遊輪上，你看到的世界與靜止時無異。你無法確認遊輪在運動。

這樣的觀點被稱為相對性原則 The Principle of Relativity。

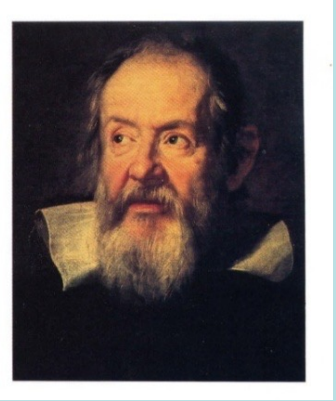
沒有任何力學實驗與觀測可以讓你決定觀察者的絕對運動速度！

換言之，絕對運動速度是沒有意義的概念！速度永遠是相對的。

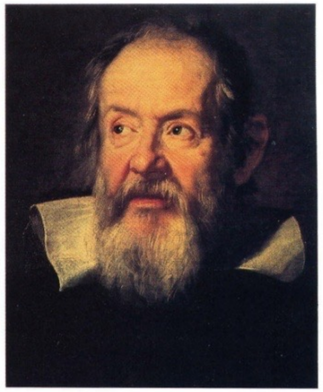




以上兩張圖中的物理現象看起來不同，但都是合理的。



在船艙裡盡可能找到一間大房間，然後將一群人關進去，同時設法弄進一些蚊子、蝴蝶或其他類似的小昆蟲，再拿一個裝滿水的器皿，裡面放一些魚；另外，在房間的屋頂掛上一個小桶子，裡面先裝滿水，然後讓水能從上面的桶子一滴滴地滴進一個事先放置在地板上的細頸器皿。現在請仔細觀察，只要船還保持靜止，然後讓船以任意的速度移動：你將會發現——只要船的移動是有節奏的，而不是毫無目的地搖搖晃晃——船上的所有現象都沒有發生任何改變；也就是說，沒有任何徵兆可以讓你察覺船究竟是在停止或是在航行的狀態中。如果這時你在船上跳遠，你能跳出的距離和船靜止時是一樣的；這也就是說，即使船以很快的速度前進，你也無法期待在往船尾方向跳躍騰空之際，船的前進會將地板從你的腳下帶往船首的方向，使你因此跳得更遠。如果你想朝同伴扔擲物體，你花費的力量是一樣的，無論是你在船尾而你的朋友站在船首或是相反。屋頂水桶中的水還是會滴進地面的器皿中，沒有任何一滴會滴到器皿外靠船尾方向的地板上，儘管水滴還在空中時船已經往前行進了一段距離。最後，我們也知道蚊子和蝴蝶都能朝所有的方向繼續飛行，絕不會被迎面而來的牆壁壓迫，也不必費力追趕快速前進的船隻，儘管牠們在空中飛行時是與船體分離的。如果在船艙內焚香，就會產生一些煙，不久後上升的煙會形成一朵煙雲，讓我們無法分辨出煙飄的方向。所有這些現象的一致性原因在於，船的運動本身對所有在船上的事物，包括空氣，都有相同的影響。

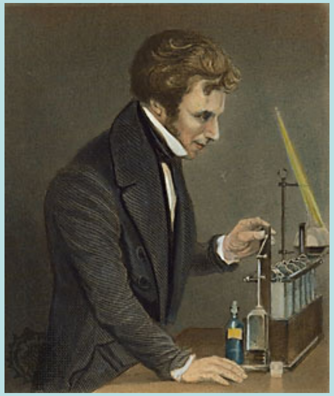


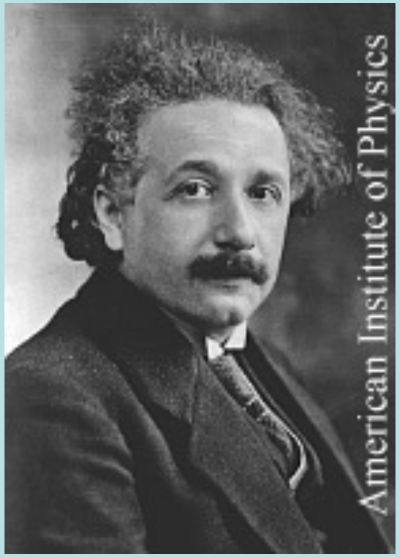
如果在平穩移動的火車上，你觀察不到與靜止時有任何差異。

如此，看到的光應該沒有分別才對。

因此你測量到的光速必定與你靜止時無異！

[redacted]



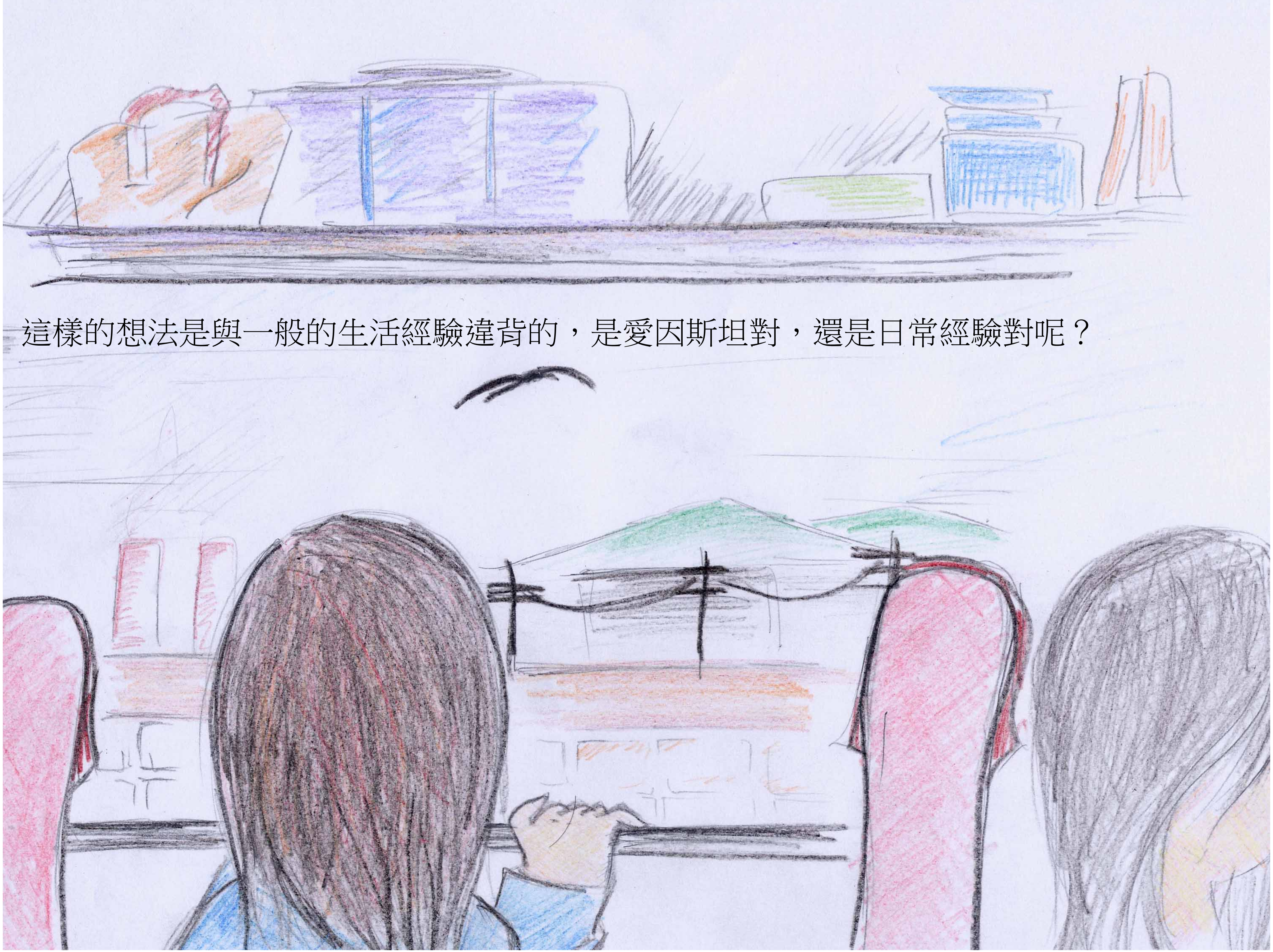


電磁方程式預測電磁波是以一定速$c = \frac{1}{\sqrt{\mu_0 \epsilon_0}}$傳播。

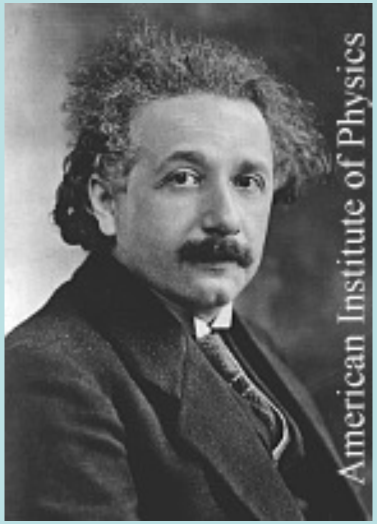
根據相對性原則，我們無法透過光學實驗，來判斷觀察者的運動狀態。

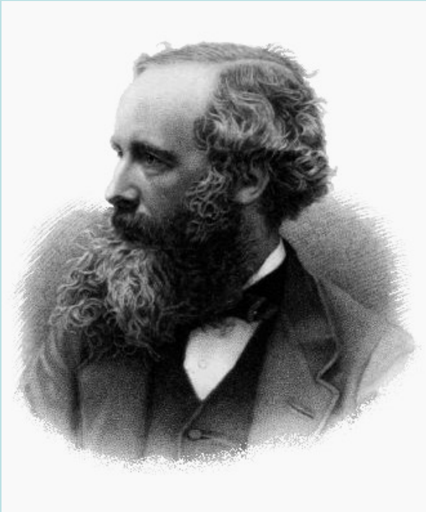
那麼光速與測量者的運動狀態必須無關，永遠是c。

$$\boxed{c = c'}$$


這樣的想法是與一般的生活經驗違背的，是愛因斯坦對，還是日常經驗對呢？

大對決！





馬克斯威爾方程式遵守相對性原則！　馬克斯威爾方程式不遵守相對性原則！

電磁波無介質！　存在無質量的介質以太。

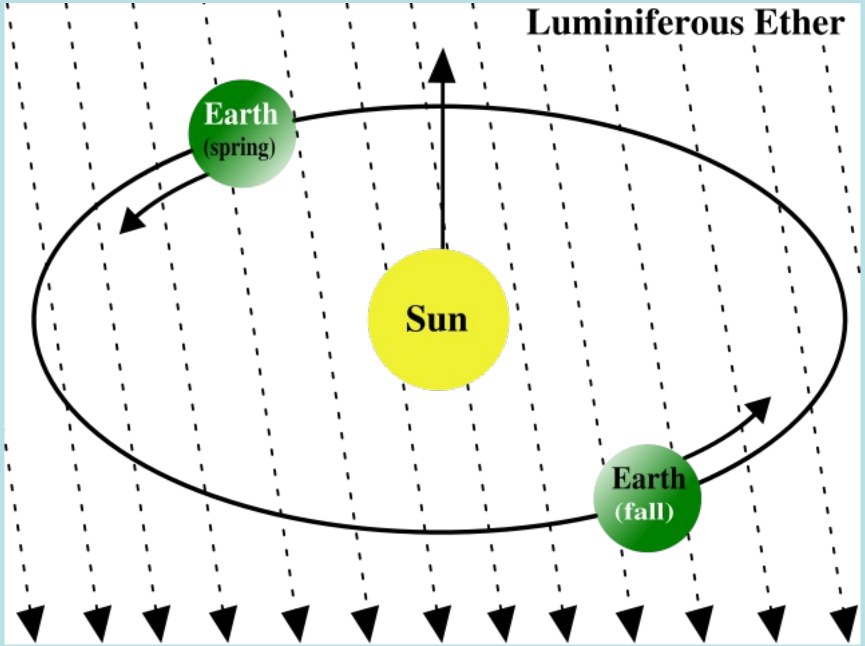
光速與觀察者無關！　相對於以太移動的觀察者，會測到不同的光速。

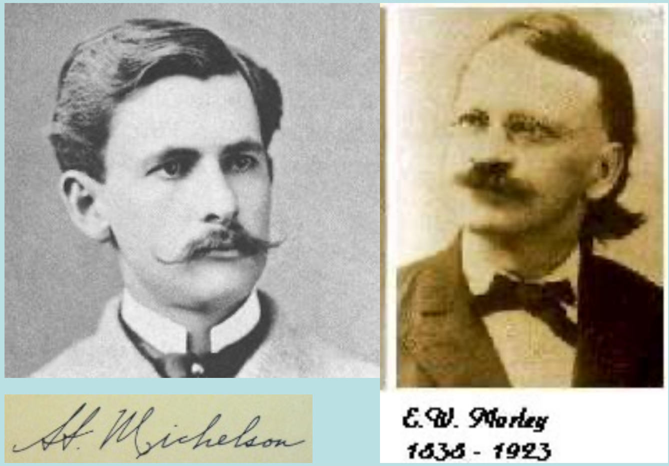
誰對？

物理的對決不是由份量來決定

只有實驗可以判定誰對誰錯！

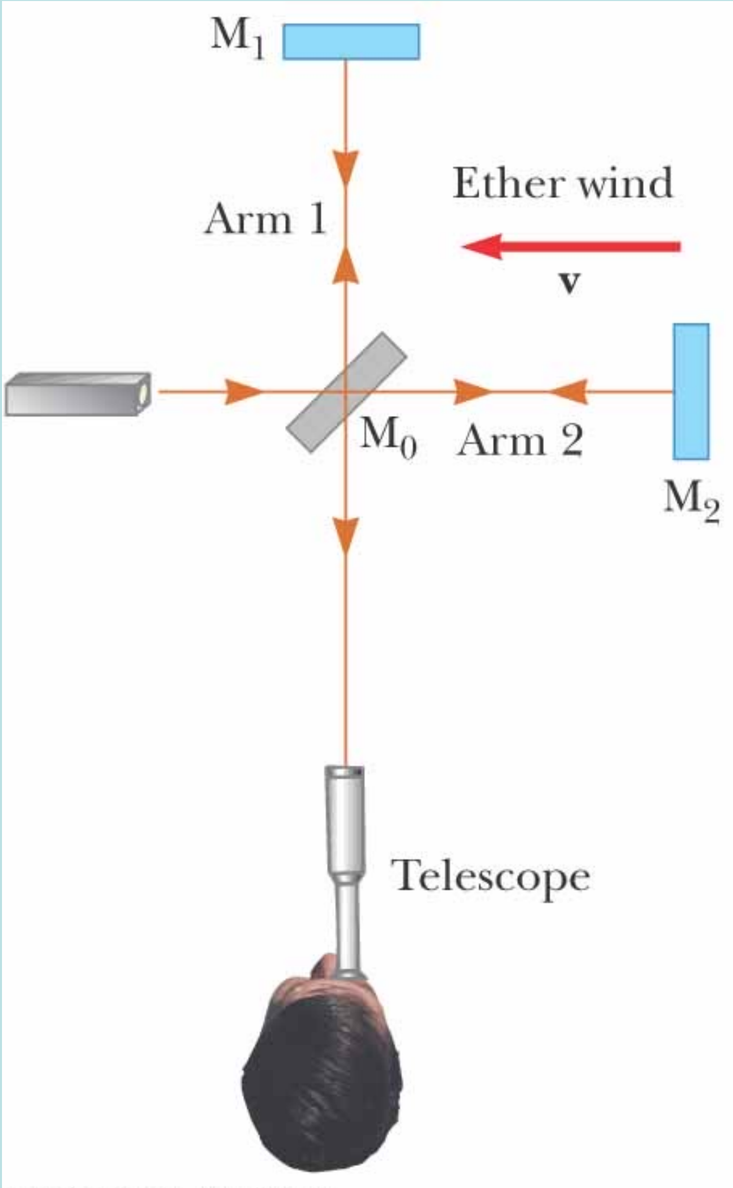
只有實驗能決定！ Michelson and Morley 干涉儀



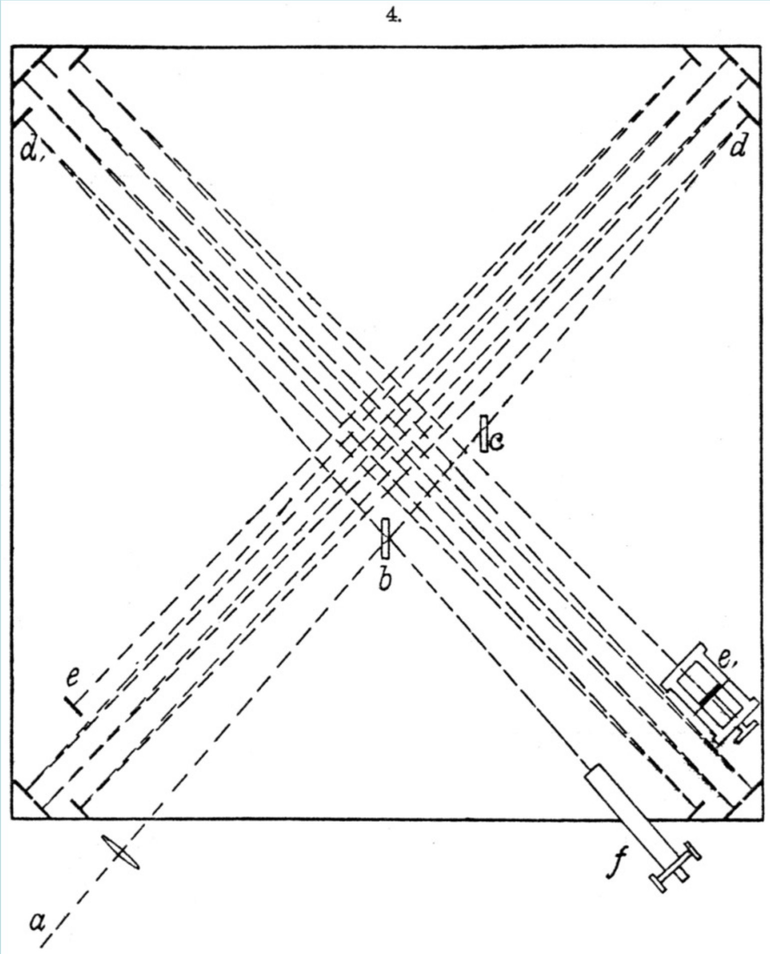


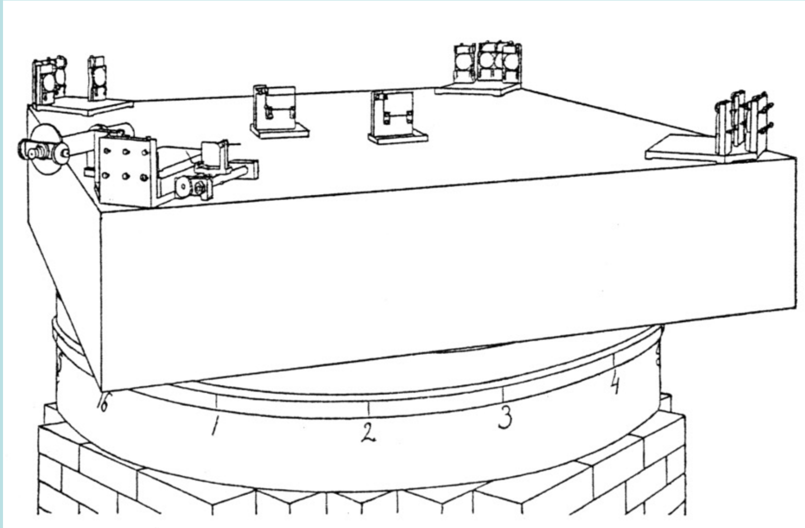
Michelson and Morley (1887)

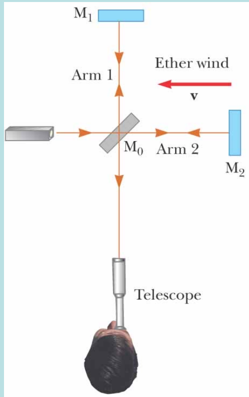
若光速與觀察者的運動有關，那地球表面上不同方向測得的光速不相同。

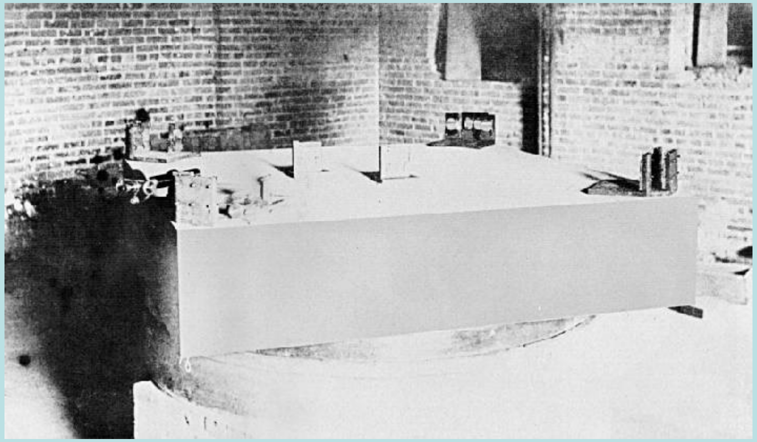


若光速與觀察者的運動有關，那地球表面上不同方向測得的光速不相同。
圖上不同段落的光速就不相同。









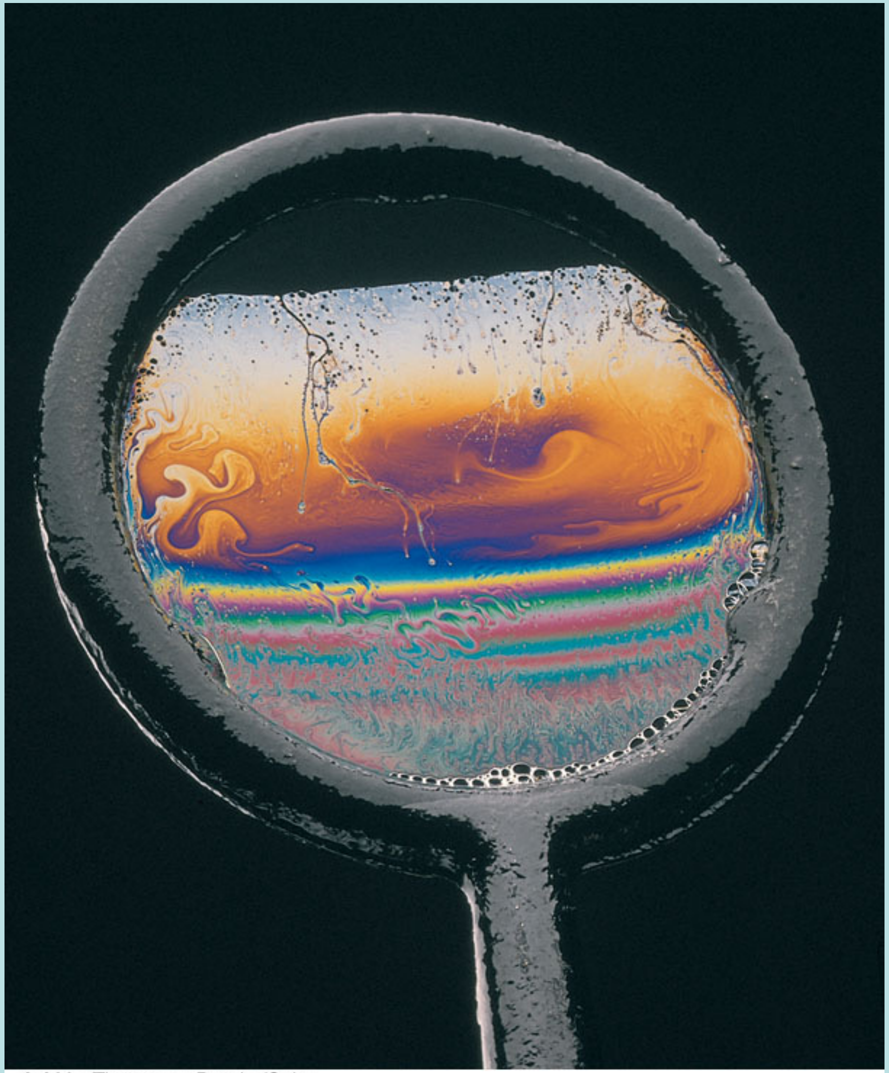
將兩條路徑長調整為相同。

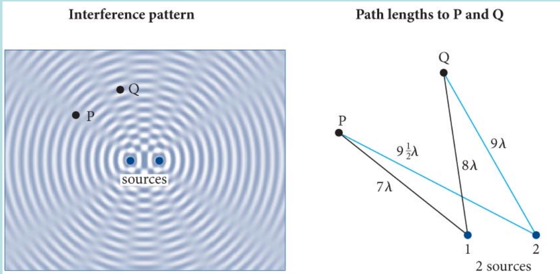
若不同方向的光速不同，則兩道光走完全程時間不同。

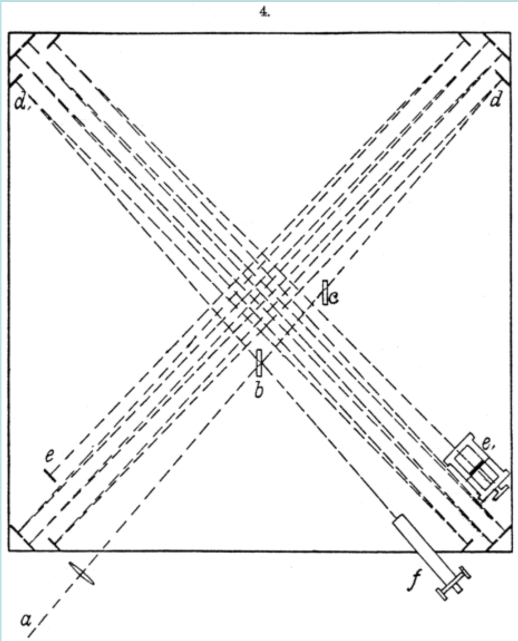
但差距只有 $\sim\Delta t \cdot \frac{v_{地球}}{c} \sim \frac{10\mathrm{m}}{3\times10^{8}\mathrm{m/s}} \cdot \frac{3\times10^{4}\mathrm{m/s}}{3\times10^{8}\mathrm{m/s}} \sim 10^{-12}\mathrm{s}$

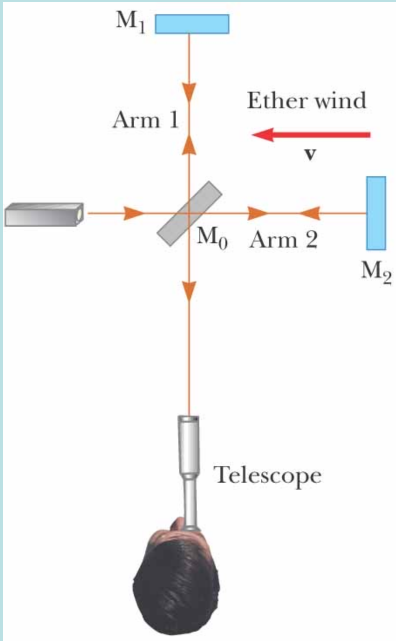
時間如何能測得如此精準？

薄膜干涉





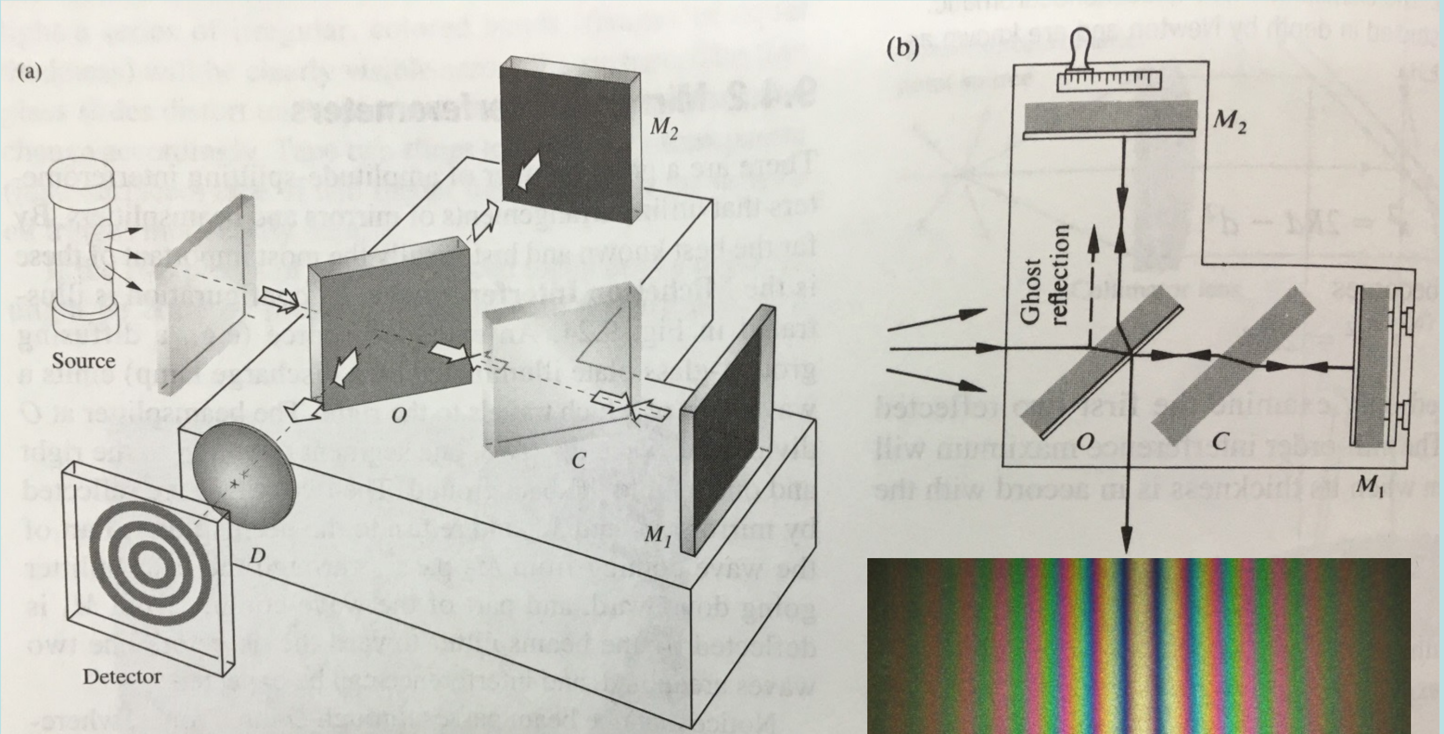


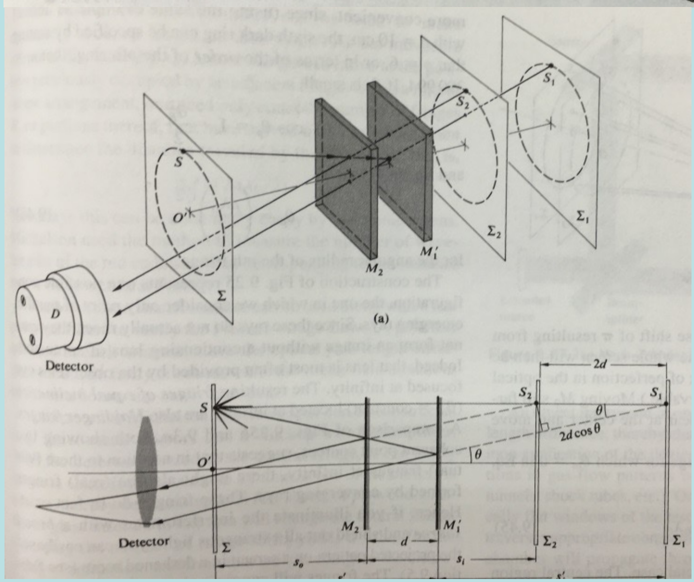


Michelson實驗以不同路徑到達觀察者的兩道光，就如干涉現象的兩個波源的波。

若不同方向光速不同，則兩道光走完全程時間不同。因此兩者會有干涉的現象。

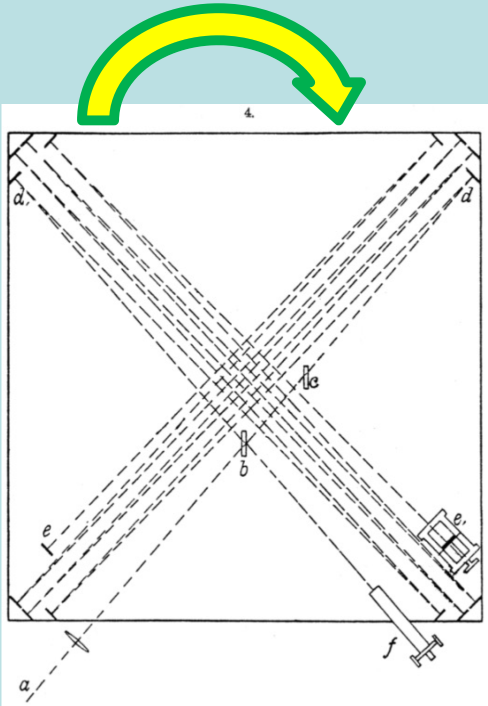
因為光源及透鏡都有大小，觀察者在鏡頭中看到的會是一個干涉條紋：

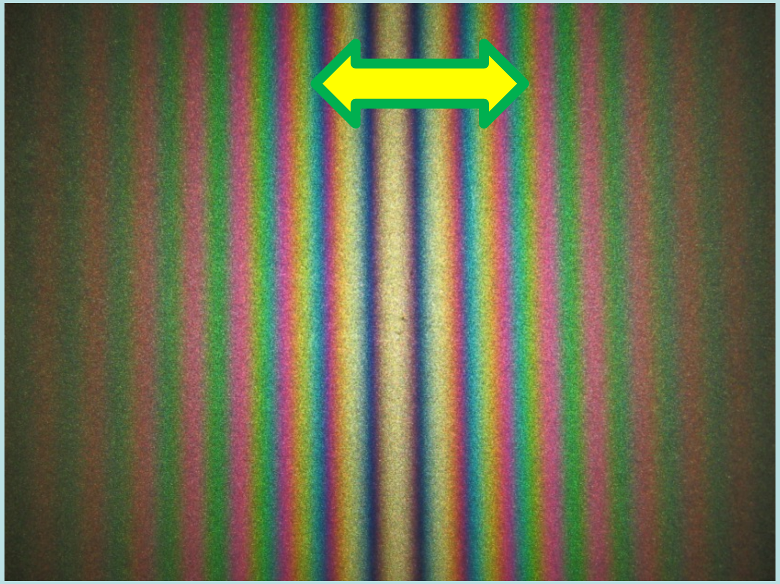


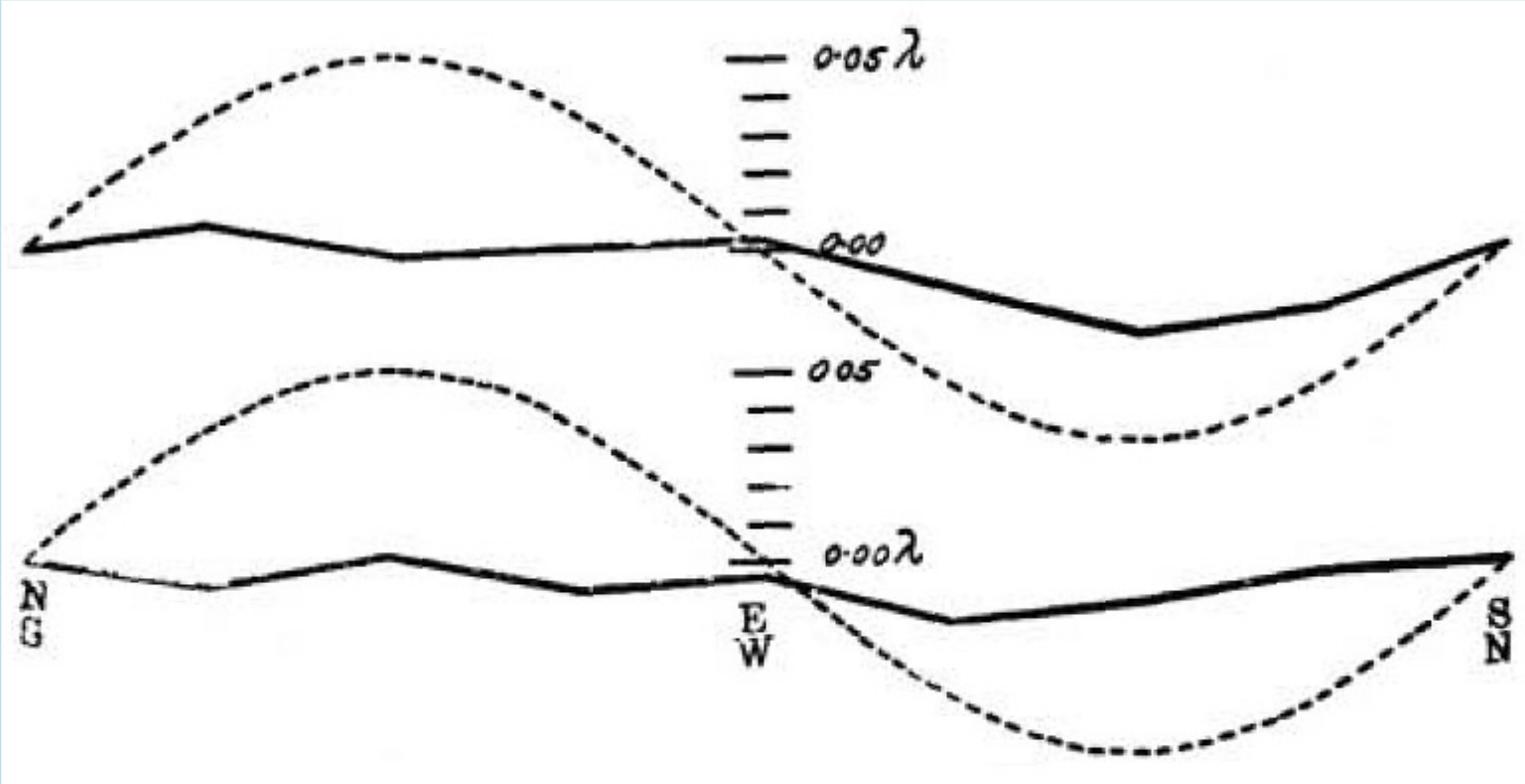


旋轉整個儀器，兩道光的時間差就會跟著變化。干涉亮度跟著改變。

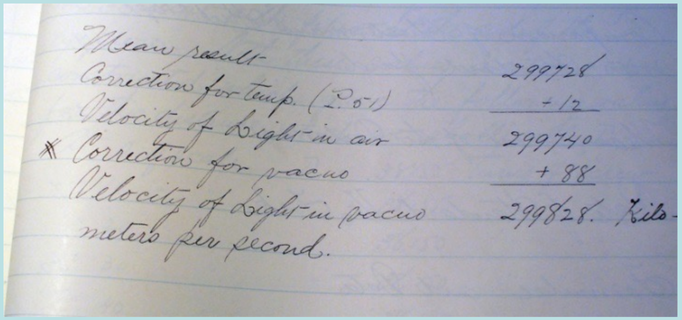
當干涉儀被轉動時，干涉條紋應該會移動。







兩道光走的時間一直相同，光速與觀察者的運動無關。


Mean result 299728
Correction for temp. (2.51) +12
Velocity of Light in air 299740
* Correction for vacuo +88
Velocity of Light in vacuo 299828. Kilo-
meters per second.

THE

AMERICAN JOURNAL OF SCIENCE.

[THIRD SERIES.]

ART. XXXVI.—*On the Relative Motion of the Earth and the Luminiferous Æther*; by ALBERT A. MICHELSON and EDWARD W. MORLEY.*

THE discovery of the aberration of light was soon followed by an explanation according to the emission theory. The effect was attributed to a simple composition of the velocity of light with the velocity of the earth in its orbit. The difficulties in this apparently sufficient explanation were overlooked until after an explanation on the undulatory theory of light was proposed. This new explanation was at first almost as simple as the former. But it failed to account for the fact proved by experiment that the aberration was unchanged when observations were made with a telescope filled with water. For if the tangent of the angle of aberration is the ratio of the velocity of the earth to the velocity of light, then, since the latter velocity in water is three-fourths its velocity in a vacuum, the aberration observed with a water telescope should be four-thirds of its true value.†

* This research was carried out with the aid of the Bache Fund.

† It may be noticed that most writers admit the sufficiency of the explanation according to the emission theory of light; while in fact the difficulty is even greater than according to the undulatory theory. For on the emission theory the velocity of light must be greater in the water telescope, and therefore the angle of aberration should be less; hence, in order to reduce it to its true value, we must make the absurd hypothesis that the motion of the water in the telescope carries the ray of light in the opposite direction!

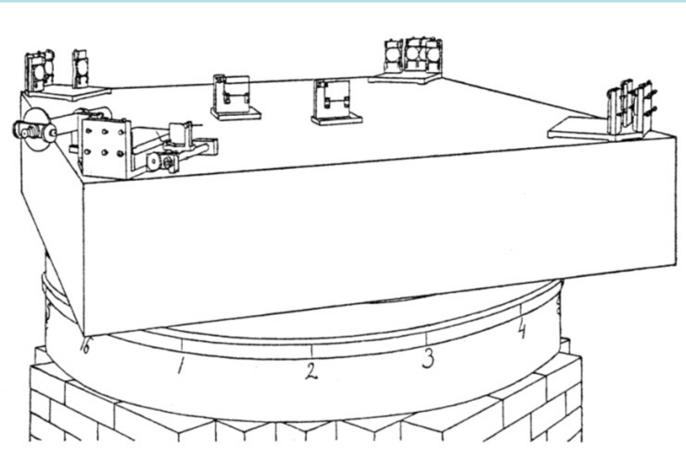
displacement should be $2D\frac{v^2}{V^2}=2D\times10^{-8}$. The distance D was about eleven meters, or 2×10^7 wave-lengths of yellow light; hence the displacement to be expected was 0·4 fringe. The actual displacement was certainly less than the twentieth part of this, and probably less than the fortieth part. But since the displacement is proportional to the square of the velocity, the relative velocity of the earth and the ether is probably less than one sixth the earth's orbital velocity, and certainly less than one-fourth.

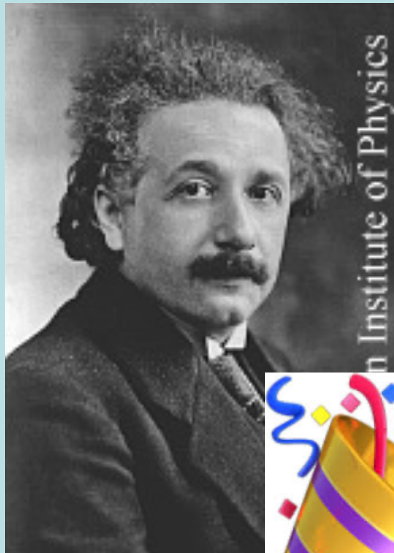
In what precedes, only the orbital motion of the earth is considered. If this is combined with the motion of the solar system, concerning which but little is known with certainty, the result would have to be modified; and it is just possible that the resultant velocity at the time of the observations was small though the chances are much against it. The experiment will therefore be repeated at intervals of three months, and thus all uncertainty will be avoided.

It appears, from all that precedes, reasonably certain that if there be any relative motion between the earth and the luminiferous ether, it must be small; quite small enough entirely to refute Fresnel's explanation of aberration. Stokes has given a theory of aberration which assumes the ether at the earth's surface to be at rest with regard to the latter, and only requires in addition that the relative velocity have a potential; but Lorentz shows that these conditions are incompatible. Lorentz then proposes a modification which combines some ideas of Stokes and Fresnel, and assumes the existence of a potential, together with Fresnel's coefficient. If now it were legitimate to conclude from the present work that the ether is at rest with regard to the earth's surface, according to Lorentz there could not be a velocity potential, and his own theory also fails.

這個實驗本來是要測量地球相對於以太的速度。但怎麼都測不到。

唯一可能的結論是以太並不存在。電磁波並沒有介質！

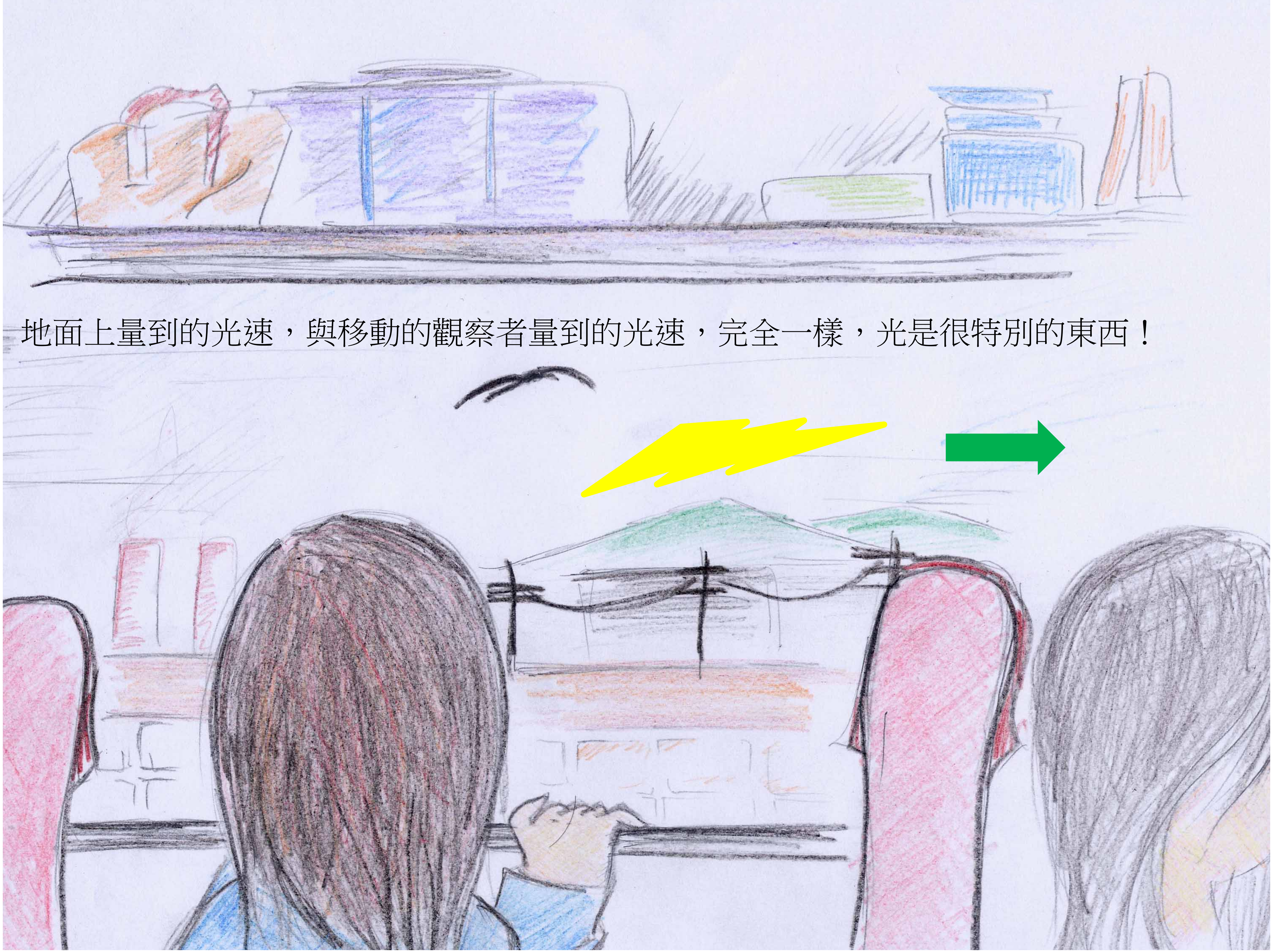




勝！

根據實驗的結果，光速與測量者及光源的運動狀態無關，永遠是c。

$\boxed{c = c'}$ 這對大家都是一個驚奇。


地面上量到的光速，與移動的觀察者量到的光速，完全一樣，光是很特別的東西！

Albert Einstein, 1905

Annus Mirabilis (Miracle Year)

愛因斯坦的天才使他進一步看出別人未察覺的光速恆定所隱含的爆炸性結論！

Mileva Maric and Albert Einstein lived at 49 Kramgasse (second apartment from the left) in Berne, Switzerland. At the end of the street is Berne's famous clock tower.

這一年Einstein發表了四篇撼動物理學基礎的論文！

3. ***Zur Elektrodynamik bewegter Körper;***
von A. Einstein.

Daß die Elektrodynamik Maxwells — wie dieselbe gegenwärtig aufgefaßt zu werden pflegt — in ihrer Anwendung auf bewegte Körper zu Asymmetrien führt, welche den Phänomenen nicht anzuhaften scheinen, ist bekannt. Man denke z. B. an die elektrodynamische Wechselwirkung zwischen einem Magneten und einem Leiter. Das beobachtbare Phänomen hängt hier nur ab von der Relativbewegung von Leiter und Magnet, während nach der üblichen Auffassung die beiden Fälle, daß der eine oder der andere dieser Körper der bewegte sei, streng

ON THE ELECTRODYNAMICS OF MOVING BODIES

運動物體的電動力學

By A. EINSTEIN

June 30, 1905

It is known that Maxwell's electrodynamics—as usually understood at the present time—when applied to moving bodies, leads to asymmetries which do not appear to be inherent in the phenomena. Take, for example, the reciprocal electrodynamic action of a magnet and a conductor. The observable phenomenon here depends only on the relative motion of the conductor and the magnet, whereas the customary view draws a sharp distinction between the two cases in which either the one or the other of these bodies is in motion. For if the magnet is in motion and the conductor at rest, there arises in the neighbourhood of the magnet an electric field with a certain definite energy, producing a current at the places where parts of the conductor are situated. But if the

光的移動速度，與觀察者的運動狀態無關。

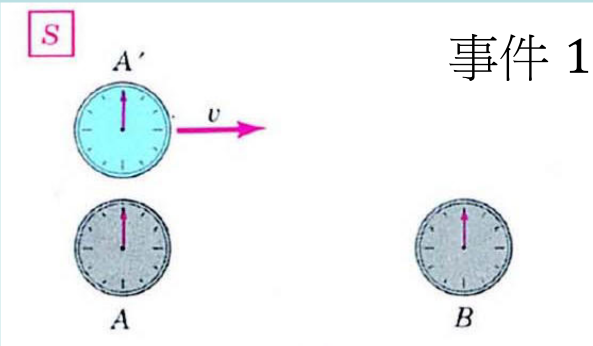
[redacted]

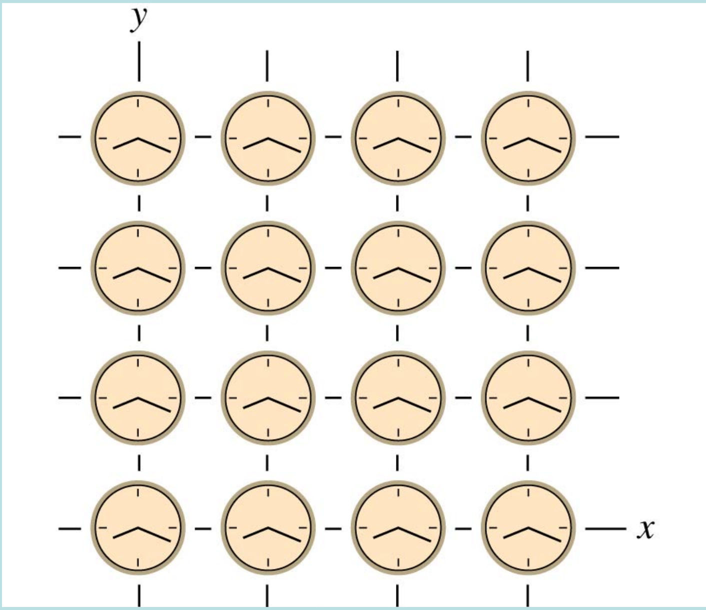
隱含(imply)

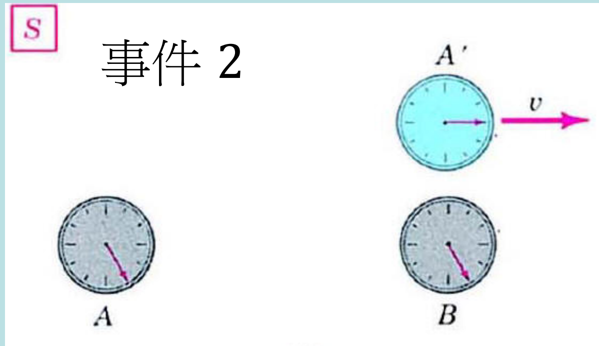
當測量同一段時間時，移動的時鐘，與靜止的時鐘，得到的結果一定不同！

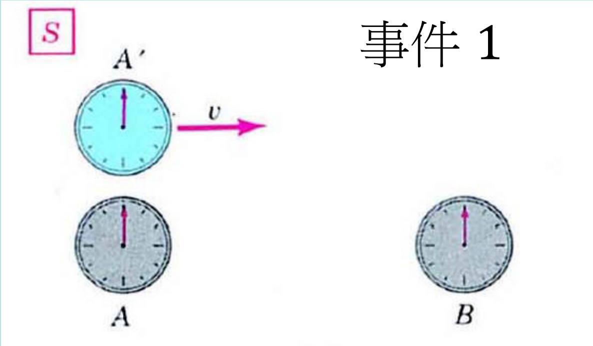
一個移動的時鐘，與一個靜止的時鐘，兩者一交會就分開，無從再次比較。

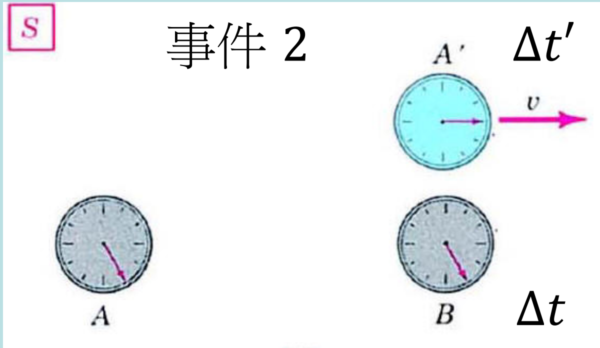
要在各個位置都架設靜止的、校準過的一系列時鐘。隨時隨處都可以作比較。











考慮移動的時鐘走了$\Delta t'$的這一段時間，位置移動了！

地面靜止的校準過的系列時鐘在前後兩個位置，測得的兩個時間的差記為：Δt。

常識與牛頓力學告訴我們時鐘走的速度固定，時間差與觀察者無關：$\Delta t' = \Delta t$

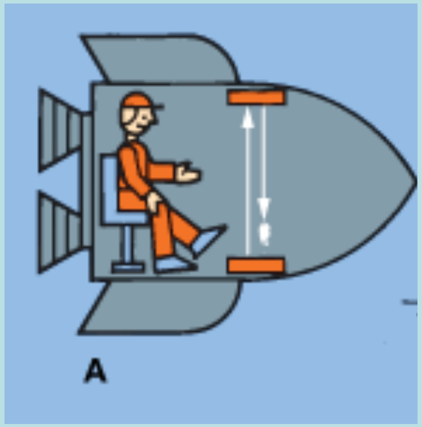
光的移動速度，與觀察者的運動狀態無關。

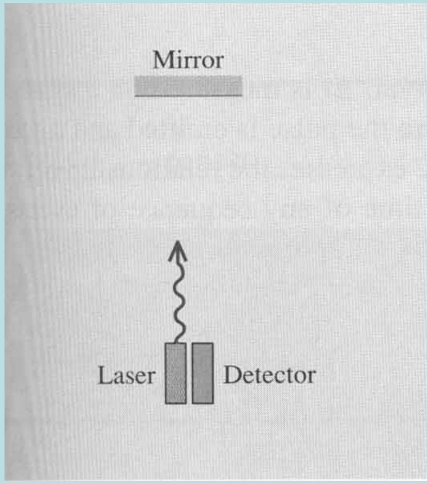
隱含(imply)

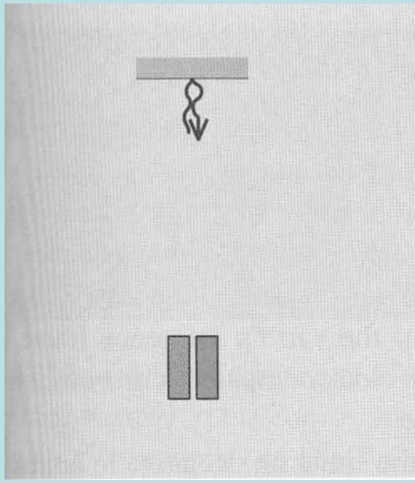
地面量到的時間 $\Delta t >$ 太空船量到的時間 $\Delta t'$ 攏統地說：移動的時鐘走得慢！

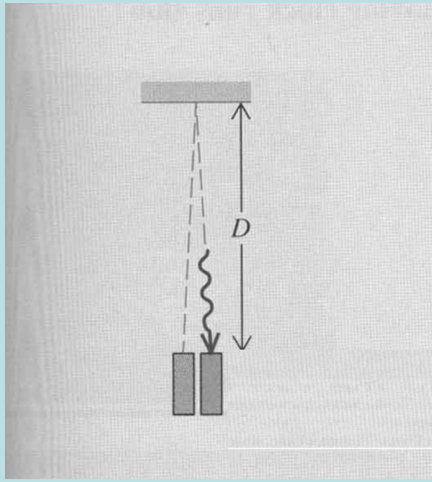
愛因斯坦用一個想像實驗（邏輯推理，不需要真的作）來證明：

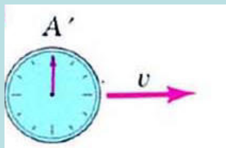
以火箭上一道雷射光在兩片鏡子間來回反射的時間為$\Delta t'$！

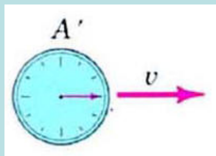


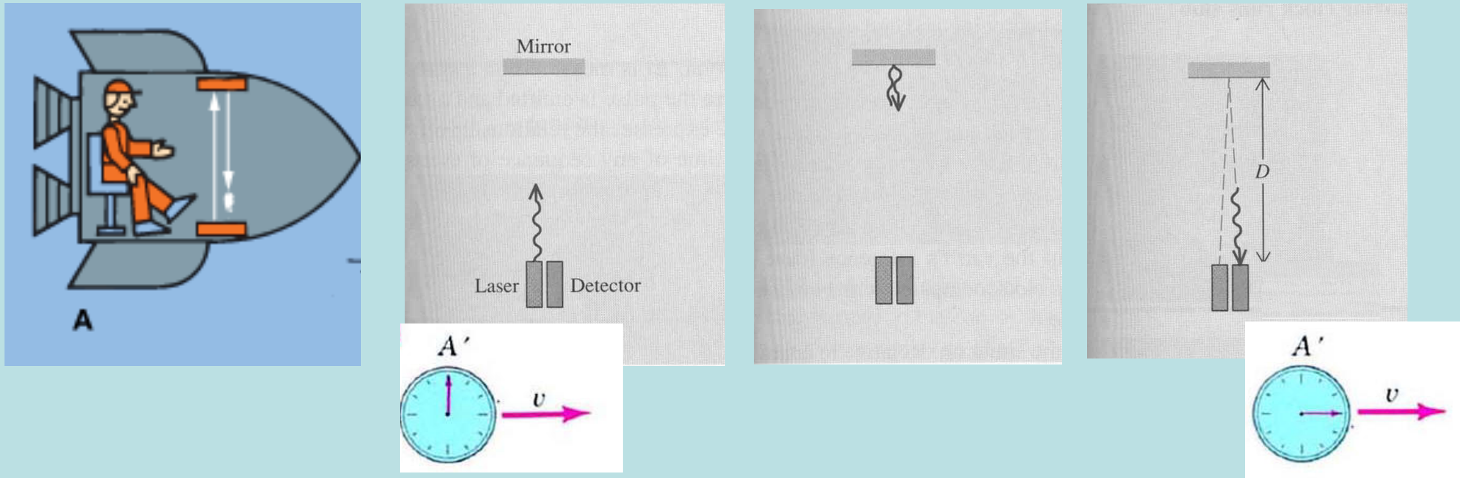






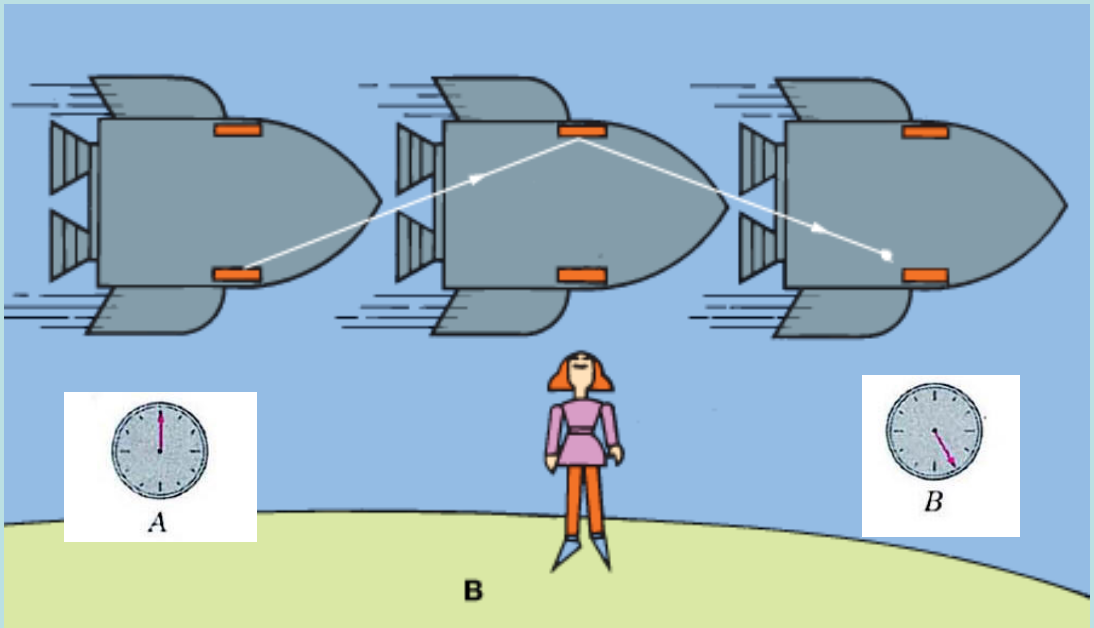


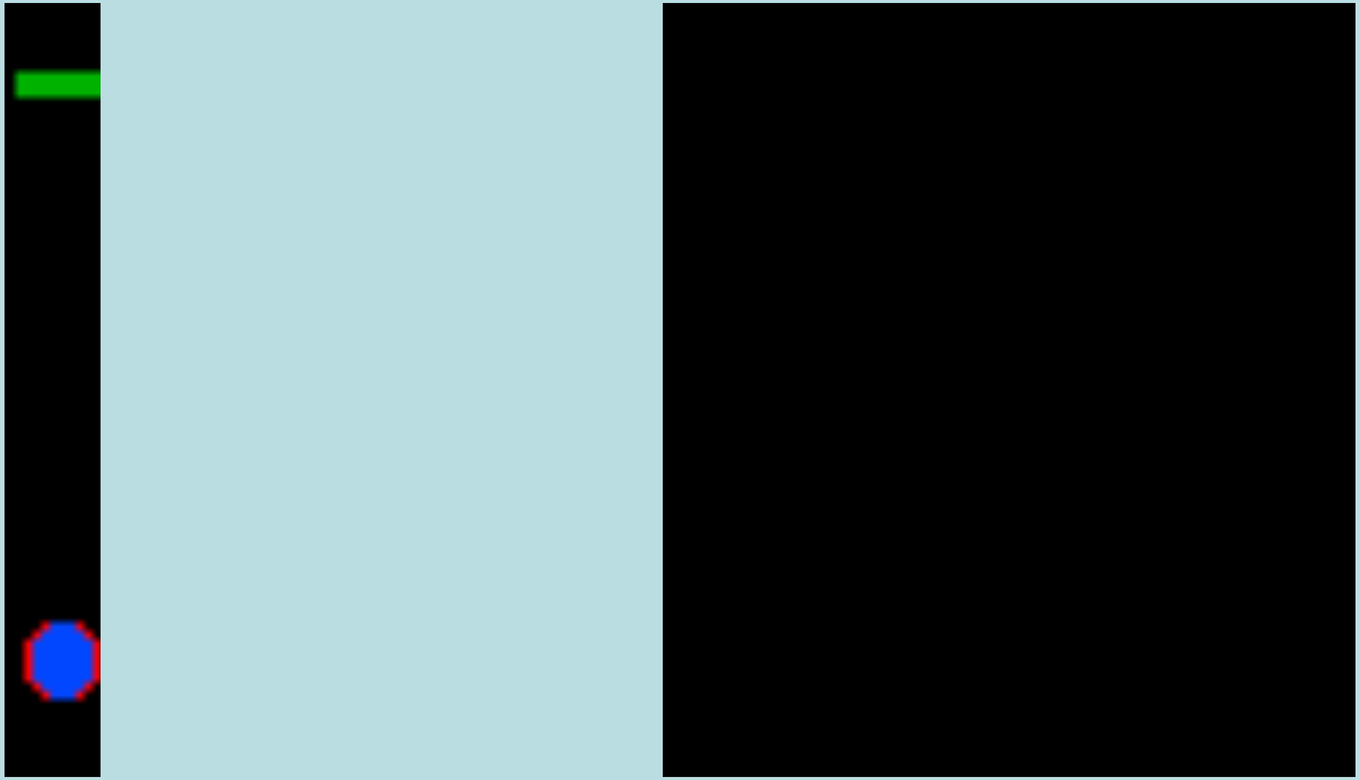


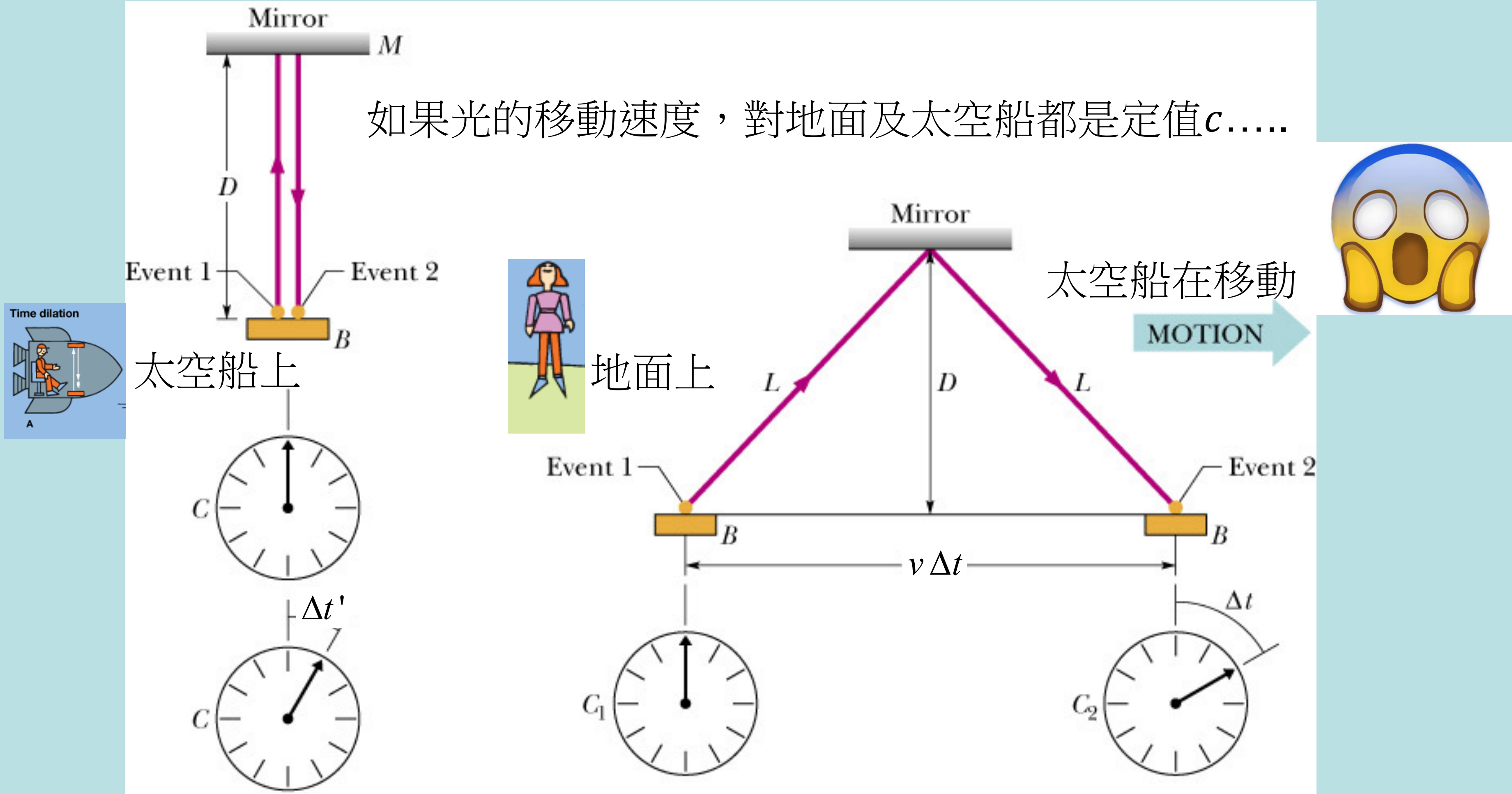


從地面上觀察，鏡子的位置在這段時間內移動了！

這道雷射光看來應該是斜射的！







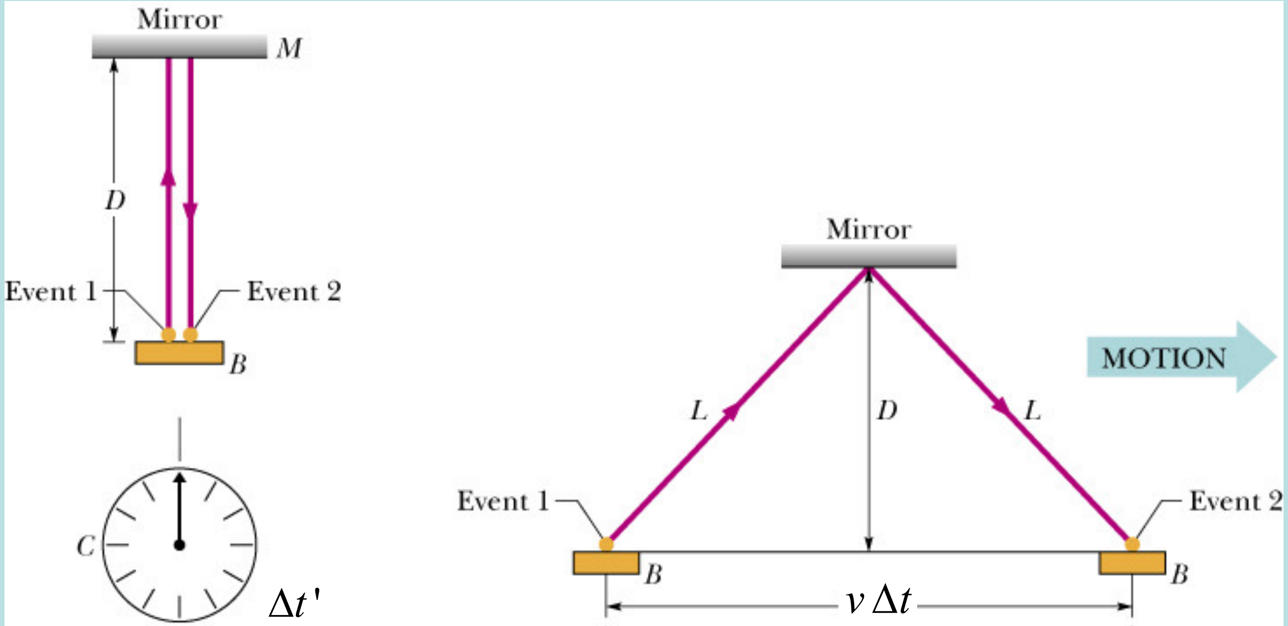
太空船上的時鐘測得 $\Delta t' = \dfrac{2D}{c}$ 地面上的時鐘測得 $\Delta t = \dfrac{2L}{c}$

太空船上量的時間$\Delta t'$ < 地面上量的時間Δt

發生在太空船上的同一位置的這一段時間$\Delta t'$，從地面上量起來為較長的Δt 。

發生在太空船上的同一位置的任一段時間，從地面上量起來都較長的。

兩者的關係很容易計算出來：



太空船上量的時間$\Delta t'$

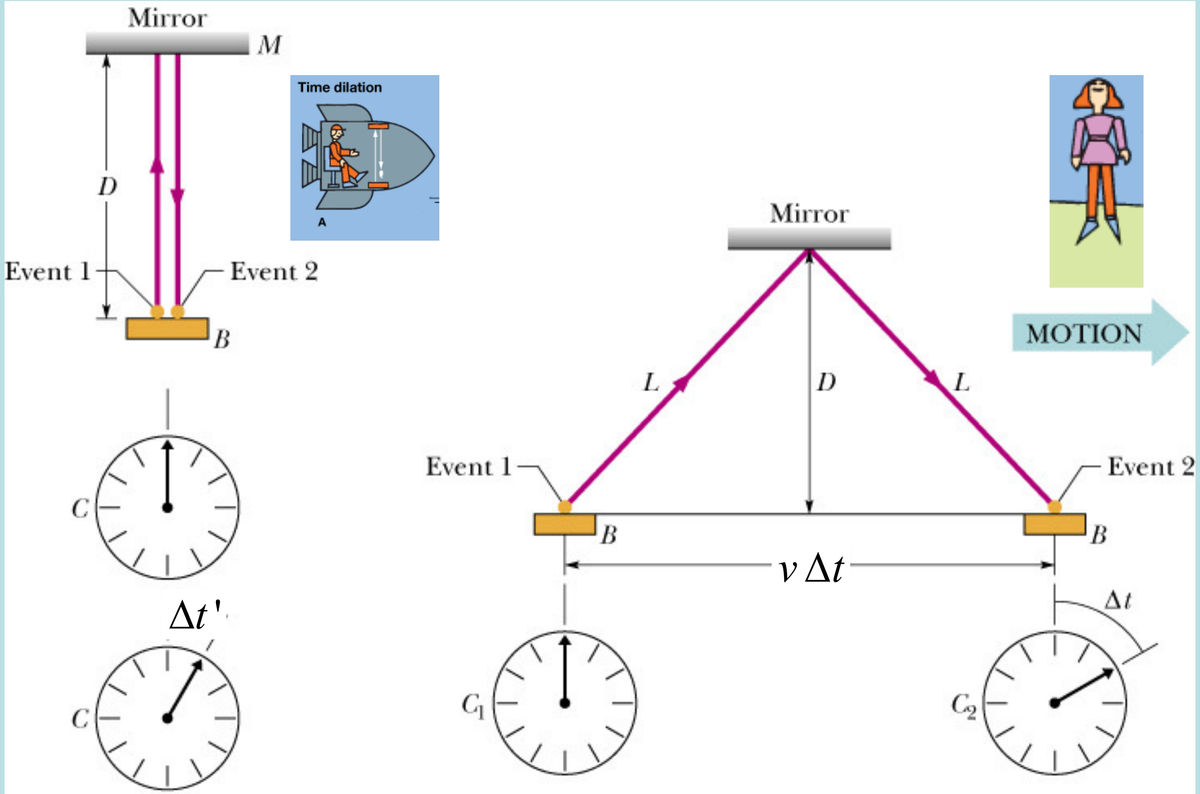
地面上量的時間Δt

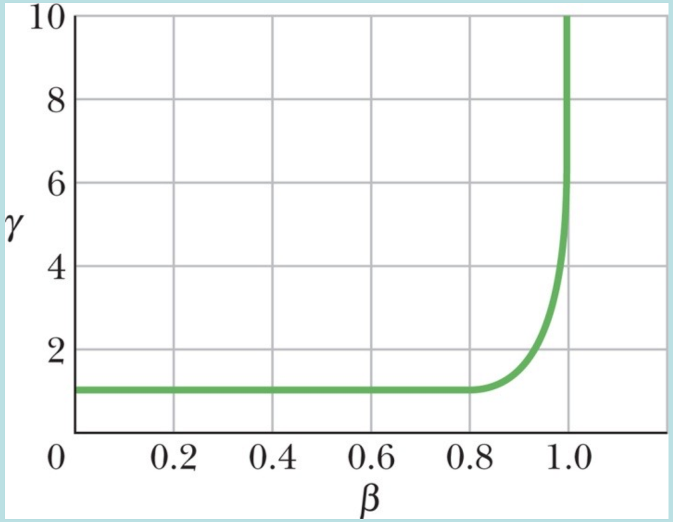
$$\Delta t' = \frac{2D}{c}$$

$$\Delta t = \frac{2L}{c} = \frac{2\sqrt{D^2 + \left(\frac{v\Delta t}{2}\right)^2}}{c} = \frac{\sqrt{4D^2 + v^2(\Delta t)^2}}{c}$$

$$(\Delta t)^2 = \frac{4D^2}{c^2} + \frac{v^2}{c^2}(\Delta t)^2$$

$$\Delta t = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}} \cdot \frac{2D}{c} = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}} \cdot \Delta t' \equiv \gamma \Delta t'$$





$$\Delta t = \frac{\Delta t'}{\sqrt{1 - \frac{v^2}{c^2}}} \equiv \gamma \Delta t'$$

$\gamma > 1$，$\Delta t > \Delta t'$

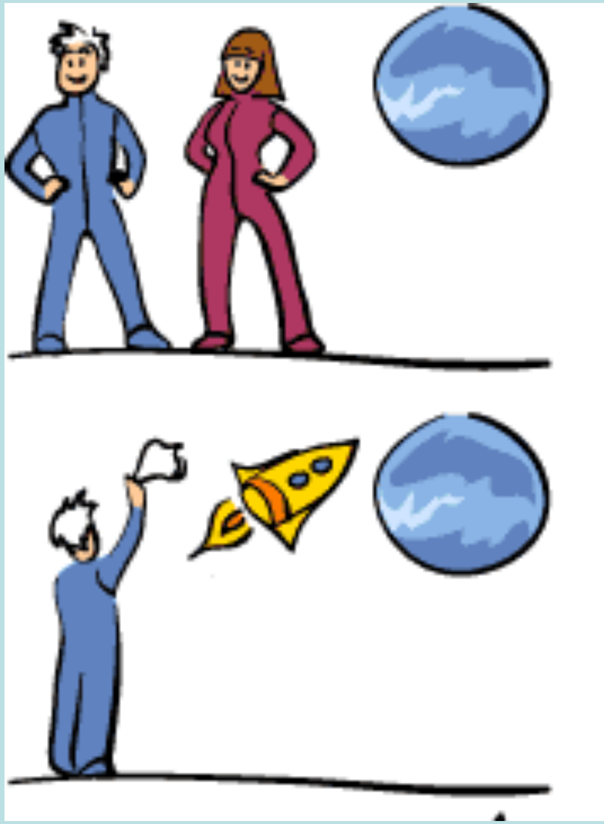
移動的時鐘上的一段時間$\Delta t'$，從靜止的觀察者量起來是比較長的Δt，

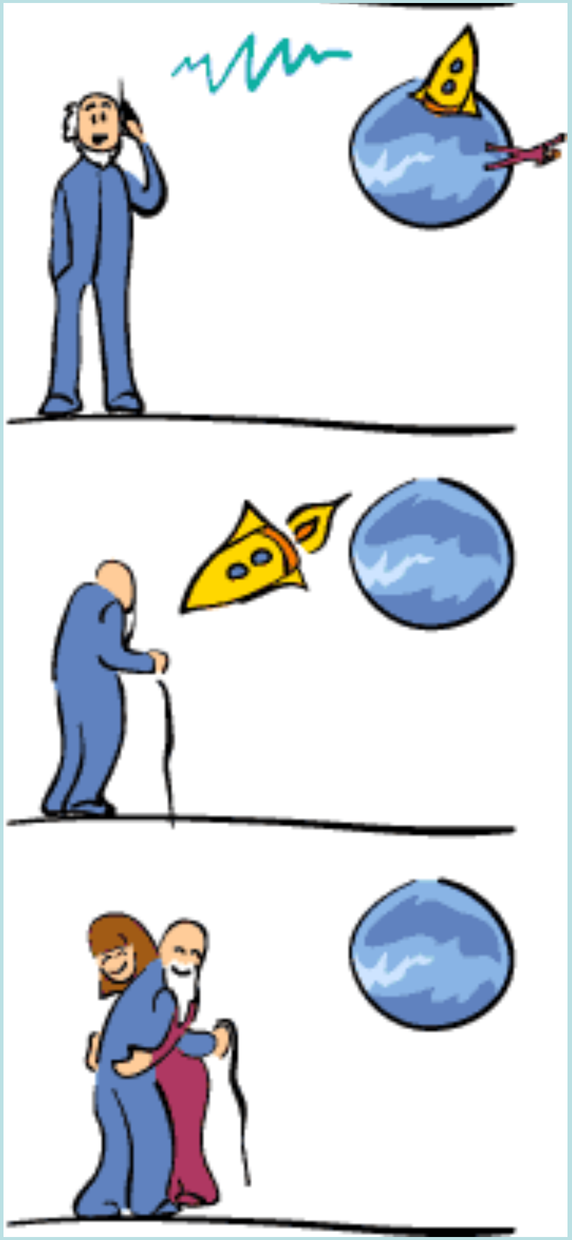
移動中的鐘看起來（相對於靜止的觀察者）較靜止時走得慢！

Time Dilation 時間膨脹


鏡好聽
MIRROR VOICE
發現
節目
有聲書
課程
節目主持人/有聲書主播
立即訂閱
登入 / 註冊
節目
知識好好玩
EP12｜為何移動的時鐘走得比較慢【物理好好玩第一季】
主持人｜張嘉泓
單曲長度｜00:14:00
發布時間｜2021-12-07
#張嘉泓
#物理好好玩
#原子彈
#法拉利
#緲子
#能量守恆定律
#光速
#普羅米修斯
前往試聽 ›
查看節目資訊
張嘉泓
專長是理論粒子物理，畢業於台大物理系，在美國哈佛大學取得博士學位後，曾在清華大學進行研究，現在於臺灣師範大學物理系任教。除...
追蹤
27
作品
2
追蹤
Screenshot

移動的時鐘與靜止的時鐘如果走速不同，那可以讓兩者比較一下嗎？



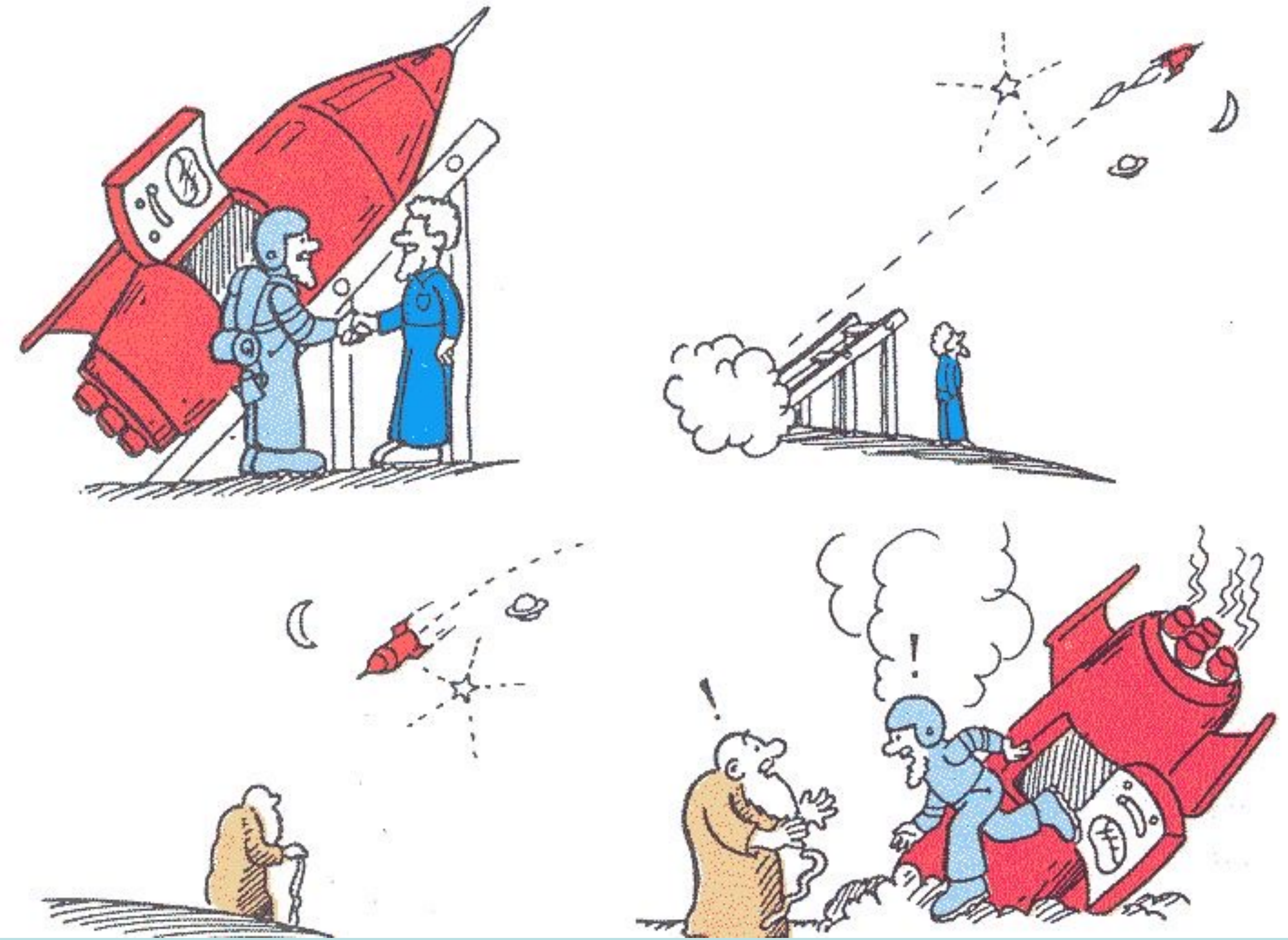


$\Delta t > \Delta t'$

Δt五十年 $> \Delta t'$五個月

想像一對孿生姊弟！姊姊去太空旅行。

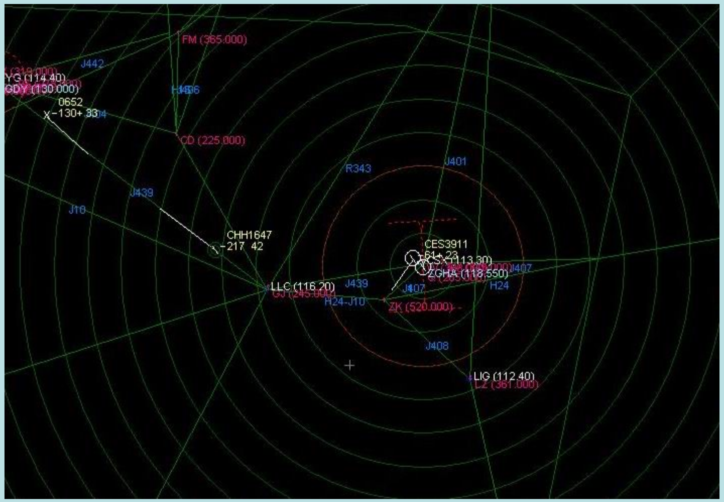
離開地球的孿生姊姊一直在運動，她的時鐘較慢，再相見時姊姊會比弟弟年輕！



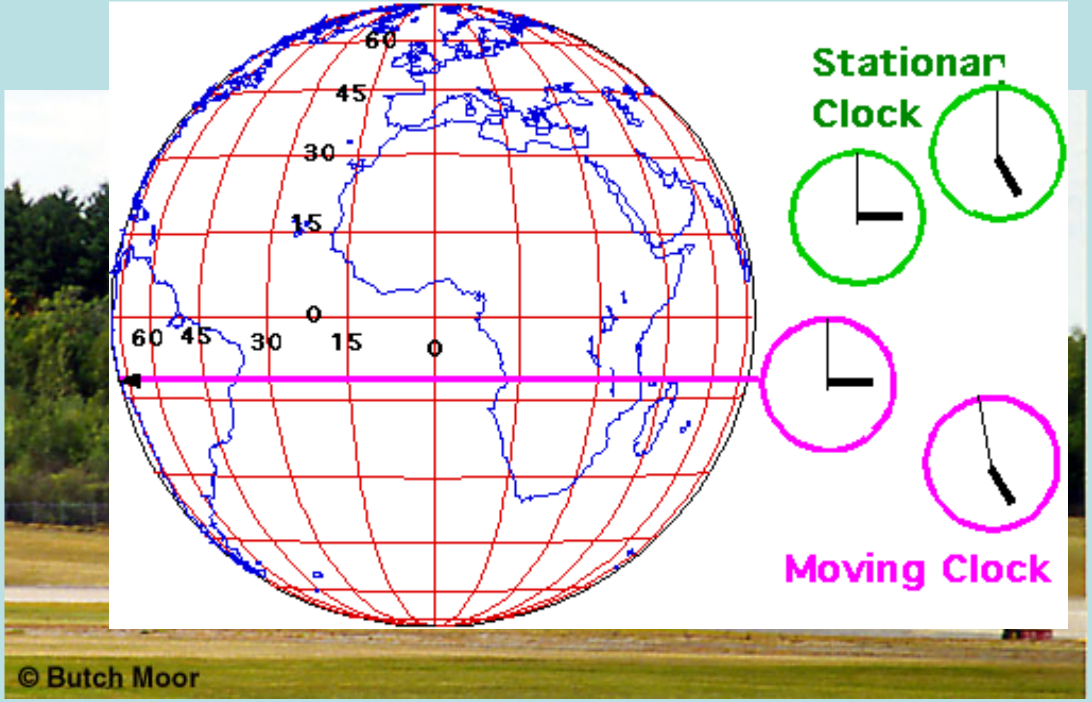
司機的時鐘跑的比較慢！

(所以誤點是正常的？哈哈！)

機師的時鐘從塔台看來走的較慢。



時間膨脹的驗證



1977 Hafele and Keating flew four atomic clocks twice around the globe. Time lost by moving clocks ~ 190 ns.

A few years later, another team flew round and round above Chesapeake bay for 15H. For a sonic jet, the dilation is about 10^{-8}s. Predictions are good within 1%.

Einstein's "Time Dilation" Prediction Verified

Experiments at a particle accelerator have confirmed the "time dilation" effect predicted by Albert Einstein's special theory of relativity

nature

Sep 22, 2014 | By Alexandra Witze and Nature magazine |

Physicists have verified a key prediction of Albert Einstein's special theory of relativity with unprecedented accuracy. Experiments at a particle accelerator in Germany confirm that time moves slower for a moving clock than for a stationary one.

The work is the most stringent test yet of this 'time-dilation' effect, which Einstein predicted. One of the consequences of this effect is that a person travelling in a high-speed rocket would age more slowly than people back on Earth.

Few scientists doubt that Einstein was right. But the mathematics describing the time-dilation effect are "fundamental to all physical theories", says Thomas Udem, a physicist at the Max Planck Institute for Quantum Optics in Garching, Germany, who was not involved in the research. "It is of utmost importance to verify it with the best possible accuracy."

To test the time-dilation effect, physicists need to compare two clocks — one that is stationary and one that moves.

Test of Time Dilation Using Stored Li^+ Ions as Clocks at Relativistic Speed

Benjamin Botermann,[1] Dennis Bing,[2] Christopher Geppert,[1,3,4] Gerald Gwinner,[5] Theodor W. Hänsch,[6] Gerhard Huber,[7] Sergei Karpuk,[7] Andreas Krieger,[1] Thomas Kühl,[3] Wilfried Nörtershäuser,[1,3,8] Christian Novotny,[4] Sascha Reinhardt,[6] Rodolfo Sánchez,[4] Dirk Schwalm,[2] Thomas Stöhlker,[3] Andreas Wolf,[2] and Guido Saathoff[6]
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[3]*GSI Helmholtzzentrum für Schwerionenforschung, 64291 Darmstadt, Germany*
[4]*Helmholtzinstitut Mainz, 55128 Mainz, Germany*
[5]*Department of Physics and Astronomy, University of Manitoba, Winnipeg, Manitoba R3 T 2N2, Canada*
[6]*Max-Planck-Institut für Quantenoptik, 85748 Garching, Germany*
[7]*Johannes Gutenberg-Universität Mainz, Institut für Physik, 55128 Mainz, Germany*
[8]*TU Darmstadt, Institut für Kernphysik, 64289 Darmstadt, Germany*
(Received 30 May 2014; published 16 September 2014)

We present the concluding result from an Ives-Stilwell-type time dilation experiment using $^7Li^+$ ions confined at a velocity of $\beta = v/c = 0.338$ in the storage ring ESR at Darmstadt. A Λ-type three-level system within the hyperfine structure of the $^7Li^+ {}^3S_1 \rightarrow {}^3P_2$ line is driven by two laser beams aligned parallel and antiparallel relative to the ion beam. The lasers' Doppler shifted frequencies required for resonance are measured with an accuracy of $< 4 \times 10^{-9}$ using optical-optical double resonance spectroscopy. This allows us to verify the special relativity relation between the time dilation factor γ and the velocity β, $\gamma\sqrt{1-\beta^2} = 1$ to within $\pm 2.3 \times 10^{-9}$ at this velocity. The result, which is singled out by a high boost velocity β, is also interpreted within Lorentz invariance violating test theories.

DOI: 10.1103/PhysRevLett.113.120405 PACS numbers: 03.30.+p, 41.75.Ak, 42.62.Fi

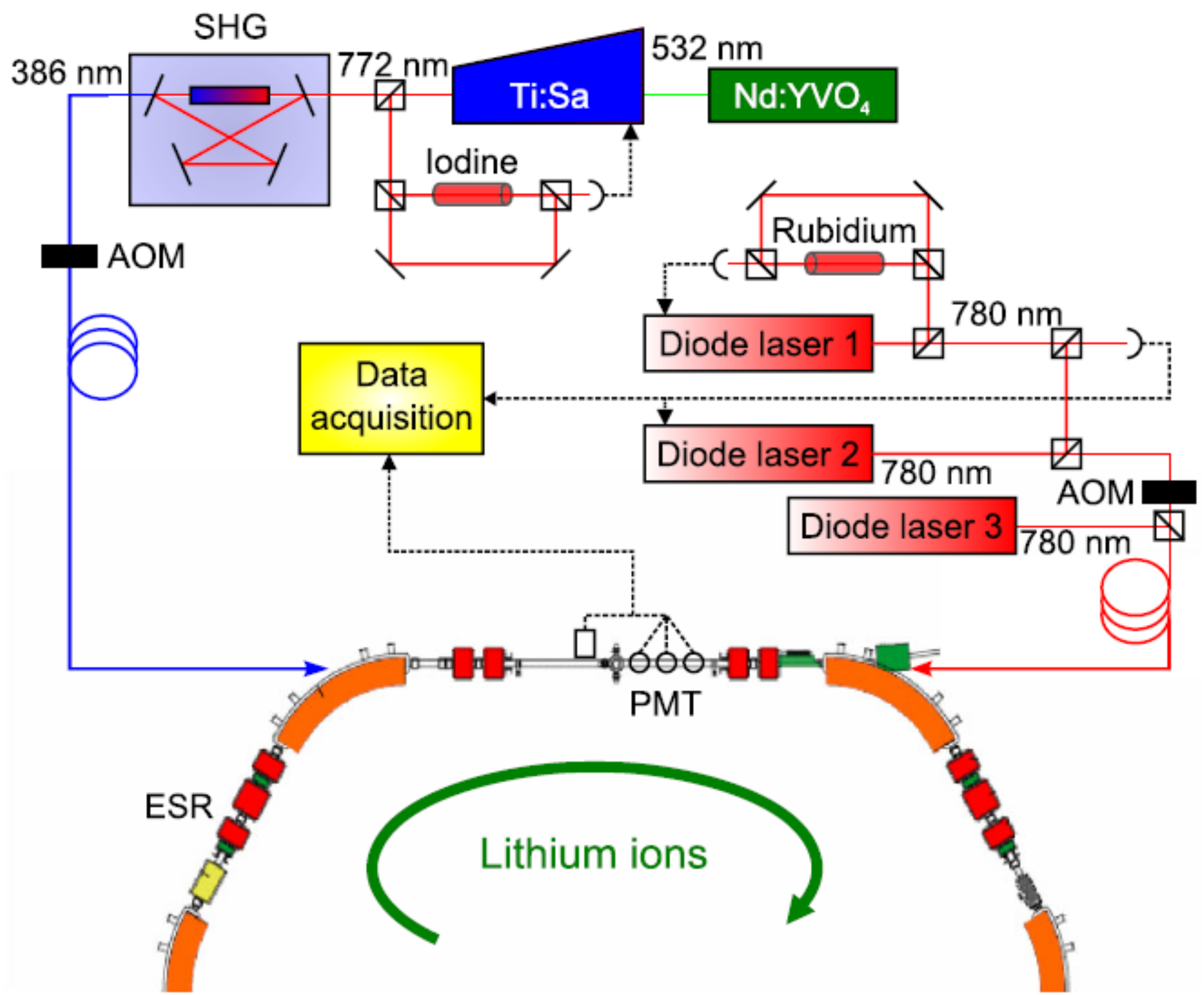
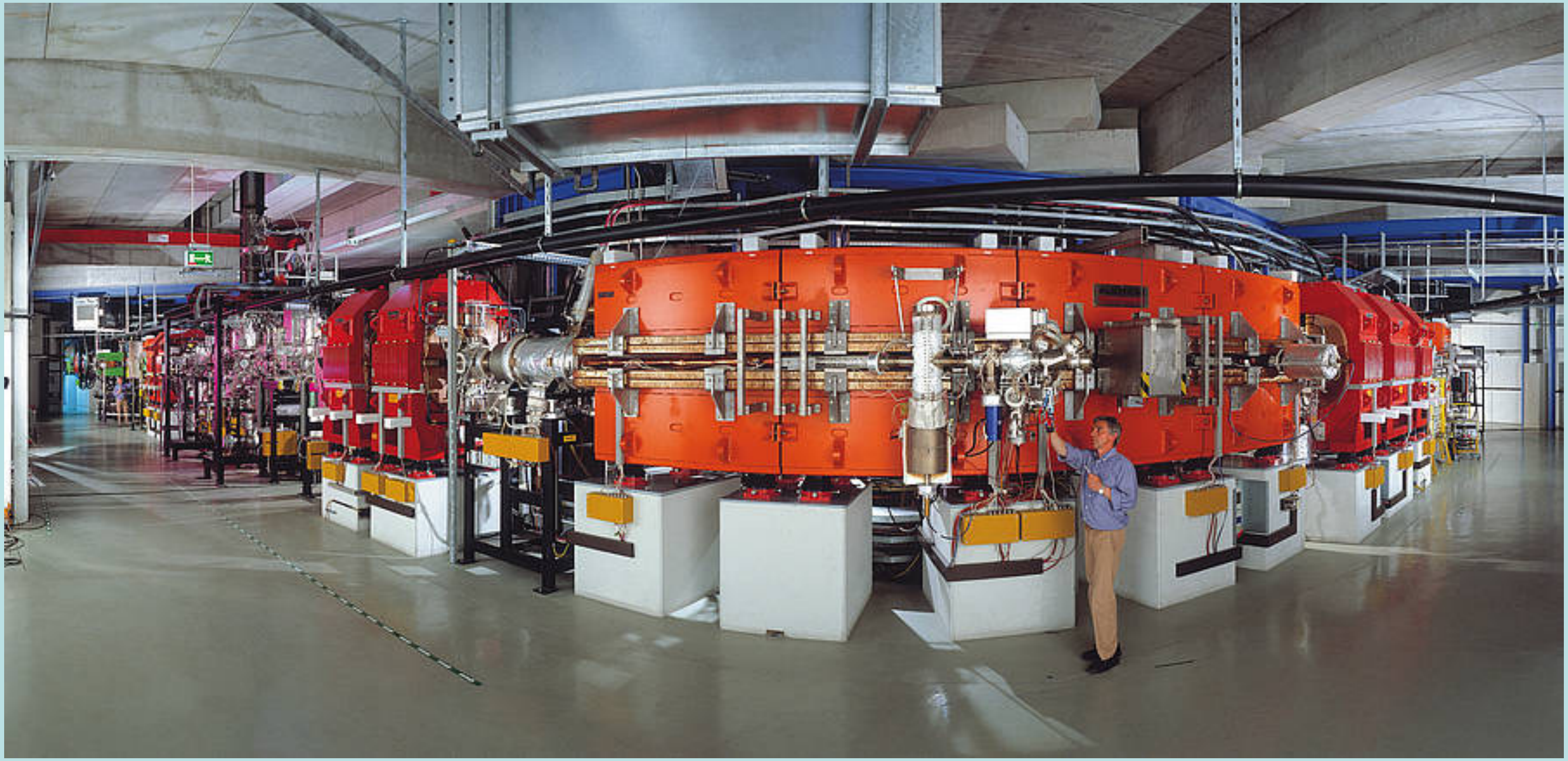
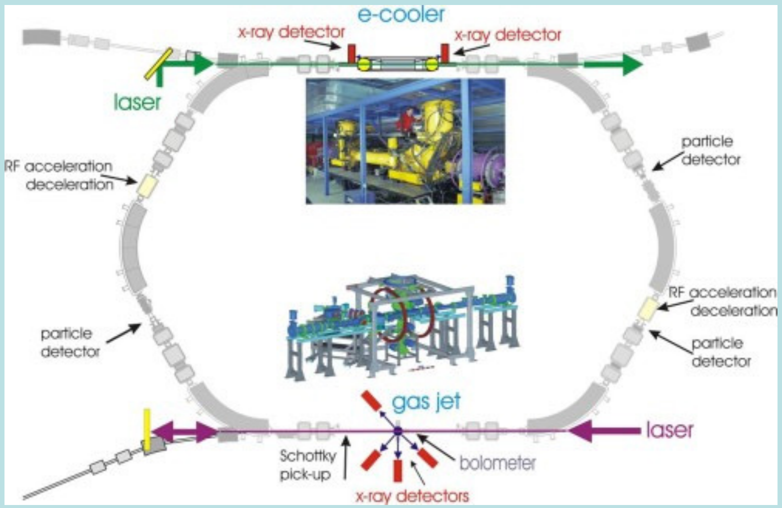
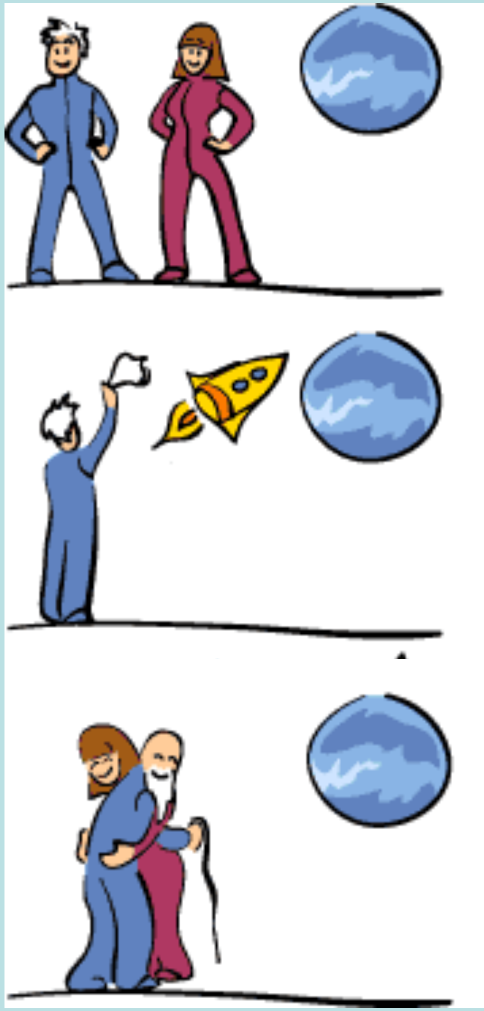


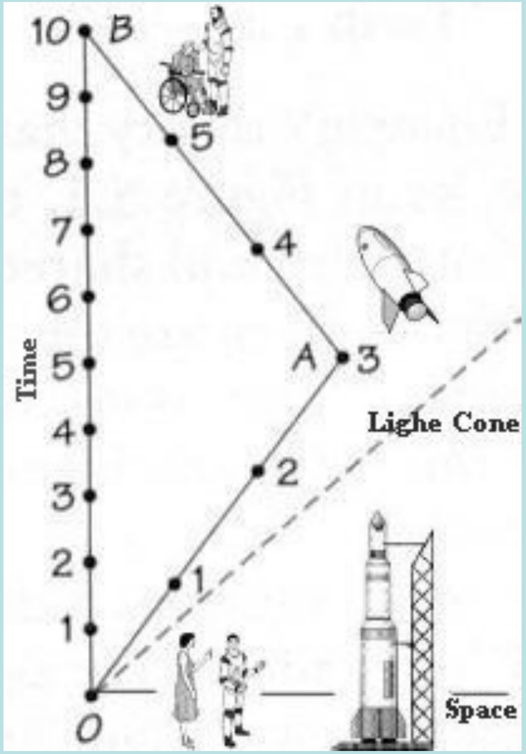
FIG. 1 (color online). Left: Experimental setup. Laser system and data acquisition are inside a laser laboratory from which the light is guided to the ESR via polarization maintaining glass fibers.




e-cooler
x-ray detector
x-ray detector
laser
particle detector
RF acceleration deceleration
RF acceleration deceleration
particle detector
particle detector
gas jet
laser
Schottky pick-up
bolometer
x-ray detectors

$\Delta t > \Delta t'$





離開地球的孿生姊姊一直在運動，時鐘較慢，再相見時姊姊會比弟弟年輕！

離開地球的孿生姊姊也會以為自己是靜止的，運動的地球時鐘慢，弟弟會年輕！

兩個敘述是矛盾的。

但第二個敘述是錯的，因為姊姊必須停止在反向，她會知道自己不是靜止的！

在去程與回程，弟弟量測姊姊的時鐘的一段時間$\Delta t'$，會得到比較長的Δt。

來回加起來，弟弟較老。

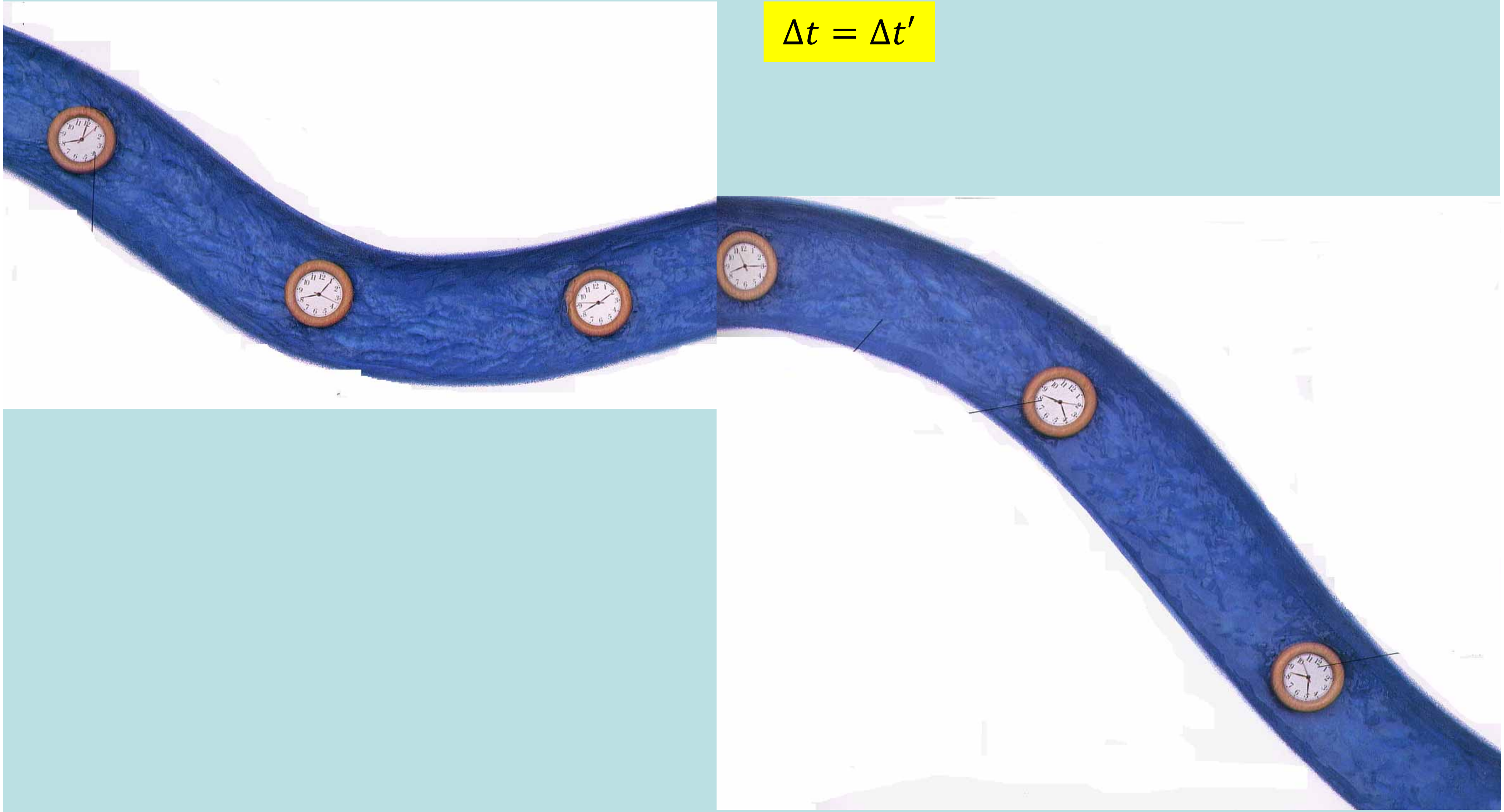
移動中的鐘，較靜止時走得慢！

這完全是光速恆定現象的邏輯結果！

我們一直相信：即使位置與狀態不同，時間是共有的。

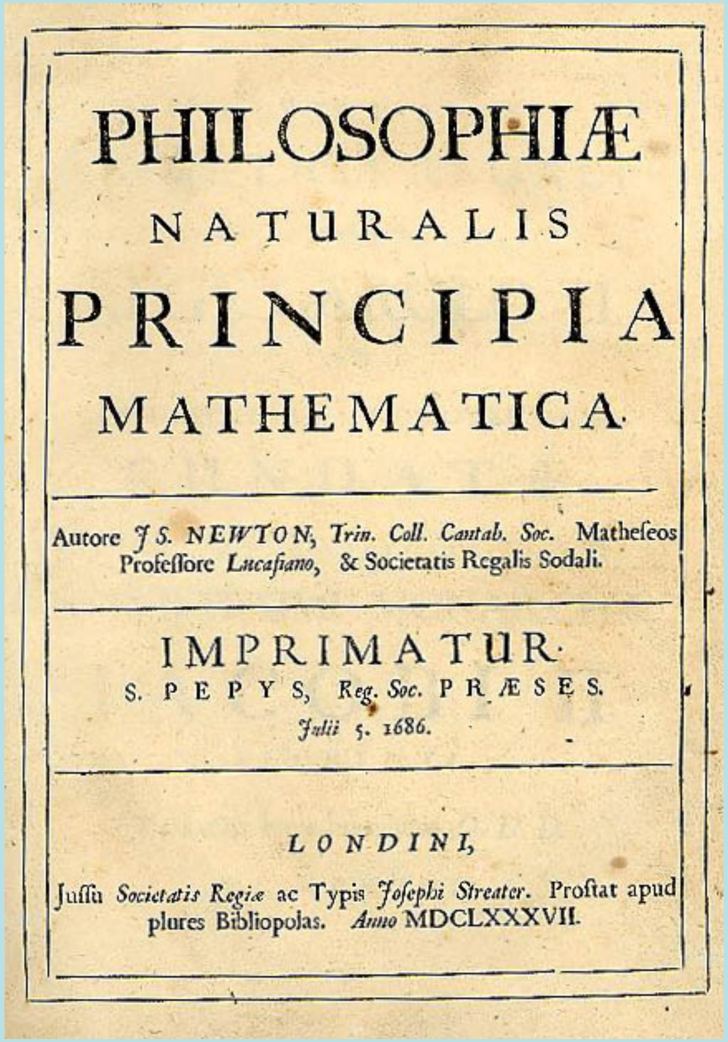
時間是絕對的，獨立於觀察者之外。如一條穩定的長河！

$\Delta t = \Delta t'$



絕對時間

絕對、真實和數學的時間本身自會均等地前進，與外在事物毫無關聯！

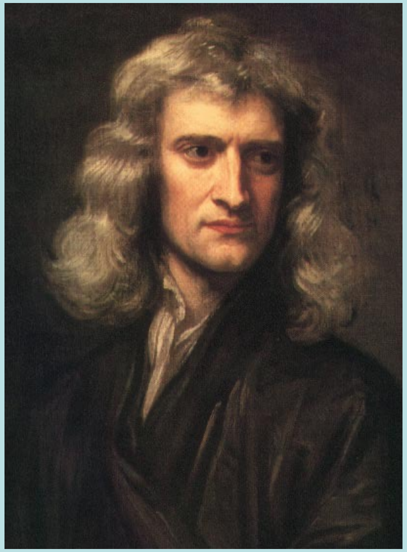


PHILOSOPHIÆ
NATURALIS
PRINCIPIA
MATHEMATICA.

Autore J. S. NEWTON, Trin. Coll. Cantab. Soc. Matheseos Professore Lucasiano, & Societatis Regalis Sodali.

IMPRIMATUR.
S. PEPYS, Reg. Soc. PRÆSES.
Julii 5. 1686.

LONDINI,
Jussu Societatis Regiæ ac Typis Josephi Streater. Prostat apud plures Bibliopolas. Anno MDCLXXXVII.



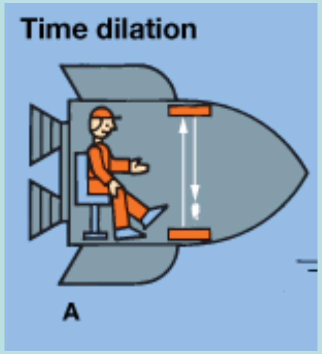
Isaac Newton

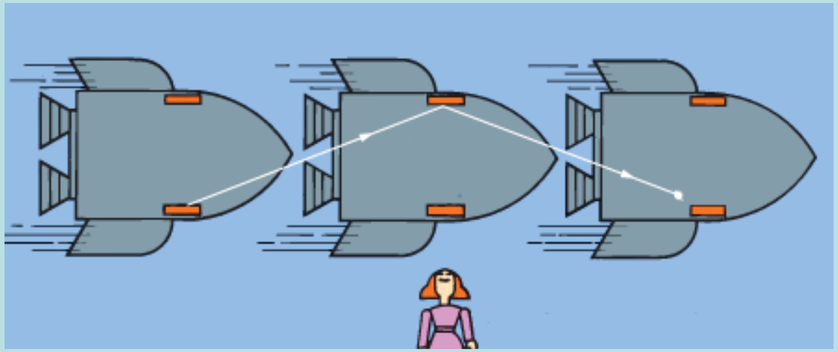
(1642-1727)

光的移動速度，與觀察者的運動狀態無關。

[redacted]

隱含(imply)





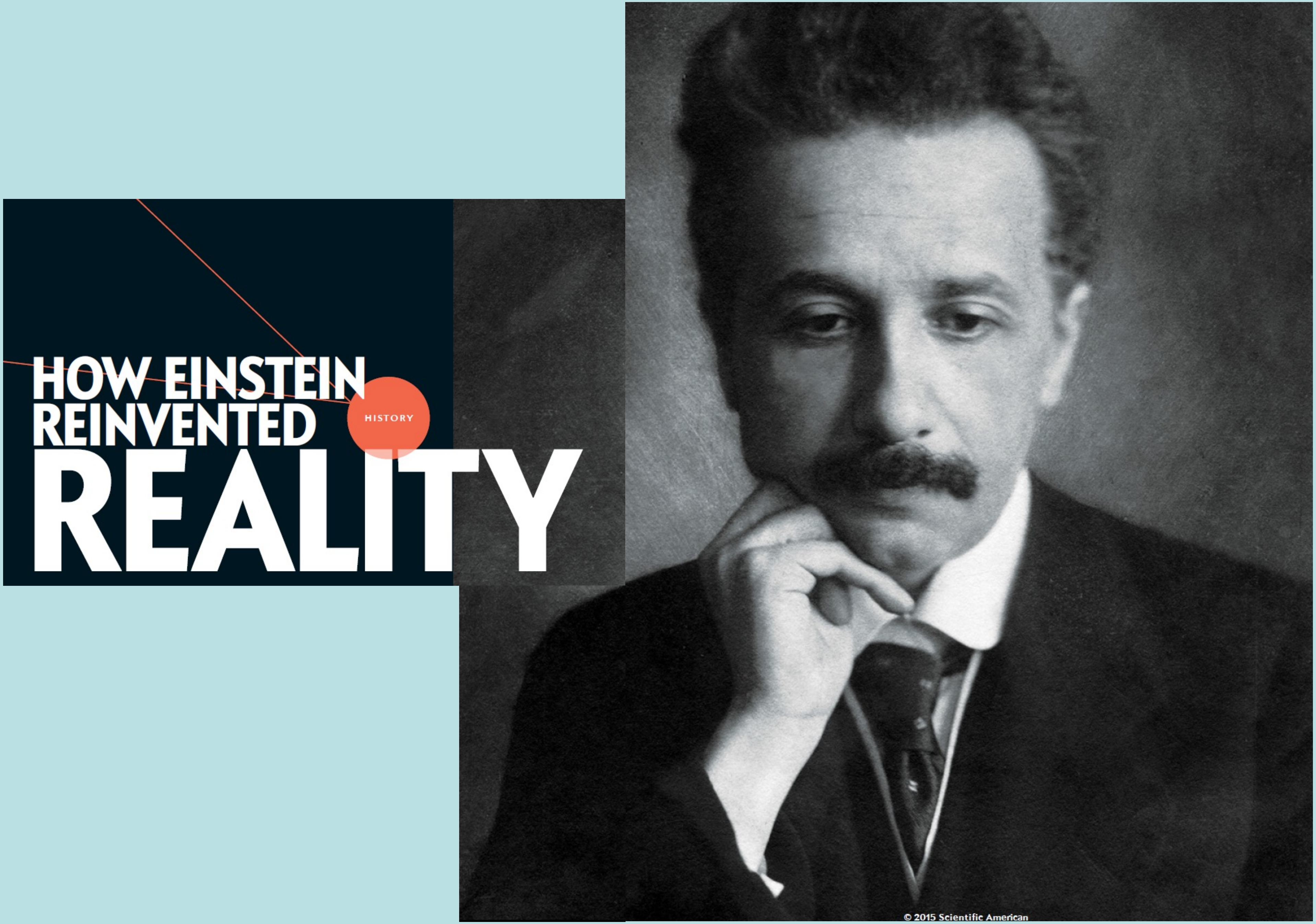
$\Delta t'$

Δt

太空船上量的時間$\Delta t'$ < 地面上量的時間Δt

時間不是絕對的，而與測量者的運動狀態有關！

我們必須放棄絕對時間！這就是狹義相對論的精髓！

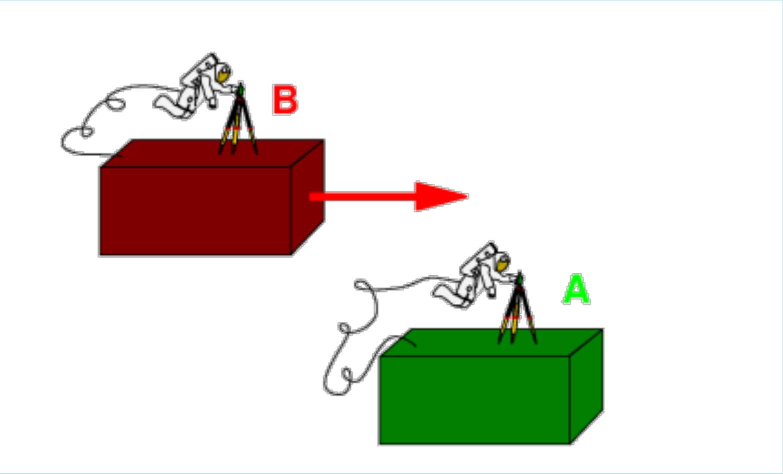


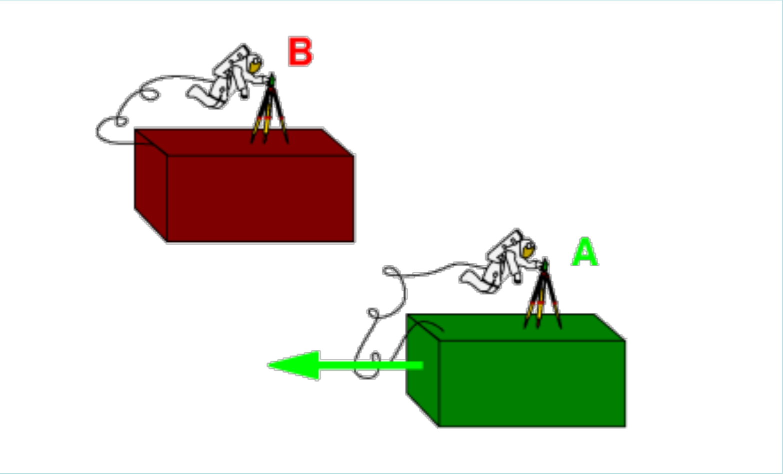
我們自然以為是真實的絕對時間，其實不是真實的。 $\Delta t \neq \Delta t'$

如果連時間都不是絕對的，觀察者也不是絕對的。

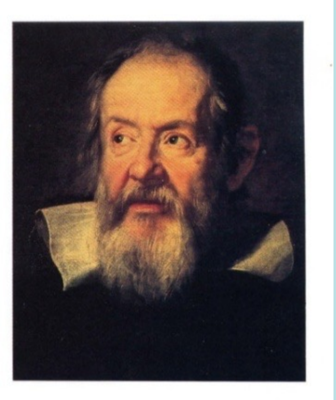
每一個觀察者都必須被同等的尊重。沒有所謂絕對的運動速度！

這就是相對性原則 The Principle of Relativity。



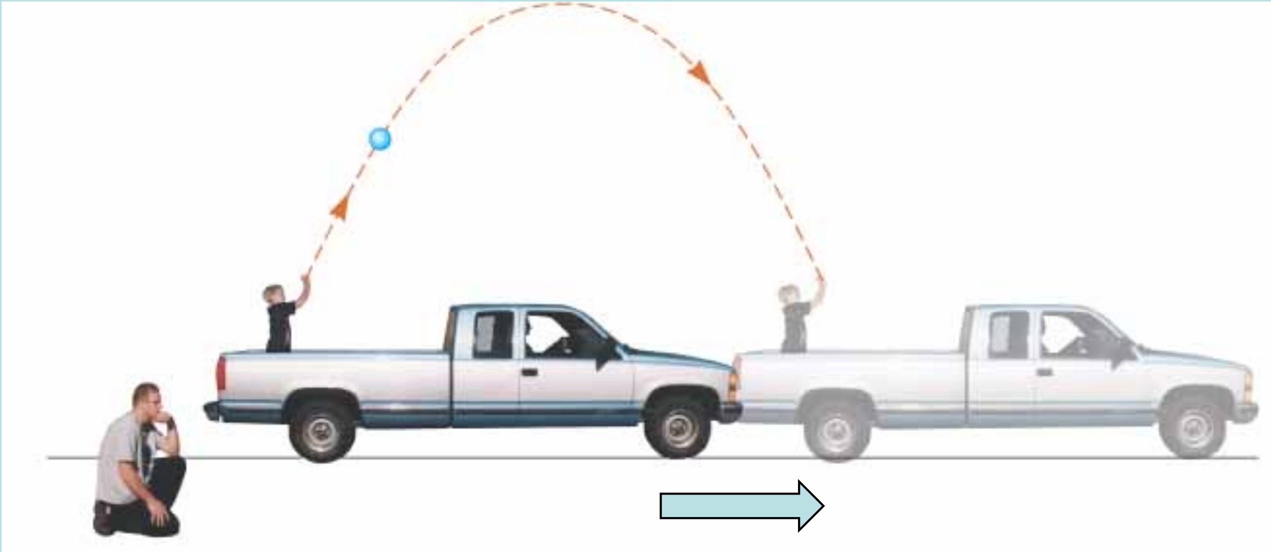


以上兩張圖中的物理現象看起來不同，但都是合理的。速度是相對的。



等速運動的觀察者，及靜止的觀察者，

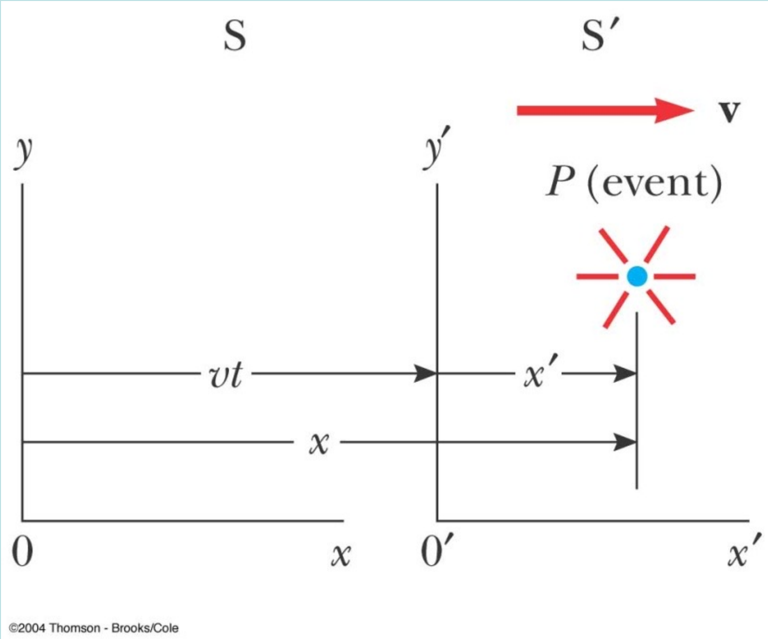
觀察同一個對象，兩者顯然得到不同的結果。

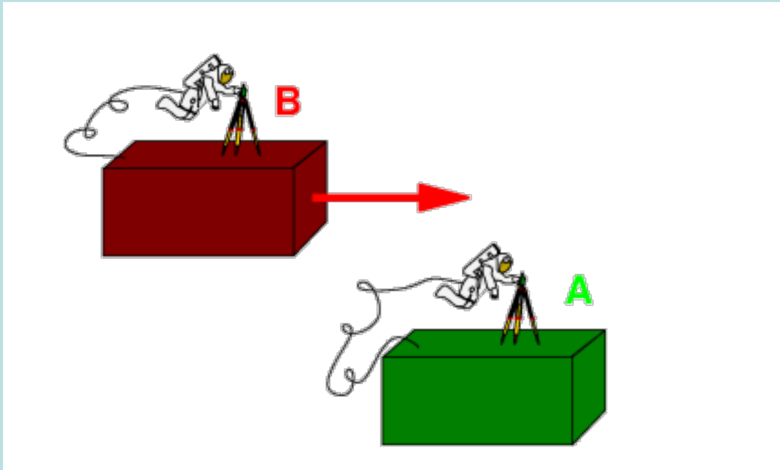


不同觀察者所測量到的時間與空間，必須分開標記：

一個紀錄為x, t，相對於它以速度移動的觀察者看到的紀錄為x', t'。

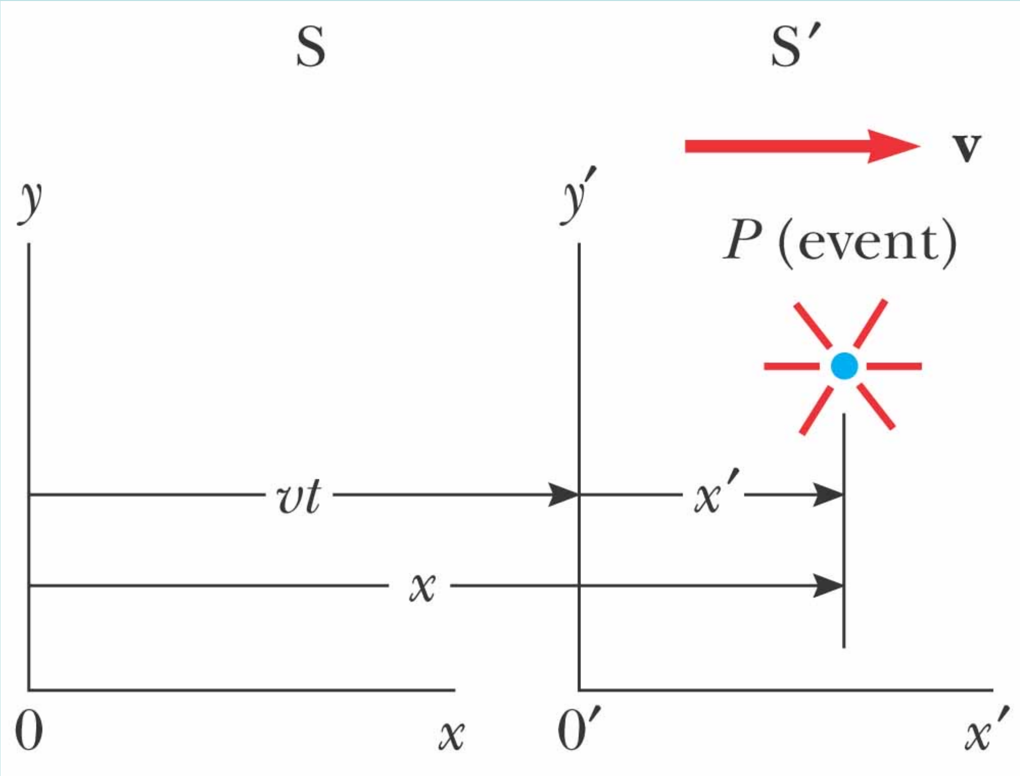
兩者滿足一定關係，我喜歡稱為翻譯表！

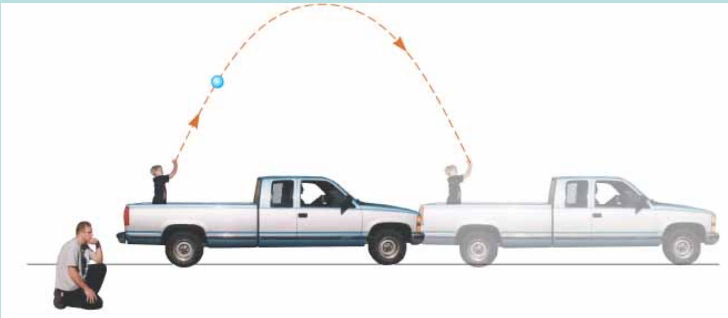




這兩個以定速相對運動的觀察者，稱為兩個慣性座標系！

根據日常生活經驗， x,t與x',t'滿足以下關係：





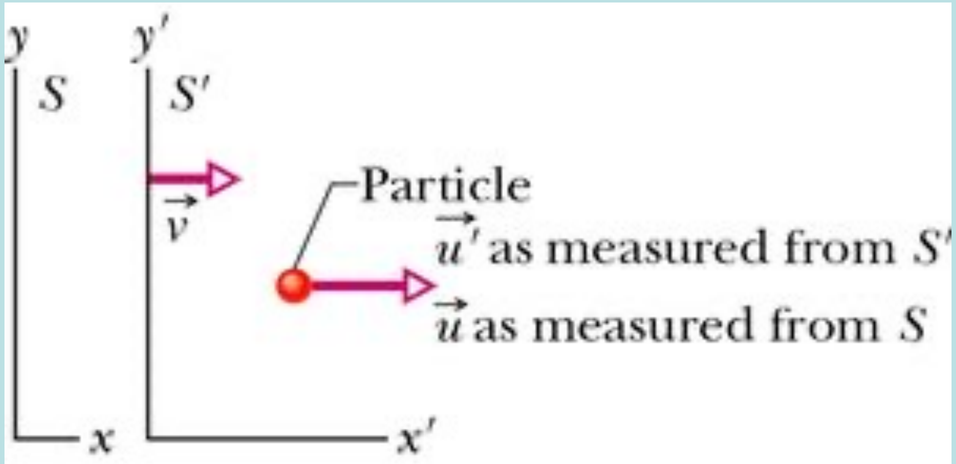
$$x' = x - vt$$

$$y' = y$$

$$t' = t$$

伽利略變換

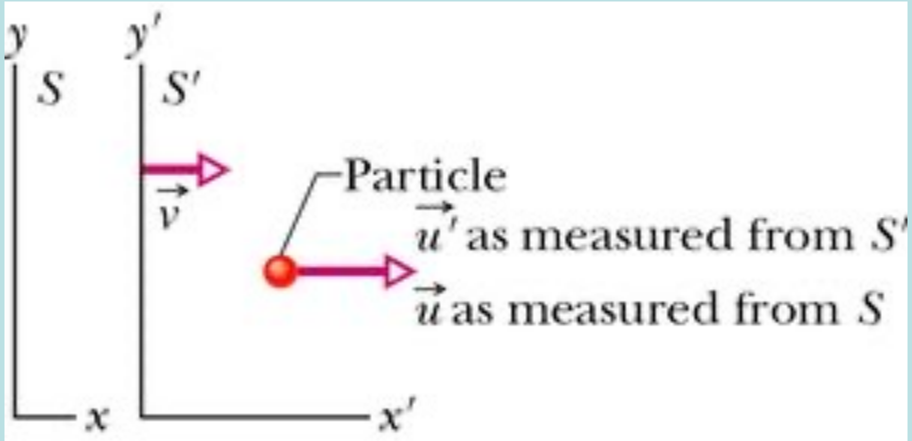
從伽利略變換可以推導出慣性座標系之間的速度的變換



$$u'_x = \frac{dx'}{dt} = \frac{d(x - vt)}{dt} = \frac{dx}{dt} - v = u_x - v$$

$$u'_x = u_x - v \qquad u'_y = u_y$$

慣性座標系之間的速度的變換

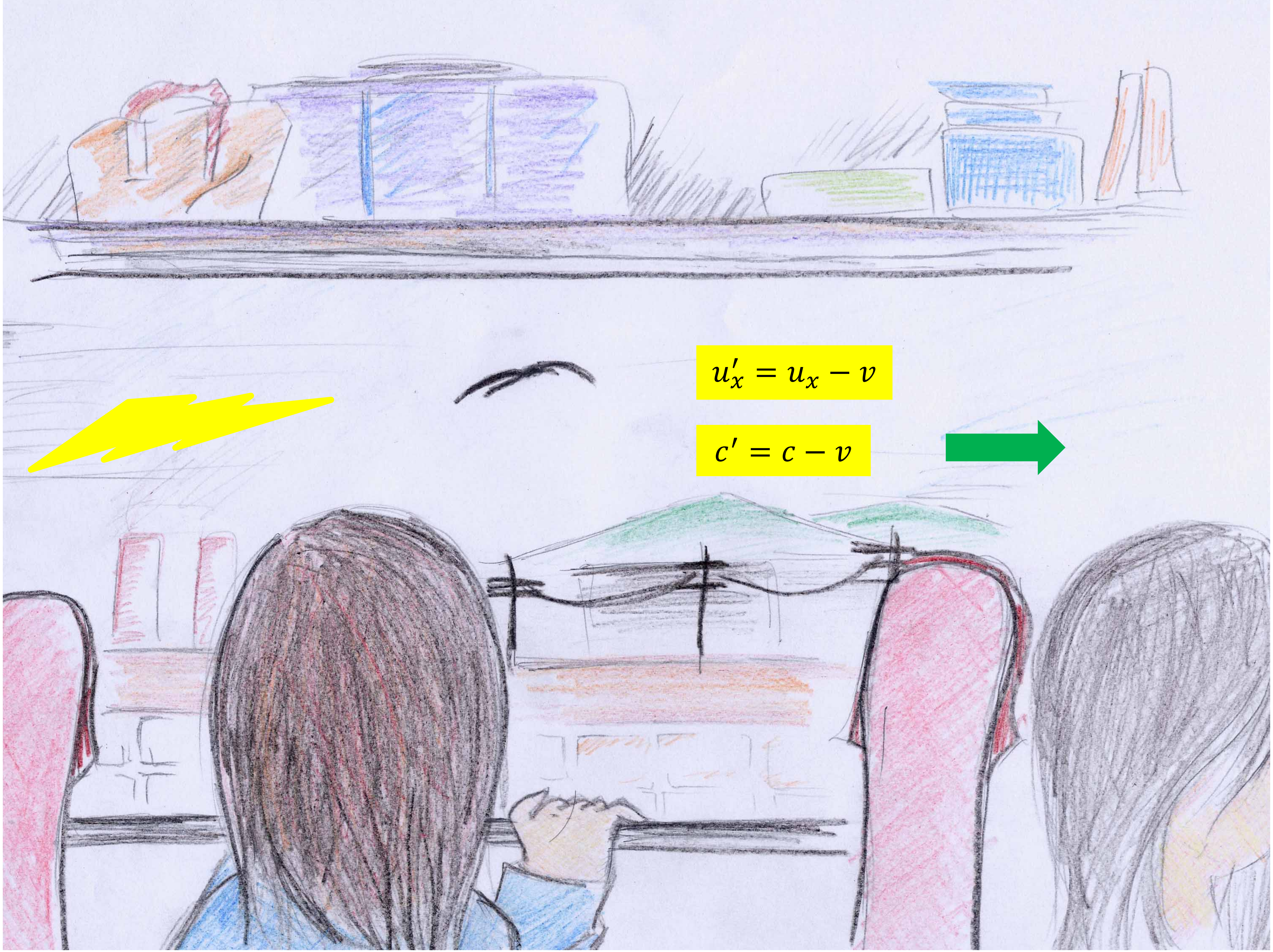


$$u'_x = \frac{\Delta x'}{\Delta t} = \frac{\Delta(x - vt)}{\Delta t} = \frac{\Delta x}{\Delta t} - v = u_x - v$$

$$u'_x = u_x - v \qquad u'_y = u_y$$

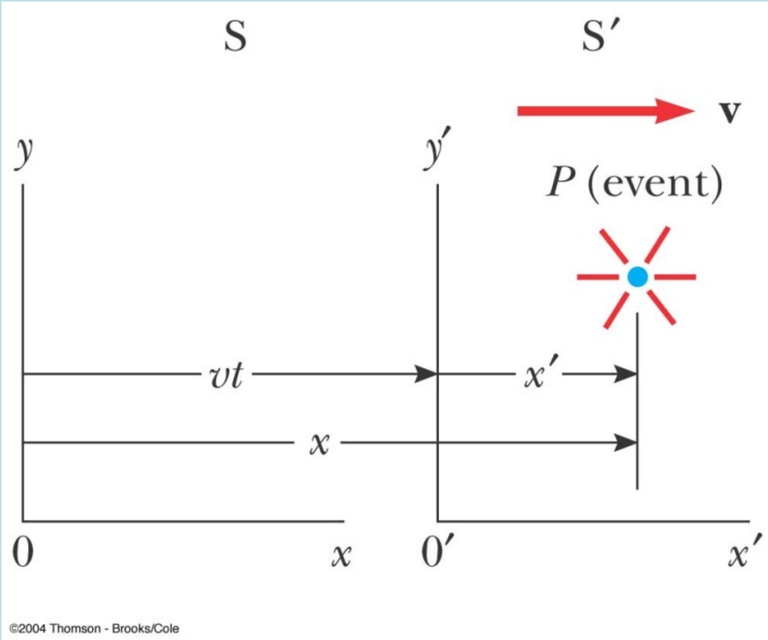
$$c' = c - v$$

但$c' = c$，因此伽利略變換需要修正！


$u_x' = u_x - v$
$c' = c - v$

根據伽利略變換，光速與觀察者的狀態有關：

$$c' = c - v$$



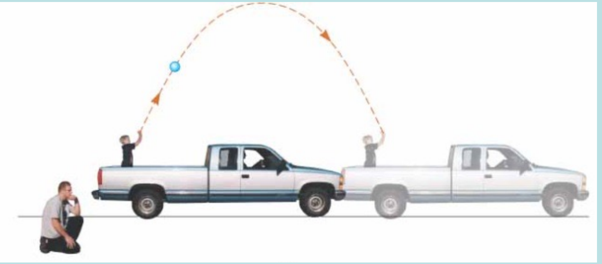
$t' = t$ 絕對時間

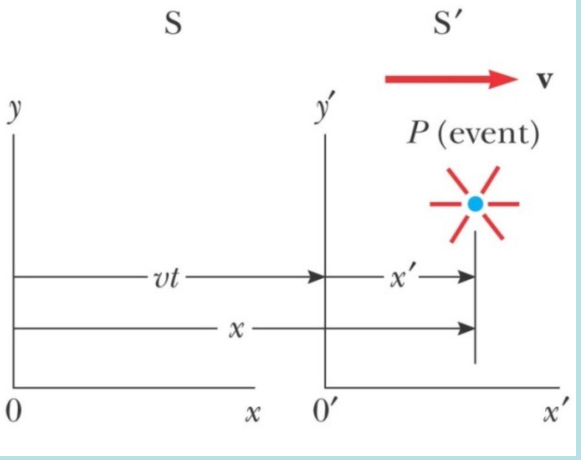
$$\Delta t' = \Delta t$$

移動的時鐘上的一段時間$\Delta t'$，從靜止的觀察者量起來是比較長的Δt，

因此伽利略變換必須修正

如果要求光速恆定，可以證明：
兩個相對移動的觀察者，所測量到的時間與空間x, t，x', t'必須滿足以下關係：
羅倫茲變換是唯一能維持光速恆定的時間與空間的線性變換！





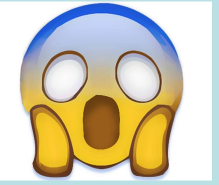
$$x' = \frac{x - vt}{\sqrt{1 - \frac{v^2}{c^2}}}$$

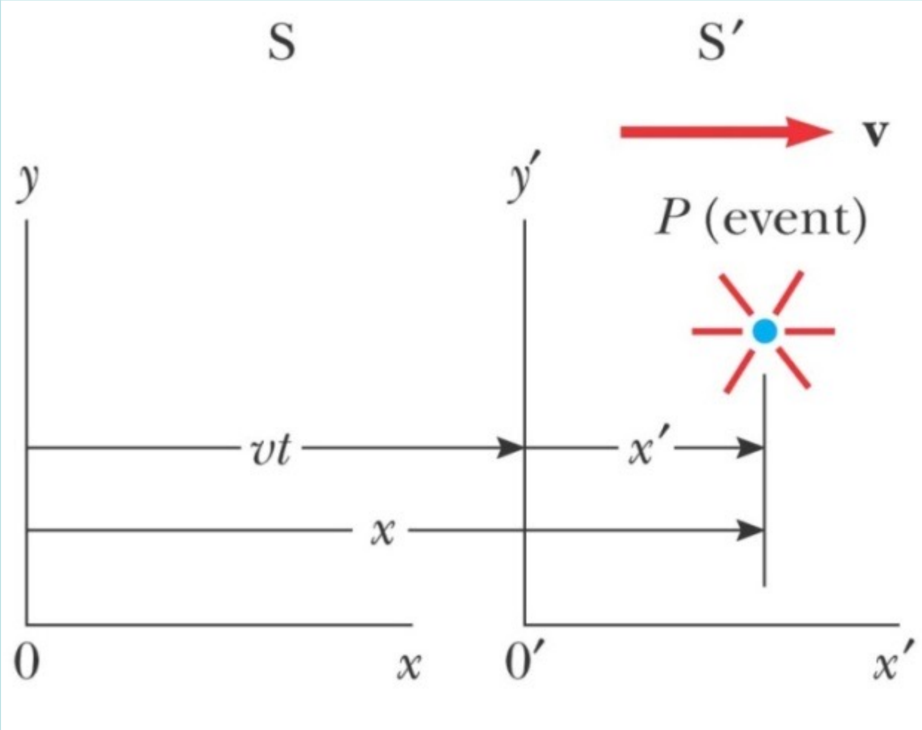
$$t' = \frac{t - \frac{v}{c^2}x}{\sqrt{1 - \frac{v^2}{c^2}}}$$

羅倫茲變換
Lorentz Transformation

相對運動的兩人量到的時間是不一樣的！ $\Delta t \neq \Delta t'$

時間的測量與測量者的運動狀態有關。





羅倫茲變換

Lorentz Transformation

$$x' = \frac{x - vt}{\sqrt{1 - \frac{v^2}{c^2}}}$$

$$x' = \gamma(x - vt)$$

$$t' = \gamma\left(t - \frac{v}{c^2}x\right)$$

$$t' = \frac{t - \frac{v}{c^2}x}{\sqrt{1 - \frac{v^2}{c^2}}}$$

$$\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$$

相對運動的兩人量到的時間是不一樣的！ $\Delta t \neq \Delta t'$

時間的測量與測量者的運動狀態有關。

速度很快的觀察者所量到的時間，有很大的一部分對靜止觀察者來說是空間。

時間與空間是分不開的。時間與空間的分別只是相對而非絕對。

$$x' = \gamma(x - vt)$$

$$t' = \gamma\left(t - \frac{v}{c^2}x\right)$$

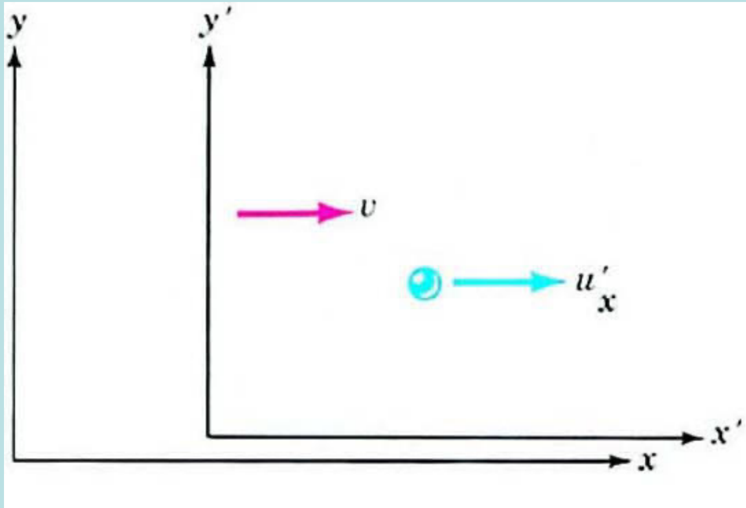
速度加成

$$\Delta x' = \gamma(\Delta x - v\Delta t)$$

$$\Delta t' = \gamma\left(\Delta t - \frac{v}{c^2}\Delta x\right)$$

兩個觀察者測量同一個粒子的速度，分別紀錄為u', u。

$$u' = \frac{\Delta x'}{\Delta t'} = \frac{\Delta x - v\Delta t}{\Delta t - \frac{v}{c^2}\Delta x} = \frac{\frac{\Delta x}{\Delta t} - v}{1 - \frac{v}{c^2}\frac{\Delta x}{\Delta t}} \xrightarrow[\Delta t \to 0]{} \frac{u - v}{1 - \frac{uv}{c^2}}$$



$$u' = \frac{u - v}{1 - \frac{uv}{c^2}}$$

羅倫茲變換導出新的速度加成公式：

速度小$u \ll c$時: $u' \to u - v$，與日常經驗相同！

但運用於光，則光速恆定！

$$c' = \frac{c - v}{1 - \frac{cv}{c^2}} = \frac{c - v}{\frac{c - v}{c}} = c$$

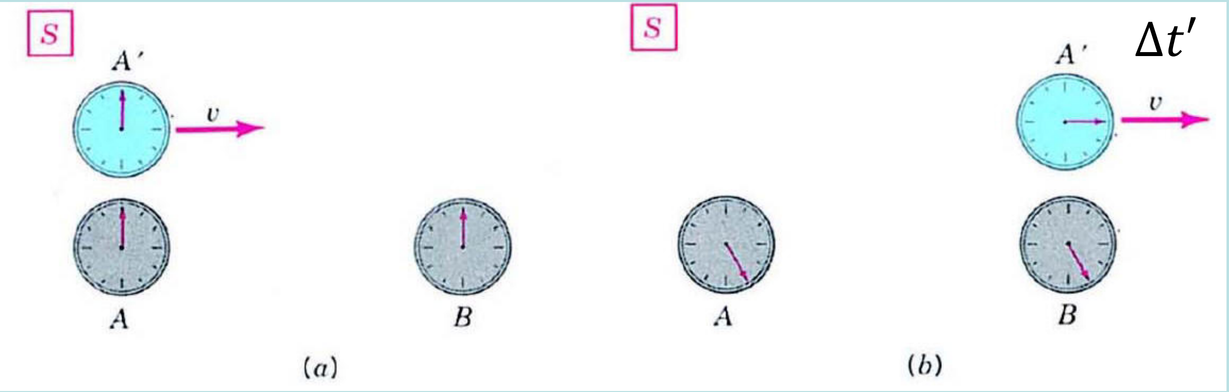
驗證羅倫茲變換可以導出時間膨脹 Time Dilation

考慮移動的時鐘走了$\Delta t'$的這一段時間的前後兩個事件！

這兩個事件的時間差與位置差：

$$\Delta x' = \gamma(\Delta x - v\Delta t)$$

$$\Delta t' = \gamma\left(\Delta t - \frac{v}{c^2}\Delta x\right)$$



這前後兩個事件在太空船看來時間差為$\Delta t'$，位置差$\Delta x' = 0$，代入就解出Δt及Δx。

捷徑

靜止觀察者相對於移動觀察者是以$-v$移動！

同樣轉換式將移動座標與靜止座標互換，速度以$-v$代入即可。

注意時鐘靜止於移動座標系： $\Delta x' = 0$

$$\Delta x = \gamma(\Delta x' + v\Delta t')$$

$$\Delta t = \gamma\left(\Delta t' + \frac{v}{c^2}\Delta x'\right)$$

$$\Delta t = \gamma\Delta t' = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}}\cdot\Delta t'$$

長度縮短效應 Length Contraction

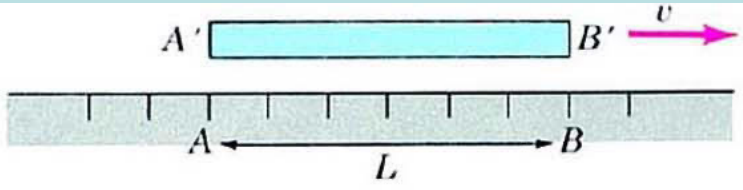


圖 39.11
為了量取運動中的棒子之長，在 A 、B 的觀察者同時記下兩端的位置。但是，對於和棒子一起運動的觀察者而言，這兩個量度並非同時。

$$\Delta x' = \gamma(\Delta x - v\Delta t)$$

$$\Delta t' = \gamma\left(\Delta t - \frac{v}{c^2}\Delta x\right)$$

$$\Delta t = 0$$

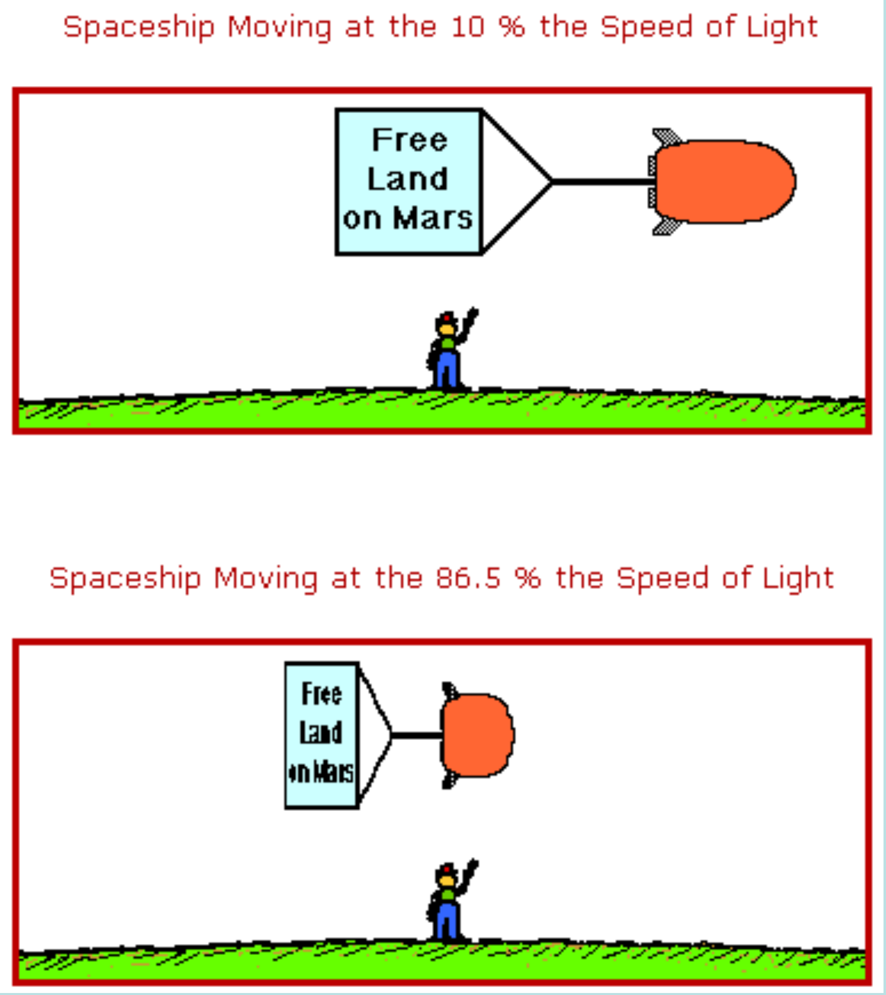
在地面上的同時測量尺的兩端！

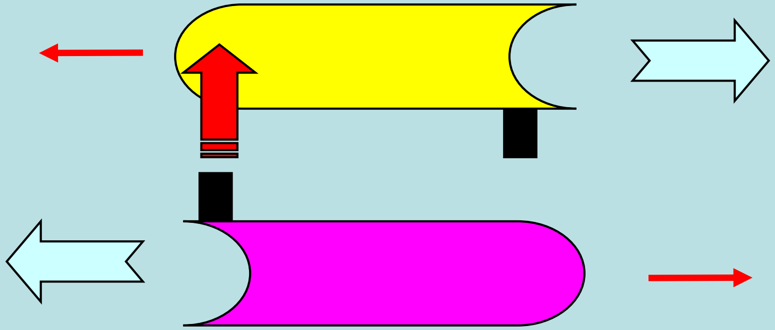
移動中的尺看起來較靜止時縮短！

$$\Delta x' = \gamma\Delta x$$

$$\Delta x = \sqrt{1 - \frac{v^2}{c^2}} \cdot \Delta x' < \Delta x'$$

長度縮短


Spaceship Moving at the 10 % the Speed of Light
Free
Land
on Mars
Spaceship Moving at the 86.5 % the Speed of Light
Free
Land
on Mars

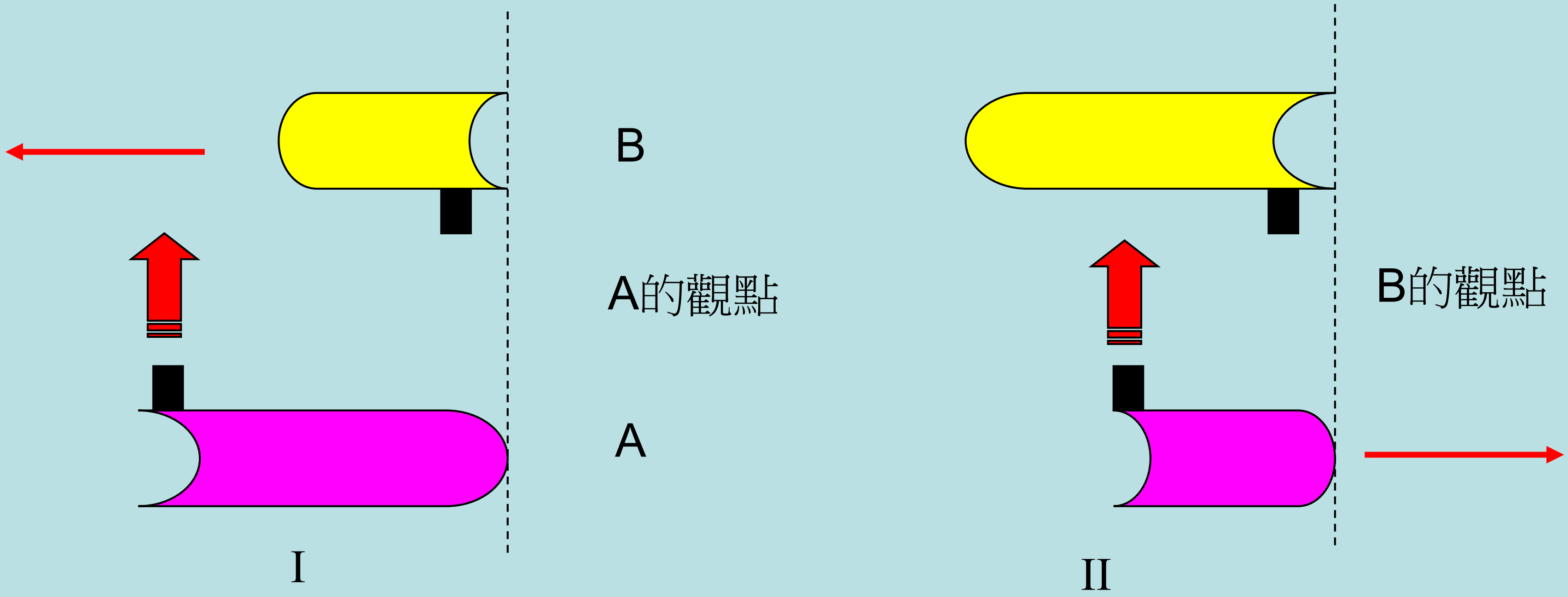


星際大戰

未可慮相對論效應

靜止時等長的兩船，在A的船首與B船尾重合的同時， A船長命令A船尾開炮！

移動中的太空船看起來較靜止時縮短！



仔細分析事件1對齊及事件2發砲的時間差

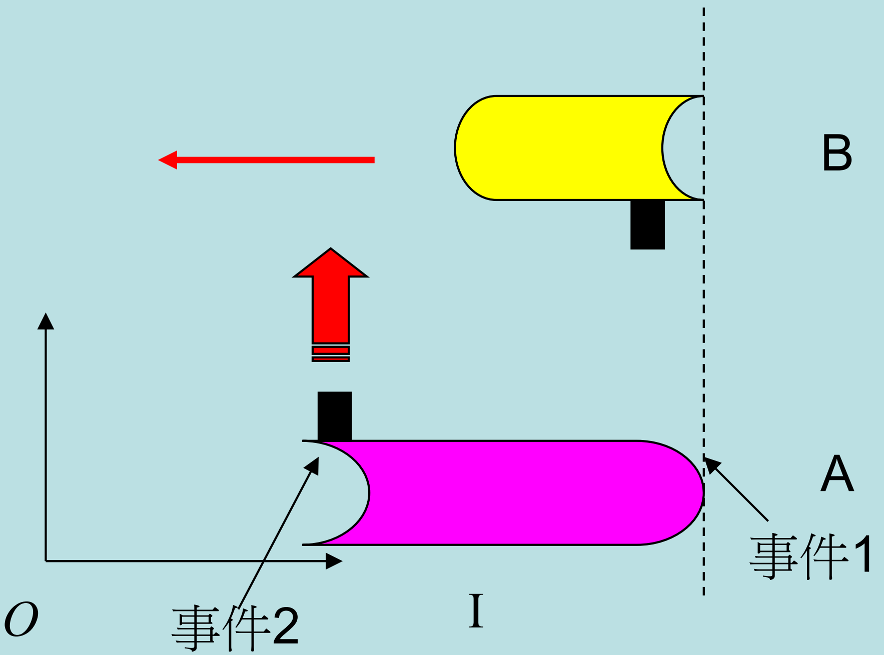
$$\Delta t' = \frac{\Delta t + \frac{v}{c^2}\Delta x}{\sqrt{1-\frac{v^2}{c^2}}} = \frac{\frac{vL}{c^2}}{\sqrt{1-\frac{v^2}{c^2}}} > 0$$

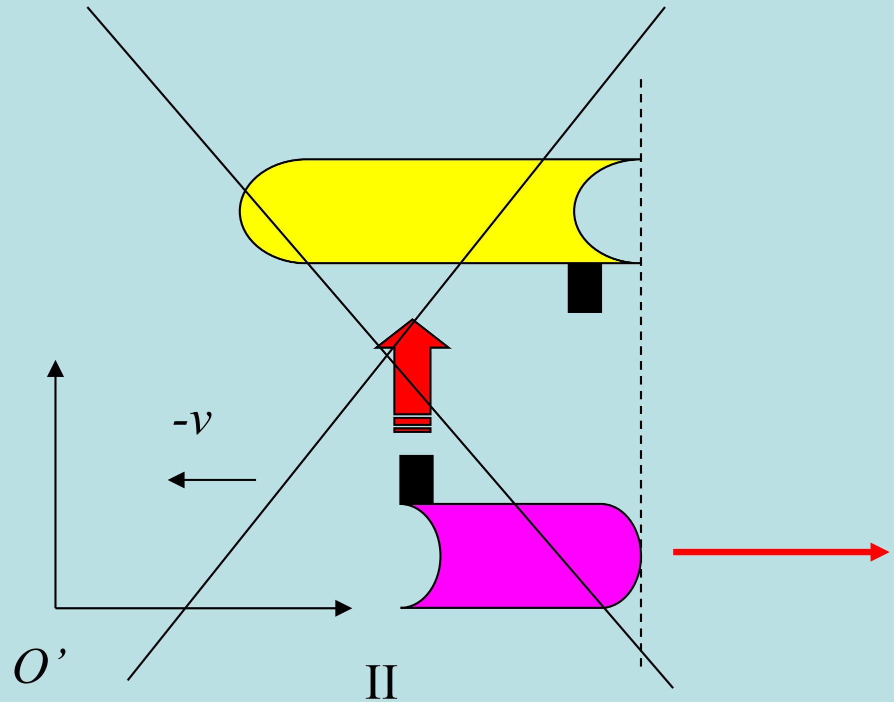
對齊與發砲是在 A座標系中同時

$$\Delta t = 0, \Delta x = L$$

$$t_1' > t_2'$$

故還未對齊，已經發砲



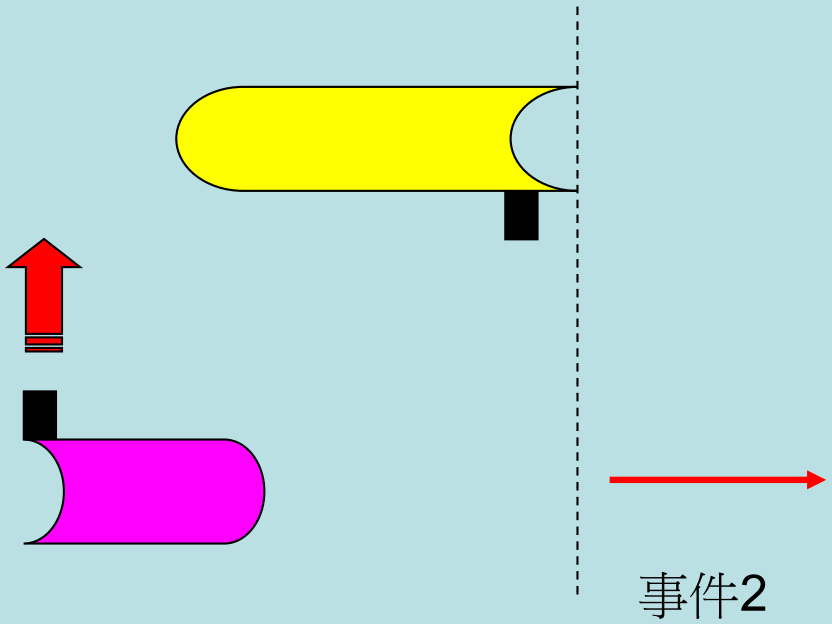


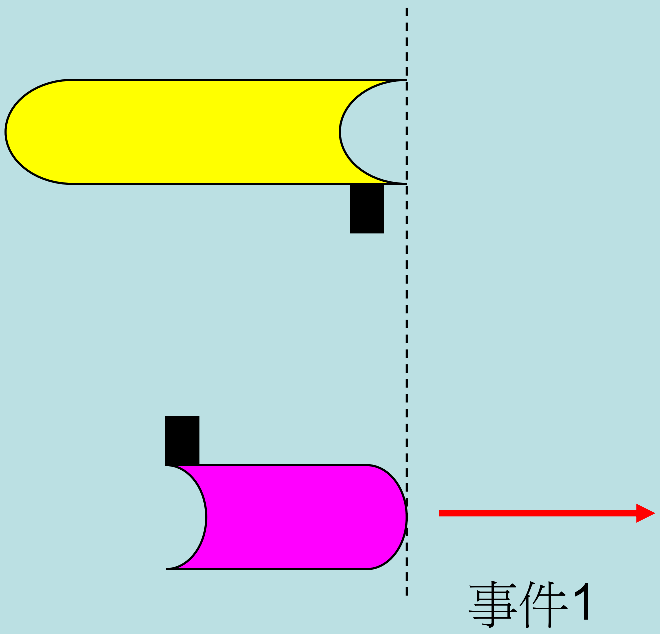
仔細分析事件1對齊及事件2發砲的時間差

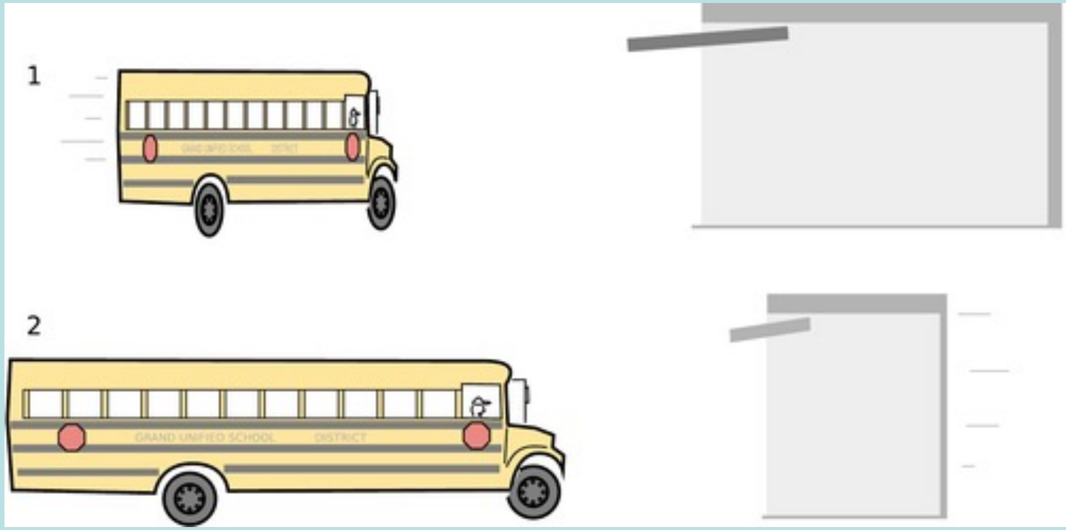
$$\Delta t' = \frac{\Delta t + \frac{v}{c^2}\Delta x}{\sqrt{1-\frac{v^2}{c^2}}} = \frac{\frac{vL}{c^2}}{\sqrt{1-\frac{v^2}{c^2}}} > 0$$

$$t_1' > t_2'$$

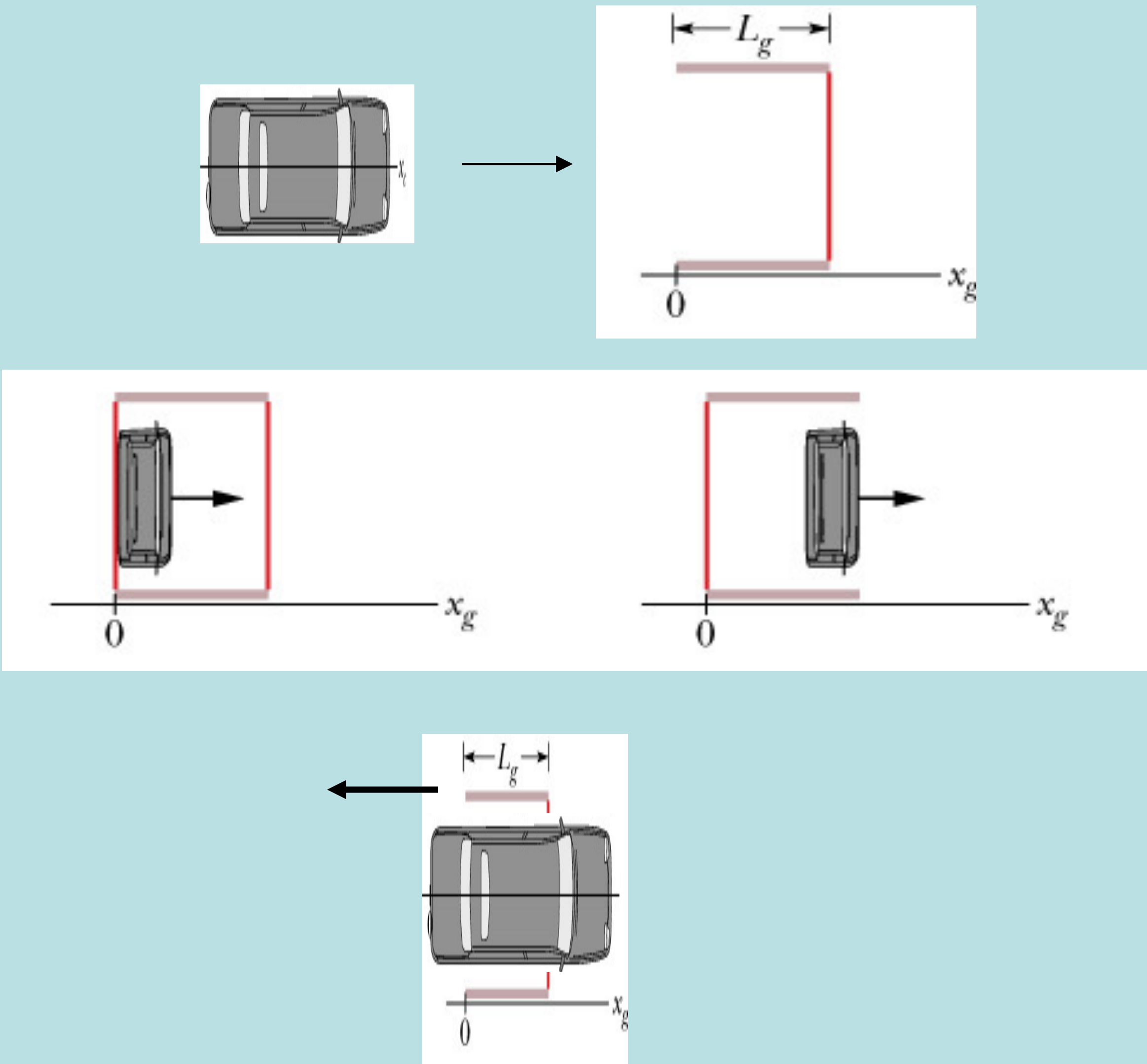
故還未對齊，已經發砲

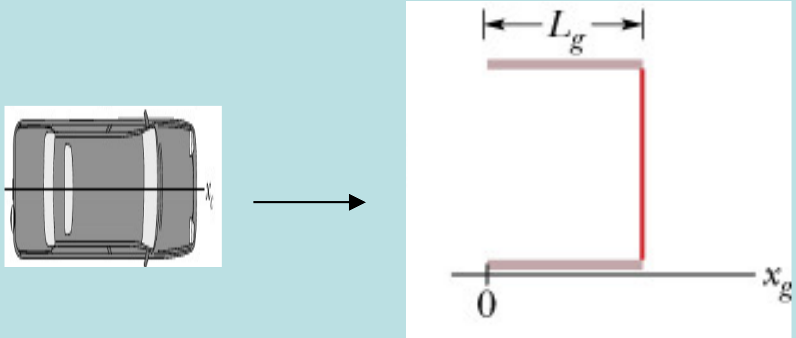


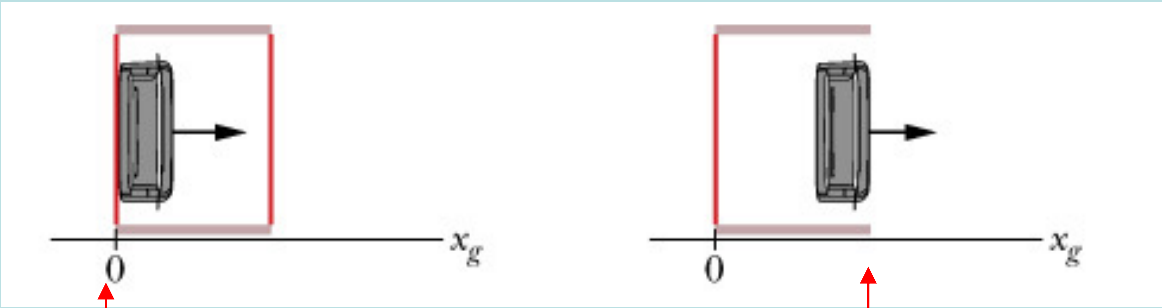


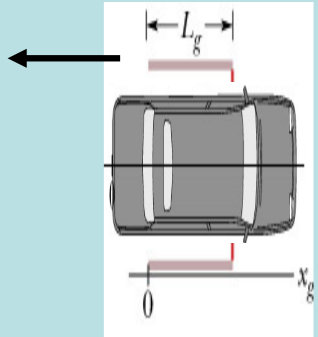

1
2
GRAND UNIFIED SCHOOL
DISTRICT

停車問題









I

II

$$\Delta x = L, \Delta t = \frac{L - \gamma^{-1} L}{v} > 0$$

$$\Delta t' = \gamma\left(\Delta t - \frac{v\Delta x}{c^2}\right) = \gamma\left(\frac{L - \gamma^{-1}L}{v} - \frac{v}{c^2}L\right)$$

$$= \gamma\left(\frac{L}{v} \times \left(\gamma^{-2} - \gamma^{-1}\right)\right) = \left(\frac{L}{v} \times \left(\gamma^{-1} - 1\right)\right) < 0$$

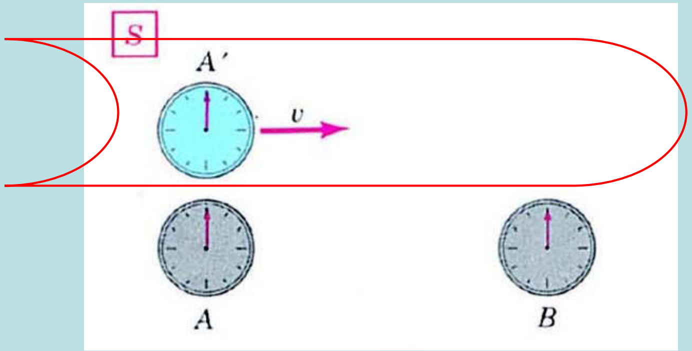
I早於II

II早於I

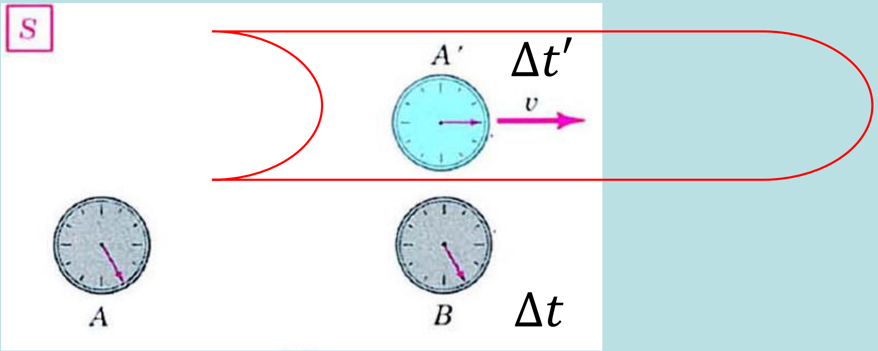
時間先後也是相對的

地面觀點

事件 1



事件 2



$\Delta t' < \Delta t$

移動中的鐘走得慢！可是跟著時鐘移動的觀察者會以為自己是靜止的！

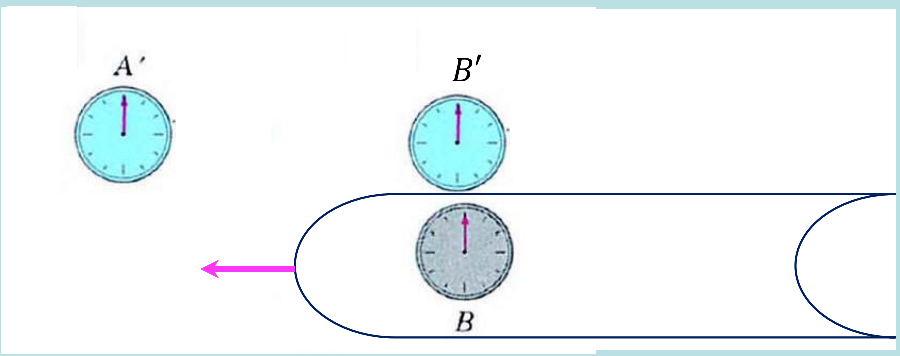
地面的鐘對他來說反而在移動，因此應該是地面的時鐘走得慢！如下圖：

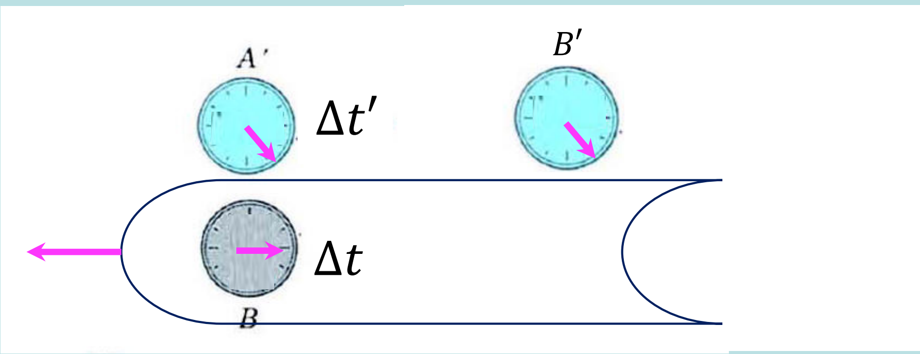
太空船觀點

事件 3

$\Delta t' > \Delta t$

事件 4



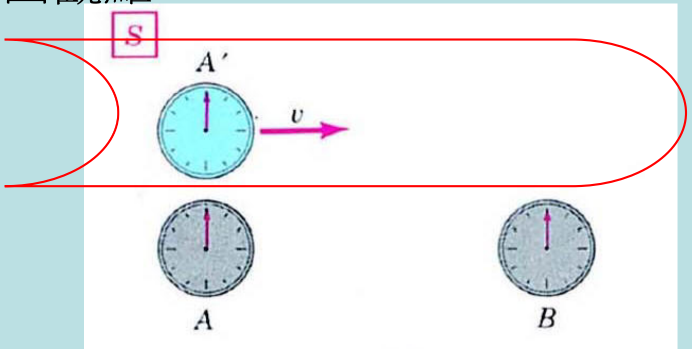


這兩個圖自然都是正確的！結論卻完全相反。

但仔細看一下，其實是兩種不同的情節！

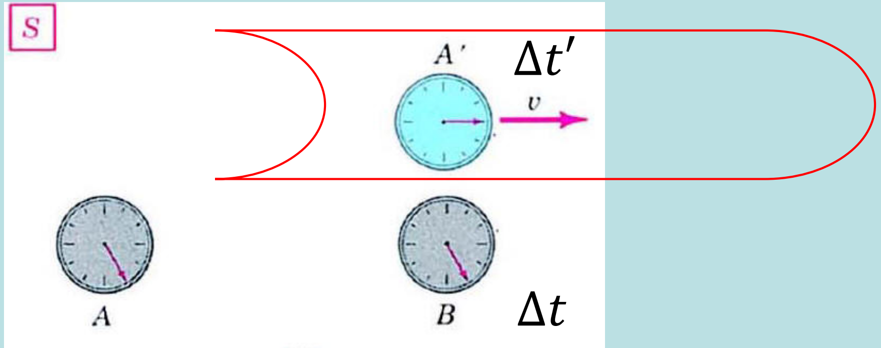
地面觀點

事件 1



$\Delta t' < \Delta t$

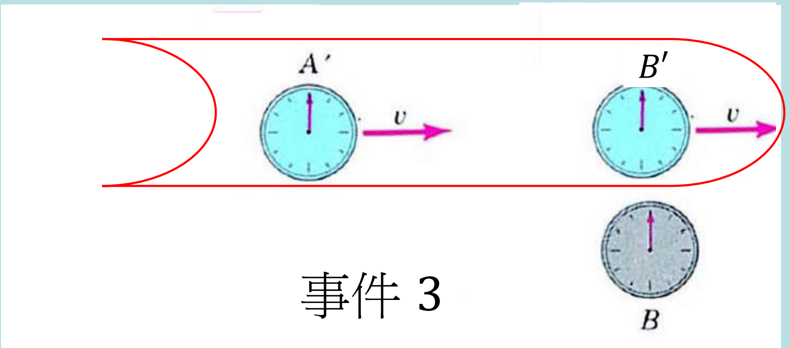
事件 2

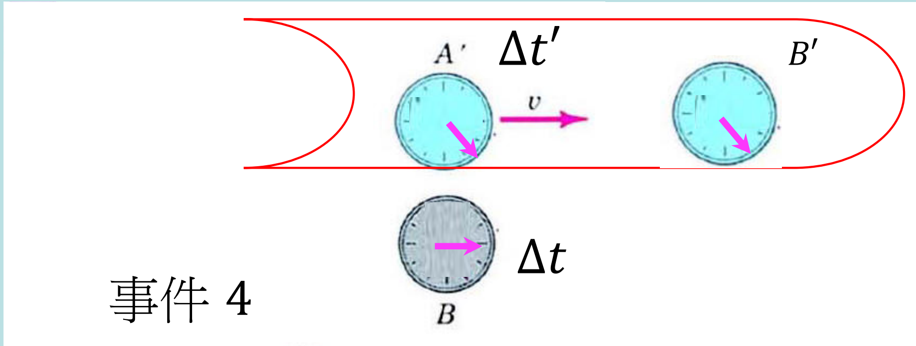


太空船上同一個時鐘上的一段時間！

地面觀點　原來這是兩種不同的情節！

$\neq$



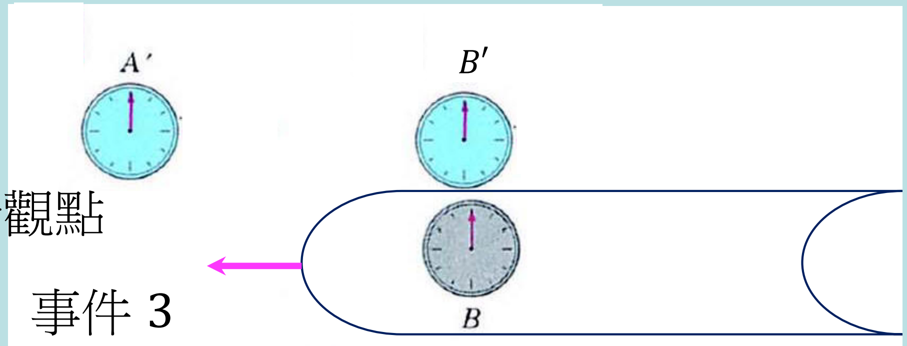


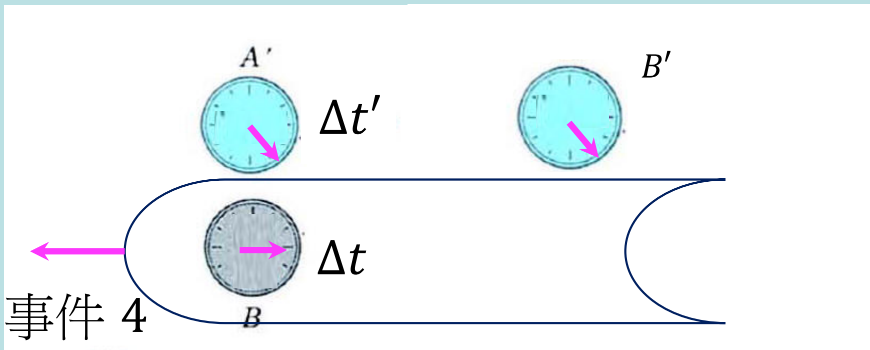
地面上同一個時鐘上的一段時間！

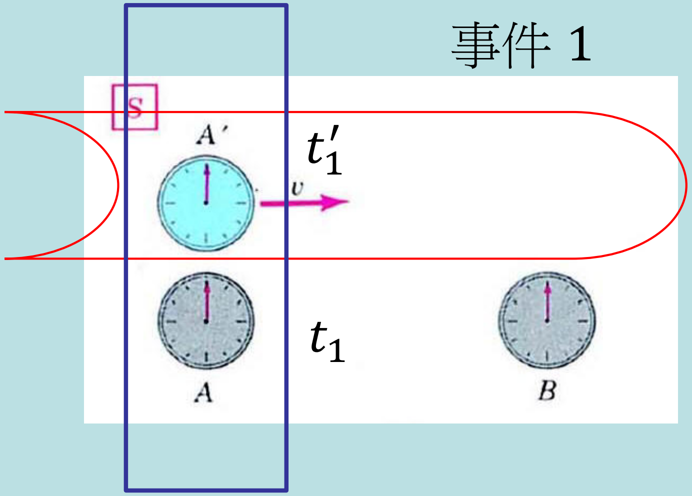
$\Delta t' > \Delta t$

$=$

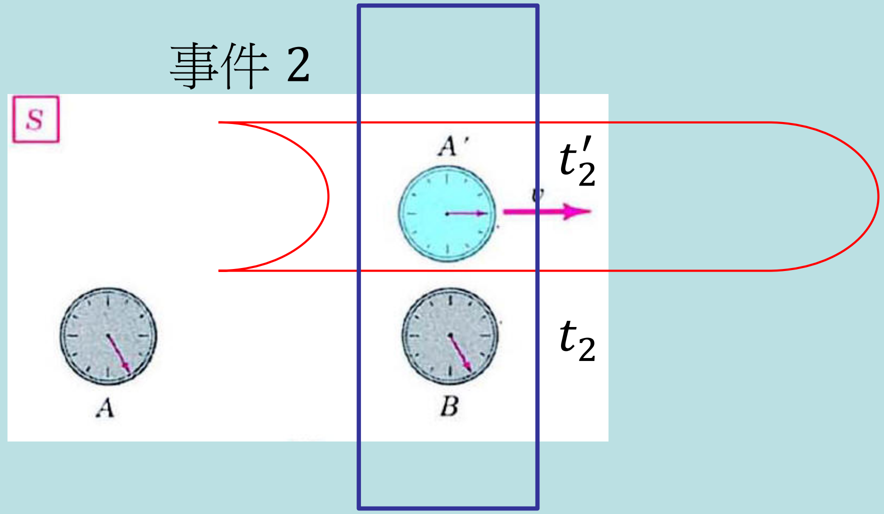
太空船觀點





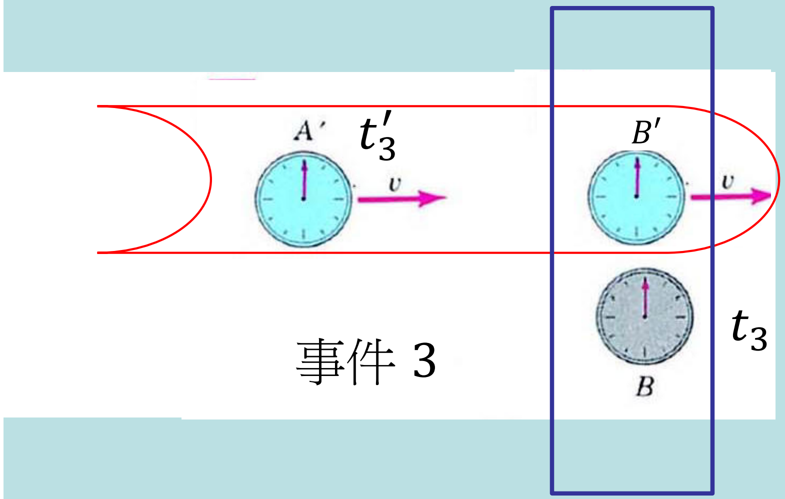


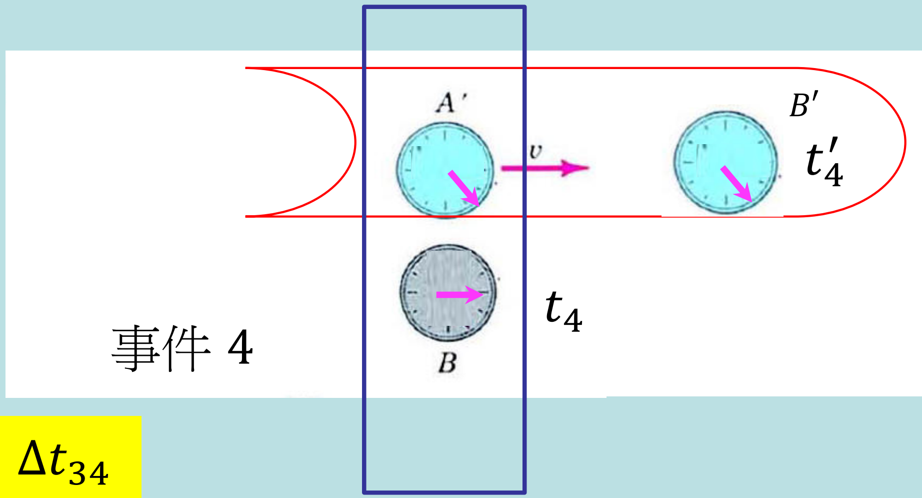
$\Delta t_{12}' < \Delta t_{12}$



事件1：A'與A交會，事件2：A'與B交會，此兩事件發生在太空船上的同一位置。
時間差在太空船上量起來$\Delta t'$，比從地面上量起來Δt較短。

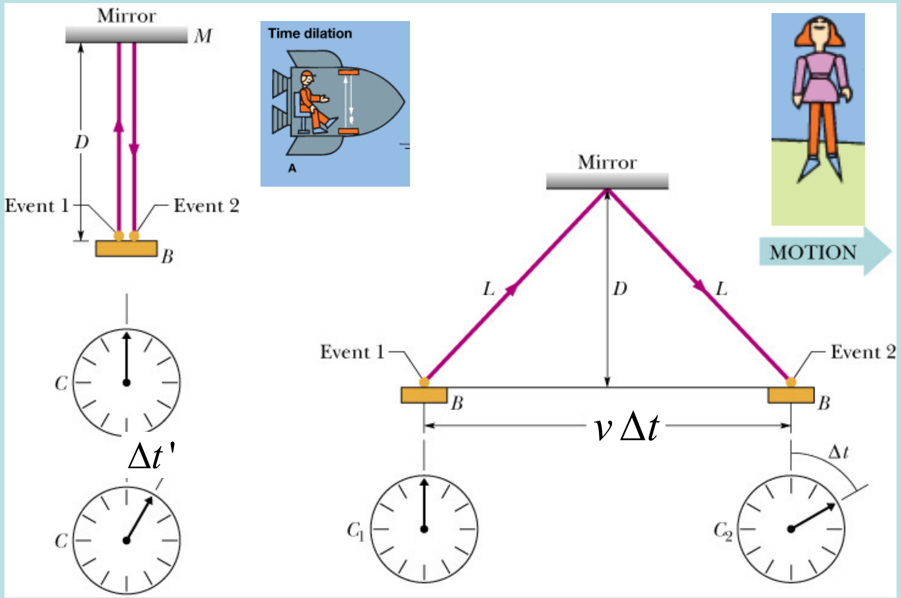
$\neq$

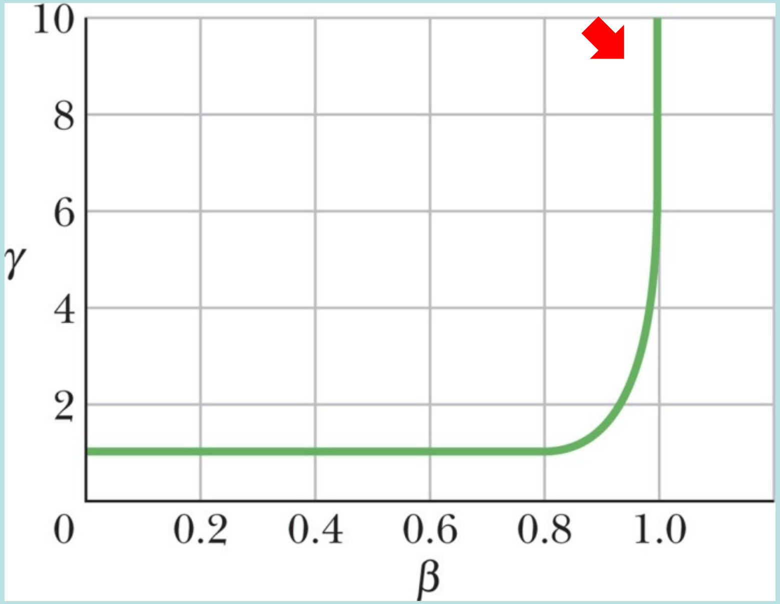




$\Delta t_{34}' > \Delta t_{34}$

事件3：B'與B交會，事件4：A'與B交會，此兩事件發生在地面上的同一位置。
時間差在太空船上的一段時間Δt，比從太空船上量起來$\Delta t'$較短。

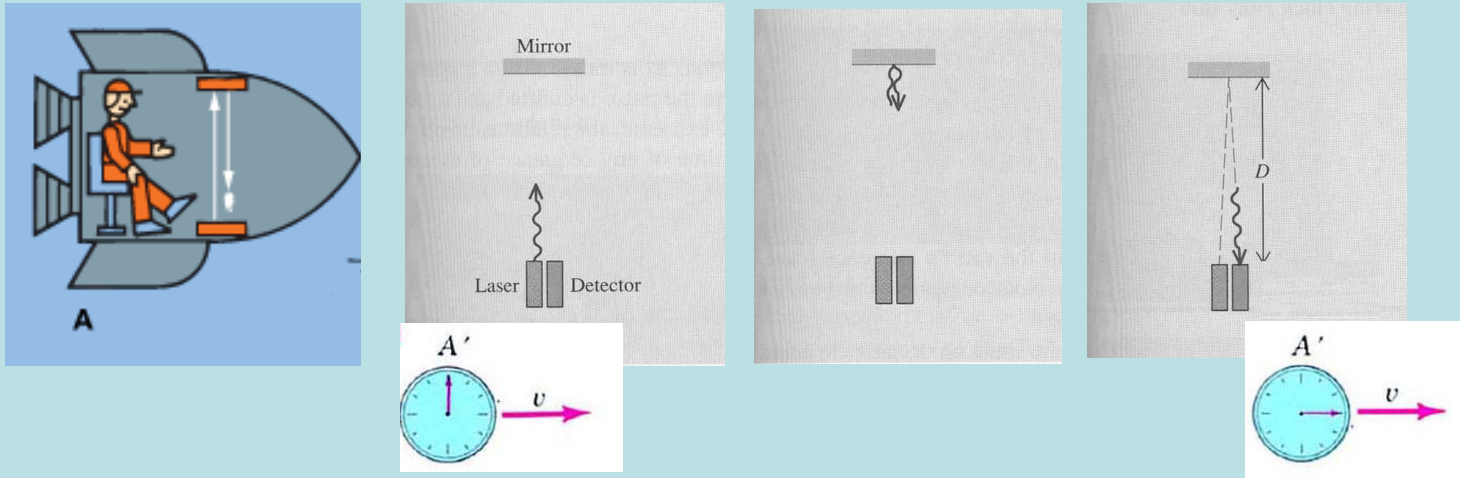




$$\Delta t = \frac{\Delta t'}{\sqrt{1 - \frac{v^2}{c^2}}} \equiv \gamma \Delta t'$$

$v \to c, \gamma \to \infty$

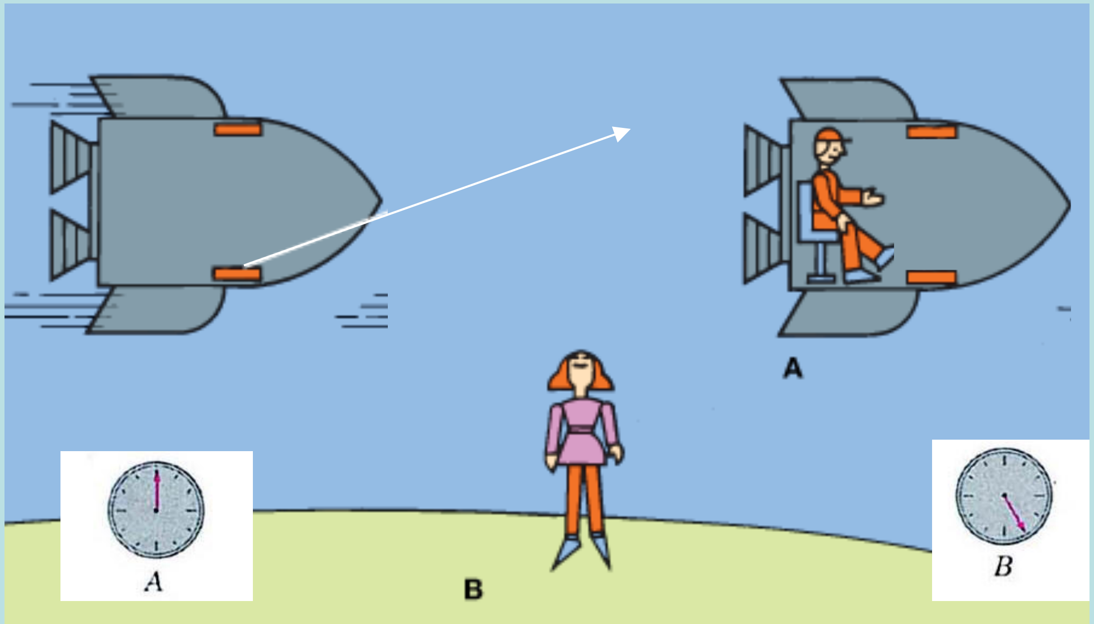
觀察者火箭無法加速到與光一樣快！



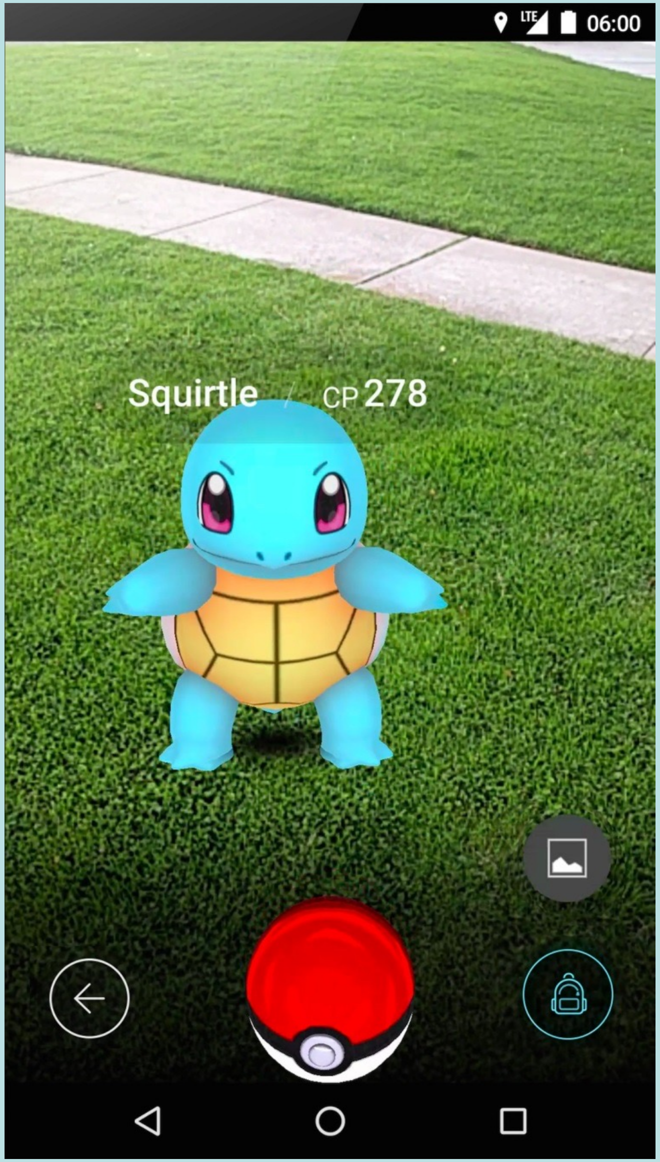
如果觀察者火箭加速到比光還快，

從地面上觀察，斜射以光速移動的雷射光，永遠追不上比光速快的鏡子！

物體運動不能超過光速。



更嚴格的分析：



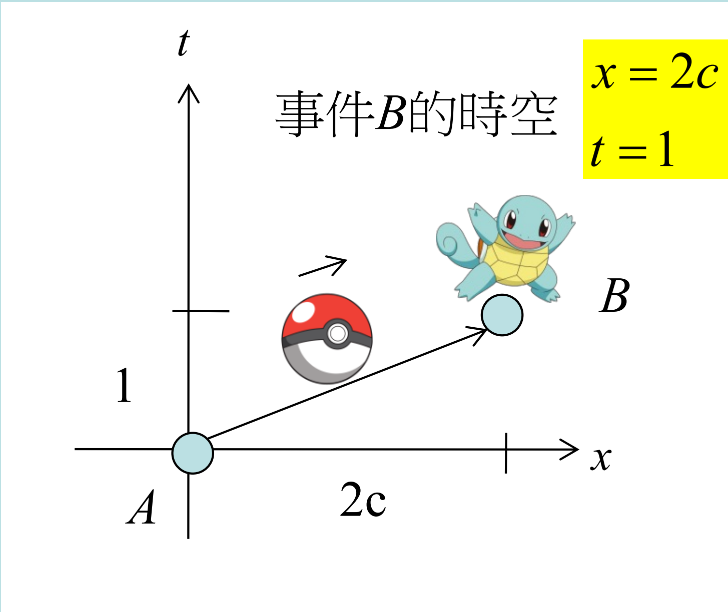
在距離2c處發現一個神奇寶貝！

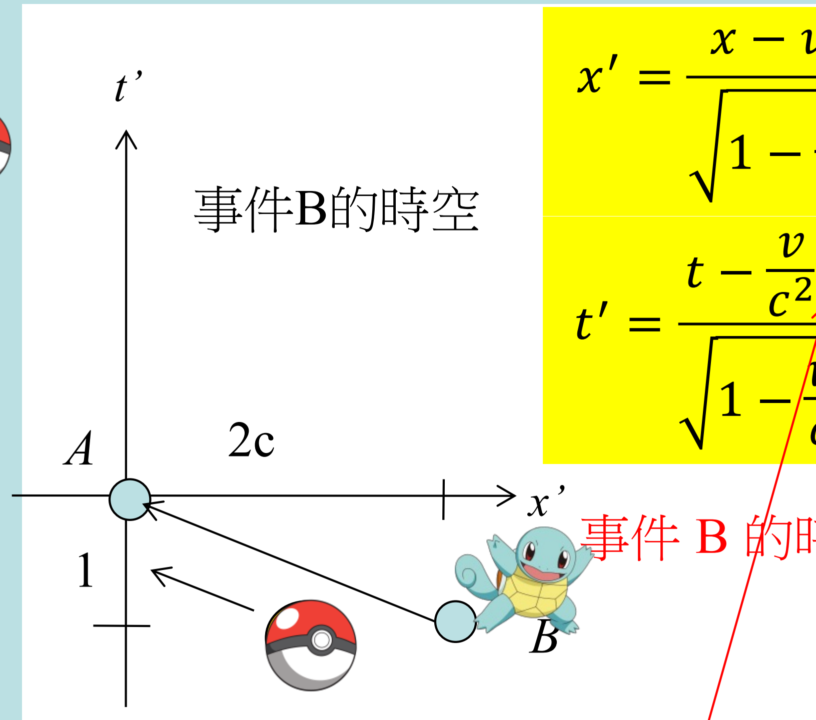
從一個以4/5 c 速度移動的座標系來觀察：

在距離2c處發現一個神奇寶貝！

朝他發射一以兩倍光速移動的寶貝球。

由A出發，一秒鐘後到達B，打中寶貝。





$$x' = \frac{x - vt}{\sqrt{1 - \frac{v^2}{c^2}}} = 2c$$

$$t' = \frac{t - \frac{v}{c^2}x}{\sqrt{1 - \frac{v^2}{c^2}}} = -1$$

事件 B 的時間變號

A發射球在後， B打中寶貝在前，

因此寶貝球是由B走到A

A發射球是因，B打中寶貝是果。得分。

B打中寶貝是因， A發射球是果。寶貝得分！

如果有這樣的寶貝球，因果就完全錯亂！

因此以兩倍光速移動的寶貝球不存在！

t'變號是因x很大

可以證明超過光速運動的物體都會造成這樣的因果錯亂。

物體運動不能超過光速。

訊息傳遞不能快過光速。

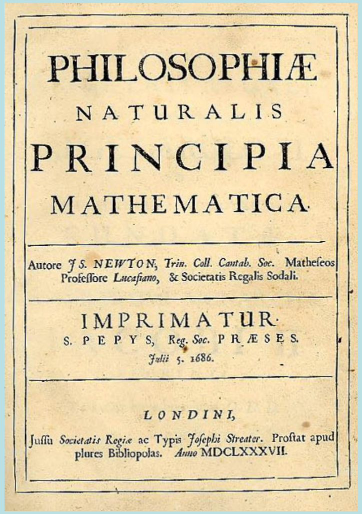
這兩個事實是光速恆定的直接邏輯結果！

超光速火箭是不可能的！星際旅行幾乎是不可能的。

難道我們不能一直對物體加入能量，使他的動能 $\frac{1}{2}mv^2$ 越來越大？

動能還是 $\frac{1}{2}mv^2$ 嗎？

既然牛頓力學所需要的絕對時間假設證實為誤，牛頓力學必須重新改寫！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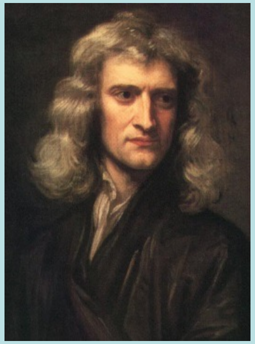
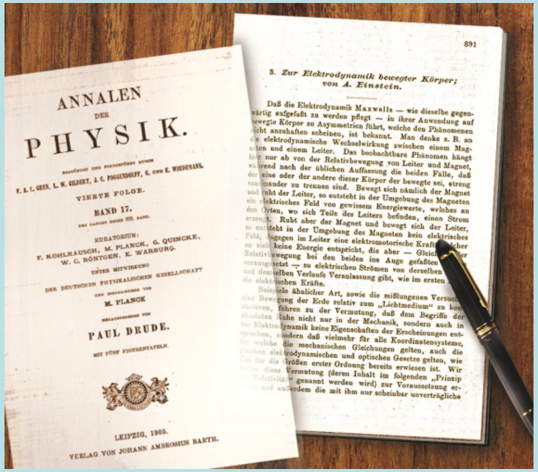
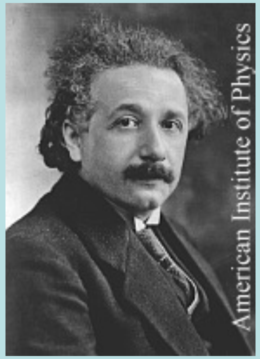
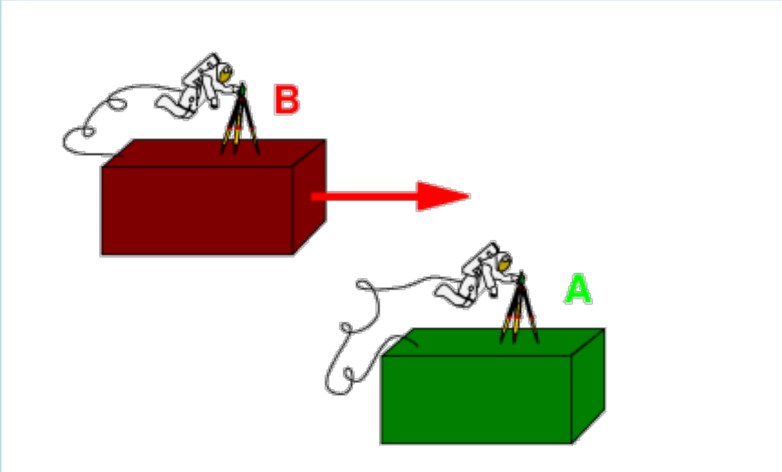
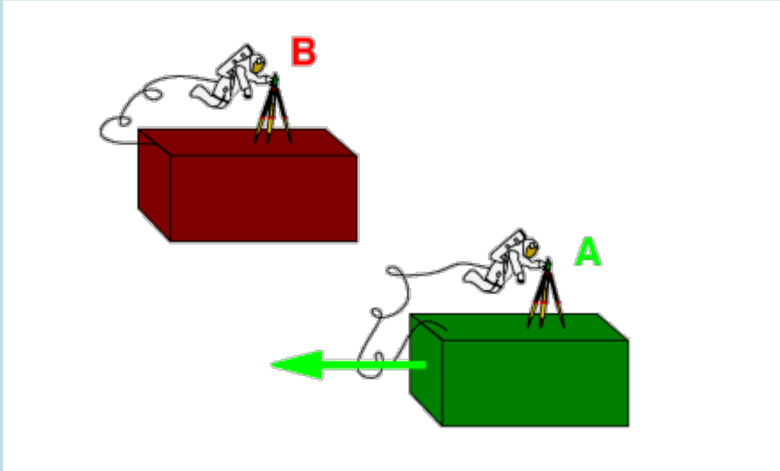










相對性原則 The Principle of Relativity還有另一個講法：

以上兩張圖中的物理現象看起來不同，但都是合理的。速度是相對的。

那麼，覺得自己是如右圖靜止的實驗者B，由實驗結果歸納的物理定律，

與在左圖中靜止的A所歸納的物理定律應該一模一樣！

符合這個條件的物理定律才是正確的物理定律。

因此，相對性原則成為物理定律是否正確的一個新的檢驗標準！

所有還沒檢驗過的都要拿來確認一下！

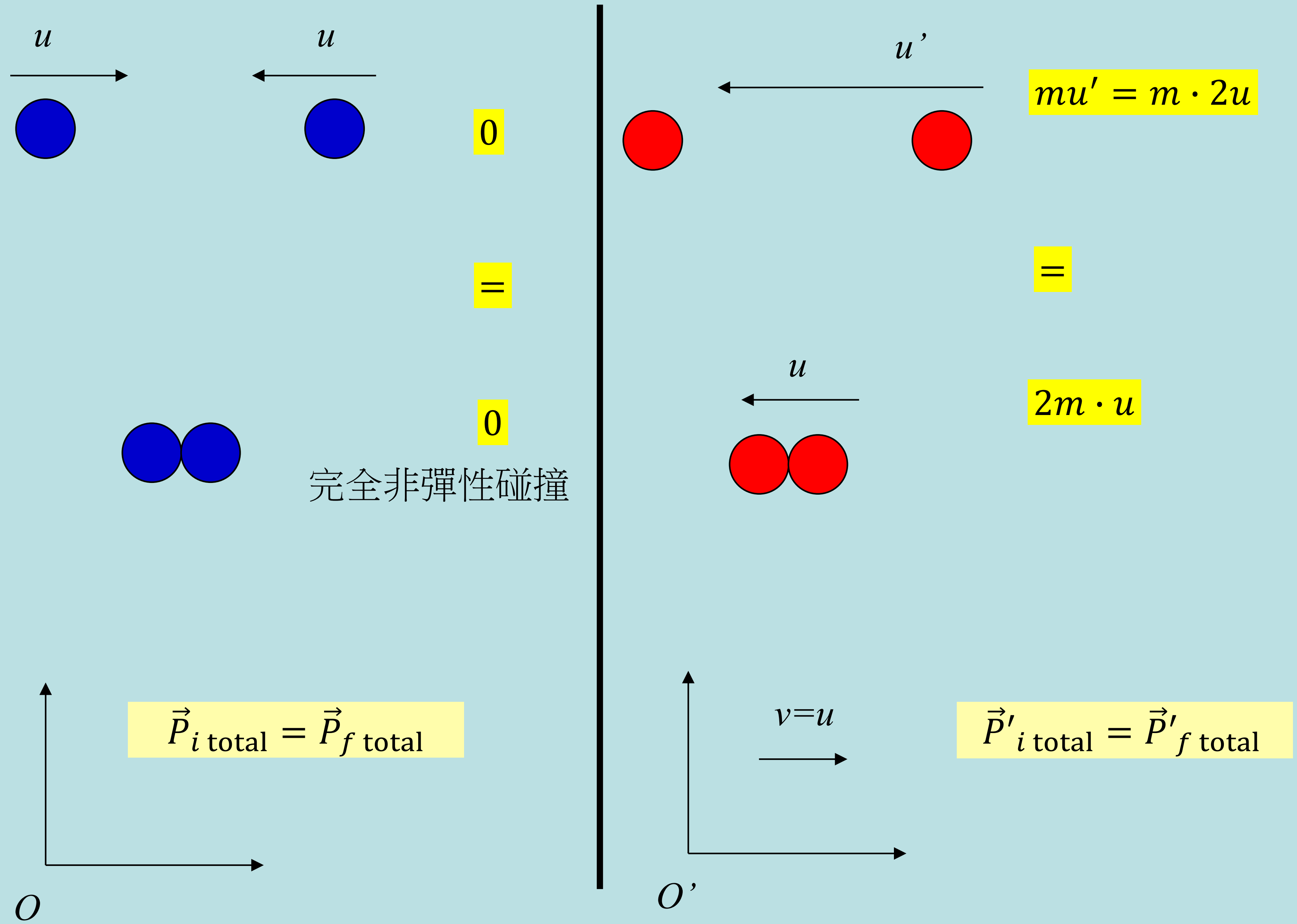
生長屬性		野生 魚/蝦		野生 貝/頭足海鮮		人工養殖 魚/蝦	
供貨來源		江醫師の魚舖子	一般市售	江醫師の魚舖子	一般市售	江醫師の魚舖子	一般市售
檢驗項目	重金屬5項	V	X	V	X	V	3-5種
	漂白劑	V	X	V	X	V	X
	增色劑	V	X	V	X	V	X
	甲醛	V	X	V	X	V	X
	防腐劑11項	V	X	V	X	V	X
	戴奧辛17項	V	X	V	X	V	X
	多氯聯苯12項	V	X	V	X	V	X
	藥殘190項					V	23種
	農藥216項					V	2種
	三聚氰胺					V	?
	三聚氰酸					V	X
	總計	共計48項	共計0項	共計48項	共計0項	共計456項	共計30項
檢驗方式		逐批檢驗	X	逐批檢驗	X	逐批檢驗	抽驗
處理方式		HACCP	X	HACCP	X	HACCP	?
包裝方式		真空包裝	一般	真空包裝	一般	真空包裝	一般
儲藏方式		-40℃急速冷凍	?	-40℃急速冷凍	?	-40℃急速冷凍	?
運送方式		全程冷凍鏈	?	全程冷凍鏈	?	全程冷凍鏈	?

檢驗的標準為何？

動量與能量守恆定律在羅倫茲變換下會不會變？

動量與能量守恆定律滿不滿足相對性原則？

牛頓版動量守恆 $\vec{P} = m\vec{v}$



牛頓版的動量守恆遵守伽利略變換下的相對性原則

但？如果考慮相對性效應.....

$$u' = \frac{u+u}{1+\frac{u^2}{c^2}} \neq 2u$$

u u

u' ?

0

$mu' \neq m \cdot 2u$

=

$\neq$

u

0

$2m \cdot u$

完全非彈性碰撞

$v=u$

$\vec{P}_{i\,\text{total}} = \vec{P}_{f\,\text{total}}$

$\vec{P}'_{i\,\text{total}} \neq \vec{P}'_{f\,\text{total}}$

O'

O

動量守恆定律在左方是正確，但在右方就不正確，反之亦然

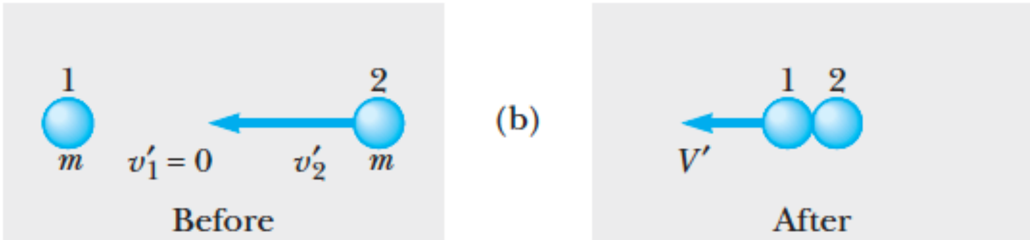
動量守恆定律在羅倫茲轉換後就不像動量守恆了！

看來動量得重新定義，使動量守恆定律在羅倫茲轉換前後都是正確的！

Momentum is conserved according to S

$p_{\text{before}} = mv + m(-v) = 0$

$p_{\text{after}} = 0$



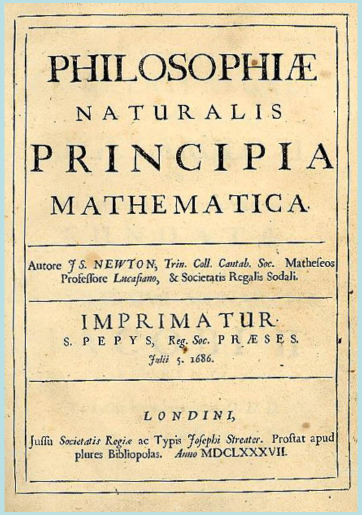
Momentum is *not* conserved according to S′

$p'_{\text{before}} = \dfrac{-2mv}{1 + v^2/c^2}$

$p'_{\text{after}} = -2mv$

Figure 2.1 (a) An inelastic collision between two equal clay lumps as seen by an observer in frame S. (b) The same collision viewed from a frame S′ that is moving to the right with speed v with respect to S.

既然牛頓力學所需要的絕對時間假設證實為誤，牛頓力學必須重新改寫！



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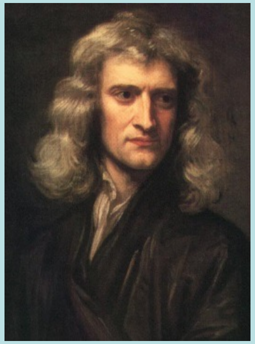
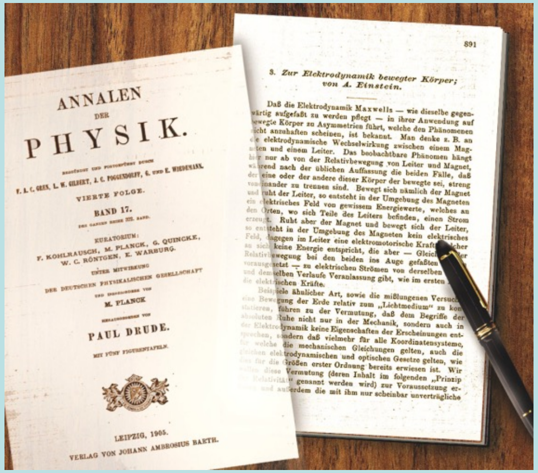
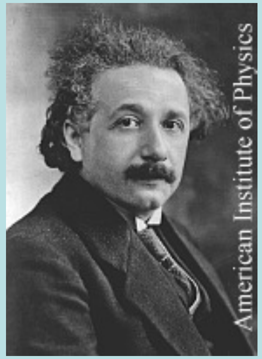






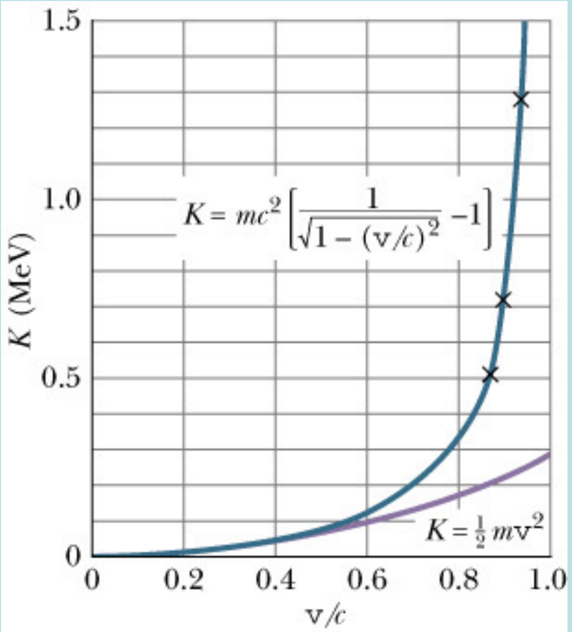
相對論的動量：

$$p = \frac{mv}{\sqrt{1 - \left(\frac{v}{c}\right)^2}}$$

如此定義的動量滿足動量守恆定律

（牛頓定義下的動量mv在高速時即不守恆）

$v << c \quad p \to mv$



相對論也修改了能量的形式，

$$E = \frac{mc^2}{\sqrt{1-\left(\frac{v}{c}\right)^2}}$$

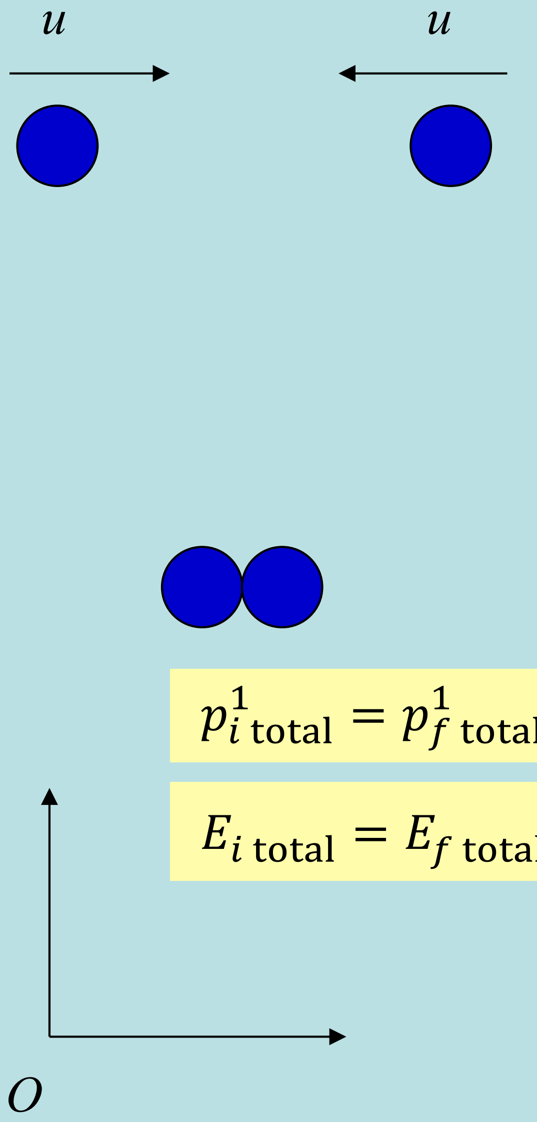
如此定義的動能才滿足能量守恆定律！

當物體靜止時，它的質量對應一個不為零的能量 $E = mc^2$

速度遠小於光速時，相對論的動能$E - mc^2$會趨近牛頓力學中的動能$\frac{1}{2}mv^2$ 。

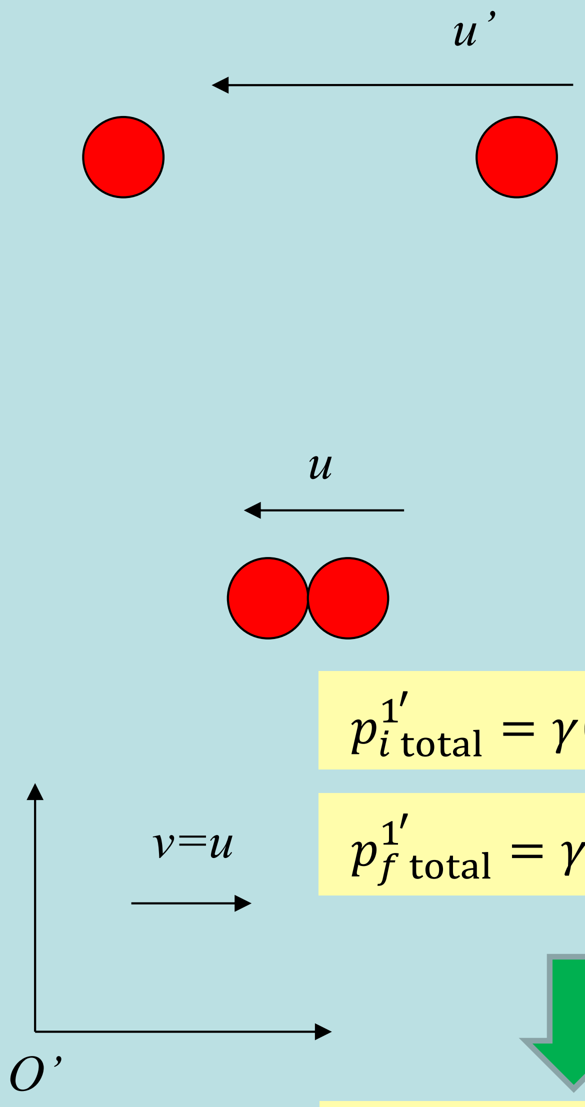
當速度等於光速 $v = c$ 時，物體的能量是無限大，

因此我們無法將物體的速度加大超過光速。



$$p_{i\,\text{total}}^{1} = p_{f\,\text{total}}^{1}$$

$$E_{i\,\text{total}} = E_{f\,\text{total}}$$



$$p_{i\,\text{total}}^{1'} = \gamma\left(p_{i\,\text{total}}^{1} - \beta E_{i\,\text{total}}/c\right)$$

$$p_{f\,\text{total}}^{1'} = \gamma\left(p_{f\,\text{total}}^{1} - \beta E_{f\,\text{total}}/c\right)$$

$$p_{i\,\text{total}}^{1'} = p_{f\,\text{total}}^{1'}$$

$$E_{i\,\text{total}}^{'} = E_{f\,\text{total}}^{'}$$

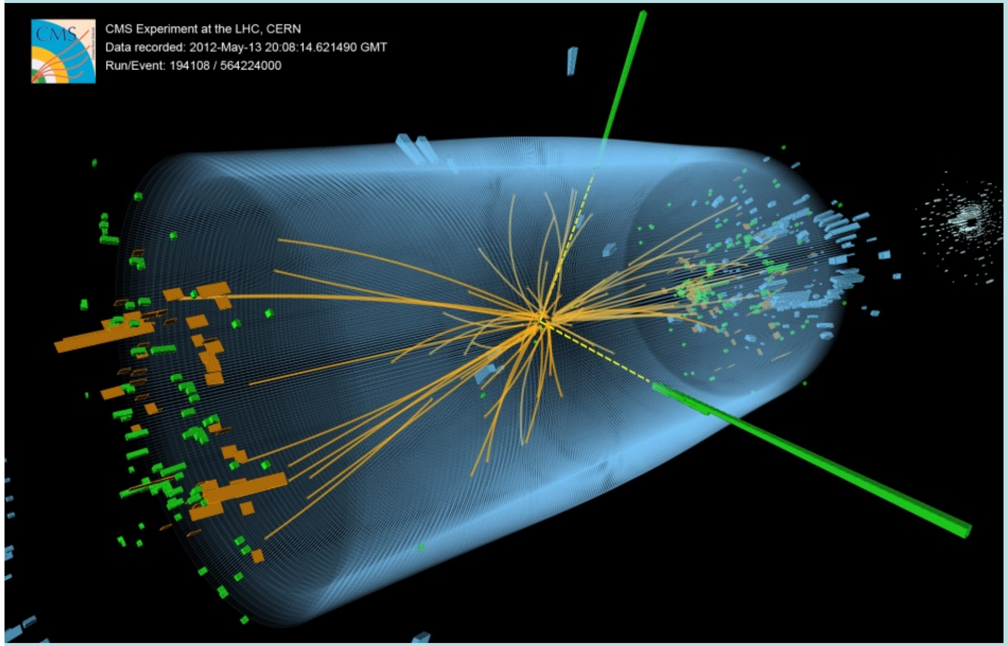
新定義使動量守恆定律遵守相對性原則

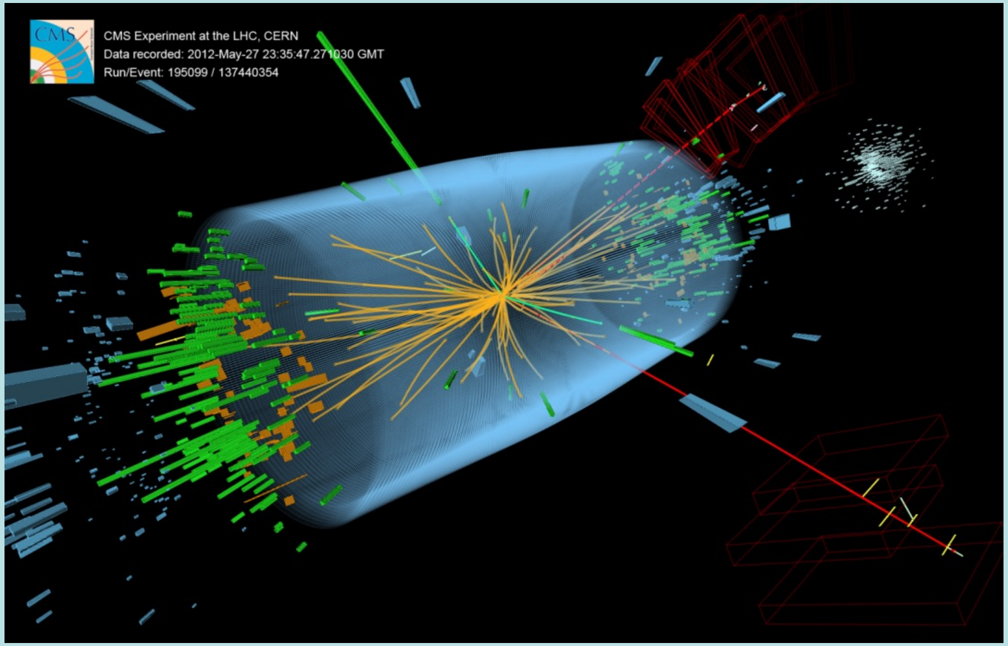
$$\left(\frac{E}{c}\right)^2 - p_x^2 = \left(\frac{mc^2}{\sqrt{1-\left(\frac{u}{c}\right)^2}}\right)^2 - \left(\frac{mu^2}{\sqrt{1-\left(\frac{u}{c}\right)^2}}\right)^2 = m^2c^2$$

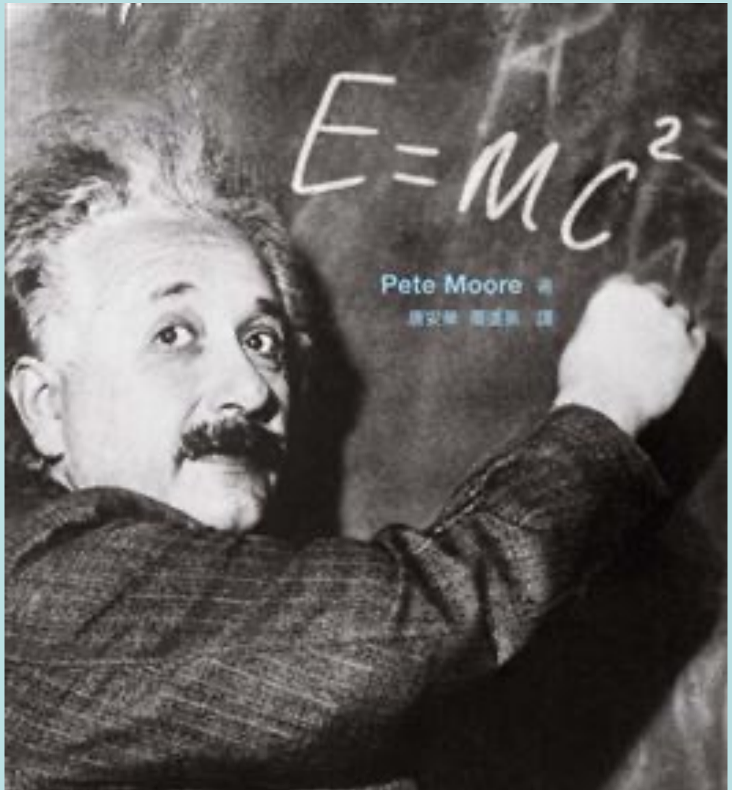
$$\frac{E^2}{c^2} - |\vec{p}|^2 = m^2c^2$$

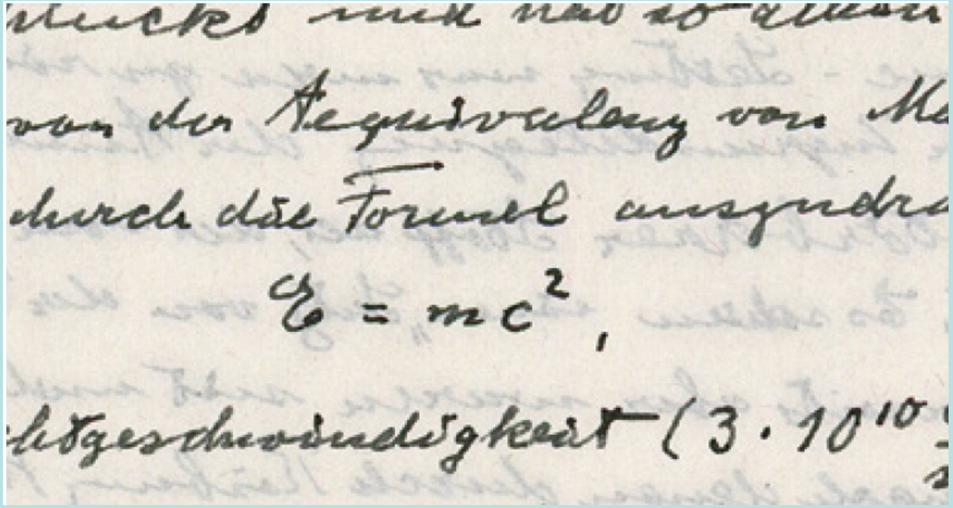
動量越大，能量就越大。這兩個量都可以直接測量。

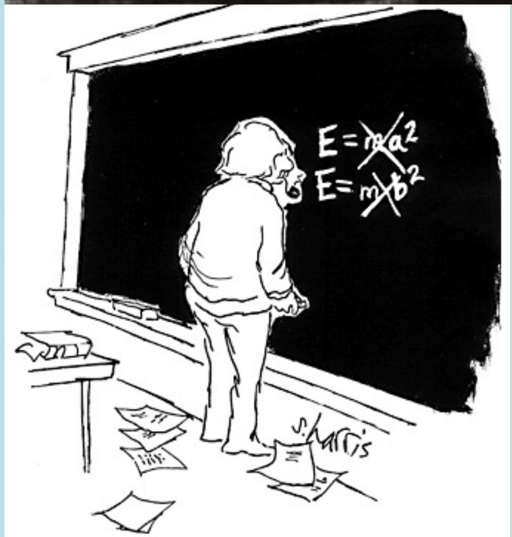
代入上式，這就是質量的現代定義！

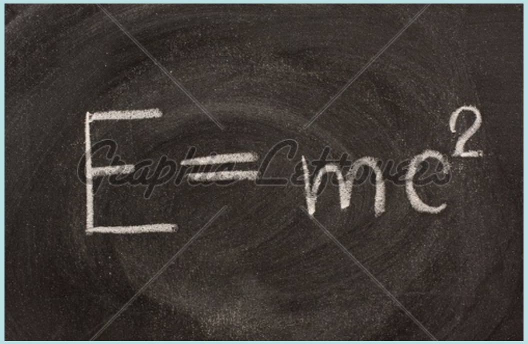












這個公式開啟了質量與能量互相轉換的可能！

質量與能量其實是互通的同一種物理量！

$$E = \frac{mc^2}{\sqrt{1-\left(\frac{v}{c}\right)^2}} \rightarrow E = mc^2$$

靜止的物體因為其質量，能量亦不為零

這個公式暗示了能量與質量可以彼此互相轉換。

$$E = mc^2 + K$$

質量的減少可能變為動能的增加！

質量是能量的一種形式，能量守恆蘊含質量可以轉換為其他形式的能量，

其他形式的能量亦可轉換為質量，質量不再守恆。Mass is not conserved.

如果可以將一個硬幣殲滅，全部化為能量……

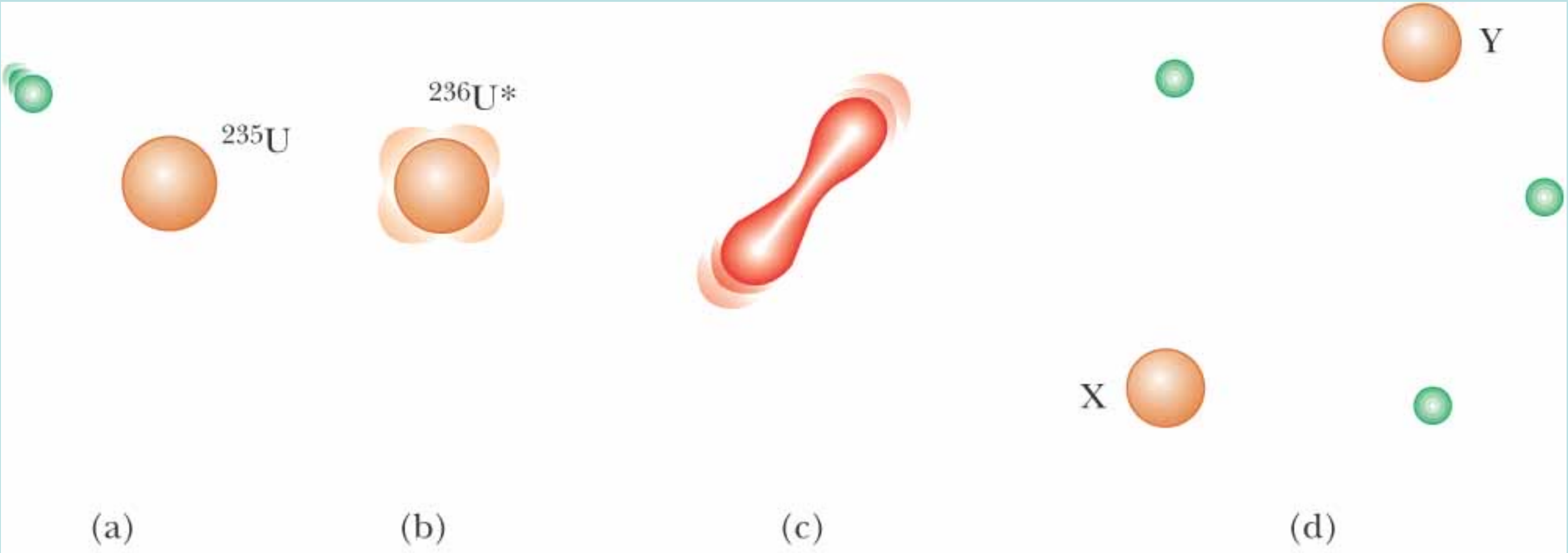
$$E = mc^2$$

$$mc^2 = 3.1\times10^{-3}\cdot(3\times10^{8})^2 \sim 2.8\times10^{14}\ \mathrm{J} \sim 78\ \mathrm{GW\cdot h}$$

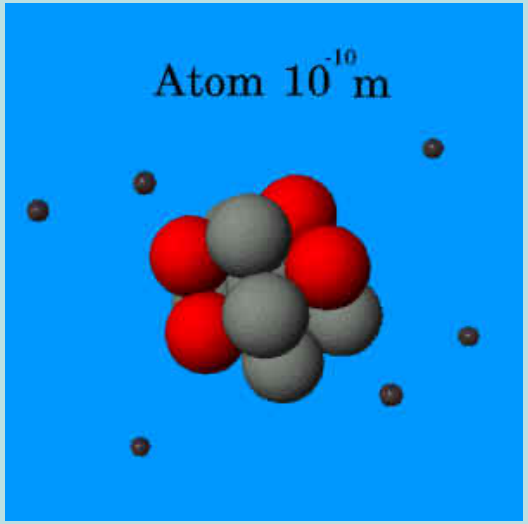
這比一座核能電廠一天產生的電能還多！

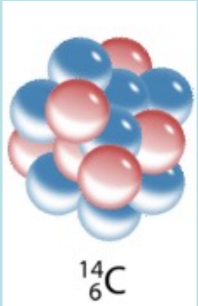
一個硬幣換一個電廠！

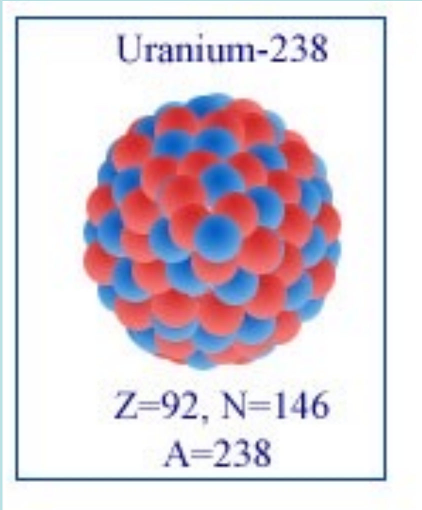
但質量不守恒的反應只有原子核反應。

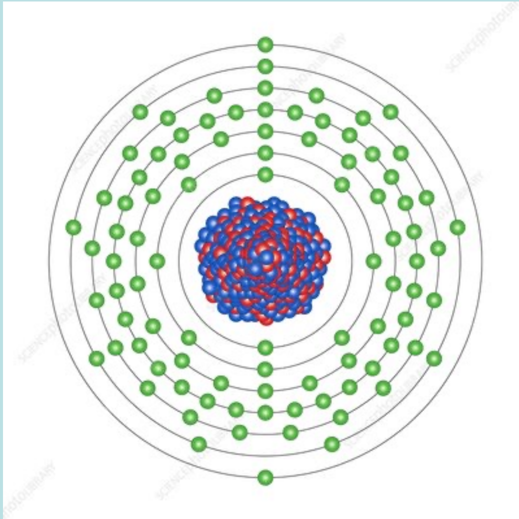


原子核由兩種核子：質子與中子組成

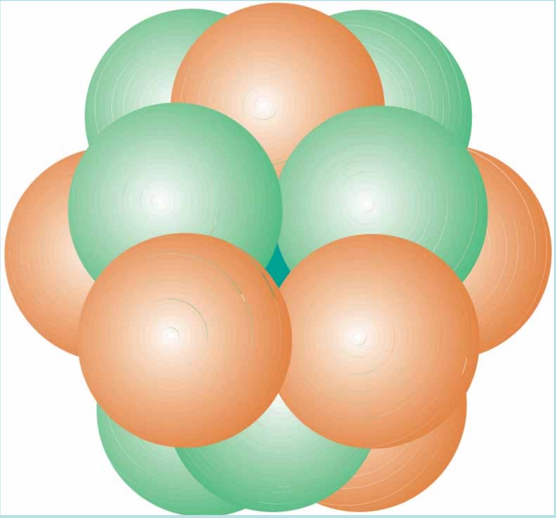


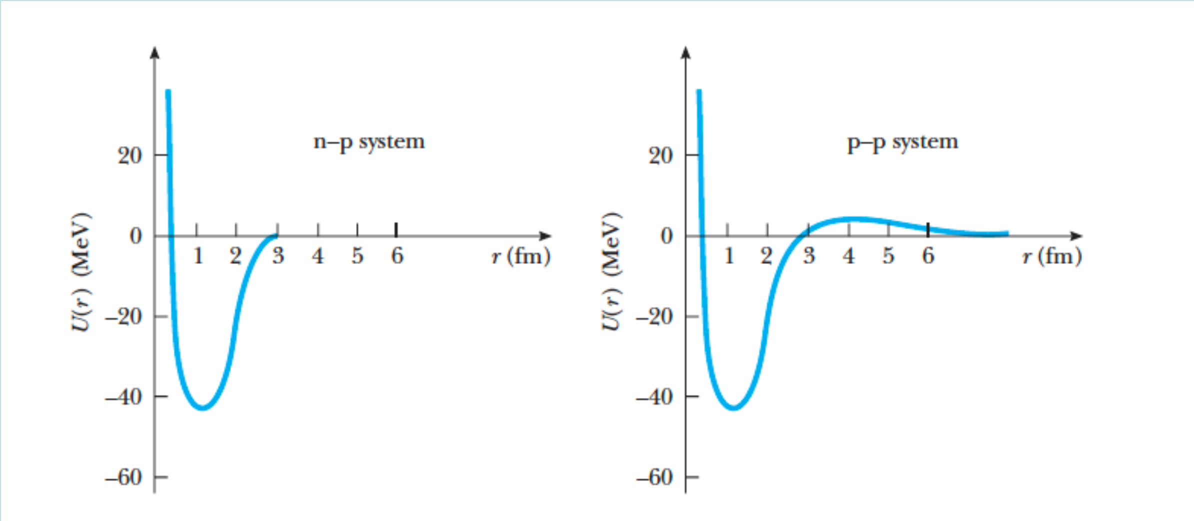






核子彼此間有核力吸引力，接近會放出束縛能！

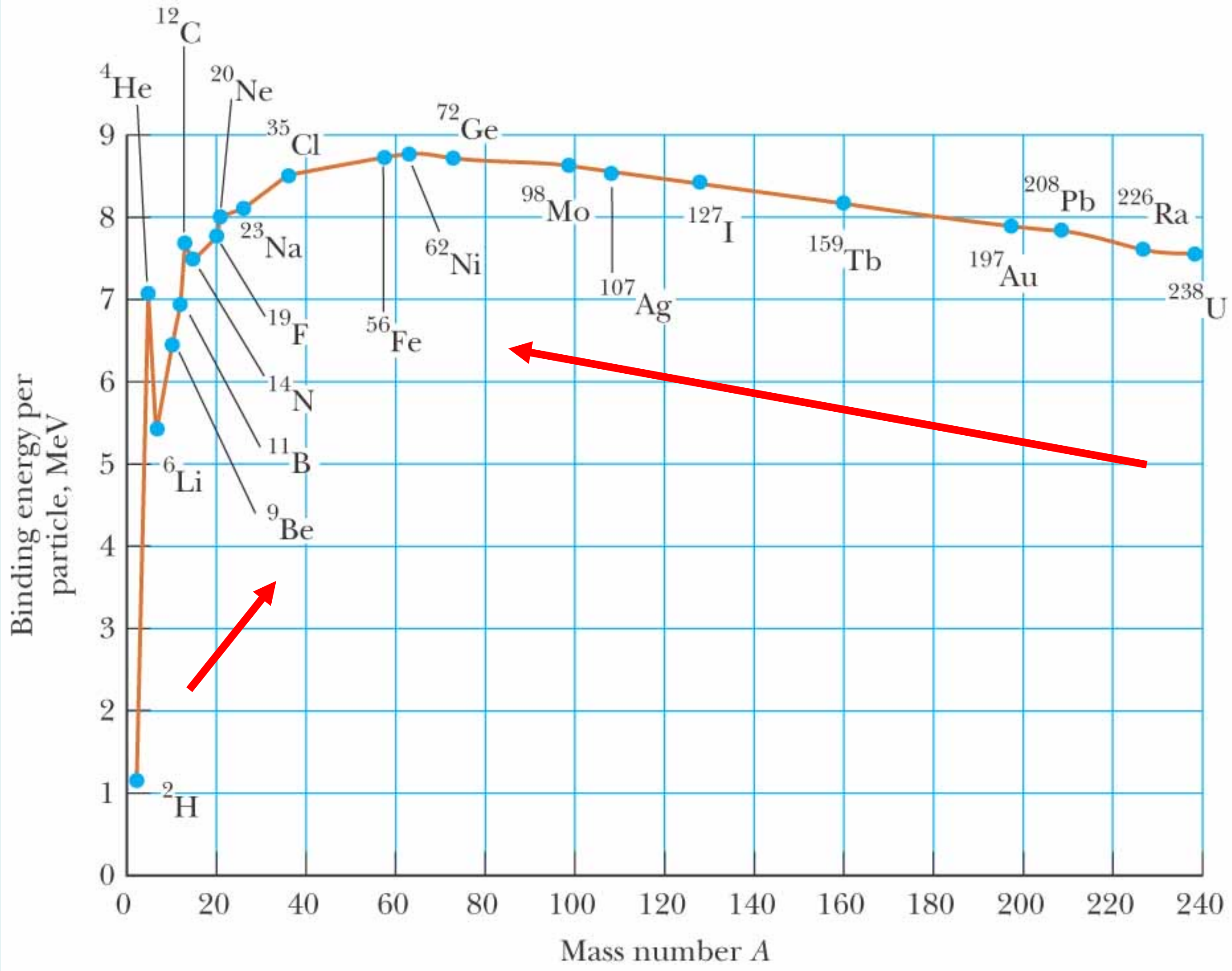




原子核質量 = 質子中子總質量 – 總束縛能/c^2

束縛能越大，質量越小。

原子核的平均束縛能竟然大致可以由質子數決定：

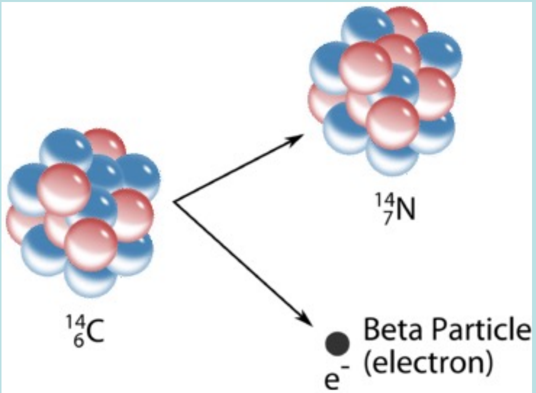


圖的中段每個核子平均束縛能最大，

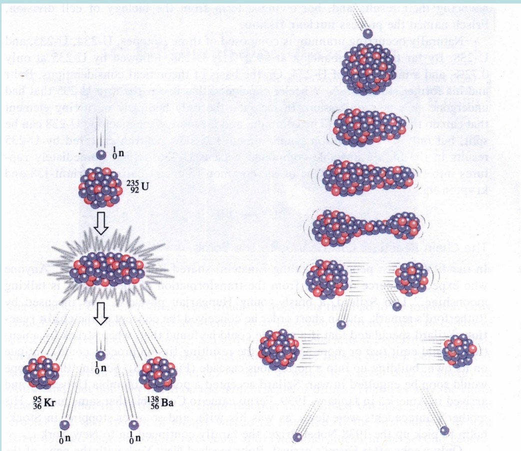
位於兩端的原子核會傾向變化為中段的核子，增加束縛能，放出能量。

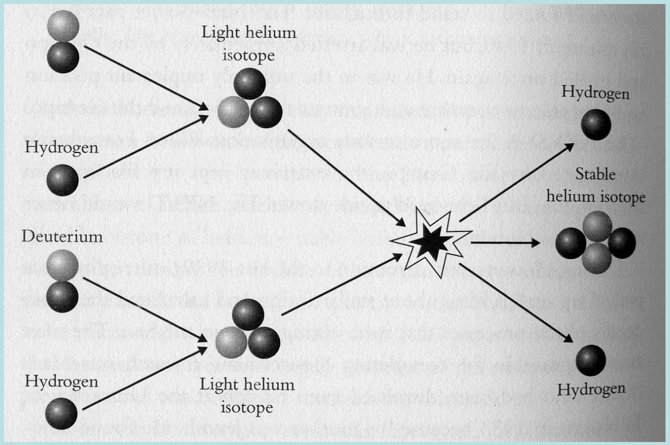
核反應原則上即是透過原子核種的變化，增加束縛能，釋放能量：

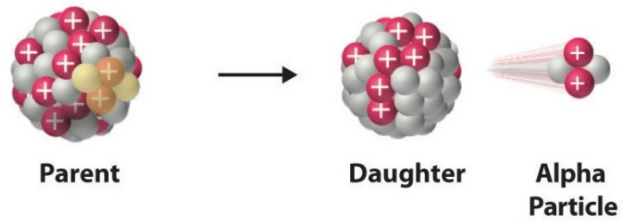
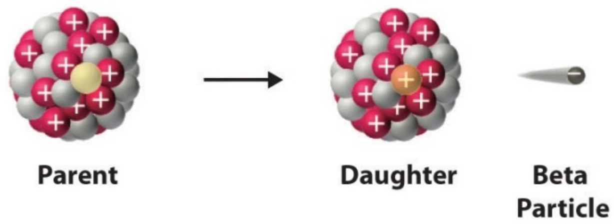
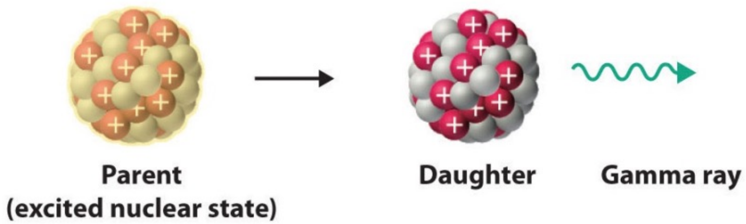
一：放射性原子核的衰變 Decay of Radioactive Nucleus



二： 能量釋放的核分裂 Nuclear Fission，及核融合Nuclear Fusion





Decay Type	Radiation Emitted	Generic Equation	Model
Alpha decay	${}^{4}_{2}\alpha$	${}^{A}_{Z}X \longrightarrow {}^{A-4}_{Z-2}X' + {}^{4}_{2}\alpha$	
Beta decay	${}^{0}_{-1}\beta$	${}^{A}_{Z}X \longrightarrow {}^{A}_{Z+1}X' + {}^{0}_{-1}\beta$	
Gamma emission	${}^{0}_{0}\gamma$	${}^{A}_{Z}X^{*} \xrightarrow{\text{Relaxation}} {}^{A}_{Z}X' + {}^{0}_{0}\gamma$	

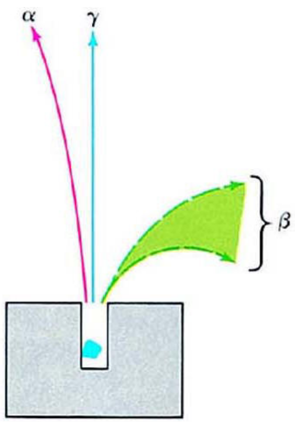
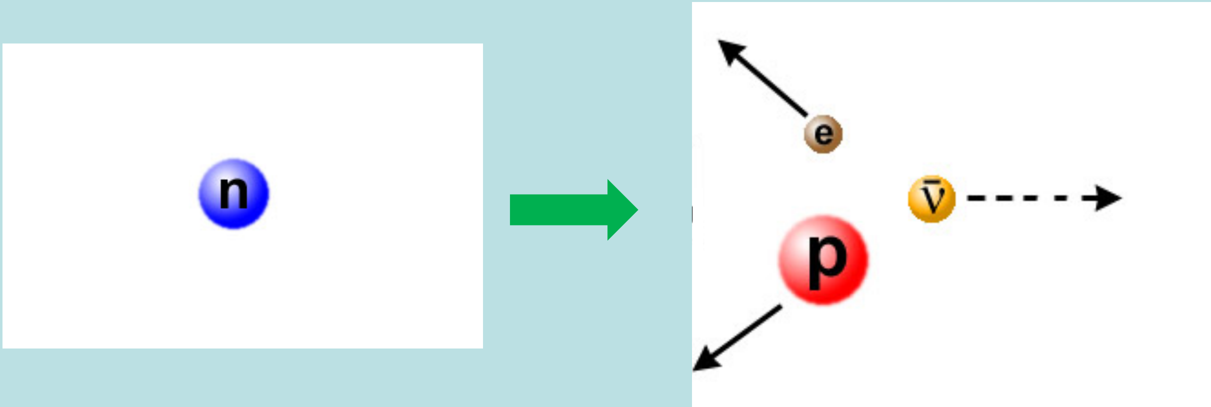


圖 43.4
三種放射線。α 粒子是帶正電的氦核，β 粒子是帶負電的電子，而 γ 射線則是高能光子。

弱交互作用 Weak Interaction：衰變的交互作用。

在自然界，單獨的中子是不穩定的。

β 衰變 $n^0 \rightarrow p^+ + e^- + \bar{\nu}_e$



β衰變所放出的電子的能量極大，因此稱為β射線，其能量分佈：

電子的速度最大可以到達接近光速的0.86。

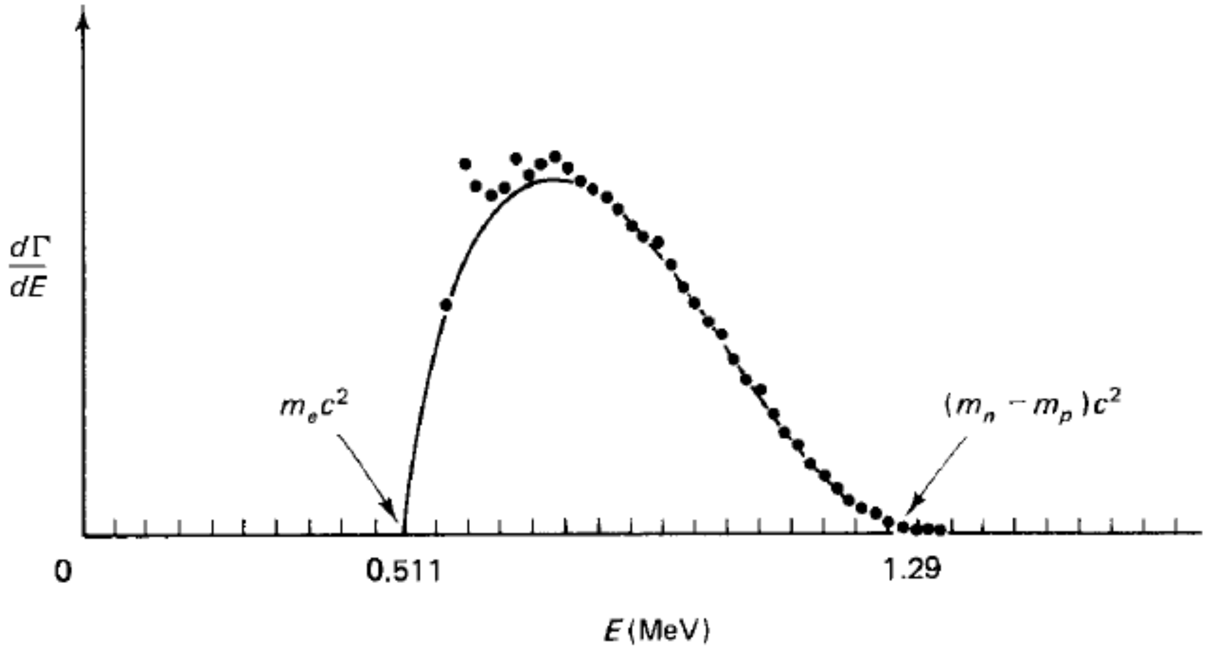
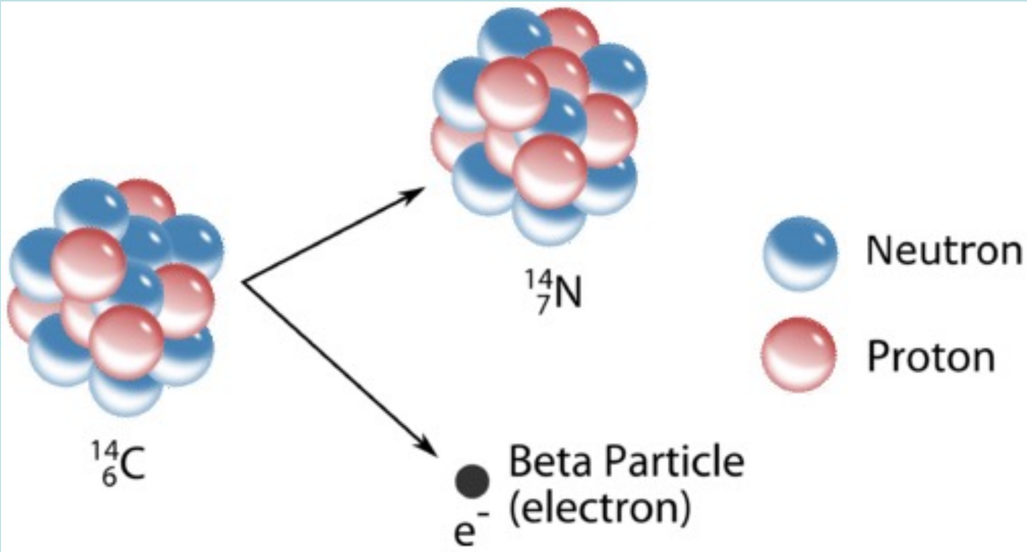
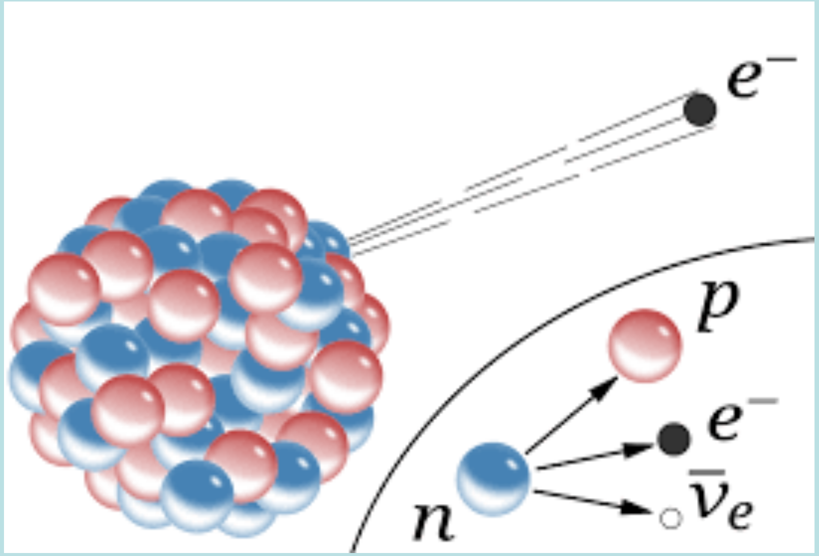


Figure 10.2 Electron energy distribution from neutron beta decay. (Solid line is the theoretical curve; dots are experimental data.) [*Source:* C. J. Christensen et al., *Phys. Rev.* **D5**, 1628 (1972), Figure 4.]





原子核中的質子數目決定原子的化學性質。

$n^0 \to p^+ + e^- + \bar{\nu}_e$ 原子核中若發生β 衰變，原子核的核種會改變！

不穩定的放射性原子核，可以透過β 衰變 ，衰變為不同的原子核，

例如：碳同位素原子核衰變為氮原子核！

$^{14}_{6}\mathrm{C} \to {}^{14}_{7}\mathrm{N} + e^- + \bar{\nu}_e$

衰變前後原子核的質量會有差異，而有能量釋放。

大部分不穩定放射性原子核的放射性，就來自 β 衰變 ！

β 衰變會不會發生，就要看產物原子核是不是被容許！

節目 知識好好玩

EP04｜玩骰子的上帝——從放射性原子核談起

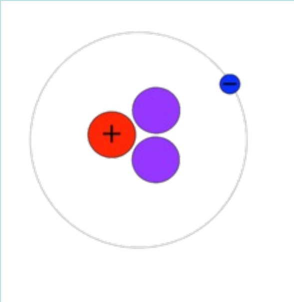
鏡好聽 MIRROR VO!CE 發現 節目 有聲書 課程 節目主持人/有聲書主播 訂閱說明 APP下載

如此的話，觀察一群一模一樣的氚原子核，等於重複同一個觀察單獨氚的實驗，照理講應該只能有一個結果。但事實就是，一群原子核不會同時衰變，如此就表示，在同樣條件下，單獨一個氚的觀察，結果將不是確定的。這就是物理學家在二十世紀初面對的局面，實驗明白顯示，一樣的因，卻可能得到不一樣的果。

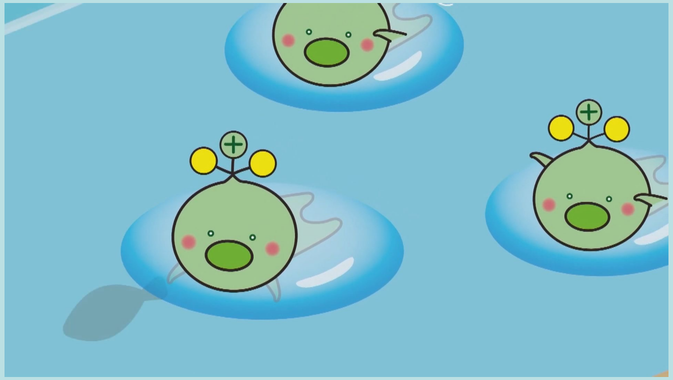
在量子世界中，物理學家能預測的只有機率！

這樣的不確定性使物理喪失了對單一原子核預測未來的能力。但話說回來，我們的確能測量或預測原子核的半衰期，這代表如果是一大群原子核，我們可以很精確預測有多少比例會衰變，有多少比例不會衰變。細心的聽眾一定認出了，這就是我們在賭場賭博時遇到的情況。我們無法預測自己這一局的結果，但是賭場老闆卻可以利用機率預測整個場子的賺賠分布。所以在量子世界中，物理學家能預測的只有機率！愛因斯坦對這個情況，完全無法接受，因此也才說出上帝是不玩骰子這句名言。愛因斯坦認為我們的不確定，只是我們對粒子的研究不夠透徹，一定有隱藏的因子，使粒子其實與上述種子是一樣的。可惜這樣的想法，在1960年，被證實是不正確的。

氚的原子核是氫原子核的同位素，一樣有一個質子，但氚多了兩個中子。因此氚原子核由三個粒子組成，這個字就是氫氣的氫，在部首的氣的下方，以一個三撇的川字取代。因為質子數目一樣，氚原子化學性質與氫原子一樣，所以可以取代氫原子，與氧

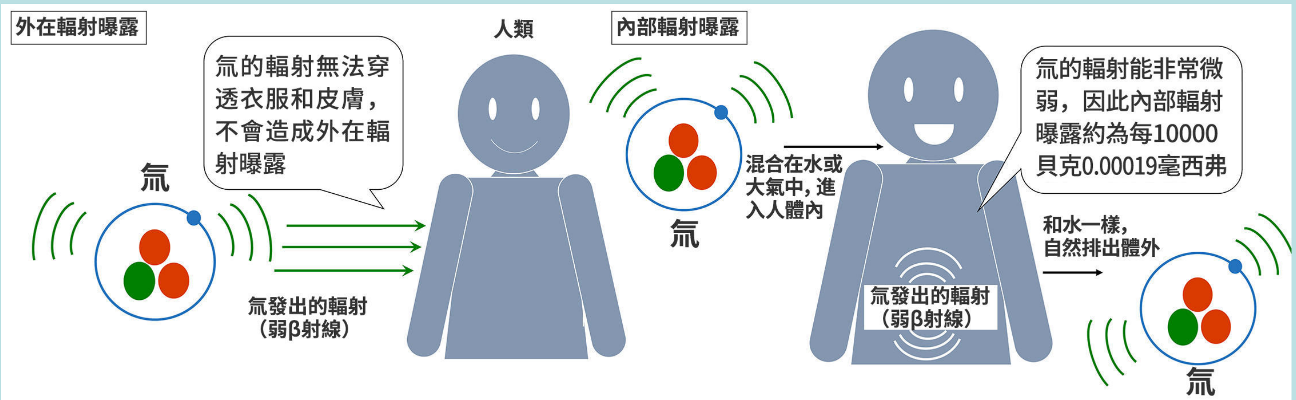


氚Tritium



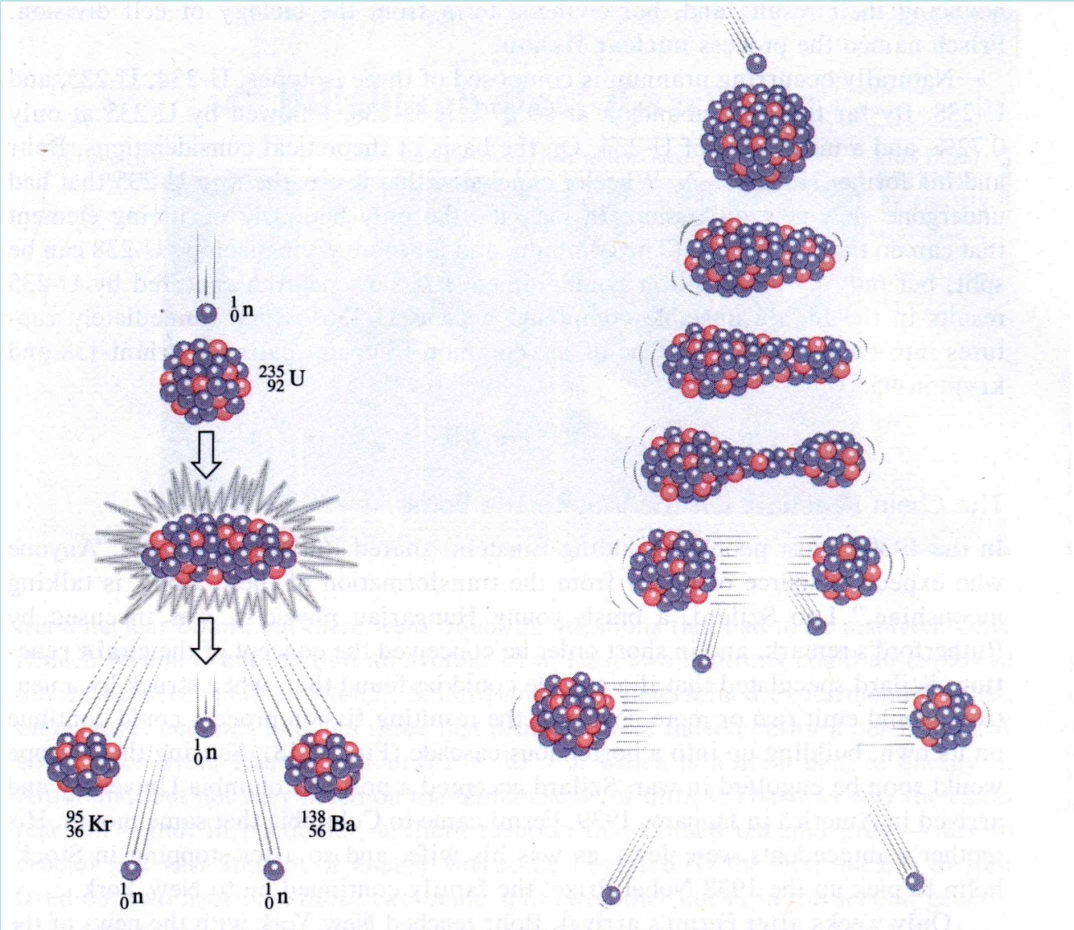
量少不代表可以放心，氚與氫不同，氚是有放射性的。意思就是氚的原子核並不穩定，它會自動消失， 而同時產生較輕的穩定氦-3 原子核，加上一個電子， 與一個不帶電的微中子。這個過程就稱為衰變。這個詞聽起來，好像食物慢慢腐敗變質，或是生

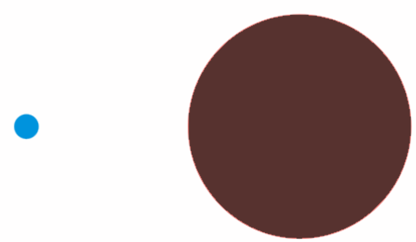
很危險，可以穿透人的皮膚，造成輻射傷害。但氚原子核的貝他衰變是罕見的例外，因為氚與氦-3 原子核質量差距不大，衰變所放出的電子的能量只有典型衰變能量的百分之一左右，根本無法穿透人的皮膚，因此氚的放射性基本上對人體是不會造成傷害



裡，中子就可以很長壽，例如穩定的原子核幾乎就是長生不老的。放射性原子核半衰期較短，但也有很大個別差異。例如核分裂產物中的放射性碘-129 半衰期可以到 1600 萬年，過程中一直有放射性，這就是核廢料難處理的原因。還好核分裂產物中最危險的碘-131，半衰期只有 8 天。氚原子核的半衰期則是 12 年，所以原則上福島儲存的放射性水，倒入海中，大約經過數十年，就會衰變殆盡，而不再有放射性了。

較大原子核分裂為多個較小原子核，使束縛能增加，總質量減少，稱核分裂。





總質量減少，消失的質量以能量形式釋出。

我們可以以中子來誘發，使較大原子核分裂為多個較小原子核後，稱核分裂。

核分裂一般來說不會改變核子的身份。

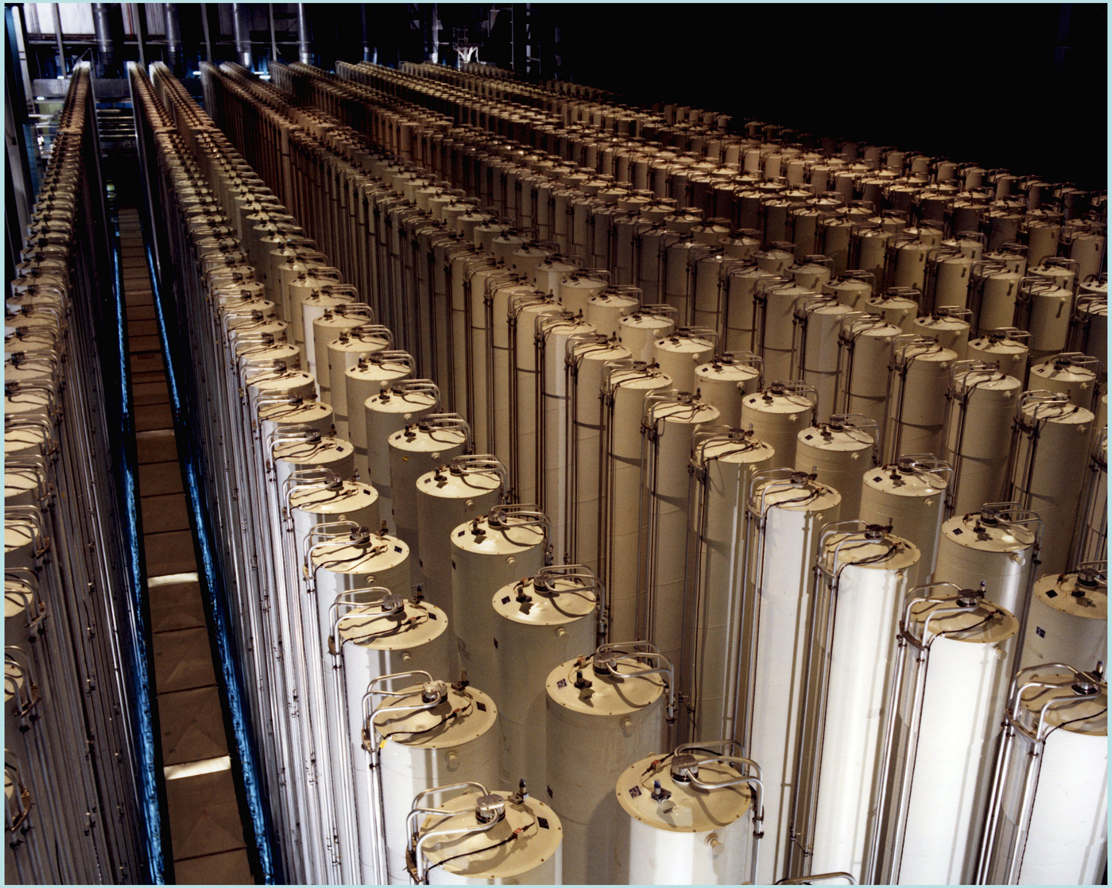
Uranium, ${}_{92}U$

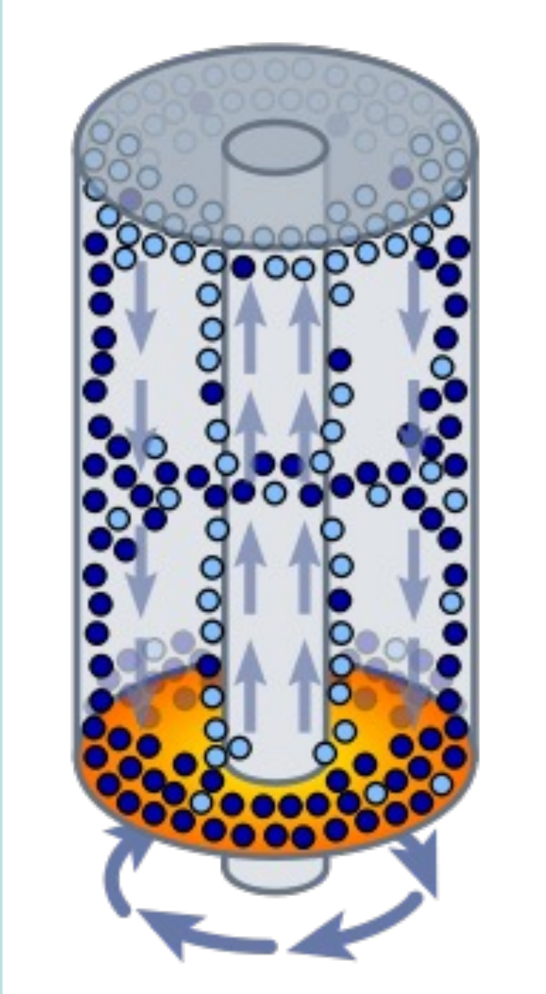
Uranium is weakly radioactive because all isotopes of uranium are unstable. Uranium decays slowly by emitting an α particle.

UO_2

Uranium-238 (99.2739–99.2752%),
Uranium-235 (0.7198–0.7202%)

The half-life of Uranium-238 is about 4.47 billion years and that of Uranium-235 is 704 million years.





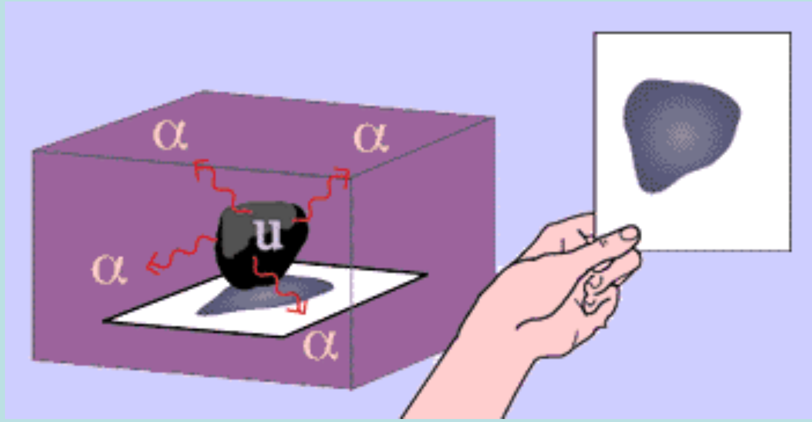
含鈾的玻璃在紫外線照射下發出螢光！

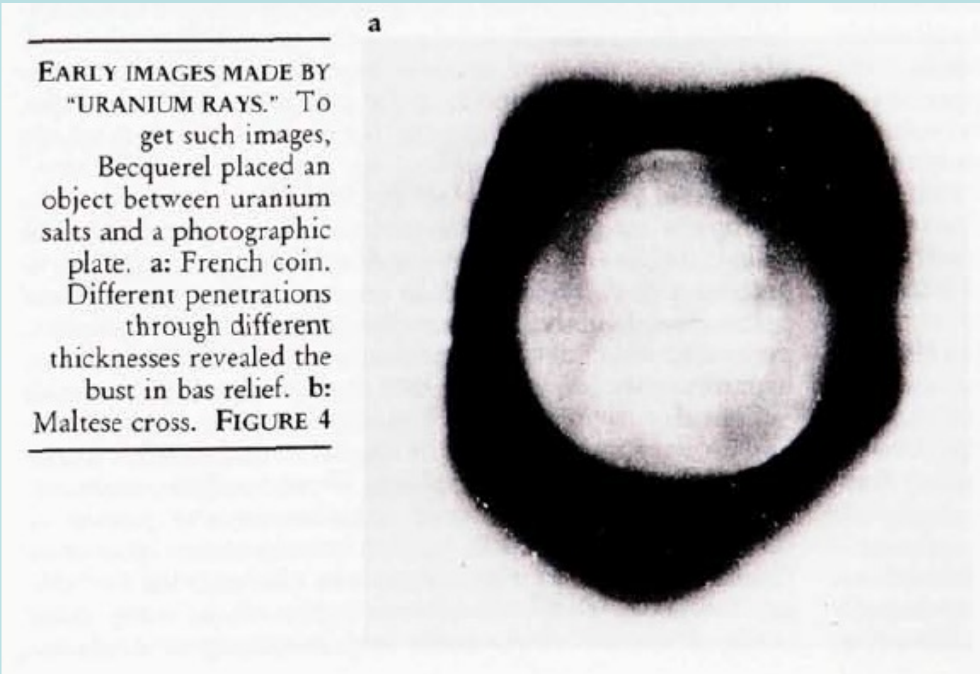
Becquerel 希望證實鈾塊在日光照射下發出的螢光是有穿透性的。

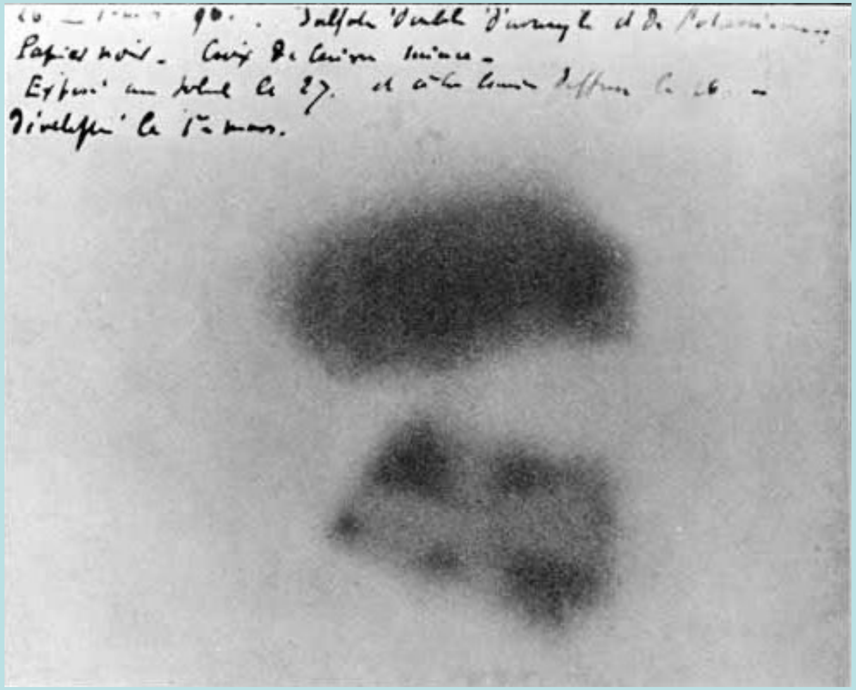
特別將底片與鈾塊間蓋上黑紙。

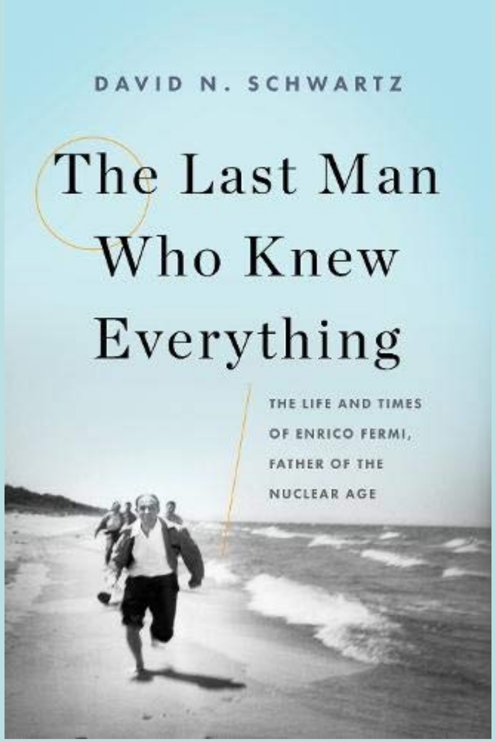
沒想到在沒有日光照射鈾塊時，也會感光。

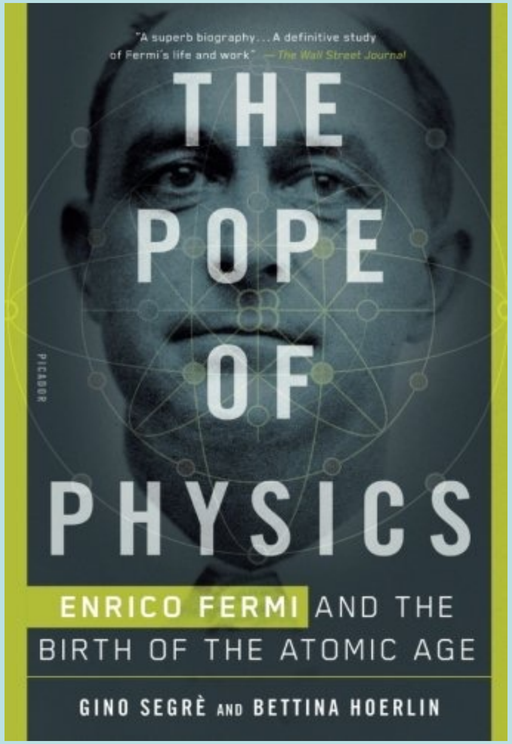
放射性鈾鹽自發放射的α射線，使底片感光。

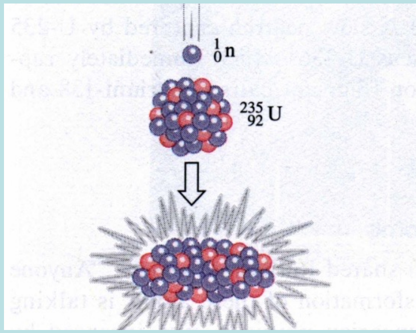












Enrico Fermi
1901 –1954

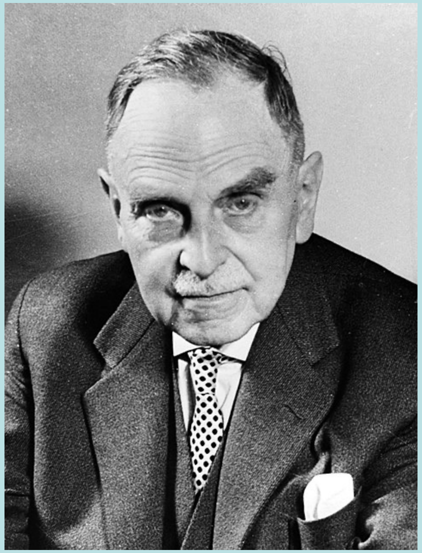
Fermi開始嘗試用慢中子撞擊穩定原子核使它不穩定。

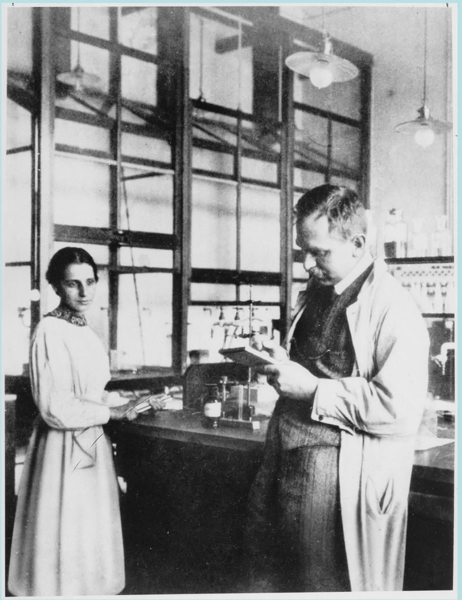
如此製造出人造的放射性原子核。

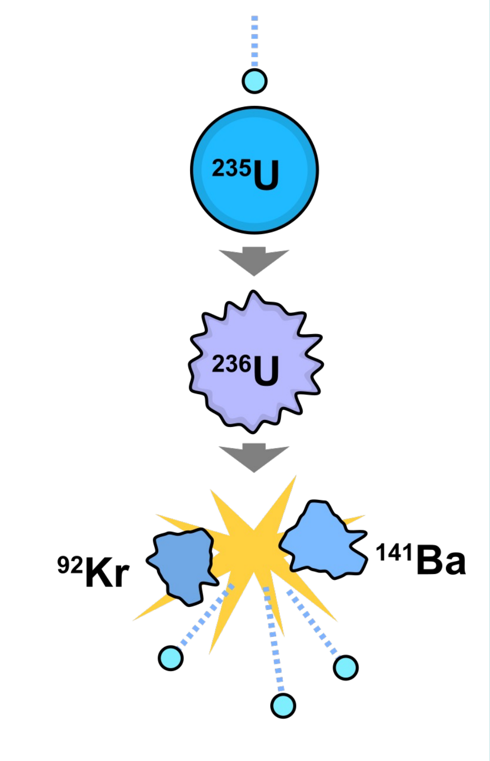
The experimental apparatus with which Otto Hahn and Fritz Strassmann discovered first nuclear fission in 1938

$$ {}^{1}_{0}\mathrm{n} + {}^{235}_{92}\mathrm{U} \longrightarrow {}^{141}_{56}\mathrm{Ba} + {}^{92}_{36}\mathrm{Kr} + 3\,{}^{1}_{0}\mathrm{n} $$

Otto Hahn
1879 – 1968







Lise Meitner 1878-1968 Hahn and Meitner, 1913,

Hahn and Strassmann 是量到了Ba，

知道原子核的核種改變了。但不知發生何事。

Meitner 提出這是核分裂的想法。

這個結果震驚了物理界！

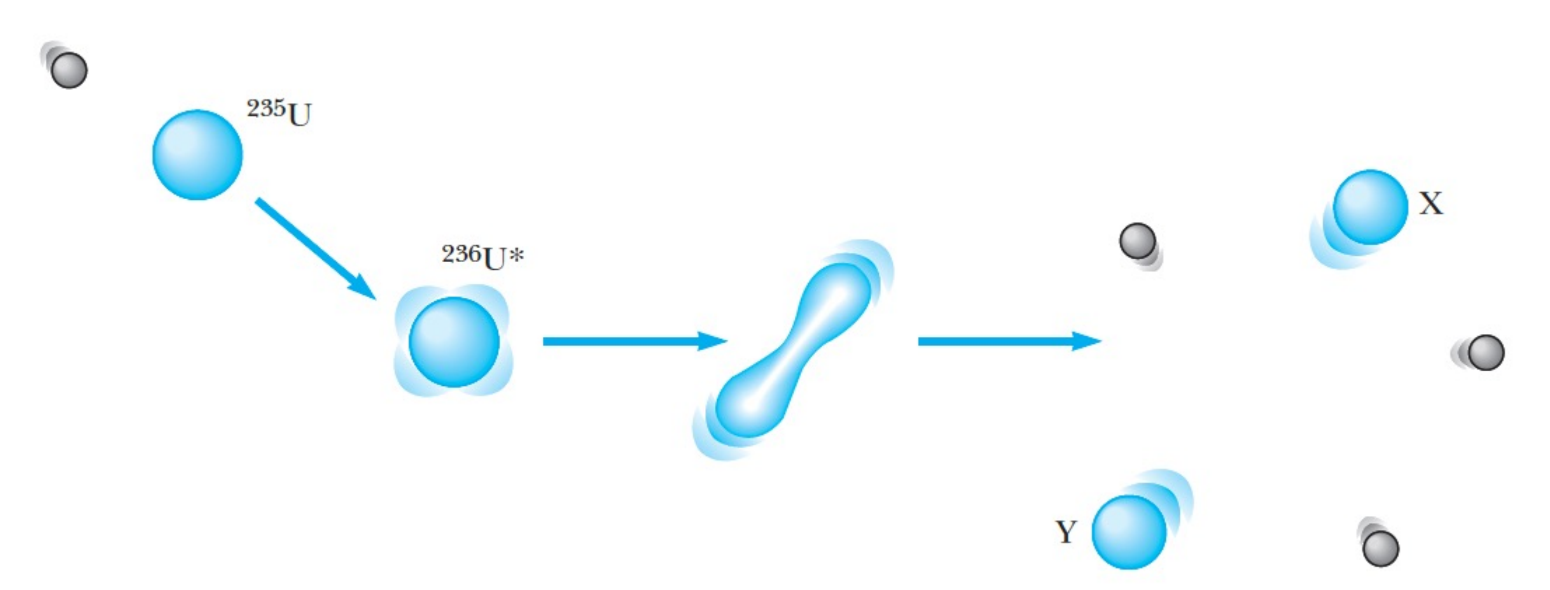
The fission of ^{235}U by thermal neutrons can be represented by

$$ {}_{0}^{1}\mathrm{n} + {}_{92}^{235}\mathrm{U} \longrightarrow {}_{92}^{236}\mathrm{U}^{*} \longrightarrow \mathrm{X} + \mathrm{Y} + \text{neutrons} \qquad (14.8) $$

where $^{236}\mathrm{U}^{*}$ is an intermediate excited state that lasts for only about 10^{-12} s before splitting into X and Y. The resulting nuclei X and Y are called **fission fragments.** There are many combinations of X and Y that satisfy the requirements of conservation of mass–energy, charge, and nucleon number. Figure

$$ {}_{0}^{1}\mathrm{n} + {}_{92}^{235}\mathrm{U} \longrightarrow {}_{56}^{141}\mathrm{Ba} + {}_{36}^{92}\mathrm{Kr} + 3{}_{0}^{1}\mathrm{n} \qquad (14.9) $$

Of the 200 MeV or so released in this reaction, most goes into the kinetic energy of the heavy fragments barium and krypton.



沒有$A = 5,8$的穩定原子核

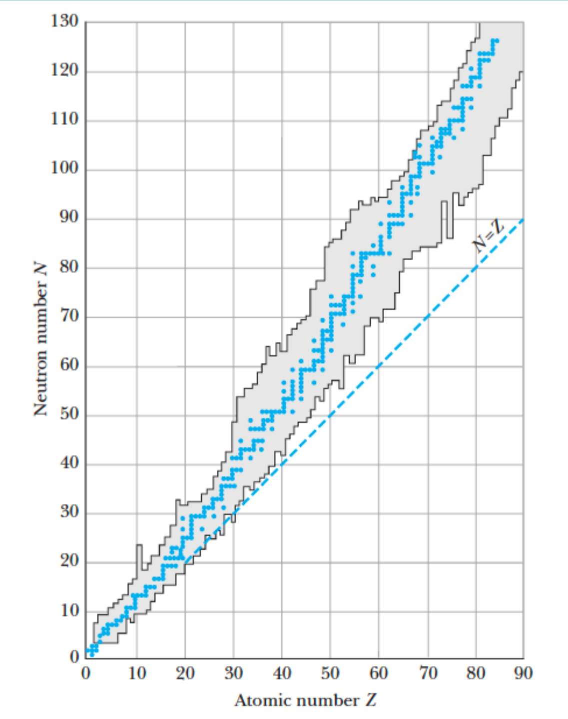


Table 13.6 Some Atomic Masses

Element	Atomic Mass (u)	Element	Atomic Mass (u)
$^{4}_{2}He$	4.002 603	$^{27}_{13}Al$	26.981 539
$^{7}_{3}Li$	7.016 003	$^{30}_{15}P$	29.978 310
$^{9}_{4}Be$	9.012 182	$^{40}_{20}Ca$	39.962 591
$^{10}_{5}B$	10.012 937	$^{42}_{20}Ca$	41.958 63
$^{12}_{6}C$	12.000 000	$^{43}_{20}Ca$	42.958 766
$^{13}_{6}C$	13.003 355	$^{56}_{26}Fe$	55.934 939
$^{14}_{7}N$	14.003 074	$^{64}_{30}Zn$	63.929 145
$^{15}_{7}N$	15.000 109	$^{63}_{29}Cu$	63.929 599
$^{15}_{8}O$	15.003 065	$^{93}_{41}Nb$	92.906 377
$^{17}_{8}O$	16.999 131	$^{197}_{79}Au$	196.966 543
$^{18}_{8}O$	17.999 160	$^{202}_{80}Hg$	201.970 617
$^{18}_{9}F$	18.000 937	$^{216}_{84}Po$	216.001 888
$^{20}_{10}Ne$	19.992 436	$^{220}_{86}Rn$	220.011 368
$^{23}_{11}Na$	22.989 768	$^{234}_{90}Th$	234.043 593
$^{23}_{12}Mg$	22.994 124	$^{238}_{92}U$	238.050 785

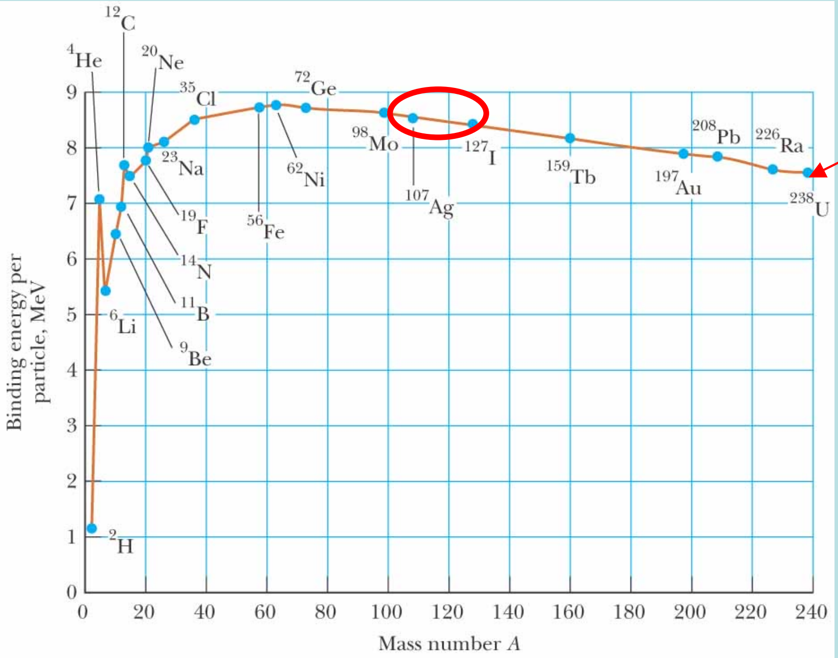
Let us estimate the disintegration energy Q released in a typical fission process. From Figure 13.10 we see that the binding energy per nucleon for heavy nuclei ($A \approx 240$) is about 7.6 MeV, whereas in the intermediate mass range, the binding energy per nucleon is about 8.5 MeV. Taking the mass number of the mother nucleus to be $A = 240$, we see that the energy released per nucleon is estimated to be

$$Q = (240 \text{ nucleons})\left(8.5\,\frac{\text{MeV}}{\text{nucleon}} - 7.6\,\frac{\text{MeV}}{\text{nucleon}}\right) = \boxed{200 \text{ MeV}}$$

About 85% of this energy appears in the form of kinetic energy in the heavy fragments. This energy is very large compared to the energy released in chemical processes. For example, the energy released in the combustion of one molecule of octane used in gasoline engines is about one-millionth the energy released in a single uranium fission event!

核分裂會釋出巨大能量。

$${}^{1}_{0}\text{n} + {}^{235}_{92}\text{U} \longrightarrow {}^{141}_{56}\text{Ba} + {}^{92}_{36}\text{Kr} + 3\,{}^{1}_{0}\text{n}$$



Leó Szilárd

Albert Einstein
Old Grove Rd.
Nassau Point
Peconic, Long Island

August 2nd, 1939

F.D. Roosevelt,
President of the United States,
White House
Washington, D.C.

Sir:

Some recent work by E.Fermi and L. Szilard, which has been communicated to me in manuscript, leads me to expect that the element uranium may be turned into a new and important source of energy in the immediate future. Certain aspects of the situation which has arisen seem to call for watchfulness and, if necessary, quick action on the part of the Administration. I believe therefore that it is my duty to bring to your attention the following facts and recommendations:

In the course of the last four months it has been made probable - through the work of Joliot in France as well as Fermi and Szilard in America - that it may become possible to set up a nuclear chain reaction in a large mass of uranium,by which vast amounts of power and large quantities of new radium-like elements would be generated. Now it appears almost certain that this could be achieved in the immediate future.

This new phenomenon would also lead to the construction of bombs, and it is conceivable - though much less certain - that extremely powerful bombs of a new type may thus be constructed. A single bomb of this type, carried by boat and exploded in a port, might very well destroy the whole port together with some of the surrounding territory. However, such bombs might very well prove to be too heavy for transportation by air.

-2-

The United States has only very poor ores of uranium in moderate quantities. There is some good ore in Canada and the former Czechoslovakia, while the most important source of uranium is Belgian Congo.

In view of this situation you may think it desirable to have some permanent contact maintained between the Administration and the group of physicists working on chain reactions in America. One possible way of achieving this might be for you to entrust with this task a person who has your confidence and who could perhaps serve in an inofficial capacity. His task might comprise the following:

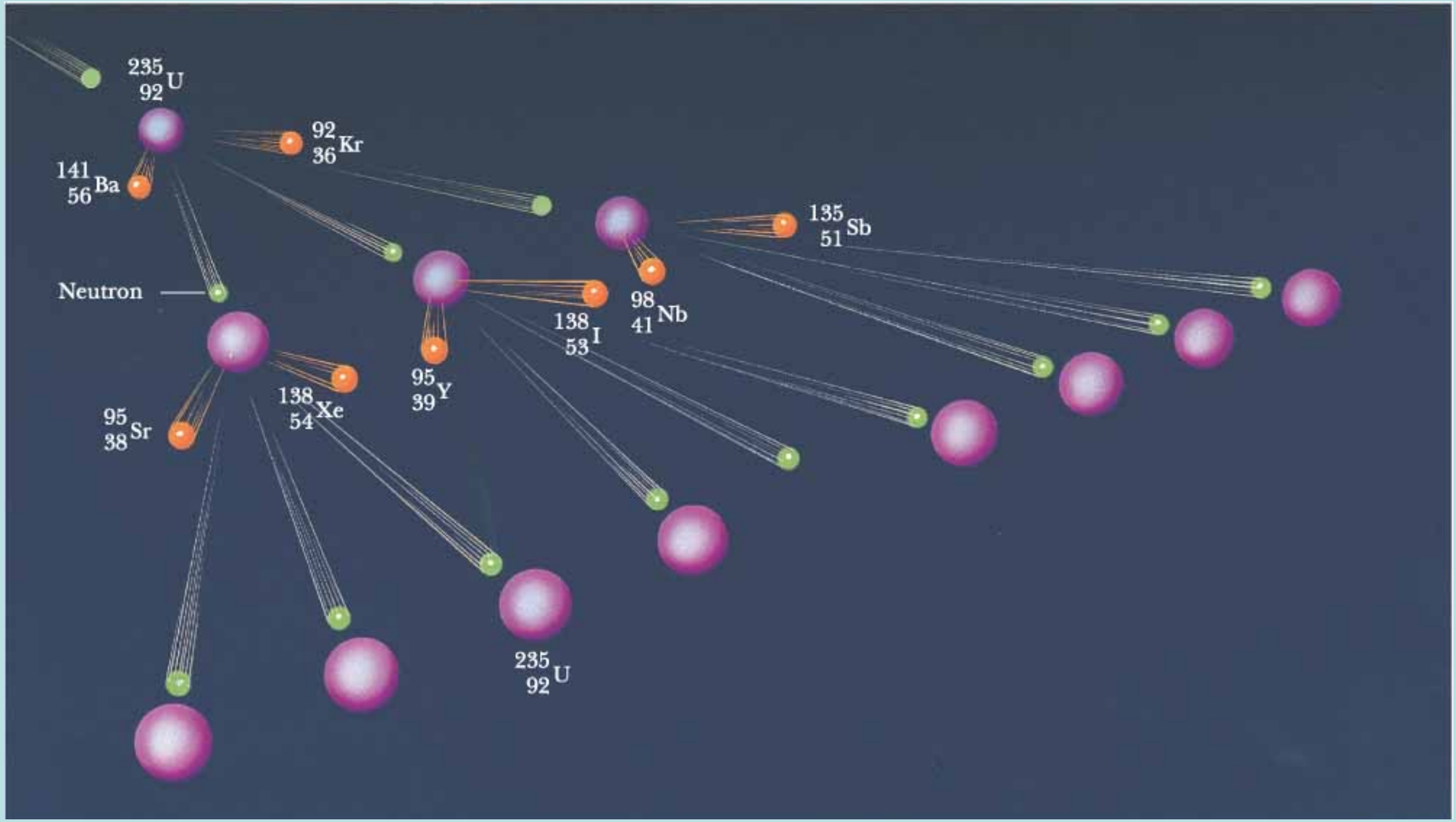
a) to approach Government Departments, keep them informed of the further development, and put forward recommendations for Government action, giving particular attention to the problem of securing a supply of uranium ore for the United States;

b) to speed up the experimental work,which is at present being carried on within the limits of the budgets of University laboratories, by providing funds, if such funds be required, through his contacts with private persons who are willing to make contributions for this cause, and perhaps also by obtaining the co-operation of industrial laboratories which have the necessary equipment.

I understand that Germany has actually stopped the sale of uranium from the Czechoslovakian mines which she has taken over. That she should have taken such early action might perhaps be understood on the ground that the son of the German Under-Secretary of State, von Weizsäcker, is attached to the Kaiser-Wilhelm-Institut in Berlin where some of the American work on uranium is now being repeated.

Yours very truly,
A. Einstein
(Albert Einstein)

這核分裂過程可以在有序可控制情況下進行，Chain reaction



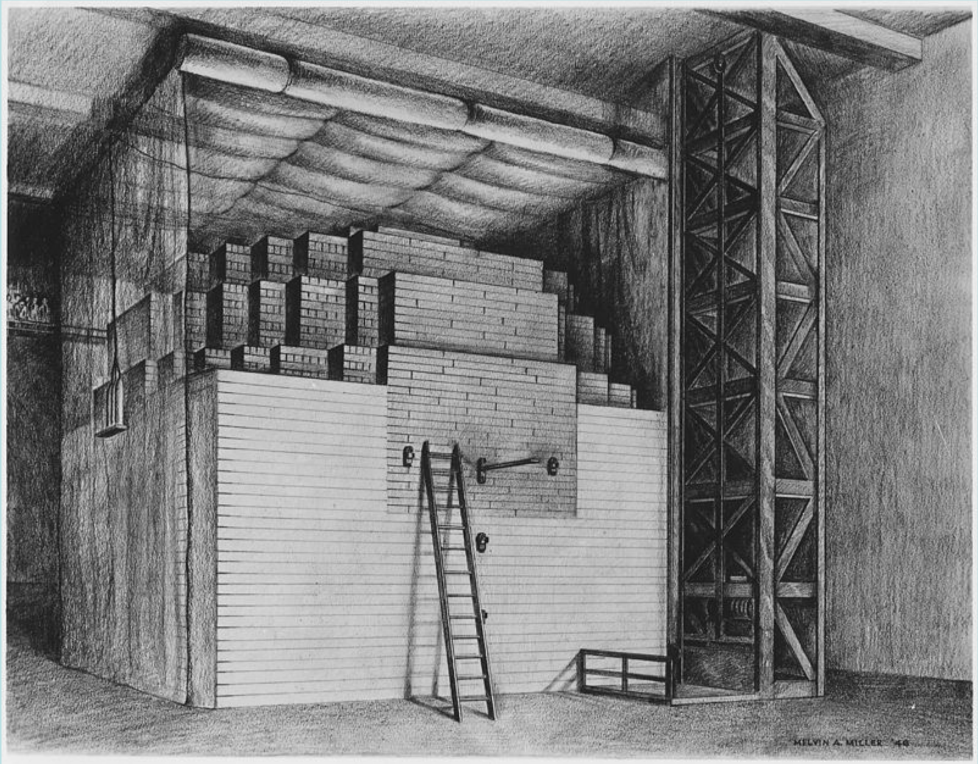
鈾的核分裂需要一個額外的中子來引發，因此原來是相對穩定。

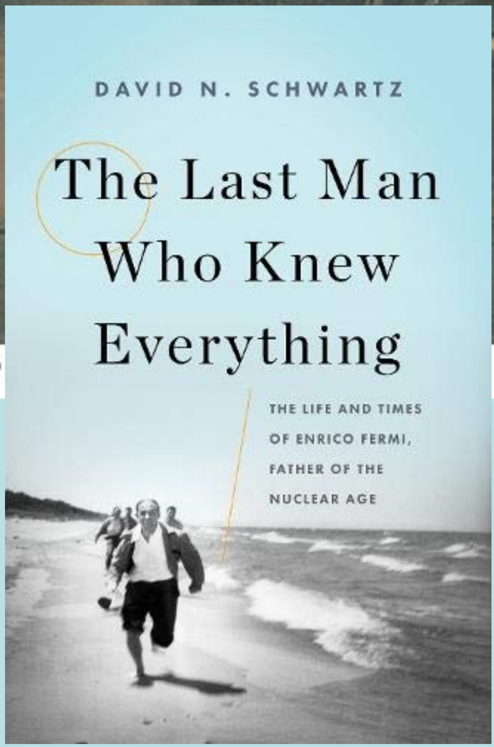
但一旦開始，鈾的核分裂會製造額外的中子，因此形成連鎖反應。

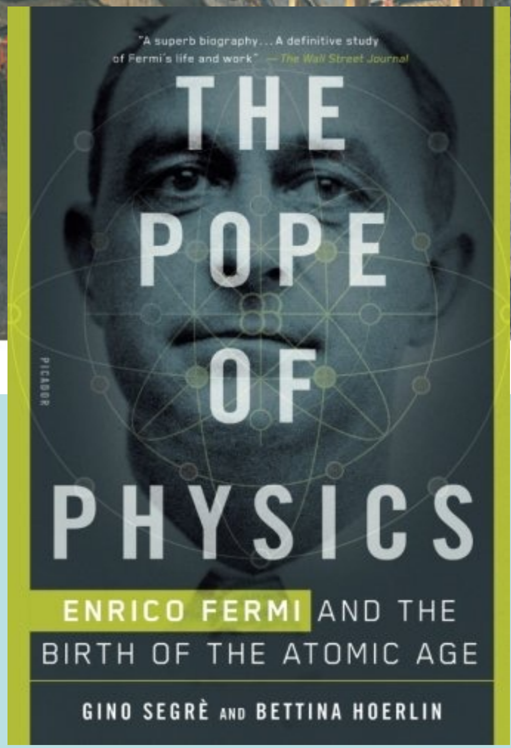
因此可以以中子的數量來控制核分裂的速度。

2 December 1942 Chicago Pile-1

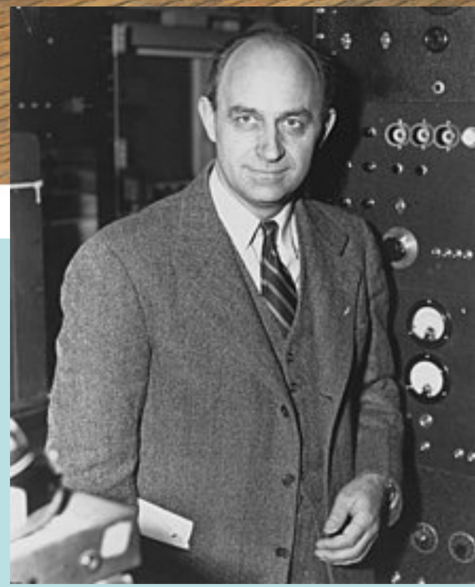
史上第一個核子反應爐：







Enrico Fermi
1901 –1954



原子爐

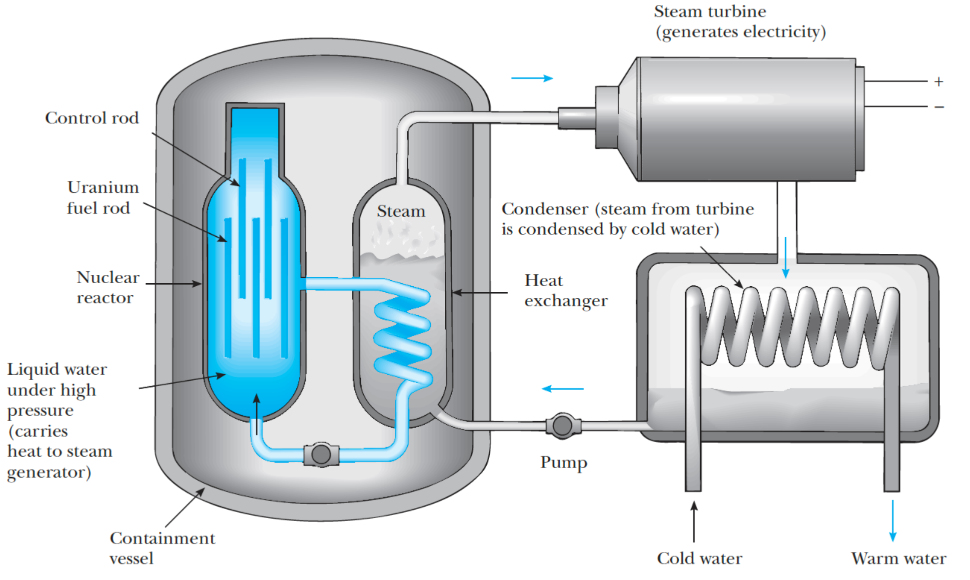


Figure 14.10 Main components of a pressurized-water reactor.

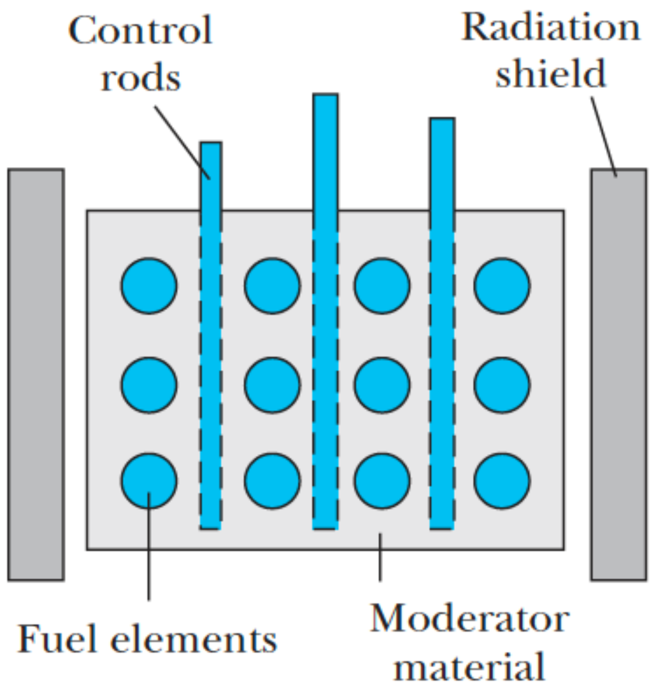
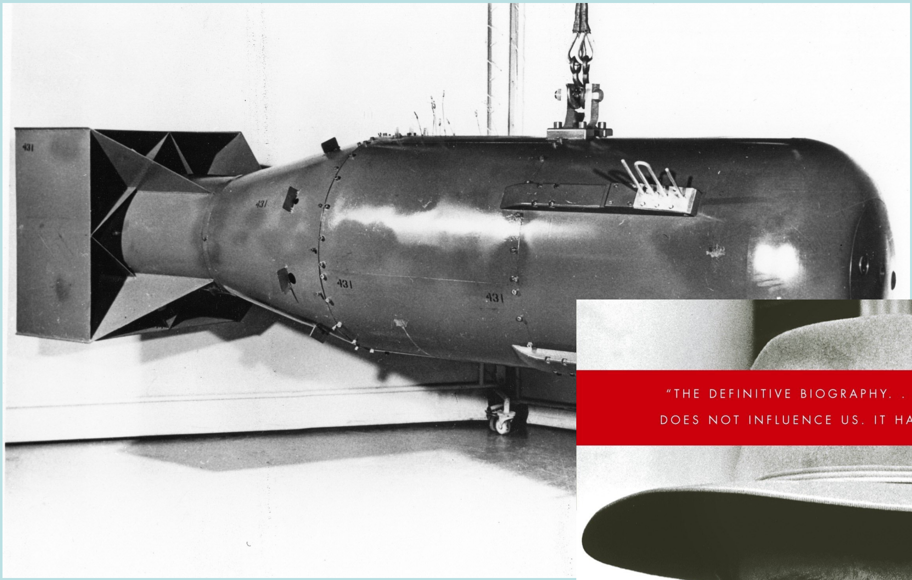


Figure 14.8 A cross section of a reactor core showing the control rods, fuel elements, and moderating material surrounded by a radiation shield.

Atomic bomb



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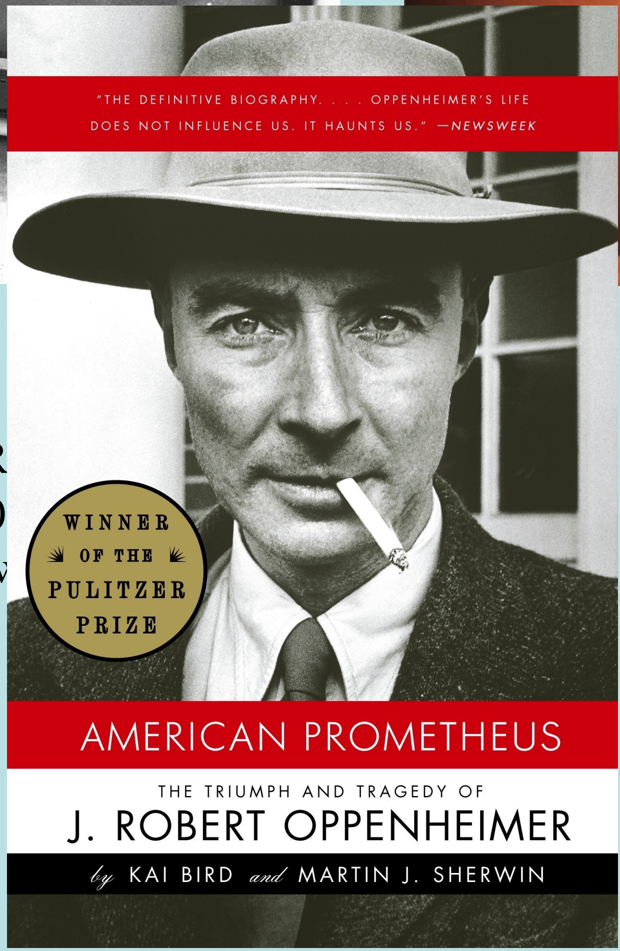
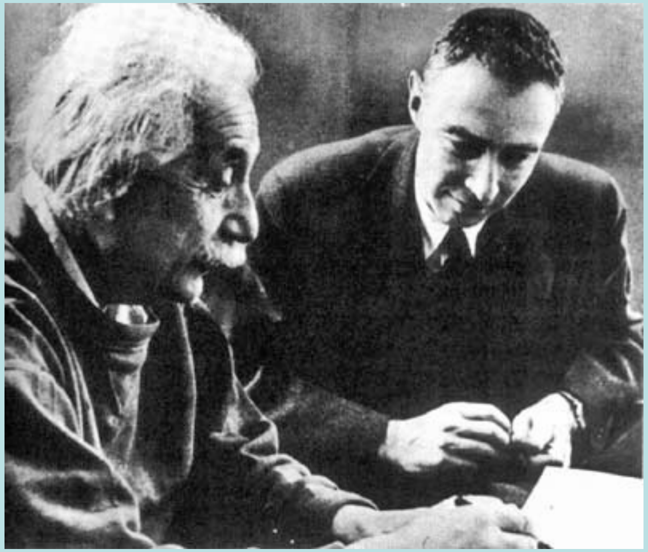
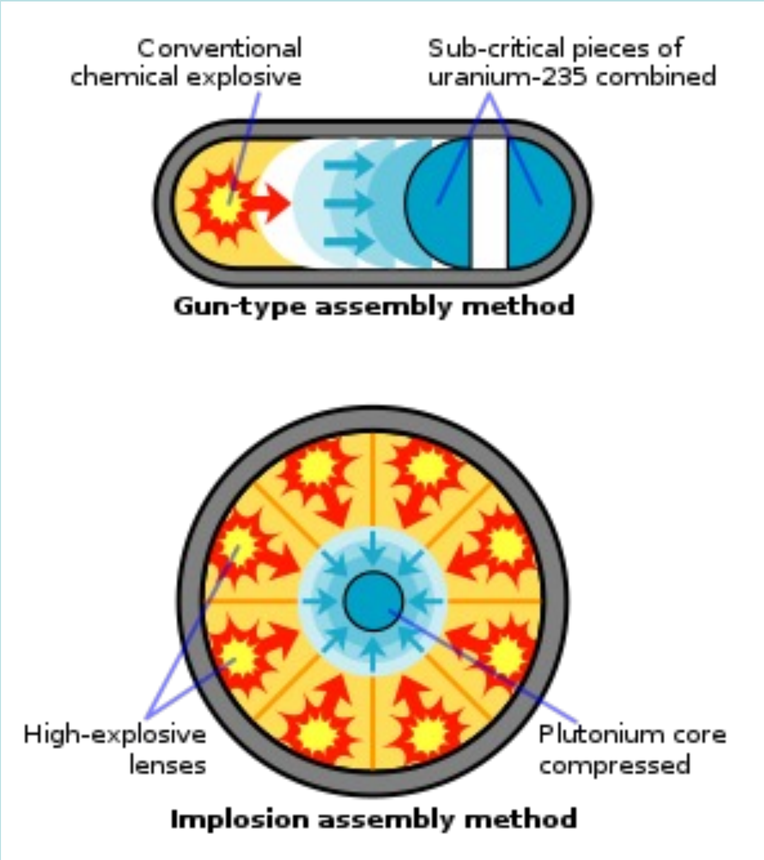
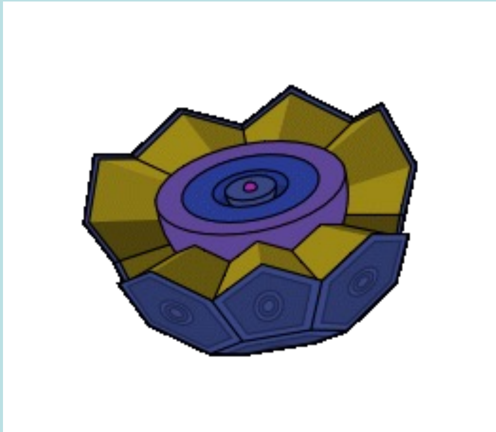




The most commonly used fissile materials for nuclear weapons applications have been uranium-235 and plutonium-239。

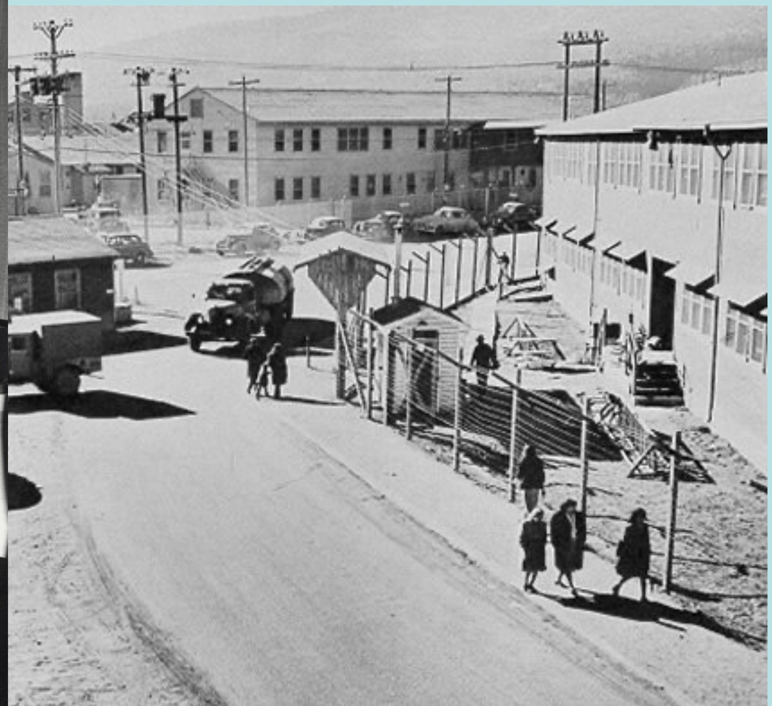
Uranium-235 became the basis of the Little Boy bomb design, first used (without prior testing) in the bombing of Hiroshima; the design used in the Trinity test, and eventually used in the bombing of Nagasaki (Fat Man), was based on plutonium.

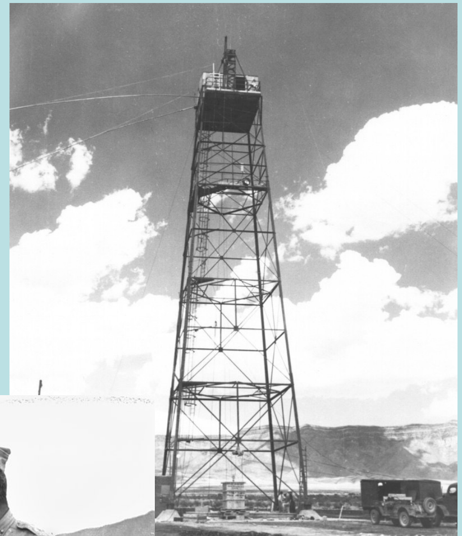




An implosion-type nuclear bomb. In the center is the neutron initiator (red). It is surrounded by the plutonium hemispheres. There is a small air gap (white, not in the original Fat Man design) and then the uranium tamper. Around that is the aluminium pusher (purple). This is encased in the explosive lenses (gold).

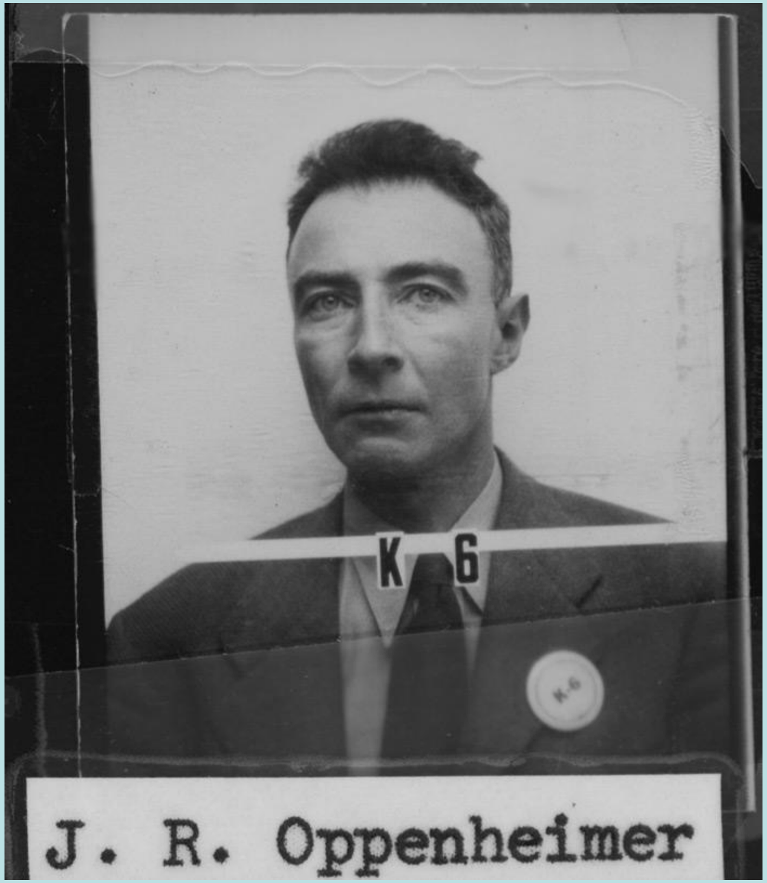
Manhattan Project

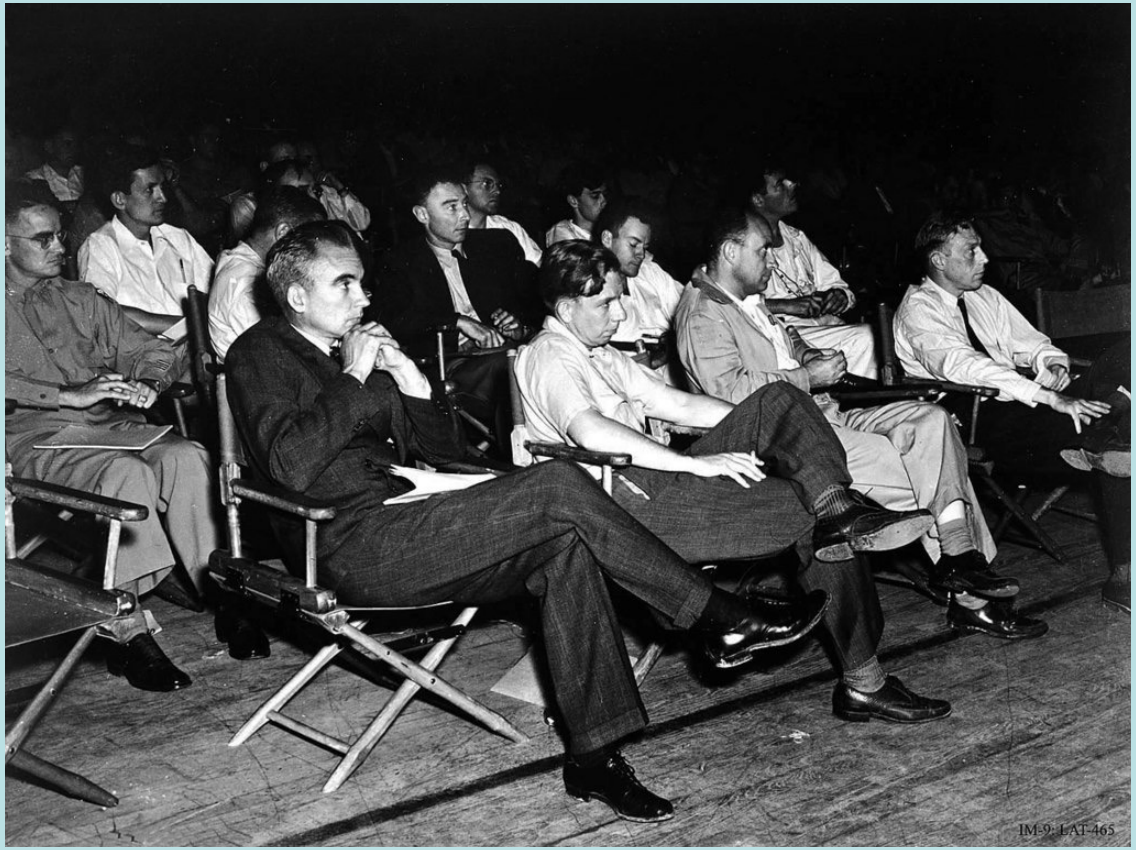




The Trinity test of the Manhattan Project was the first detonation of a nuclear device

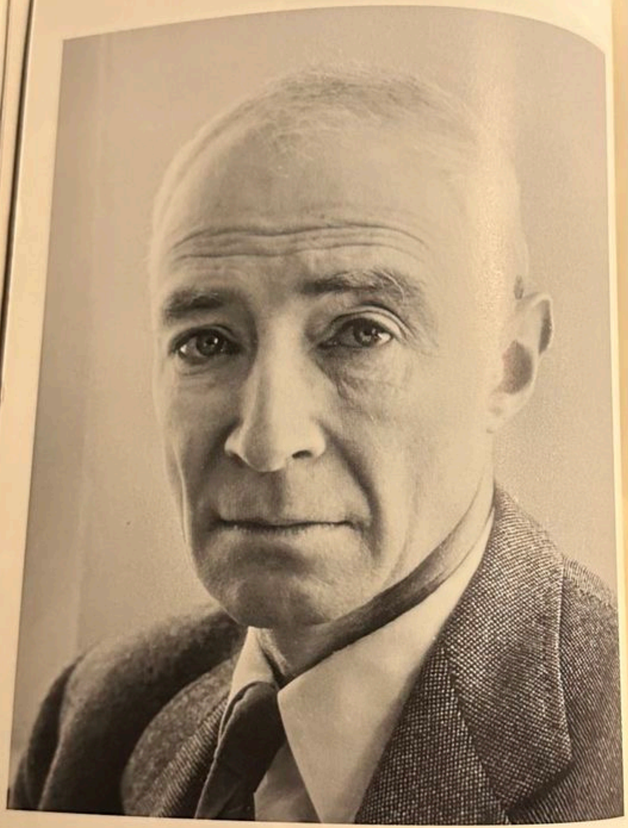
Alamogordo, New Mexico on July 16, 1945





Oppenheimer's ID badge from the Los Alamos Laboratory

Manhattan Project

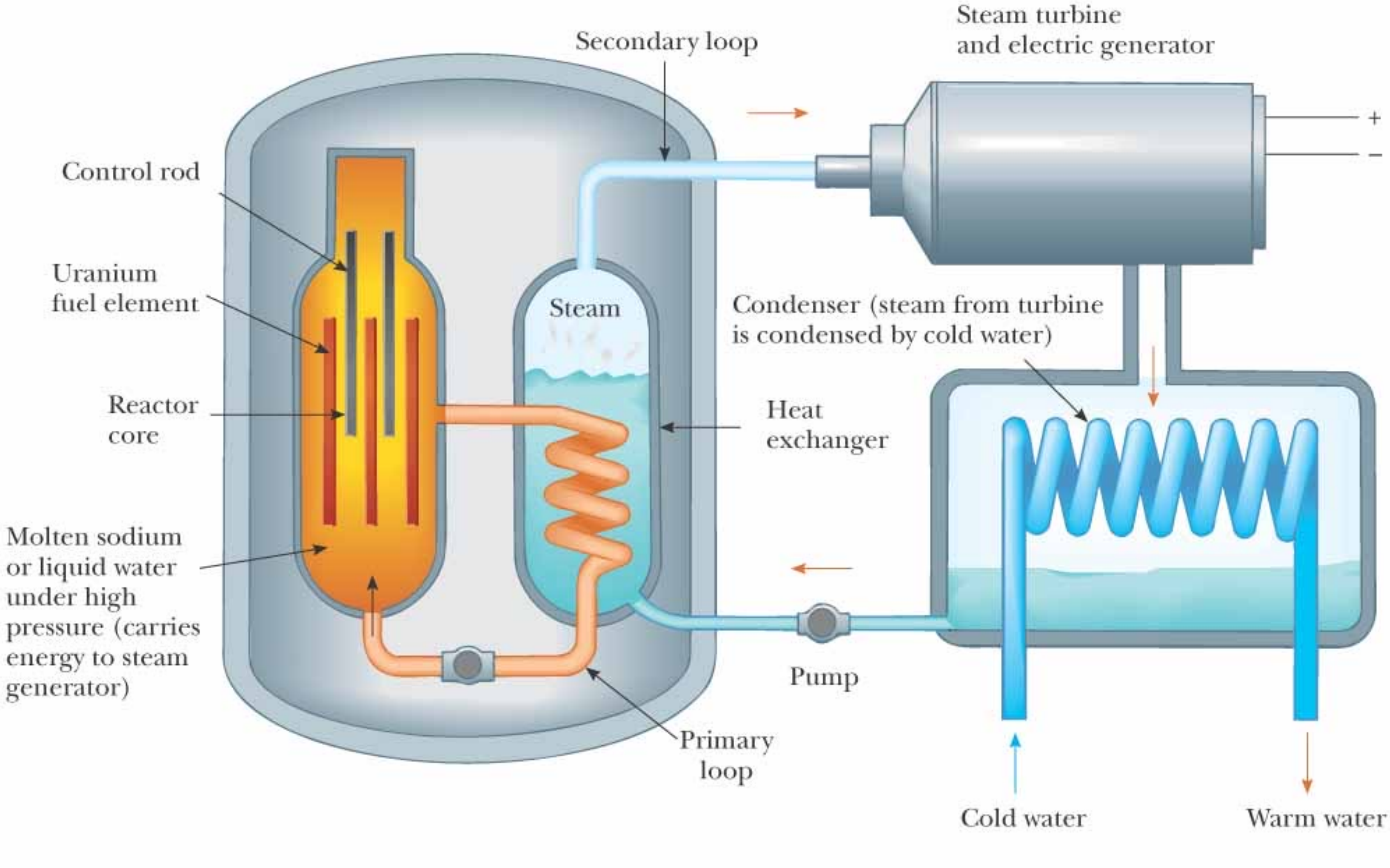


"that if we had eliminated promptly every man who had in
associations with friends who were communistically inclined
been sympathetic to the Russians at one time or another, that w
lost many of our most able scientists."

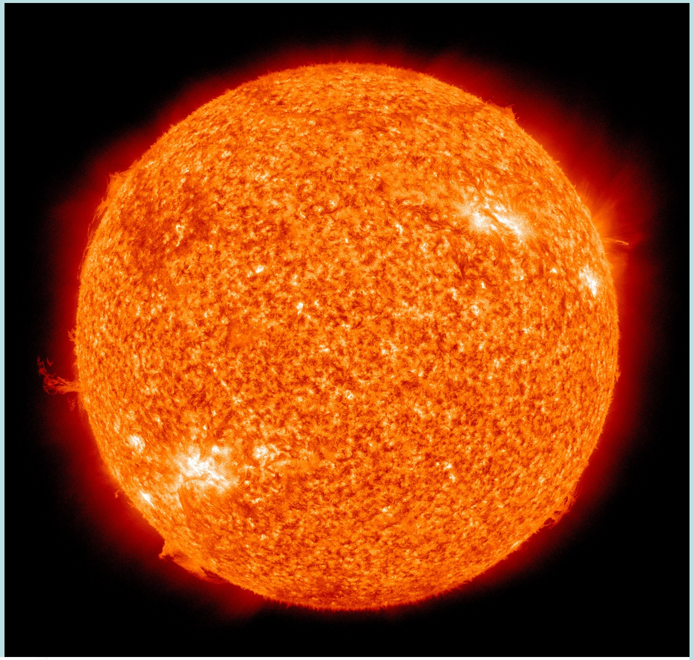
Finding Groves' defense of Oppenheimer unsatisfactory
tinued his search for incriminating information. By early De
in communication with Groves' former aide, Col. Kenneth
loathed Oppenheimer. Over the next several years, Nichols
one of Strauss' assistants and confidants. The two men bon
tility to Oppenheimer. Now Nichols gladly provided Straus
Arthur Compton's September 1945 letter to Henry Wallace
ton, allegedly speaking also for Oppenheimer, Lawrence
stated they would "prefer defeat in war" over a victory
genocidal weapon like the Super bomb. This view outra
saw in Compton's letter further evidence of Oppenhe
influence; that Compton had written the letter, and had no
and Fermi supported his argument, made no difference t

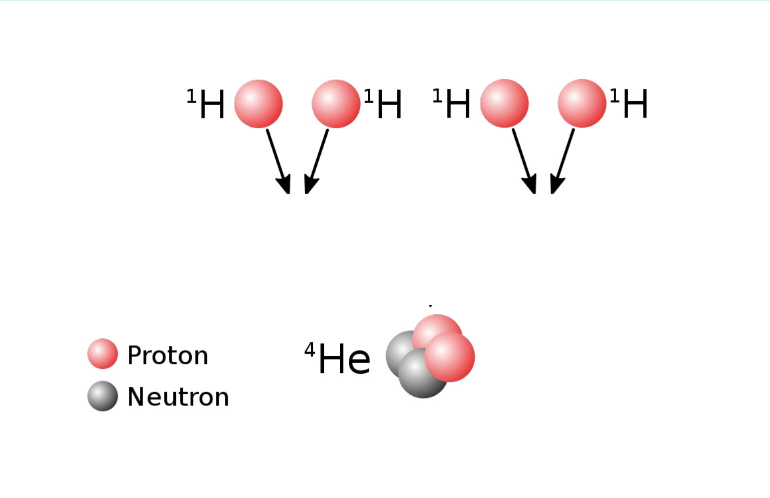
ON THE AFTERNOON of February 1, 1950, the
endorsement of the Super, Strauss received a phone
Hoover. The FBI chief informed him that Fuchs had ju
onage. Although Oppenheimer had had no hand in Fu
Alamos, Strauss nevertheless held it against him tha
occurred on his watch. The next day, Strauss wrote T
case "only fortifies the wisdom of your decision
Strauss' way of thinking, the Fuchs case also vindica
secrecy and his opposition to sharing nuclear technol
topes with the British or anyone else. And for both S
Fuchs revelation also demanded renewed scrutiny
wing past.

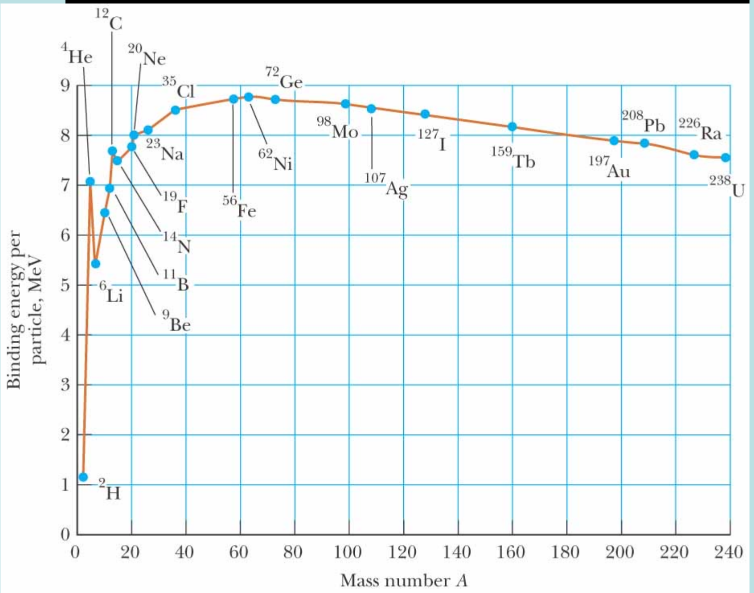
The day Oppenheimer learned of Fuchs' confess
having lunch with Anne Wilson Marks in Grand
Oyster Bar. "Have you heard the news about Fuch
Los Alamos secretary. They agreed that Fuchs had
a quiet, lonely, even pathetic character at Los Alam
by the news," recalled Wilson. On the other hand,
knowledge about the Super was probably confined
"oxcart" model. That same week he told his Inst
Pais that he hoped Fuchs had told the Russians all
because that "would set them back several years."


Steam turbine
and electric generator
Secondary loop
+
–
Control rod
Uranium
fuel element
Steam
Condenser (steam from turbine
is condensed by cold water)
Reactor
core
Heat
exchanger
Molten sodium
or liquid water
under high
pressure (carries
energy to steam
generator)
Pump
Primary
loop
Cold water
Warm water

Sun and fusion 核融合







$4p^{+} \rightarrow {}^{4}_{2}\mathrm{He}$..........

核融合是四個氫原子核融合成氦原子核，

氦原子核束縛能特別大。

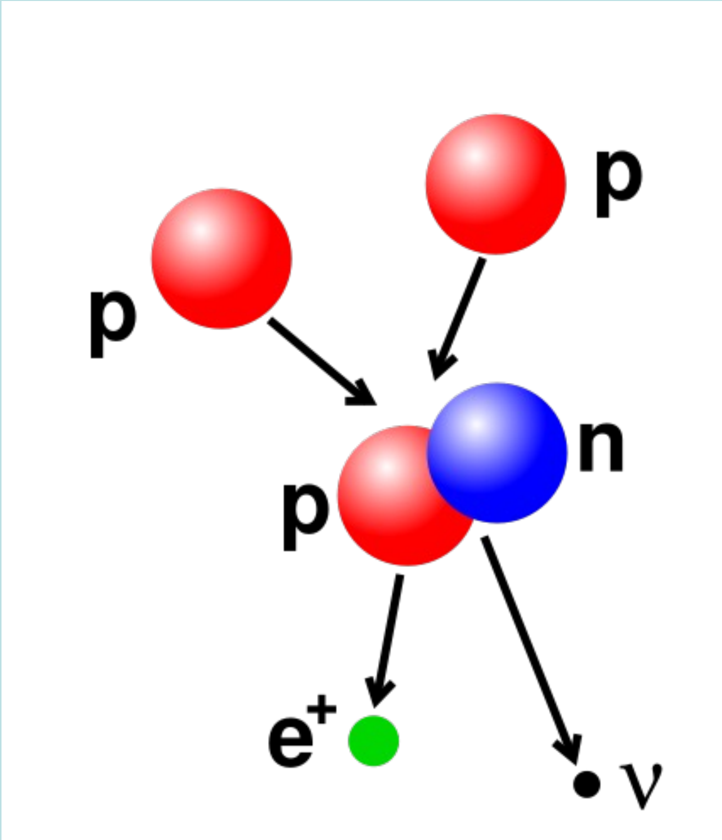
但其中兩個質子必須轉換成中子。

因此過程很複雜！

稱為Hydrogen Burning,或p-p chain。

氫原子核融合為氘($^2_1\mathrm{H} = 1p^+1n$)，可以看成其中一質子轉換為中子！

$n^0 \rightarrow p^+ + e^- + \bar{\nu}_e$ ➡ $p^+ \rightarrow n^0 + e^+ + \nu_e$



中子再與質子形成束縛態氘。

$p + p \rightarrow d + e^+ + \nu_e$

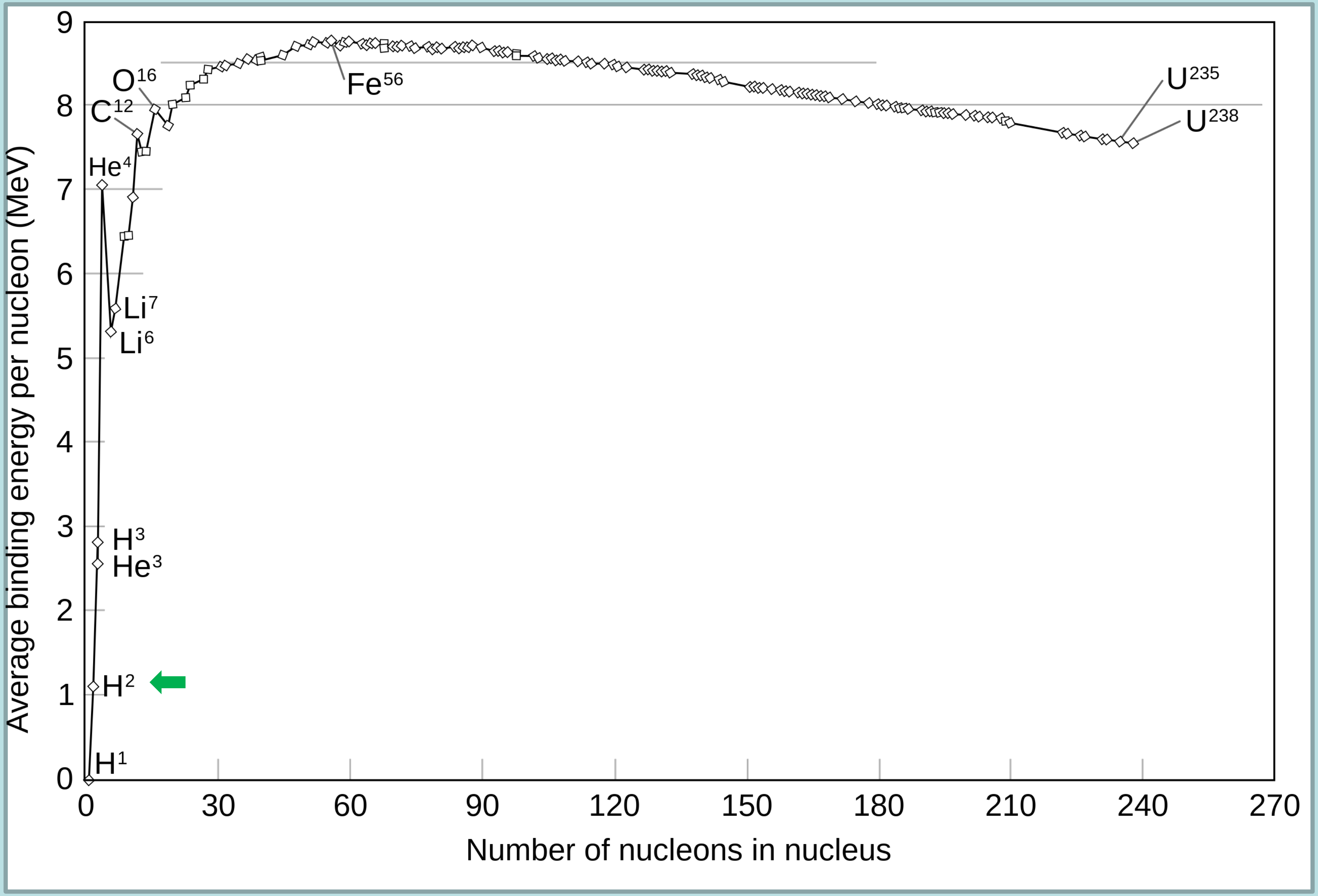
Deuterium 氘：氫的同位素

一個質子轉換成中子。這是弱交互作用！因此發生的很慢！

質子平均要花~9×10^9 yr才能與另一質子融合！這是太陽核融合的瓶頸！

而且要克服質子靠近時的庫倫排斥力，溫度必須很高。

氘原子核的每核子束縛能~1.0 MeV。



$$^{1}\mathrm{H} + {}^{1}\mathrm{H} \rightarrow {}^{2}\mathrm{H} + e^{+} + \nu \quad (Q = 0.42\ \mathrm{MeV})$$
$$e^{+} + e^{-} \rightarrow \gamma + \gamma \quad (Q = 1.02\ \mathrm{MeV})$$

$$^{1}\mathrm{H} + {}^{1}\mathrm{H} \rightarrow {}^{2}\mathrm{H} + e^{+} + \nu \quad (Q = 0.42\ \mathrm{MeV})$$
$$e^{+} + e^{-} \rightarrow \gamma + \gamma \quad (Q = 1.02\ \mathrm{MeV})$$

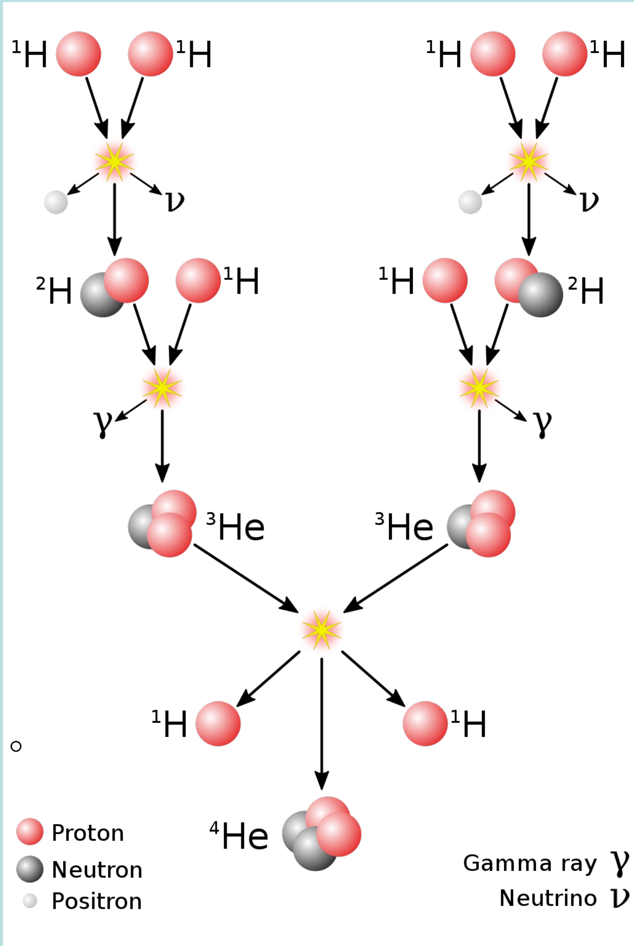
$$\downarrow$$

$$^{2}\mathrm{H} + {}^{1}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + \gamma \quad (Q = 5.49\ \mathrm{MeV})$$

$$^{2}\mathrm{H} + {}^{1}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + \gamma \quad (Q = 5.49\ \mathrm{MeV})$$

$$\downarrow$$

$$^{3}\mathrm{He} + {}^{3}\mathrm{He} \rightarrow {}^{4}\mathrm{He} + {}^{1}\mathrm{H} + {}^{1}\mathrm{H} \quad (Q = 12.86\ \mathrm{MeV})$$



接下來氘會很快與質子融合為氦同位素

$$d + p \rightarrow {}^{3}\mathrm{He} + \gamma$$

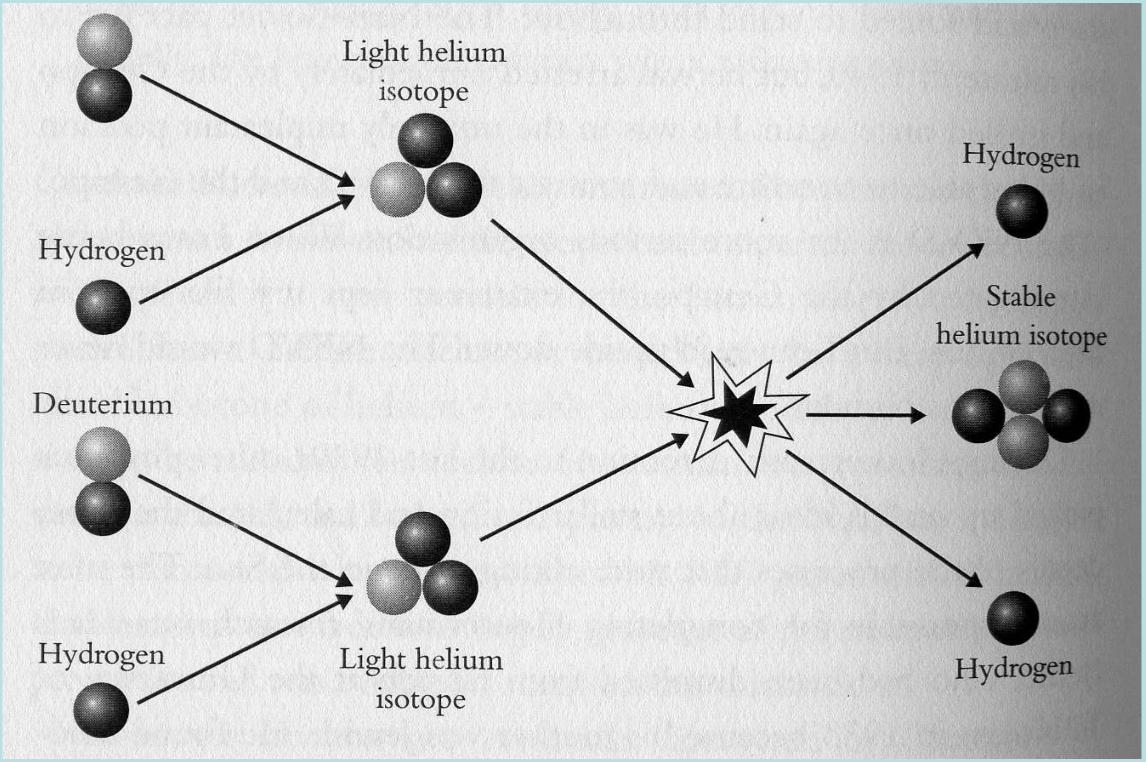
兩個氦同位素再融合為氦原子核、釋放兩個質子。

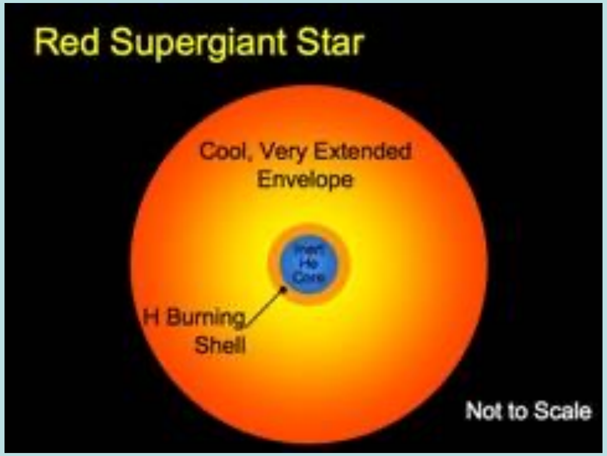
這兩個過程都很快，總的結果：

$$4p^{+} \rightarrow {}^{4}_{2}\mathrm{He} + 2p + 2e^{+} + 2\nu_{e} + \mathrm{Energy}$$

With this Hydrogen Burning, the sun will last for another ***five billion years***.

氫原子核融合

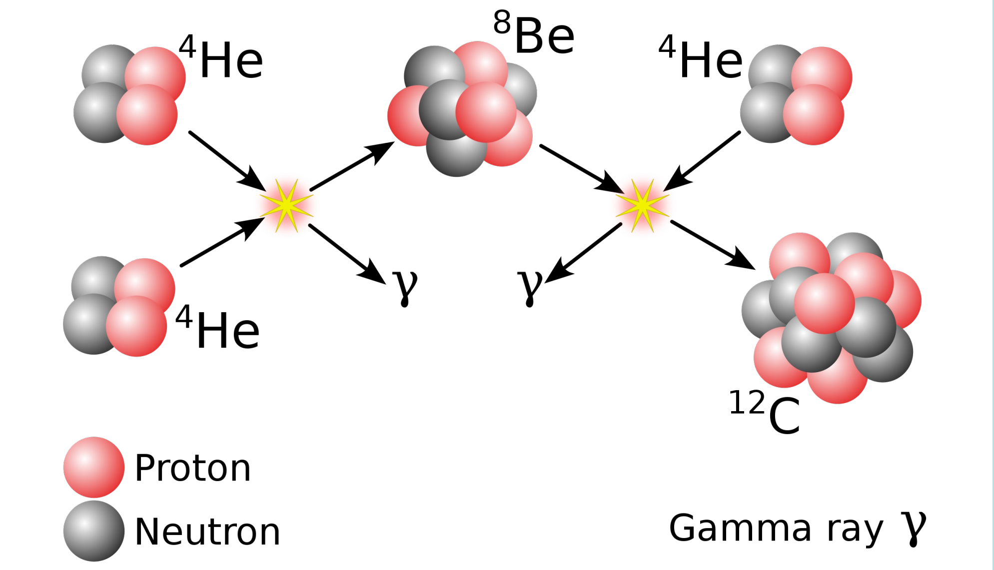

Light helium
isotope
Hydrogen
Deuterium
Hydrogen
Light helium
isotope
Hydrogen
Stable
helium isotope
Hydrogen


Red Supergiant Star
Cool, Very Extended
Envelope
H Burning
Shell
Not to Scale

Helium Burning or Triple-alpha process

Hydrogen burning at the centre of a star ceases when most of the hydrogen in the core has been converted into helium. In the absence of nuclear fusion, the core contracts and gravitational energy is converted into thermal energy. About half of this energy escapes from the core and the other half leads to an increase in temperature. The increased temperature promotes hydrogen burning in a shell surrounding the helium core, and as more helium is produced, the mass of the central core of helium increases. $\boxed{\text{If the mass of the star is large enough, around } 0.5M_\odot}$ or above, the helium core becomes hot and dense enough for helium burning, which normally takes place at temperatures between 10^8 and 2×10^8 K and densities between 10^5 and 10^8 kg m^{-3}.

$M > 0.5M_\odot$



^{8}Be不是穩定原子核，所以這過程一定要一路到達產生碳原子核為止。

這個過程就是地球上碳原子核的起源。

Helium Burning

Helium burning is hindered by the absence of stable nuclei with masses 5 and 8 to act as stepping stones to the formation of carbon. But the

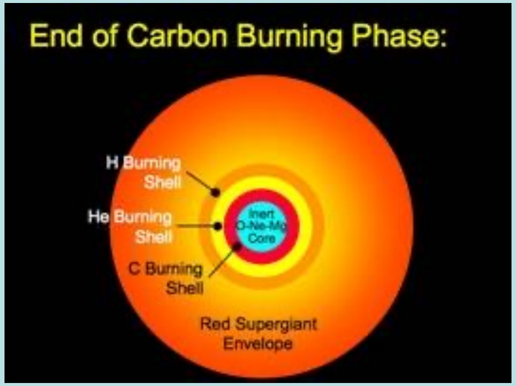
$${}^{4}_{2}\mathrm{He} + {}^{4}_{2}\mathrm{He} + {}^{4}_{2}\mathrm{He} \rightarrow {}^{4}_{2}\mathrm{He} + {}^{8}_{4}\mathrm{Be} \rightarrow {}^{12}_{6}\mathrm{C}$$

碳原子核一出現，又能與氦原子核融合為氧原子核及氖原子核。

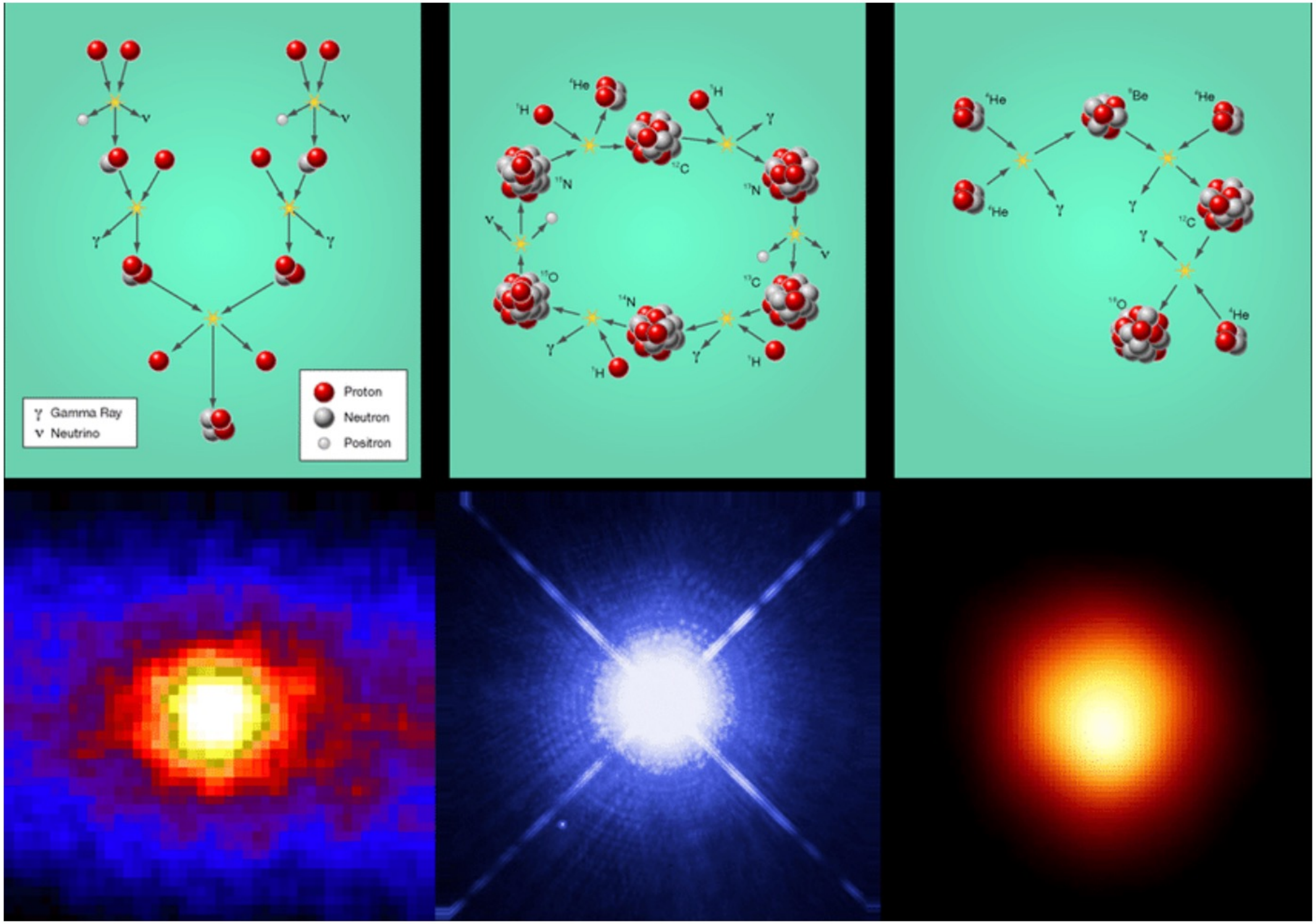
$${}^{4}_{2}\mathrm{He} + {}^{12}_{6}\mathrm{C} \rightarrow {}^{16}_{8}\mathrm{O} + \gamma$$

$${}^{4}_{2}\mathrm{He} + {}^{16}_{8}\mathrm{O} \rightarrow {}^{20}_{10}\mathrm{Ne} + \gamma$$

最後星球會出現富含氧與碳的核心。



We also note that helium burning involves a jump from helium to carbon. It bypasses the stable nuclei between $A = 6$ and $A = 11$, namely ${}^{6}\mathrm{Li}$, ${}^{9}\mathrm{Be}$, ${}^{10}\mathrm{B}$ and ${}^{11}\mathrm{B}$. This is consistent with the observed low abundance of these light nuclei in the solar system. These nuclei are not produced in stars, but are primarily produced by spallation reactions in the interstellar medium, i.e. collisions between high energy cosmic ray protons and nuclei like ${}^{12}\mathrm{C}$. They were also produced in very small quantities during the big bang.



The main energy production processes during stellar hydrogen burning and helium burning. (Top left) the pp reaction, which controls the main energy production in low-mass main sequence stars like our sun (neutrino image, bottom left). (Top center) the first CNO cycle as main energy source in massive main sequence stars such as Sirius (shown at bottom center). (Top right) the main reactions of stellar helium burning such as the triple α process and the subsequent α capture on 12 C, which control the energy production for red giant stars such as Betelgeuse (bottom right). (Illustration: Alan Stonebraker; solar neutrino image courtesy Robert Svoboda, Louisiana State University; Sirius and Betelgeuse images from NASA/Hubble Space Telescope)

Carbon Burning

As a massive star evolves, there is a sequence of nuclear burning stages as the temperature and density at the centre of the star progressively increase. If the mass of a star is large enough, greater than $8M_\odot$ or thereabouts, it will evolve beyond helium burning to advanced burning stages involving heavy nuclei. The following processes are thought to occur:

$M > 8M_\odot$

1. When helium burning at the centre of a star ceases, a core of carbon and oxygen contracts and the temperature rises. Carbon burning begins when the temperature approaches 5×10^8 K at a density of about 3×10^9 kg m^{-3}. Carbon burning produces neon, sodium and magnesium via reactions of the form

$$^{12}C + {}^{12}C \rightarrow {}^{20}Ne + {}^{4}He, \tag{4.69}$$

$$^{12}C + {}^{12}C \rightarrow {}^{23}Na + p, \tag{4.70}$$

$$^{12}C + {}^{12}C \rightarrow {}^{23}Mg + n. \tag{4.71}$$

2. Neon burning occurs after carbon burning if the temperature reaches 10^9 K. At this temperature, high energy thermal photons begin to break up ^{20}Ne nuclei by the photodisintegration reaction

$$\gamma + {}^{20}Ne \rightarrow {}^{16}O + {}^{4}He. \tag{4.72}$$

The ^{4}He nuclei released can then react with undissociated ^{20}Ne nuclei to form ^{24}Mg,

$$^{4}He + {}^{20}Ne \rightarrow {}^{24}Mg + \gamma. \tag{4.73}$$

3. After neon burning, the core of the star consists mainly of ^{16}O and ^{24}Mg. The oxygen burning phase begins if the temperature

reaches 2×10^9 K, the most important product being ^{28}Si which is produced by the reaction

$$^{16}O + ^{16}O \rightarrow ^{28}Si + ^4He. \tag{4.74}$$

4. Silicon burning begins if the temperature reaches 3×10^9 K. At

$$^{28}Si + ^4He \rightleftharpoons ^{32}S + \gamma,$$

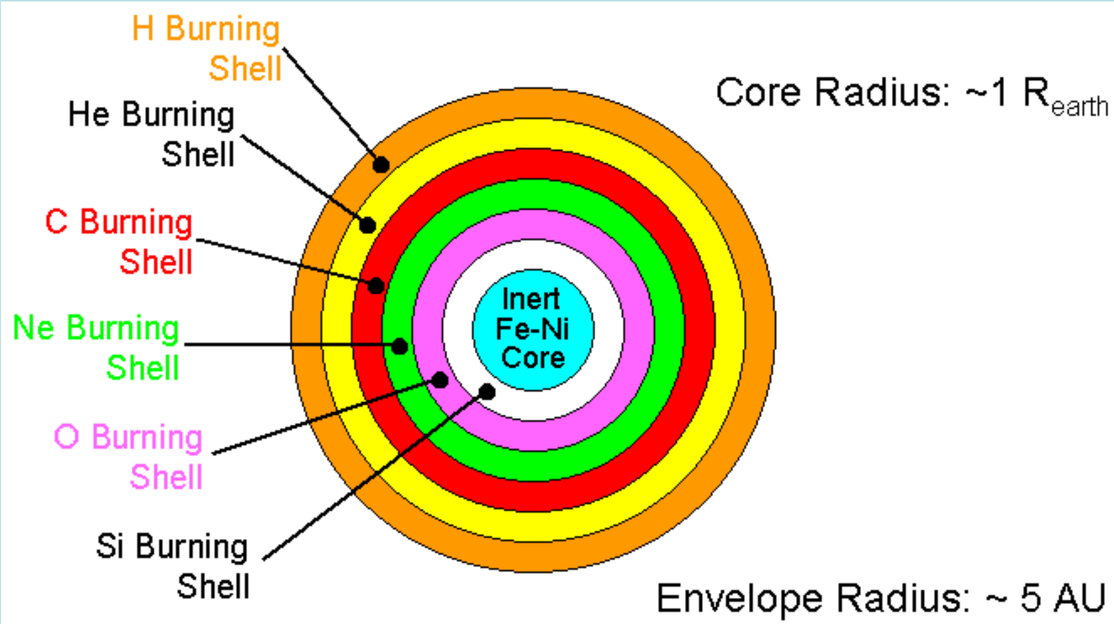
$$^{32}S + ^4He \rightleftharpoons ^{36}Ar + \gamma,$$

$$^{36}Ar + ^4He \rightleftharpoons ^{40}Ca + \gamma,$$

and so on, until

$$^{52}Fe + ^4He \rightleftharpoons ^{56}Ni + \gamma.$$

Silicon Burning



Stage	Timescale	Temperature (10^9 K)	Density (kg m^{-3})
Hydrogen burning	7×10^6 years	0.06	5×10^4
Helium burning	5×10^5 years	0.23	7×10^5
Carbon burning	600 years	0.93	2×10^8
Neon burning	1 year	1.7	4×10^9
Oxygen burning	6 months	2.3	1×10^{10}
Silicon burning	1 day	4.1	3×10^{10}

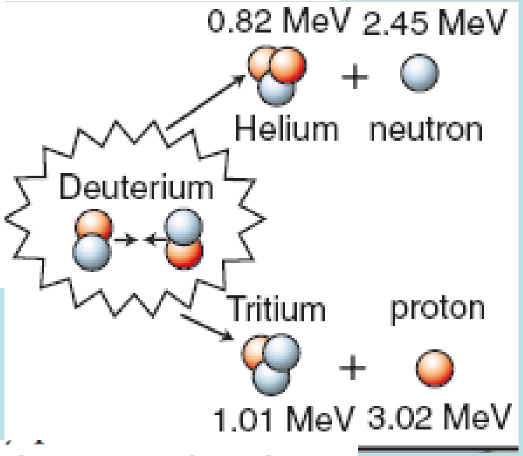
We have seen that the Sun's energy is based, in part, upon a set of reactions in which hydrogen is converted to helium. Unfortunately, the proton–proton interaction is not suitable for use in a fusion reactor, because this reaction requires very high pressures and densities. The process works in the Sun only because of the extremely high density of protons in the Sun's interior.

The fusion reactions that appear most promising for a terrestrial fusion power reactor involve deuterium (^2_1H) and tritium (^3_1H):

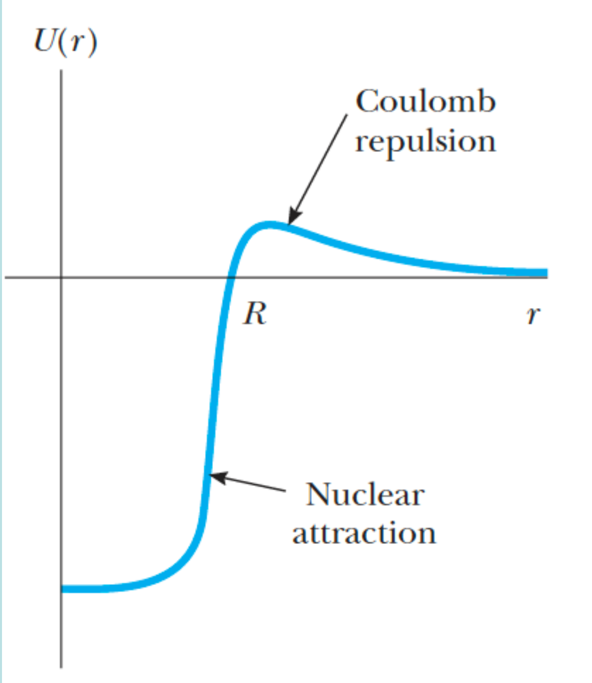
$$^2_1H + ^2_1H \longrightarrow ^3_2He + ^1_0n \qquad Q = 3.27\ \text{MeV}$$

$$^2_1H + ^2_1H \longrightarrow ^3_1H + ^1_1H \qquad Q = 4.03\ \text{MeV}$$

$$^2_1H + ^3_1H \longrightarrow ^4_2He + ^1_0n \qquad Q = 17.59\ \text{MeV}$$

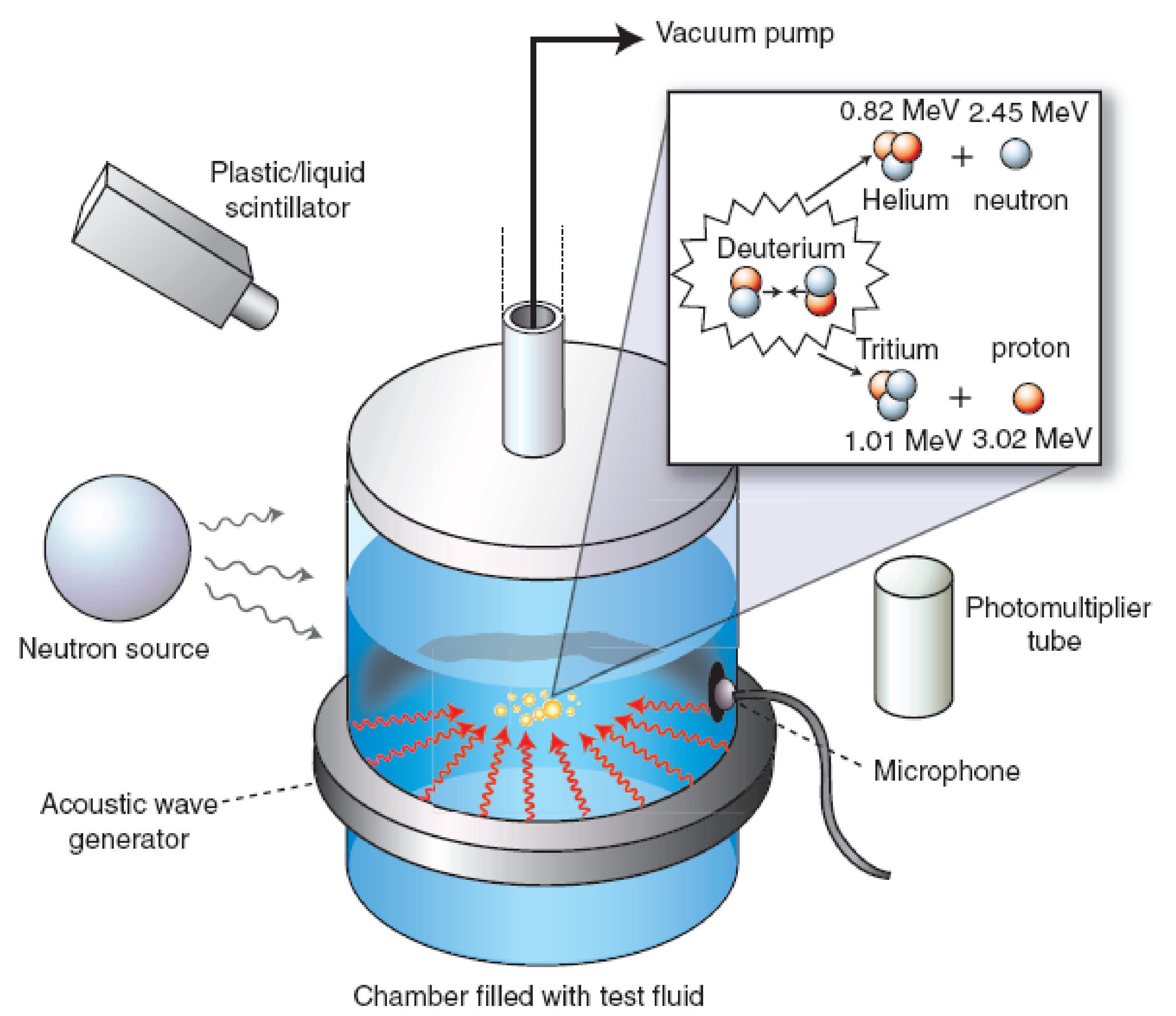


One of the major problems in obtaining energy from any fusion reaction is the fact that the Coulomb repulsion force between two charged nuclei must be overcome before they can fuse. The potential energy as a function of particle separation for two deuterons (each with charge $+e$) is shown in Figure 14.11. The potential energy is positive in the region $r > R$, where the Coulomb repulsive force dominates, and negative in the region $r < R$, where the strong nuclear force dominates. The fundamental problem, then, is to give the two nuclei enough kinetic energy to overcome this repulsive potential barrier. This can be accomplished by heating the fuel to extremely high temperatures (about 10^8 K, far greater than the interior temperature of the Sun). At these high temperatures, the atoms are ionized and the system consists of a collection of electrons and nuclei, commonly referred to as a **plasma.**

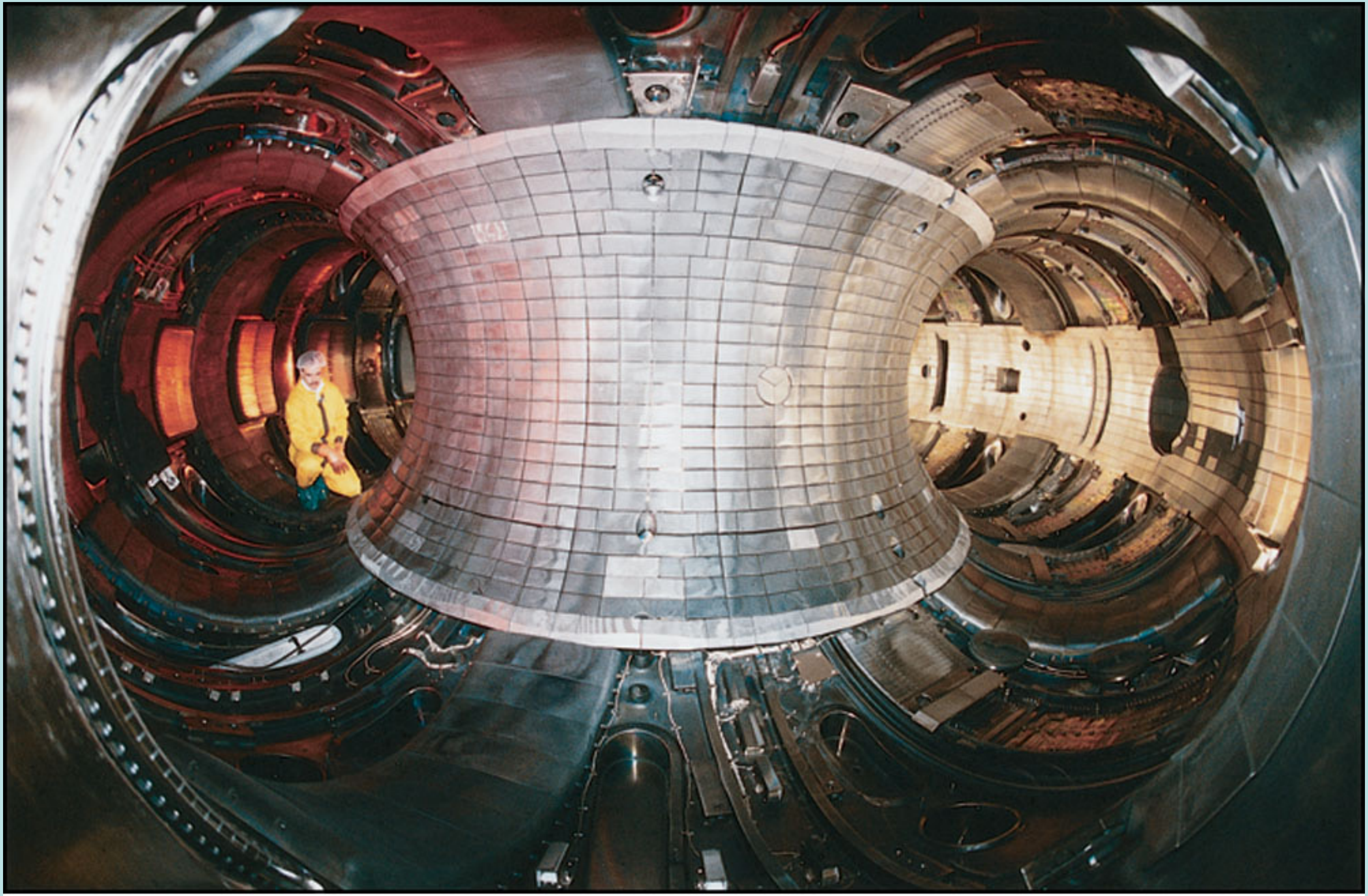


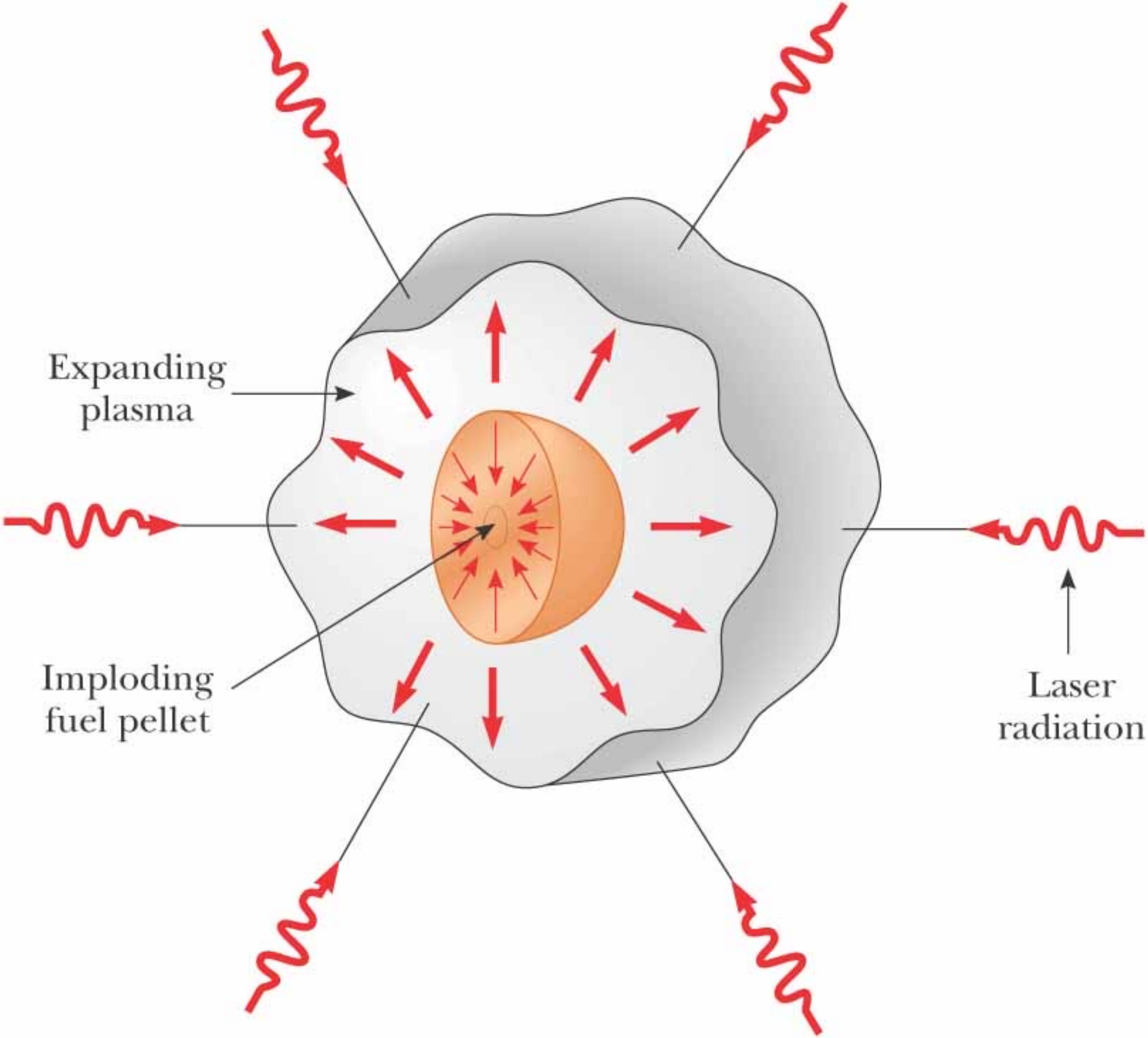
Example 14.6 suggests that deuterons must be heated to about 5×10^8 K to achieve fusion. This estimate of the required temperature is too high, however, because the particles in the plasma have a Maxwellian speed distribution, and therefore some fusion reactions are caused by particles in the high-energy "tail" of this distribution. Furthermore, even the particles without enough energy to overcome the barrier have some probability of tunneling through the barrier. When these effects are taken into account, a temperature of "only" 4×10^8 K appears adequate to fuse two deuterons.

Tabletop fusion



Pop! Embattled paper suggests deuterium nuclei undergo fusion inside sonoluminescent bubbles.




Expanding plasma
Imploding fuel pellet
Laser radiation

不著邊際、抽象的時空推理

卻為人類帶來史無前例幾乎可以自我毀滅的力量。