英汉对照 世界著名科学家代表作选读

广义相对论基础

The Foundation of the General Theory of Relativity

阿尔伯特·爱因斯坦 著

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序

科学技术的发展不是一蹴而就的，它是人类经验的长期累积和修正的结果，是人类理性思维的不断探索和提高。或者说，任何新科学、新技术都是踩在前人的肩膀上向新高峰的攀登。因此，我们在关注当前新科学、新技术的发展动向的同时，了解世界上伟大思想家、科学家和经济学家的学术思想和成就甚为必要。我们还要了解这些先哲的治学方法和人格情操，如伽利略对亚里士多德权威理论的挑战，达尔文对唯心主义神造论的否定，爱因斯坦除相对论外，对社会和政治问题所表现出的极大兴趣。

对广大中国读者来说，要找到不同时期著名科学家和经济学家经典著作的中文译本有一定困难，有些译文在内容译述和文体表达方式上有待完善，这便呼唤学术界和出版社翻译和出版这方面的高质量的经典著作。如今，由河北经贸大学副校长陈叔敏先生领衔主编《英汉对照世界著名科学家代表作选读》和《英汉对照世界著名经济学家代表作选读》两套系列丛书，并由河北科学技术出版社出版，正是为了满足现代读者的需要。这两套丛书将陆续翻译有关牛顿、伽利略、爱因斯坦、巴甫洛夫、亚当·斯密、马歇尔、凯恩斯、萨缪尔森等名家的代表作。因此，这是一项具有战略意义的

出版工程，是令人无比激动的喜讯。

参加翻译的有该校和兄弟院校的资深英语教授和有关专业的专家，以确保译文的忠实性和可读性。我读了部分译稿后，感到译文达意，表述流畅，爱不释手，时有与先哲们对话之感。愿与读者们共享个中乐趣。

胡壮麟

北京大学/清华大学教授

2000年11月16日

译者前言

阿尔伯特·爱因斯坦（1879—1955），物理学家，生于德国，1933年因受纳粹政权迫害，迁居美国，1921年荣获诺贝尔物理学奖。他在物理学的许多领域中都有重大贡献，其中最重要的是20世纪初建立了狭义相对论（1905年）；并在此基础上推广为广义相对论（1916年）。

相对论是20世纪最伟大的科学发现之一，它提出了新的时空观念，改变了人们对宇宙的看法，爱因斯坦也因此被称为“20世纪的牛顿”。牛顿力学只是说明了低速运动的现象，而相对论向人类揭示了更为广阔的空间。它革新了时间、空间、物质与能量的概念。狭义相对论的原理都已得到了验证，并成为现代物理学的基石；广义相对论——爱因斯坦的杰作，是他对万有引力做出的高超的数学解释。在天文学方面，它的应用已超出了太阳系的范围。

本书采用英汉对照方式，向读者介绍了相对论中的广义相对论部分。这是一部非常实用的英汉对照读物：读者不仅可以获取相对论的有关知识，而且还可以欣赏到科技英语的语言特色。

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[①] and Newton[②].

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 nonuniform motion of K′ relatively to K.

Thus the special theory of relativity does not depart from classical mechanics through the postulate of relativity, but through the postulate of the constancy of the velocity of light *in vacuo*[③], from which, in combination with the special principle of relativity, there follow, in the well-known way, the relativity of simultaneity[④], the Lorentzian transformation[⑤], and the related laws for the behaviour of moving bodies and clocks.

The modification to which the special theory of relativity has subjected the theory of space and time is indeed far-reaching, but one important point has remained unaffected. For

一、相对性假设的基本因素

§1. 关于狭义相对论的评论

狭义相对论是建立在以下假设上的，伽利略和牛顿力学也满足这一假设。

如果我们选择一个坐标系K，使物理定律关于K以最简单的形式成立，那么同样的定律也关于相对K做匀速直线运动的坐标系K′成立。这一假设我们称为“狭义相对性原理”。“狭义”一词是指这一原理仅适用于当K′相对K做匀速直线运动的情况，而当K′相对K不做匀速直线运动时，K与K′不能等效。

因此，使狭义相对论脱离经典力学的并非相对性假设，而是光在真空中传播速度不变的假设，它与狭义相对论相结合，用众所周知的方法推导出了同时的相对性、洛伦兹变换及有关运动物体与运动钟的行为的定律。

狭义相对论对时间和空间理论的改变确实是影响深远的，但是仍有很重要的一点没有改变。因为即便是根据狭义相对

①Galileo 伽利略，意大利物理学家、天文学家。通常认为他是经典力学的先驱人物。

②Newton 牛顿，英国物理学家。他在伽利略等人工作的基础上建立了经典力学的基本体系，因此，人们常把经典力学称为“牛顿力学”。

③ in vacuo（拉丁语）在真空中。

④ relativity of simultaneity 同时的相对性。根据洛伦兹变换及相对论可知，如果两个观察者之间有一相对速度，则对一个观察者有同时性的两件事，对另一个观察者而言，未必具有同时性。

⑤ Lorentz 洛伦兹，荷兰物理学家。他提出高速运动的参照系与静止参照系之间时间、空间坐标的变换形式，称为洛伦兹变换。

the laws of geometry, even according to the special theory of relativity, are to be interpreted directly as laws relating to the possible relative positions of solid bodies at rest; and, *in a more general way*, the laws of kinematics are to be *interpreted as laws which describe the relations of measuring bodies and clocks*. To *two selected material points of a stationary rigid body*[6] there always corresponds a distance of quite definite length, which is independent of the locality and orientation of the body, and is also independent of the time. To two selected positions of the hands of a clock at rest relatively to the privileged system of reference there always corresponds an interval of time of a definite length, which is independent of place and time. We shall soon see that the general theory of relativity cannot adhere to[7] this simple physical interpretation of space and time.

§ 2. The Need for an Extension of the Postulate of Relativity

In classical mechanics, and no less in the special theory of relativity, there is an inherent epistemological defect which was, perhaps for the first time, clearly pointed out by Ernst Mach[8]. We will elucidate it by the following example: —Two fluid bodies of the same size and nature hover freely in space at so great a distance from each other and from all other masses that only those gravitational forces need be taken into account[9] which arise from the interaction of different parts of the same body. Let[10] the distance between the two bodies be invariable, and in neither of the bodies let there be any relative movements

论，几何学定律仍被直接地看做是关于静止固体之间可能存在的相对位置的定律；而且人们更普遍地认为，运动学定律是用来描述量体与钟的关系的定律。对于静止刚体上两个选定的质点，它们之间的距离总对应确定的长度，这段长度与物体的位置、方向无关，并且与时间也无关。相对于优先选定的参照系静止的钟，其指针的两个选定位置之间总对应一段确定的时间间隔，这段间隔与时间和地点无关。然而我们很快会看到，广义相对论不再忠于上述对时间和空间简单的物理解释。

§2. 扩展相对性假设的必要性

在经典力学和狭义相对论中，都存在着一个固有的认识论上的缺陷。这一缺陷或许最先是由马赫清楚地指出的。我们通过下面的例子来说明它：两个大小、性质都相同的流体自由地漂浮在空间中，它们之间的距离及同其他质量之间的距离都非常远，以至于只需要考虑同一物体中各部分间互相作用的引力。设这两个物体之间的距离保持不变，而且任何一个物体上都

⑥rigid body 刚体。在外力作用下，体积和形状都不改变的物体。

⑦adhere to 忠于；坚持。

⑧Mach 马赫，奥地利物理学家，研究物体在气体中以高速运动时的情形。

⑨take into account 对某事加以考虑。

⑩let *v*. 设；假设；令。

of the parts with respect to one another. But let either mass, as judged by an observer at rest relatively to the other mass, rotate with constant angular velocity about the line joining the masses. This is a verifiable relative motion of the two bodies. Now let us imagine that each of the bodies has been surveyed by means of measuring instruments at rest relatively *to itself*, and let the surface of S_1 prove to be a sphere, and that of S_2 an ellipsoid of revolution. Thereupon we put the question—What is the reason for this difference in the two bodies? No answer can be admitted as epistemologically satisfactory, * unless the reason given is an *observable fact of experience*. The law of causality has not the significance of a statement as to[11] the world of experience, except when *observable facts* ultimately appear as causes and effects.

Newtonian mechanics does not give a satisfactory answer to this question. It pronounces[12] as follows:—The laws of mechanics apply to the space R_1, in respect to which the body S_1 is at rest, but not to the space R_2, in respect to which the body S_2 is at rest. But the privileged space R_1 of Galileo, thus introduced, is a merely *factitious* cause, and not a thing that can be observed. It is therefore clear that Newton's mechanics does not really satisfy the requirement of causality in the case under consideration, but only apparently does so, since it makes

* Of course an answer may be satisfactory from the point of view of epistemology, and yet be unsound physically, if it is in conflict with other experiences.

不存在各部分之间的相对运动。但使其中任一物体，在相对于另一物体静止的观察者看来，围绕它们的连线以固定的角速度转动。这是两个物体之间可证实的相对运动。现在我们假设每个物体都被相对于自身静止的测量仪器测量过，并且假设已证实 S_1 表面为球面，S_2 表面为旋转椭面。那么我们会问：为什么两个物体存在这种差别？除非给出的原因是可观察到的经验事实，否则任何回答在认识论上都不会令人满意*。依照经验世界，除非最终有可观察到的事实作为原因和结果，否则因果律的表述就没有任何意义。

牛顿力学没有对这个问题做出满意的回答，它这样解释：力学定律适用于与 S_1 相对静止的空间 R_1，但不适用于与 S_2 相对静止的空间 R_2。然而，这样引入的优先伽利略空间 R_1 只不过是人为的原因，而不是可观察的事实。由于牛顿力学用人为的原因来解释物体 S_1

⑪as to 此处意为依照。

⑫ pronounce 此处意为宣称。

* 当然某个答案在认识论上可能是令人满意的，但如果与其他经验相矛盾，那么它在物理学上也是站不住脚的。

the factitious cause R_1 responsible for the observable difference in the bodies S_1 and S_2.

The only satisfactory answer must be that the physical system consisting of S_1 and S_2 reveals within itself no imaginable cause to which the differing behaviour of S_1 and S_2 can be referred. The cause must therefore lie *outside* this system. We have to take it that the general laws of motion, which in particular determine the shapes of S_1 and S_2, must be such that the mechanical behaviour of S_1 and S_2 is partly conditioned, in quite essential respects, by distant masses which we have not included in the system under consideration. These distant masses and their motions relative to S_1 and S_2 must then be regarded as the seat[13] of the causes (which must be susceptible to observation) of the different behaviour of our two bodies S_1 and S_2. They take over the role of the factitious cause R_1. Of all imaginable spaces R_1, R_2, etc., in any kind of motion relatively to one another, there is none which we may look upon as privileged *a priori*[14] without reviving the above-mentioned epistemological objection. *The laws of physics must be of such a nature that they apply to systems of reference in any kind of motion*. Along this road we arrive at an extension of the postulate of relativity.

In addition to this weighty[15] argument from the theory of knowledge, there is a well-known physical fact which favours an extension of the theory of relativity. Let K be a Galilean system of reference, i.e. a system relatively to which (at least in the

和 S_2 之间可观察到的差别，因此很明显，它只是在表面上而并不是真正满足因果律在目前这种情况下的要求。

惟一令人满意的答案一定是这样的：由 S_1、S_2 所组成的物理系统内部没有表现出任何可以想像的原因来解释 S_1 和 S_2 的不同变化，因而，原因一定在系统之外。我们必须承认那些特别决定着 S_1 和 S_2 形状的一般运动规律一定是这样的：S_1 和 S_2 的力学变化在很重要的方面部分地取决于远处我们未包含在系统内的质量。这些远处的质量及它们相对于 S_1、S_2 的运动应看做是 S_1、S_2 不同变化的原因(它们必须是可观察的)。它们接替了人为原因 R_1 的角色。在所有可以设想的空间 R_1、R_2…中，无论它们相对做何种运动，如果其中任何一个被先验地看做是优先空间，都会重复前面所提到的认识论上的缺陷。物理定律必须具有的本质是它们适用于做各种运动的参照系。沿着这条道路，我们可以达到扩展相对性假设的目的。

除了这个认识论中的重要理由，还有一个人所共知的物理事实有助于扩展相对论。设 K 是一个伽利略参照系，也就是说相对于 K 来说，离其他质量足够远的质量(至少在所考虑的四维区域中)做匀速直

⑬seat *n*. 所在地；中心；场所。

⑭a priori（拉丁语）先验的，推测的。

⑮weighty *adj*. 重要的；有影响力的。

four-dimensional region under consideration) a mass, sufficiently distant from other masses, is moving with uniform motion in a straight line. Let K′ be a second system of reference which is moving relatively to K in *uniformly accelerated* translation. Then, relatively to K′, a mass sufficiently distant from other masses would have an accelerated motion such that its acceleration and direction of acceleration are independent of the material composition and physical state of the mass.

Does this permit an observer at rest relatively to K′ to infer that he is on a "really" accelerated system of reference? The answer is in the negative; for the above-mentioned relation of freely movable masses to K′ may be interpreted equally well in the following way. The system of reference K′ is unaccelerated, but the space-time territory in question[16] is under the sway of[17] a gravitational field, which generates the accelerated motion of the bodies relatively to K′.

This view is made possible for us by the teaching of experience as to the existence of a field of force, namely, the gravitational field, which possesses the remarkable property of imparting the same acceleration to[18] all bodies.* The mechanical behaviour of bodies relatively to K′ is the same as presents itself to experience in the case of systems which we are wont to[19] regard as "stationary" or as "privileged." Therefore,

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* Eötvös[20] has proved experimentally that the gravitational field has this property in great accuracy.

线运动。设 K′是相对于 K 做匀加速直线运动的参照系，那么，相对于 K′，一个远离其他质量的质量将做加速运动，其加速度的大小及方向与其物质构成和物理状态无关。

这会使相对于 K′静止的观察者认为他正处于一个“真正”加速的参照系吗？回答是否定的；因为用下面的方法同样可以很好地解释上述自由运动质量相对于 K′的关系：参照系 K′没有做加速运动，而正在讨论的时空边界受到引力场的影响，是引力场使物体相对于 K′做加速运动。

经验使我们产生上述想法，它告诉我们有一种力场，称为引力场，它具有赋予所有物体同一加速度的特殊性质*。物体相对于 K′的力学行为与它在（经验中我们倾向于认为是）“静止的”或“优先的”系统中的表现一样。

⑯in question 在考虑中的；在议论中的。

⑰under the sway of 在…的影响下；受…的左右。

⑱impart…to 赋予。

⑲be wont to 往往…；老…；总是…；素来…。

⑳Eötvös 厄缶，匈牙利物理学家。他的实验结果为爱因斯坦的广义相对论提供了依据。

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* 厄缶已经很精确地通过实验证明了引力场具有这种性质。

from the physical standpoint, the assumption readily suggests itself that the systems K and K′ may both with equal right be looked upon as "stationary," that is to say, they have an equal title as systems of reference for the physical description of phenomena.

It will be seen from these reflexions that in pursuing the general theory of relativity we shall be led to a theory of gravitation, since we are able to "produce" a gravitational field merely by changing the system of co-ordinates. It will also be obvious that the principle of the constancy of the velocity of light *in vacuo* must be modified, since we easily recognize that the path of a ray of light with respect to K′ must in general be curvilinear, if with respect to K light is propagated in a straight line with a definite constant velocity.

§ 3. The Space-Time Continuum.[21] Requirement of General Co-Variance for the Equations Expressing General Laws of Nature

In classical mechanics, as well as in the special theory of relativity, the co-ordinates of space and time have a direct physical meaning. To say that a point-event has the X_1 co-ordinate x_1 means that the projection of the point-event on the axis of X_1, determined by rigid rods and in accordance with the rules of Euclidean geometry[22], is obtained by measuring off a given rod (the unit of length) x_1 times from the origin of co-ordinates along the axis of X_1. To say that a point-event has the X_4 co-ordinate $x_4 = t$, means that a standard clock, made to