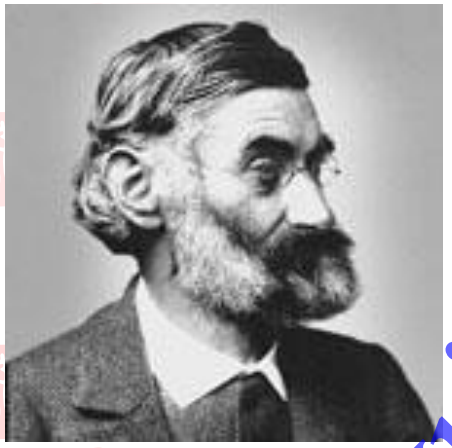
Outline

- 祝贺“首颗探月卫星‘嫦娥一号’发射成功”/2007年10月24日18时05分
- Abbe’s Principle
- Generalized Abbe’s Principle
- Bryan’s Principle
- 遵守阿贝原则的传动部件
- 天道酬勤

Abbe's Principle

- In the late 1800s, Dr. *Ernst Abbe* (1840-1905) and Dr. *Carl Zeiss* (1816-1888) worked together to create one of the world's foremost precision optics companies (*Carl Zeiss, Inc.* ZEISS)



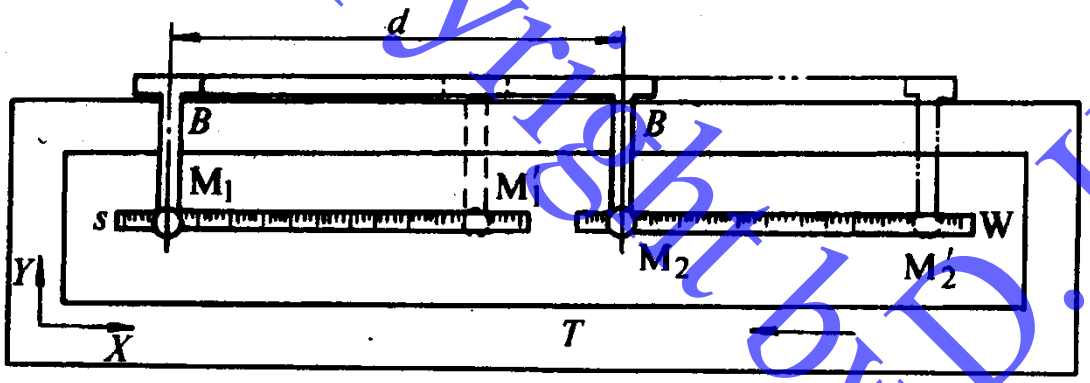
Dr. *Ernst Abbe* (1840-1905)

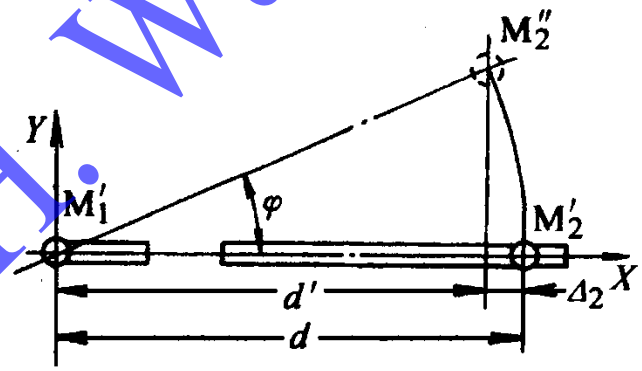
Abbe's Principle

- The Abbe Principle (Abbe's errors) resulted from observations about measurement errors
  - "If errors in parallax are to be avoided, the measuring system must be placed coaxially with the axis along which the displacement is to be measured on the workpiece."

E. Abbe, *Journal for Instrumental Information*, Vol. X, pp446-8, 1890.

Series Layout

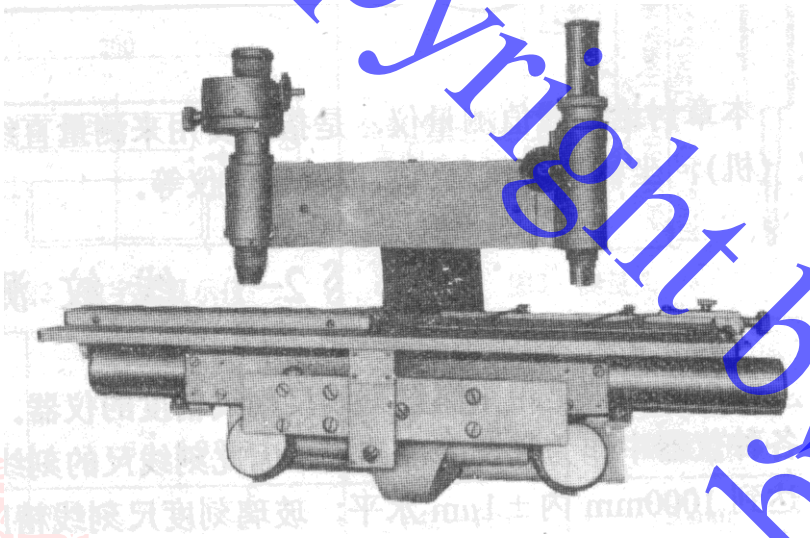


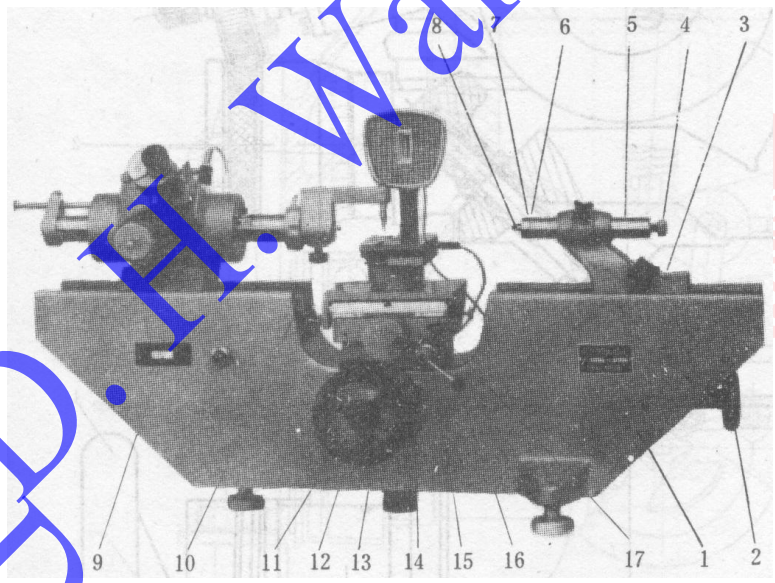


$$\Delta_2 = d - d' = d(1-\cos\varphi) \approx \frac{d\varphi^2}{2}$$

Ex: **If** $d = 1000\,\text{mm}$, $\varphi = 6''$, **then** $\Delta_2 = 4.5\times10^{-6}\,\text{mm}$

Cases Complying with Abbe's Principle



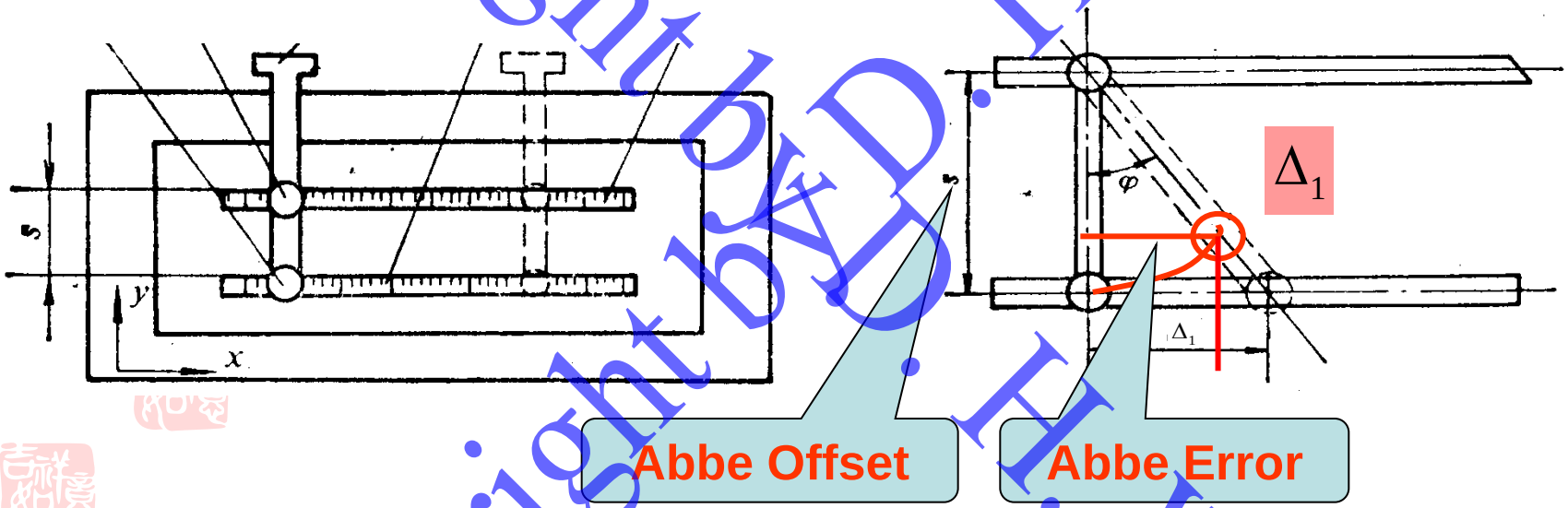


Abbe Length Measuring Machine↑

Universal Length Measuring Machine➔

Parallel Layout

- A measurement error that results when there is an angular misalignment between the desired line of measurement and the actual line of measurement.

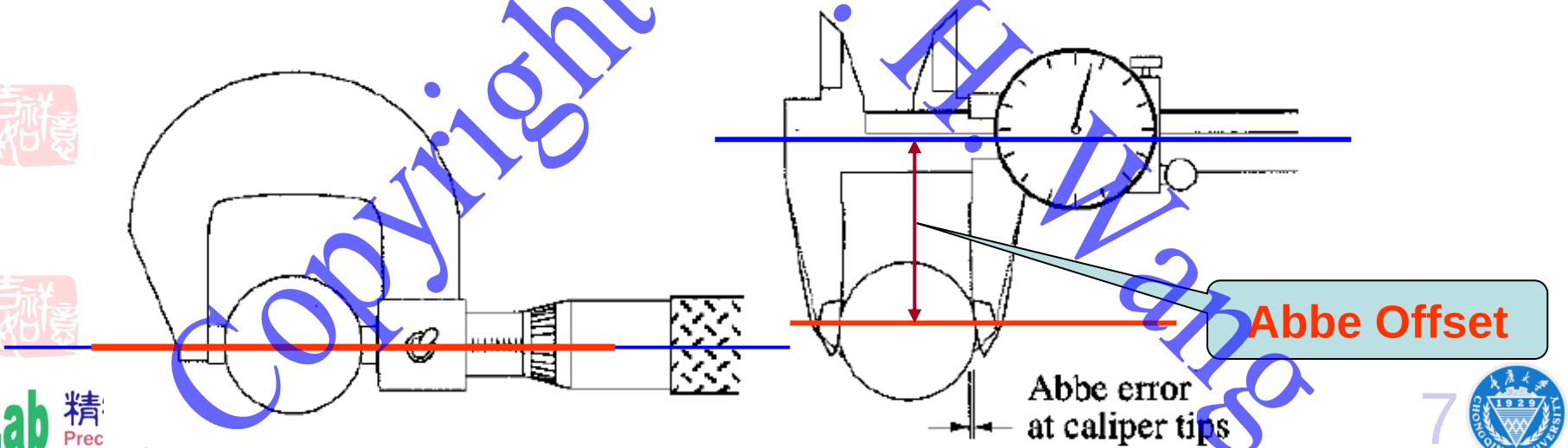


$$\Delta_1 = s\tan\varphi \approx s\varphi \qquad \Delta_1 = s\sin\varphi \approx s\varphi$$

Ex: **If** $s = 100\ \text{mm}$, $\varphi = 6''$ **, then** $\Delta_1 = 100\ \text{mm} \times 0.00003 = 0.003\ \text{mm}$

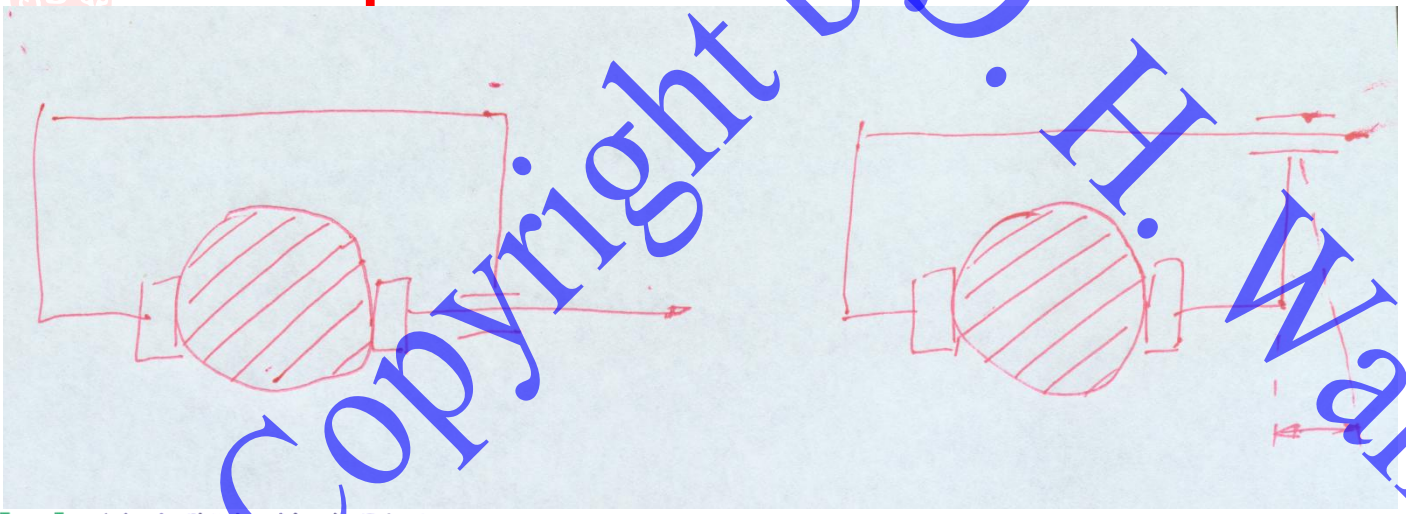
Locating Components (1/2)

- **Geometric: Angular errors are amplified by the distance from the source**
  - **Measure near the source, and move the bearings and actuator near the work!**
- **Thermal: Temperatures are harder to measure further from the source**
  - **Measure near the source!**



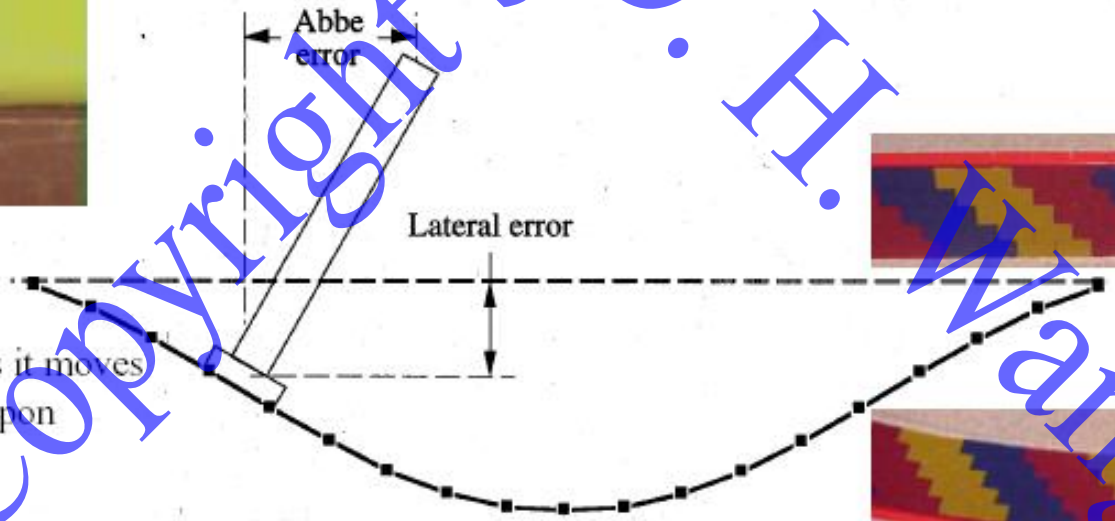
Locating Components (2/2)

- Thinking of Abbe errors, the system FRs (Function Requirements) is a powerful catalyst to help develop DPs (Design Parameters), where location of motion axes is depicted schematically.
  - Ex: Stick figures with arrows indicating motions are a powerful simple means of depicting strategy or concepts.



Cascading Errors

- A small angular deflection in one part of a machine quickly grows as subsequent layers of machine are stacked upon it…
- Designs must consider not only linear deflections, but angular deflections and their resulting Abbe Errors…

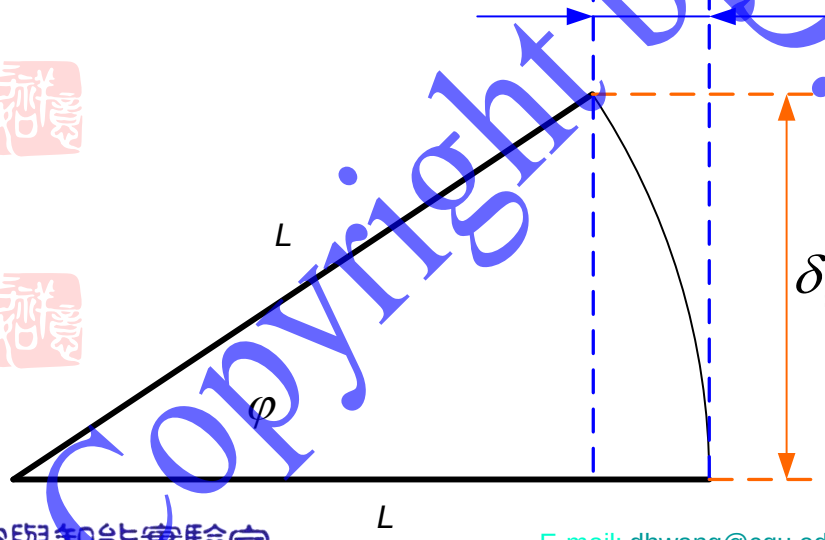


Motion of a column as it moves and deflects the axis upon which it rides

Cosine and Sine Errors

- When an angular error is amplified by a distance, to create an error in a machine's position, for example, the strict definition of the error is ***a sine or cosine error***
- ***Cosine errors*** have much less effect than ***Abbe errors***, but they are still important, particularly in large system.

$$\delta_{cosine\_error} = L(1-\cos\varphi) \approx \frac{1}{2} L\varphi^2$$



$$\delta_{\sin e\_error} = L\sin\varphi \approx L\varphi$$

Abbe's Principle

- The Abbe Principle emphasizes the significance of ***sine errors*** in a measurement system.
- In the context of Abbe, the concern is ***a changing angle (or angular motion).***
- In addition, a sine error may include a constant angular misalignment commonly referred to as a squareness error.

Abbe's Principle

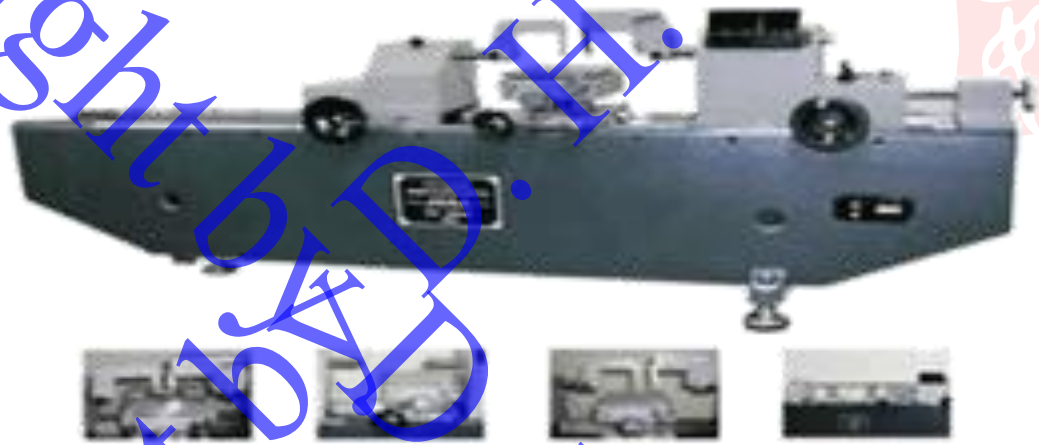
- Usually of lesser significance is the cosine error, which occurs when the distance measurement and the scale are not parallel. The cosine function is second order for small angles while the sine function is first order. Typically, the constant angular misalignment is most significant for a cosine error.
- In other words, you will get a linear error caused by the combination of an underlying angular error and a dimensional offset between the object being measured and the measuring device.
- Abbe offset and the consequential error resulting are pervasive in all kinds of instruments and equipment.

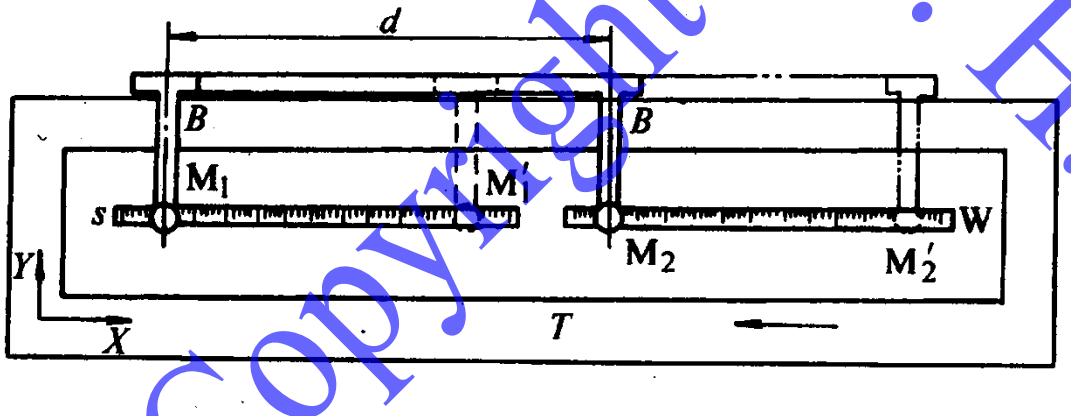
Abbe's Principle

- Be aware of Abbe's error, attempt to minimize it, or compensate for it.
- Suggestions from Abbe's Principle
  - Functional point should be in line with the measuring line
  - When the sine error exists, smaller Abbe's offset (h) required

Cases Contravening Abbe's Principle

- To abide by Abbe's Principle (*Series Layout*) will enlarge the size of the Length Measuring Machine.



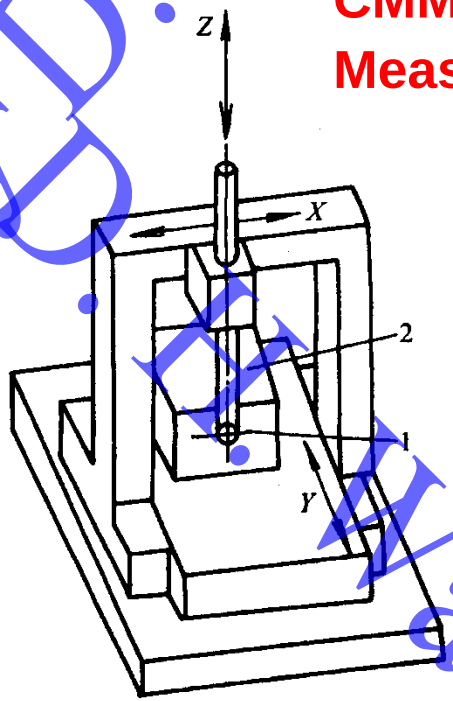


1m Projection length measuring machine

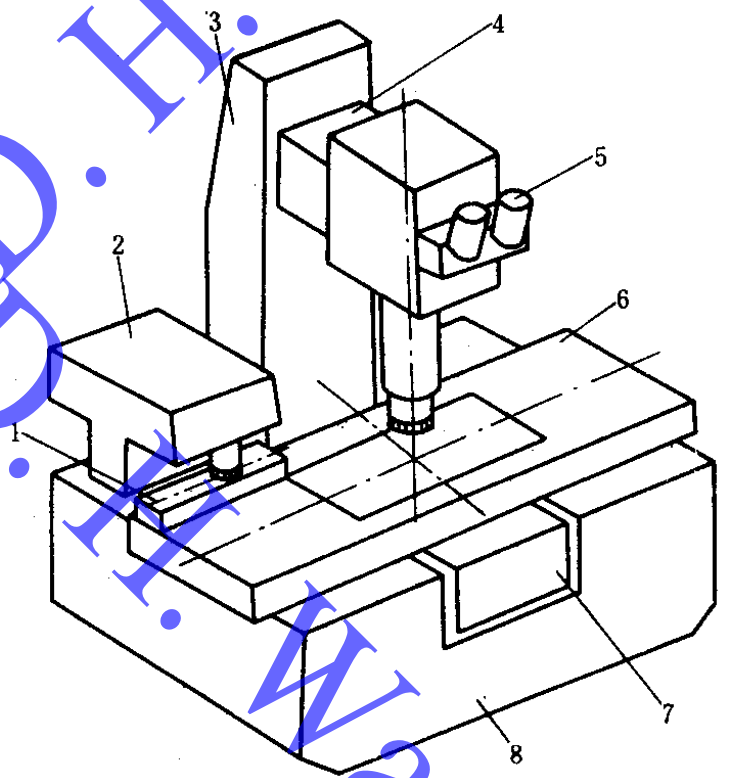
Cases Contravening Abbe's Principle

- It is generally difficult or impossible to abide by Abbe's Principle for all axes of motion on a machine without incurring additional expense for Multi-dimensional Measuring Machines.

CMM: Coordinate Measuring Machines



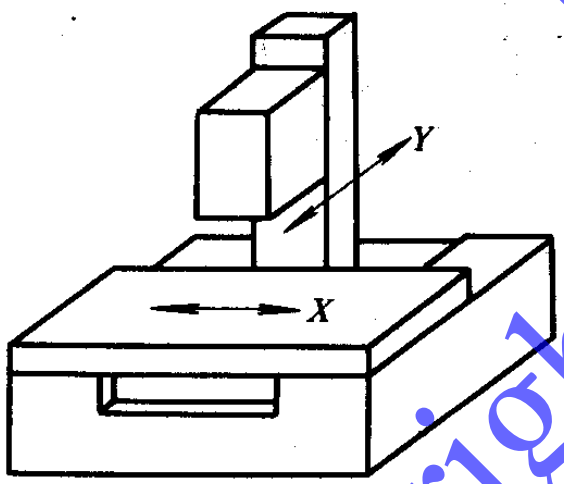
Cases Contravening Abbe's Principle

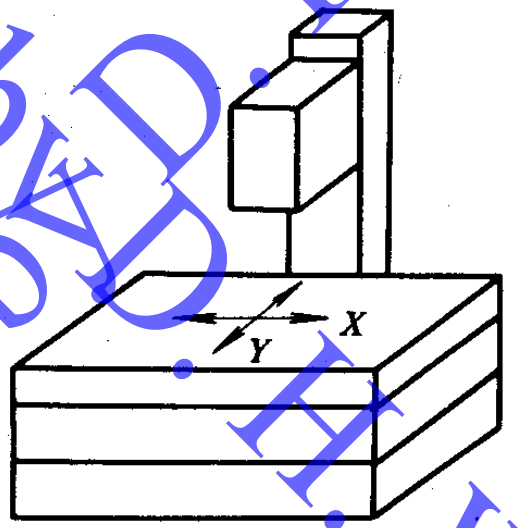


UTM--Universal Tool Microscope

Case Study: Universal Tool Microscope

- How to minimize Abbe's Error through:
  - Layout of Slideways
  - Position of Linear Scales (Sensors)



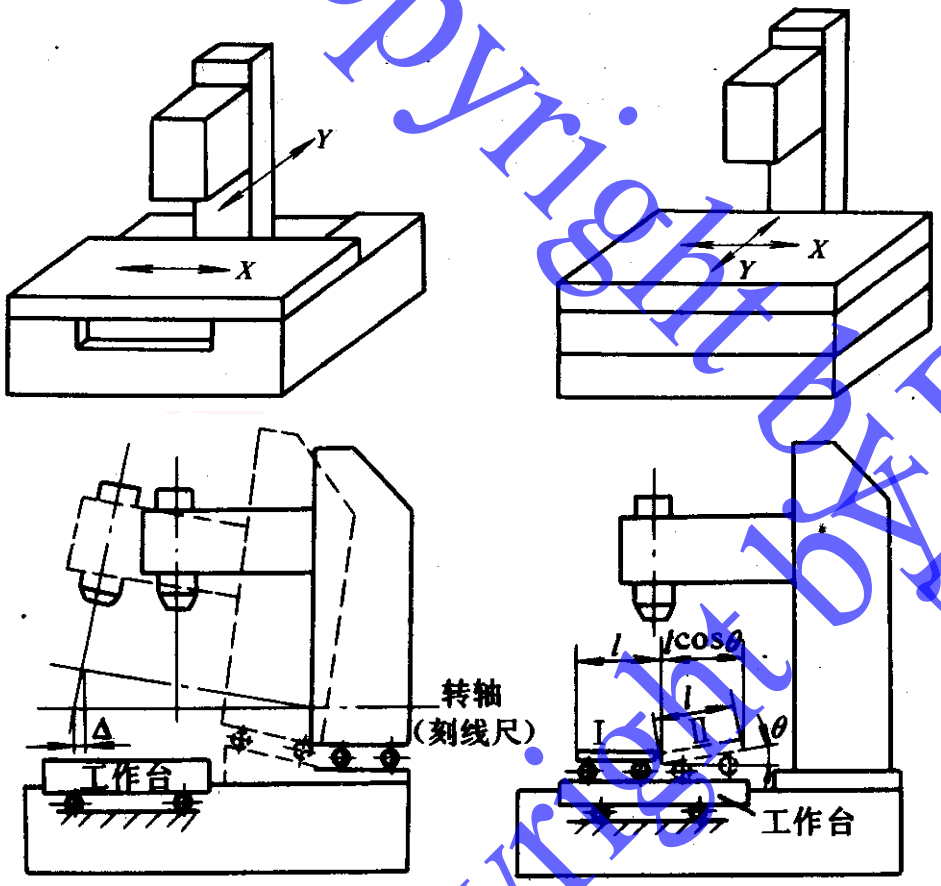


X—纵向
Y—横向

分体式(??)
立柱与横向导轨一起运动
横向（Y）标尺易于符合*Abbe原则*

合体式(??)
立柱不动
横向（Y）标尺难于符合*Abbe原则*

Case Study: Universal Tool Microscope



- How to minimize Abbe's Error by
  - Layout of Slideways
  - Position of Linear Scales (Sensors)
- 标准尺的安装是否符合阿贝原则，对仪器精度十分重要

立柱移动：Y向导轨有直线性误差⊿θ时，引起测量误差为一次误差(??)

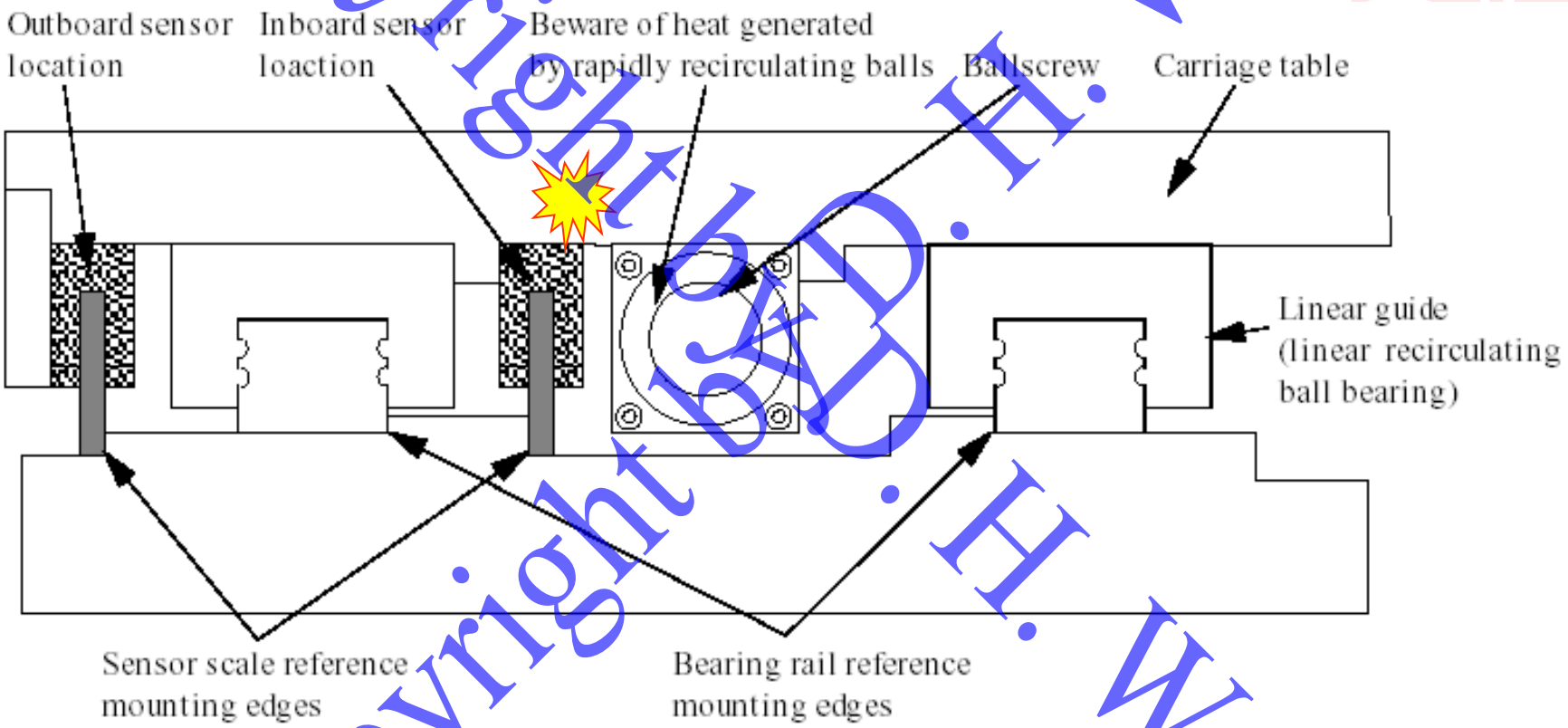
立柱不动：Y向导轨有直线性误差⊿θ时，引起测量误差为二次误差(??)

Locations of Linear Position Sensors

- The sensors must be carefully integrated into the system design.
- There are two principal options:
  - Fixed scale and moving read head, or vice versa
  - Inboard or Outboard mounting

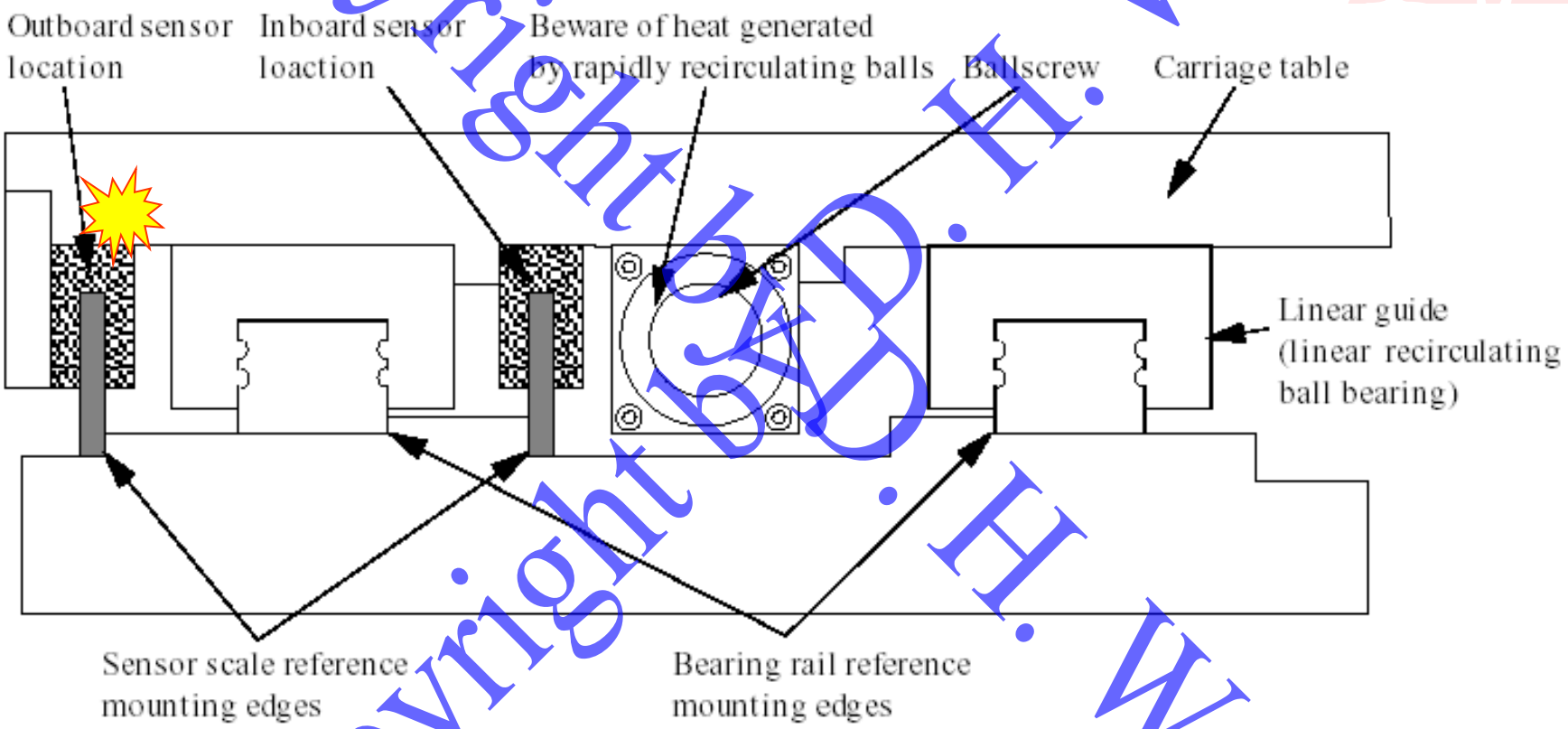
Locations of Linear Position Sensors

❒ Inboard Mounting



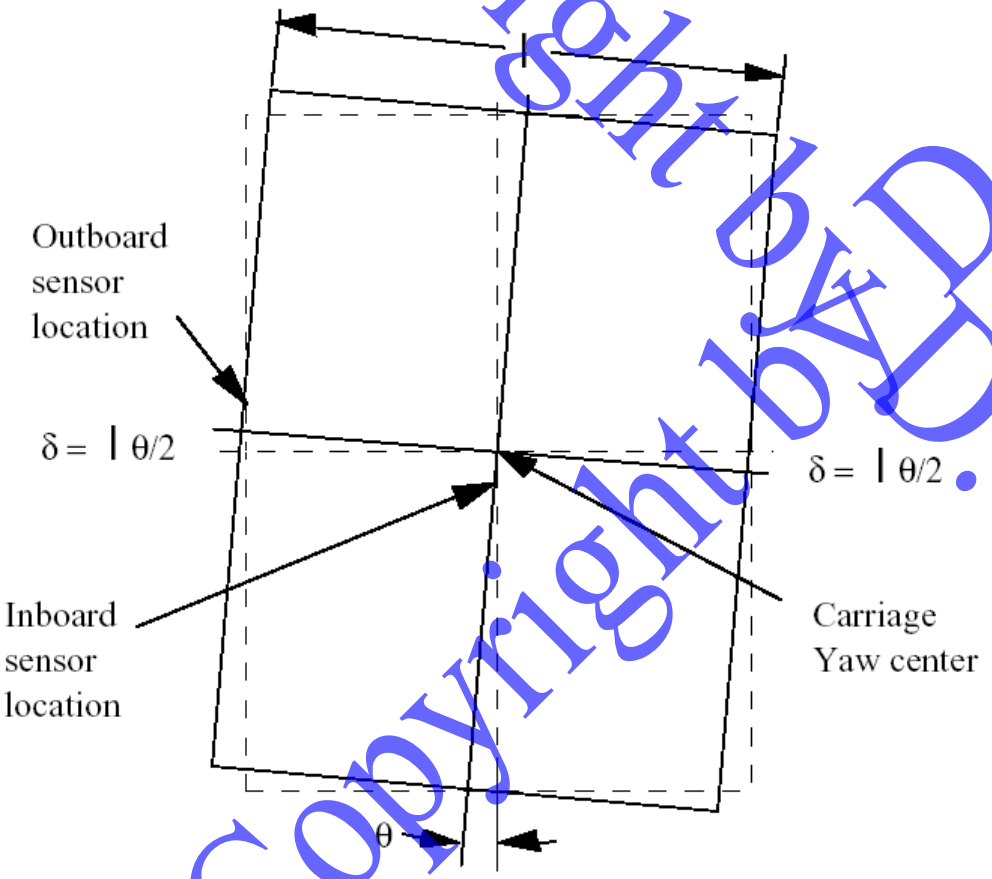
Locations of Linear Position Sensors

❒ Outboard Mounting

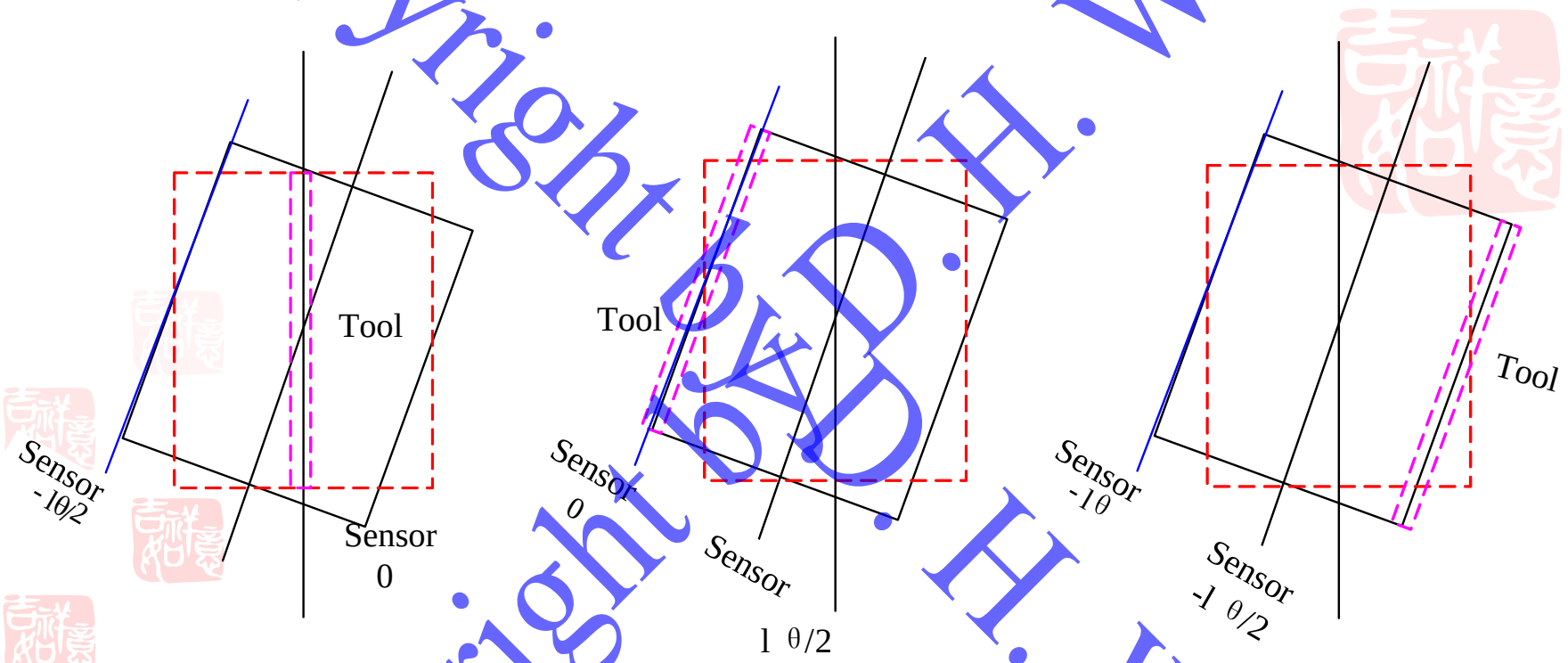


Locations of Linear Position Sensors

- **Abbe's Errors resulting from mounting a sensor at inboard and outboard locations**

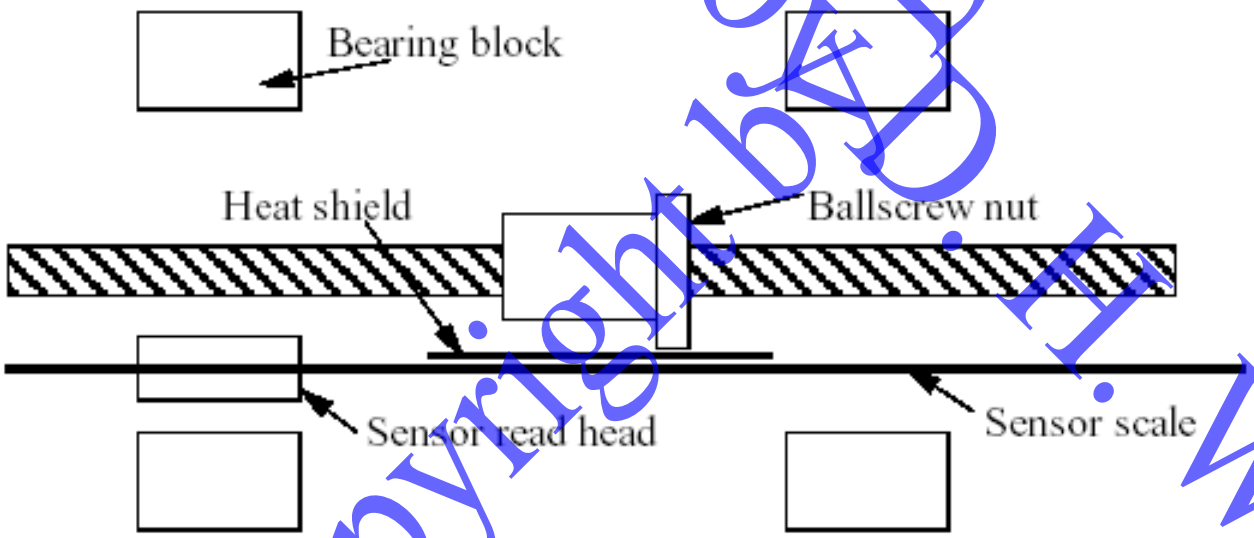


Locations of Linear Position Sensors



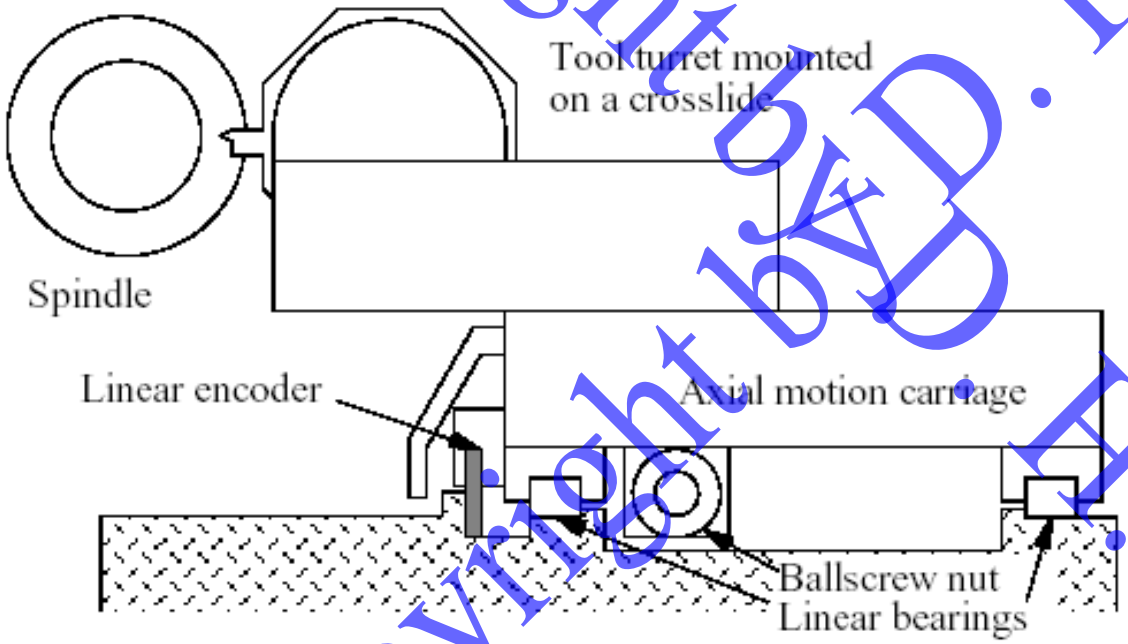
Locations of Linear Position Sensors

- For a machining center table, place the read head away from the ballscrew nut.
- Place a heat shield between the ballscrew nut and the scale.



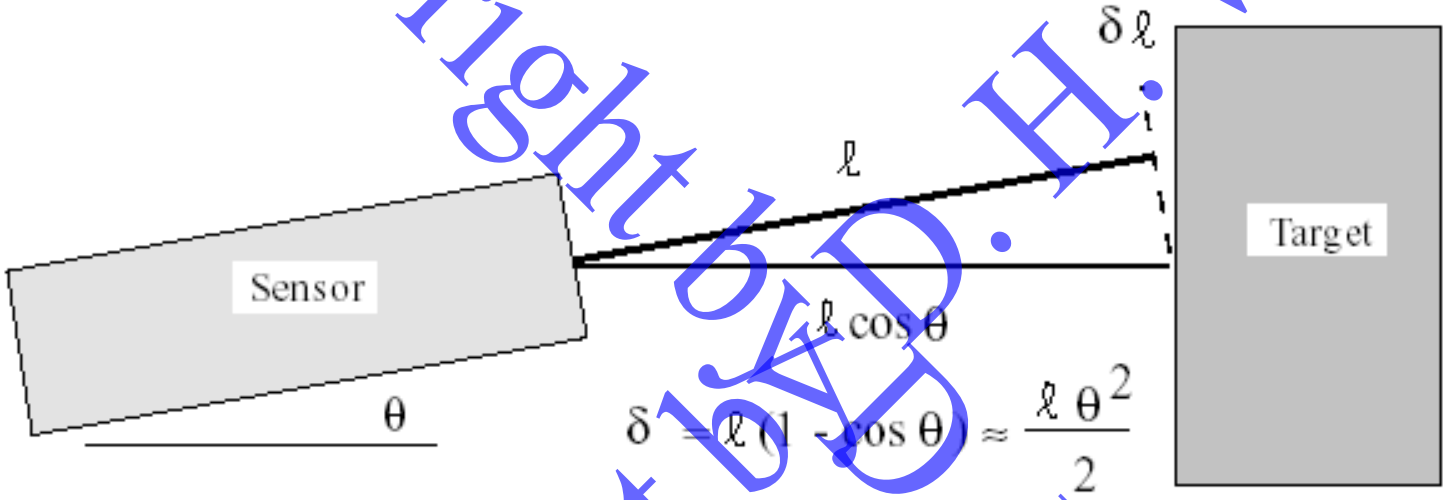
Locations of Linear Position Sensors

- For a lathe carriage, one wants the scale to be close to the spindle centerline



Locations of Linear Position Sensors

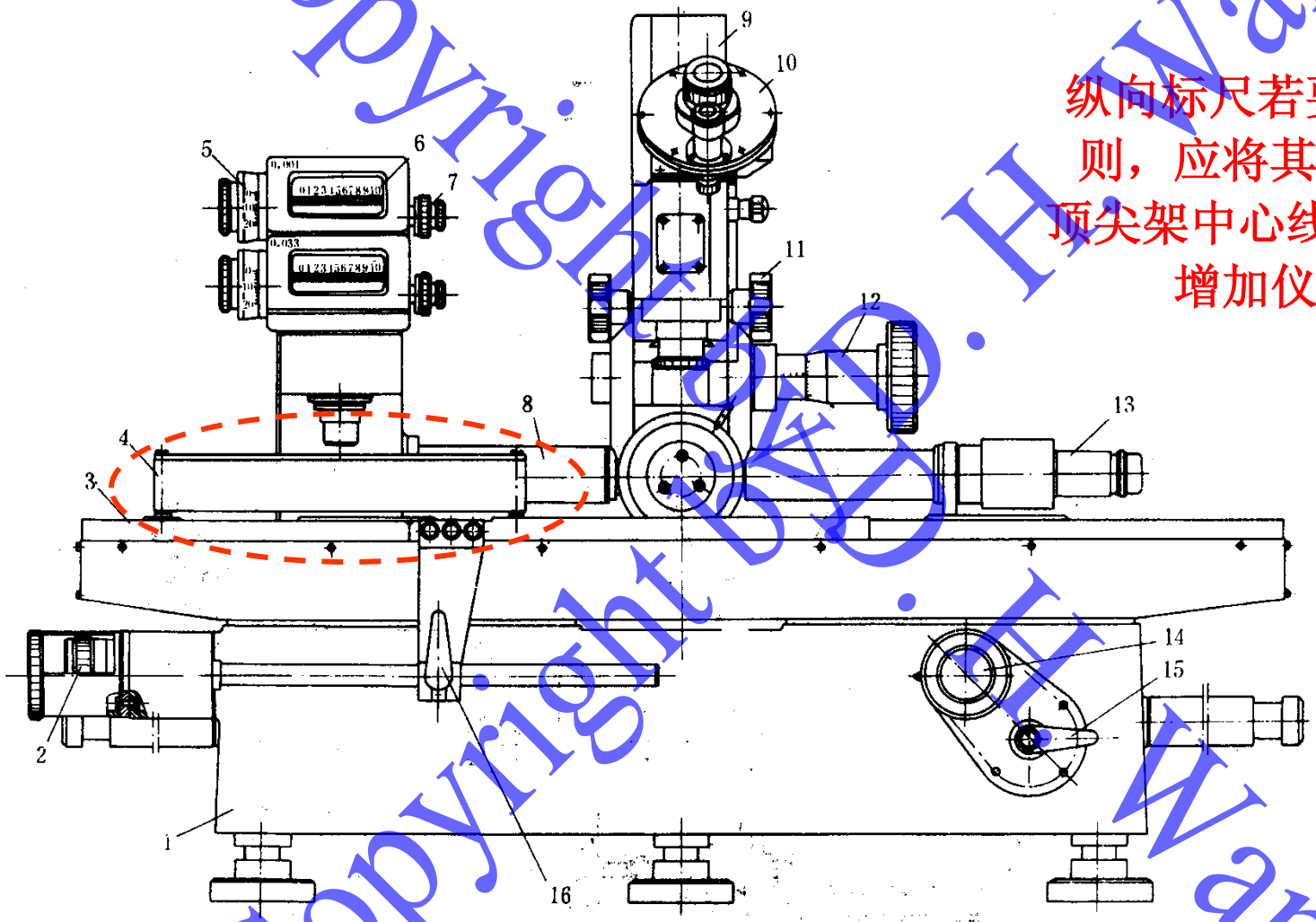
- Sensor alignment causing a *cosine error*



- Alignment surfaces machined in with other precision surfaces (e.g., bearings) can thus be very very useful!!

Alexander H. Slocum, *Precision Machine Design*, Prentice Hall, Inc., 1992

Universal Tool Microscope (19JA): 纵向标尺的安装

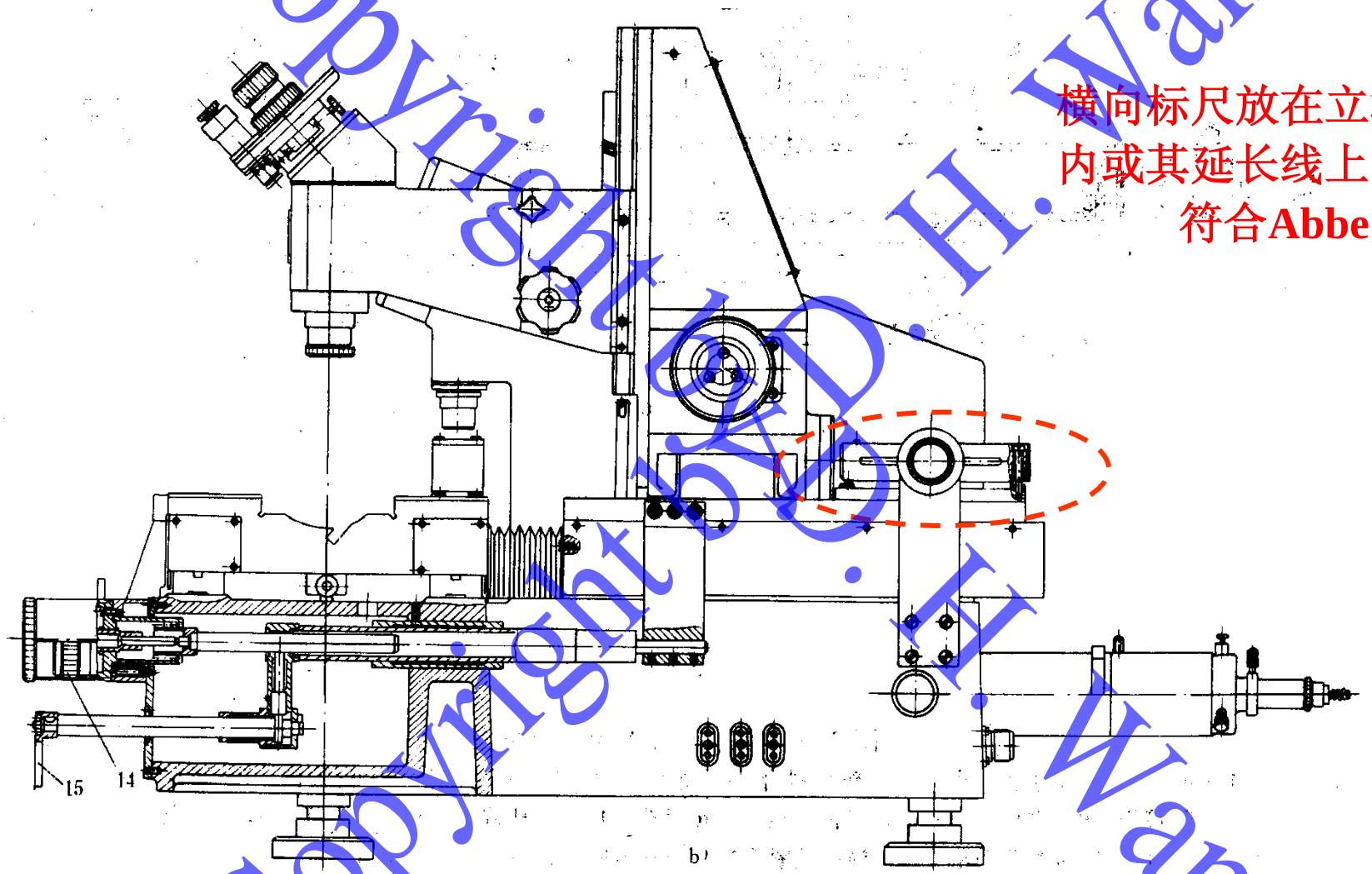


纵向标尺若要符合Abbe原则，应将其放在纵向滑台顶尖架中心线的延长线上，增加仪器纵向长度。

3--纵向滑台

4--纵向标尺

Universal Tool Microscope: 横向标尺的安装



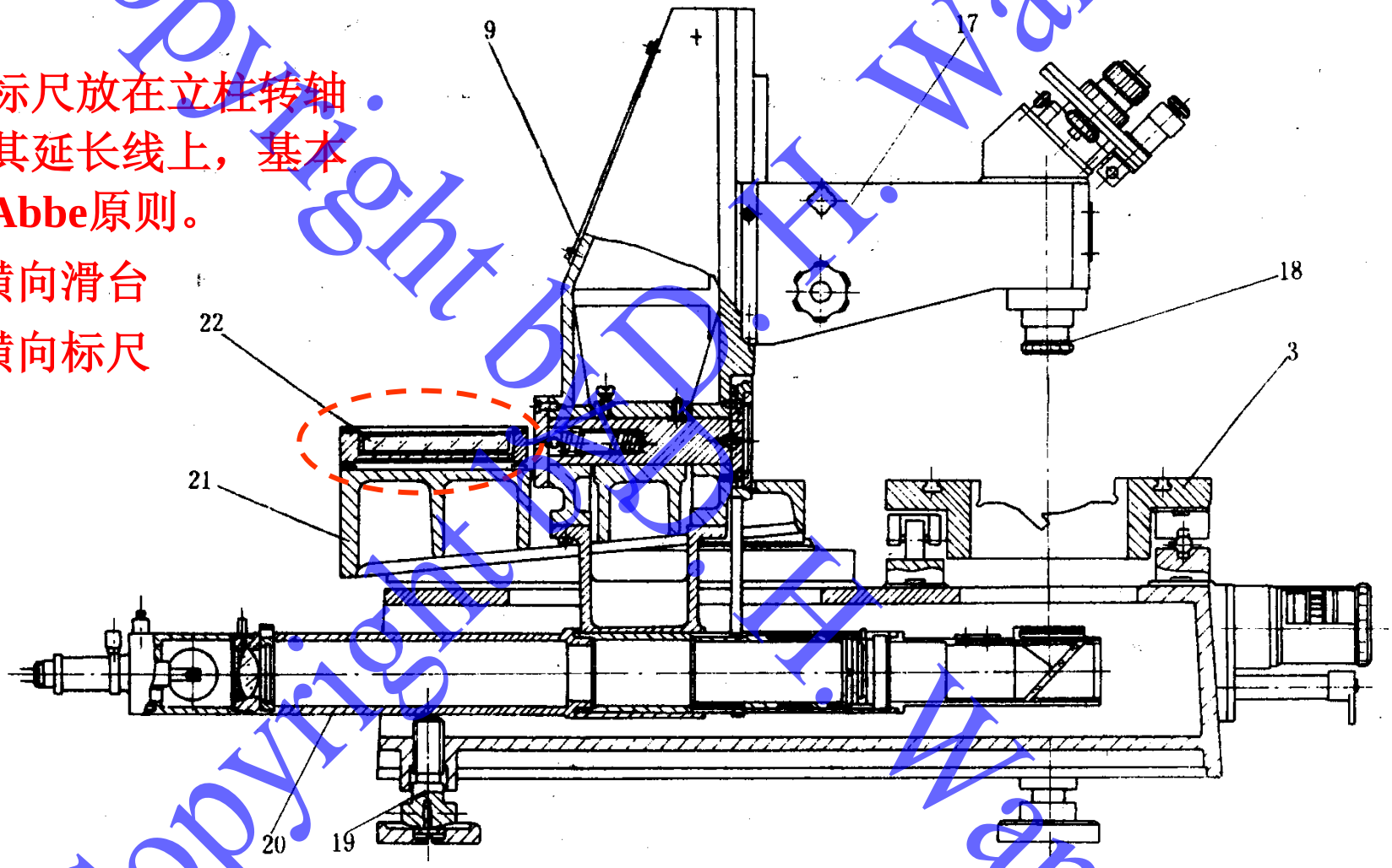
横向标尺放在立柱转轴内或其延长线上，基本符合**Abbe**原则。

Universal Tool Microscope: 横向标尺的安装

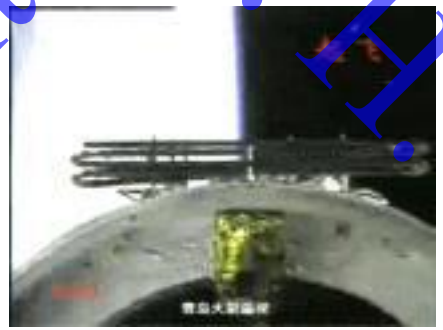
横向标尺放在立柱转轴内或其延长线上，基本符合Abbe原则。

21--横向滑台

22--横向标尺



神舟6号载人航天：飞天双人舞



“首颗探月卫星‘嫦娥一号’发射成功”/24日18时05分

Outline

- Bryan's Proposal
- Generalized Abbe's Principle
  - Functional point should be in line with the measuring line
  - Zero Angular Motion of the Slide
  - Compensating for the Abbe's Error

Bryan's Proposal

- "The displacement measuring system（位移量测量系统）should be in line with ***the functional point*** whose displacement is to be measured*. If this is not possible, either the slideways that transfer the displacement must be free of angular motion, or angular motion data must be used to calculate the consequences of the offset."

The path of the effective point of a displacement measuring system should be colinear with the path of the functional point whose displacement is to be measured.

J. B. Bryan, The Abbe Principle Revisited: An Updated Interpretation, *Precision Engineering*, Vol. 1, No. 3, 129-132, 1979.

Bryan's Proposal

- The key point of Bryan's this proposal is that the case, when we can compensate the angular motion of the measuring device by certain hardware to make it have no angular motion or to compensate the Abbe error by software, should be treated as complying with the Abbe's principle.
- The original Abbe's Principle was modified by Bryan to allow the use of modern techniques to reduce the ***sine error*** to an acceptable level either by
  - controlling the slide to have zero angular motion or
  - by measuring the angular motion and compensating for the sine error.

Generalized Abbe's Principle

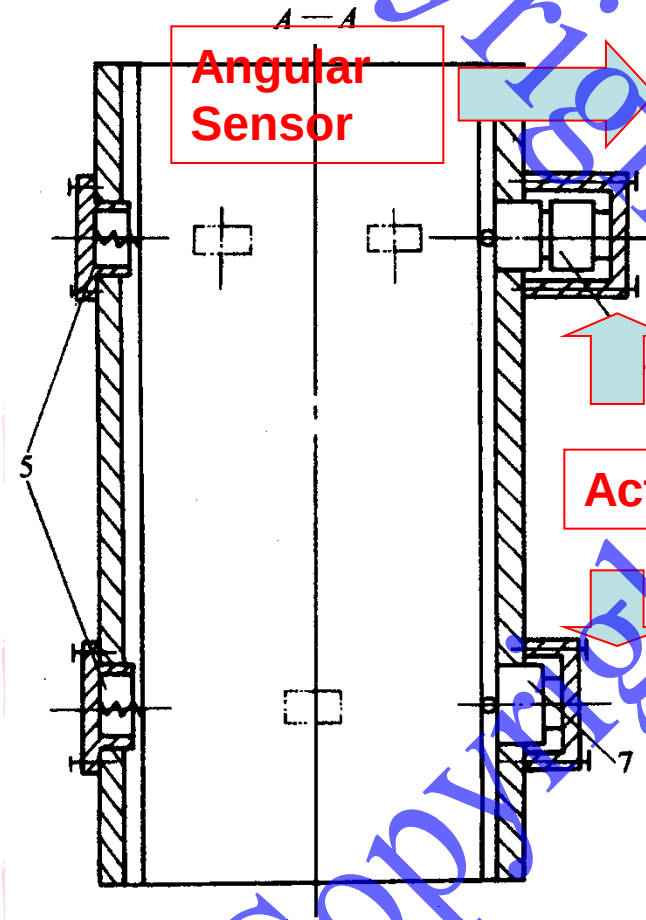
- **Extension of Abbe's Principle (*the Generalized Abbe's Principle*)**
  - ***Functional point should be in line with the measuring line;***
  - **Zero angular motion of the slide;**
  - **Measuring the angular motion and compensating for the sine error.**

Zero Angular Motion of the Slide

- 基本思路
- Ex. ***Laser 2-D CMM***

Zero Angular Motion of the Slide

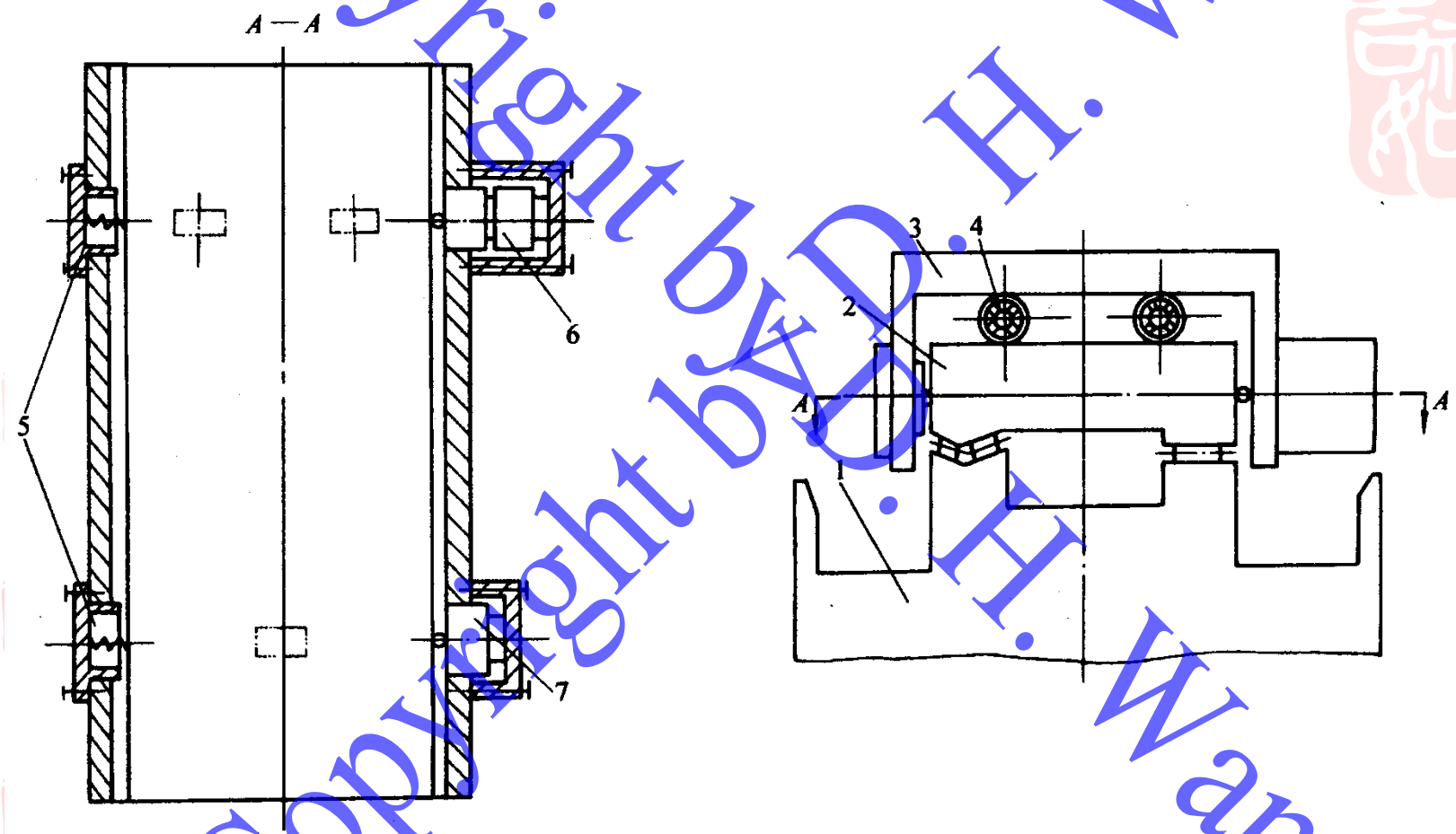
❒ 基本思路



Angular Sensor → Signal Conditioning System → Controller → Power Driver → Actuator → Angular Sensor

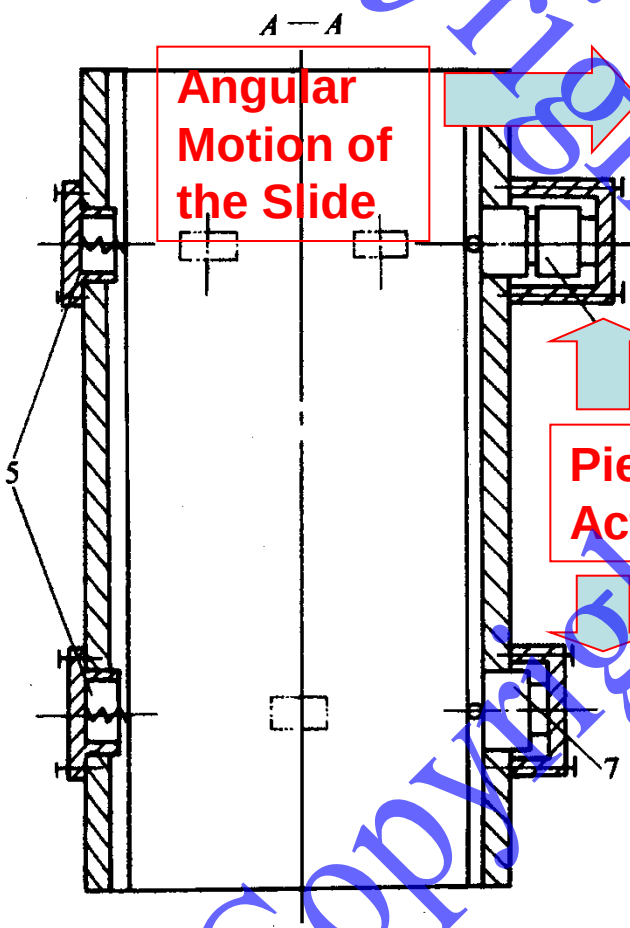
Zero Angular Motion of the Slide

❒ Configuration



Zero Angular Motion of the Slide

❒ Detailed schematic



Angular Motion of the Slide

Laser Small Angular Measuring System

Signal Conditioning

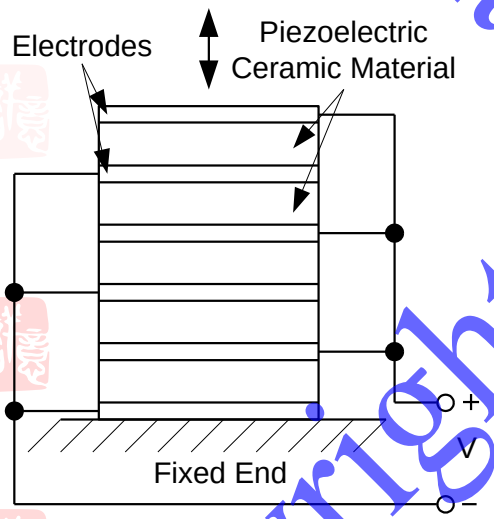
Controller

Power Driver

Piezo Actuator

Zero Angular Motion of the Slide

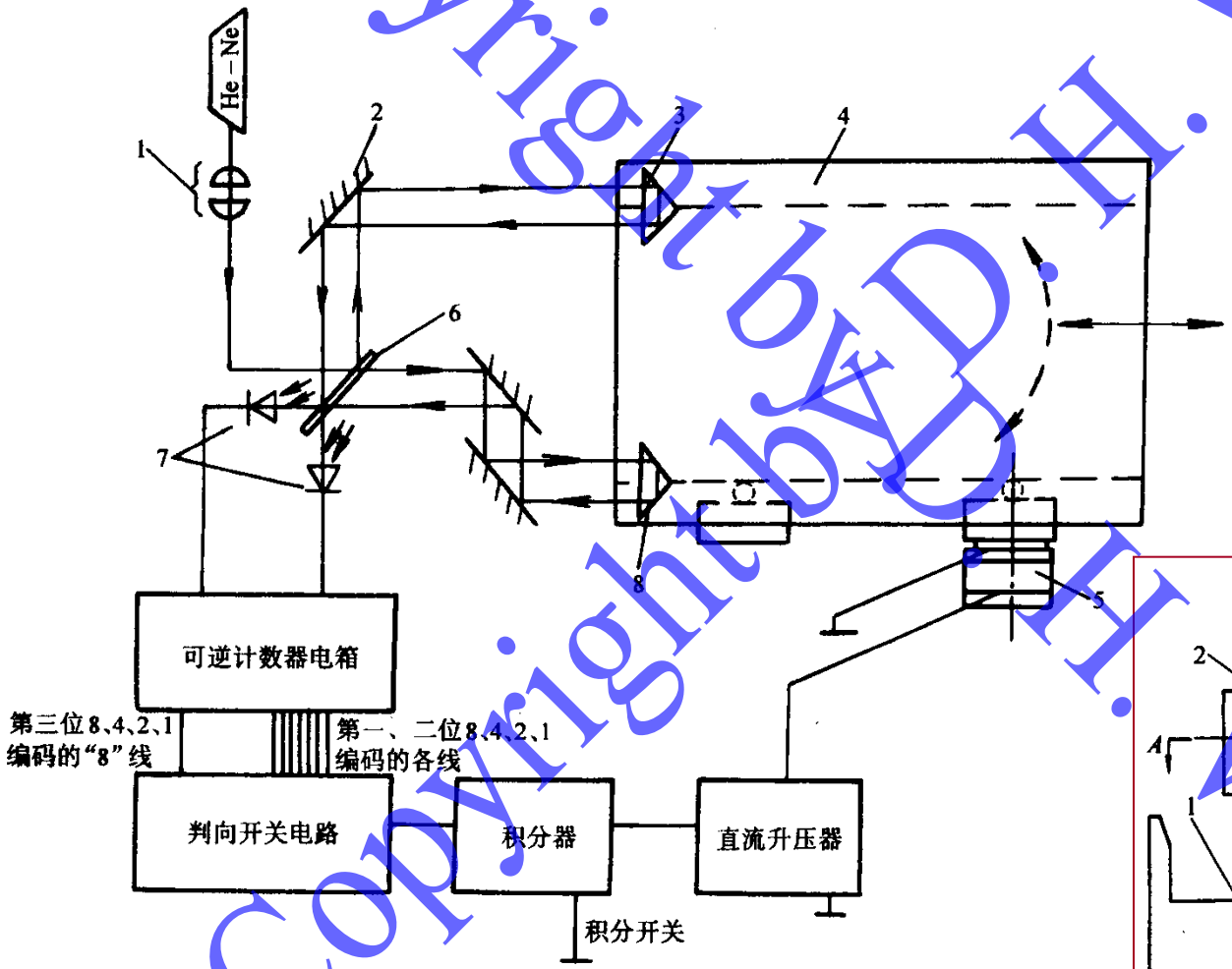
- **Sensor**
  - Laser Small Angluar Measuring System
- **Piezoelectric Effect and Piezoelectric Actuator**

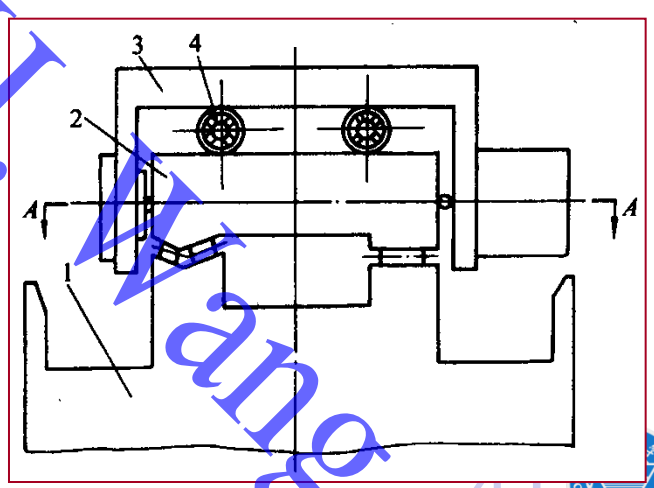


- **Controller**

Zero Angular Motion of the Slide

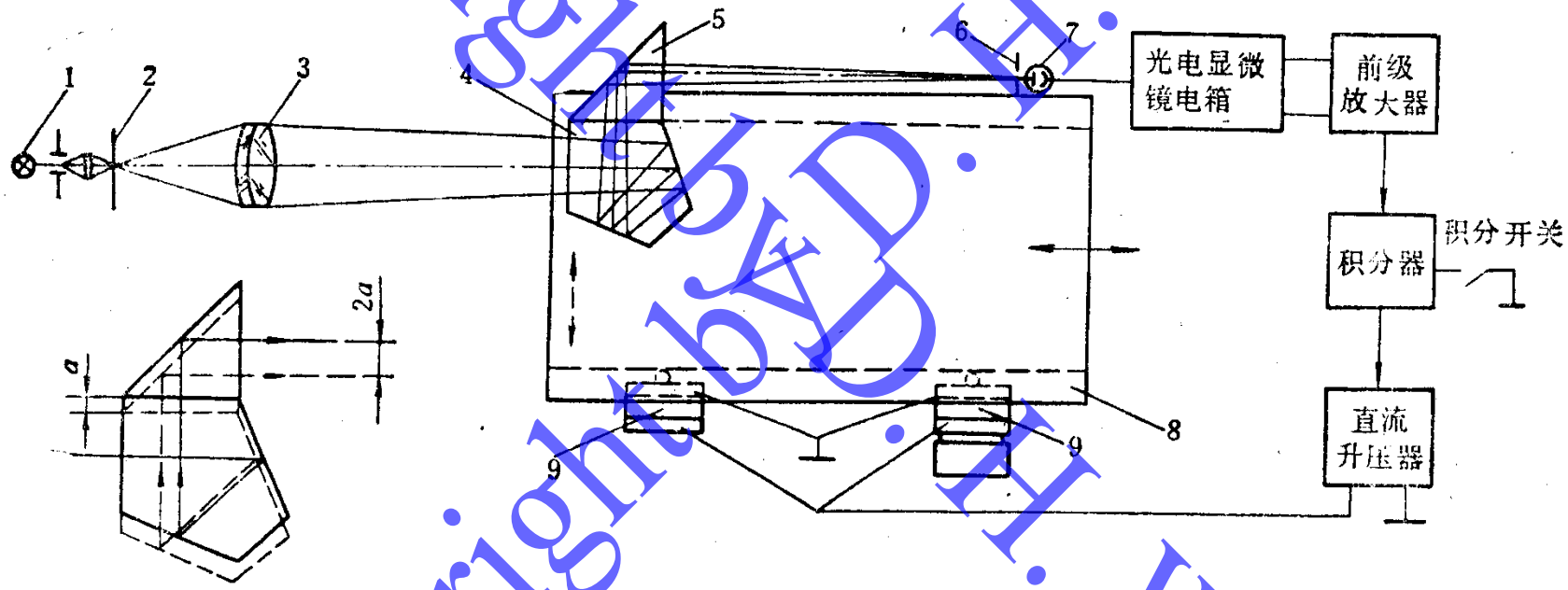
❒ Detailed schematic





Zero Angular Motion of the Slide

❒ 导轨平移的消除



Compensating for the Abbe's error

- 基本思路
- Eppenstein's Principle
  - Real-Time Corrected Abbe Error
    - 1 m Projection Length Measuring Machine
- Measuring the angular motion and compensating for the sine error

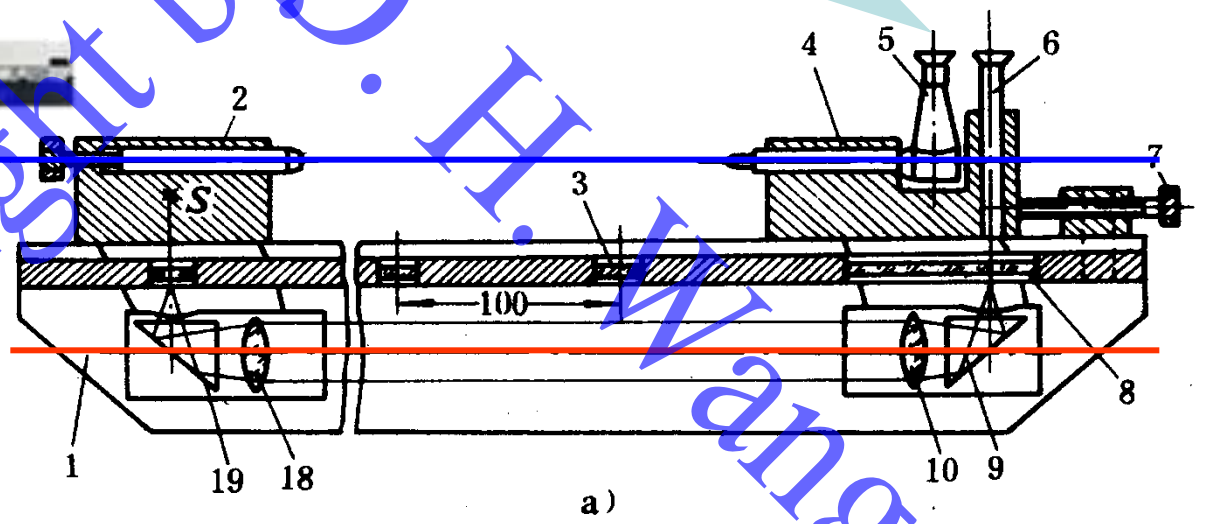
Compensating for the Abbe's error

- 基本思路
  - 通过仪器的结构设计在测量过程中自动消除

Eppenstein's Principle

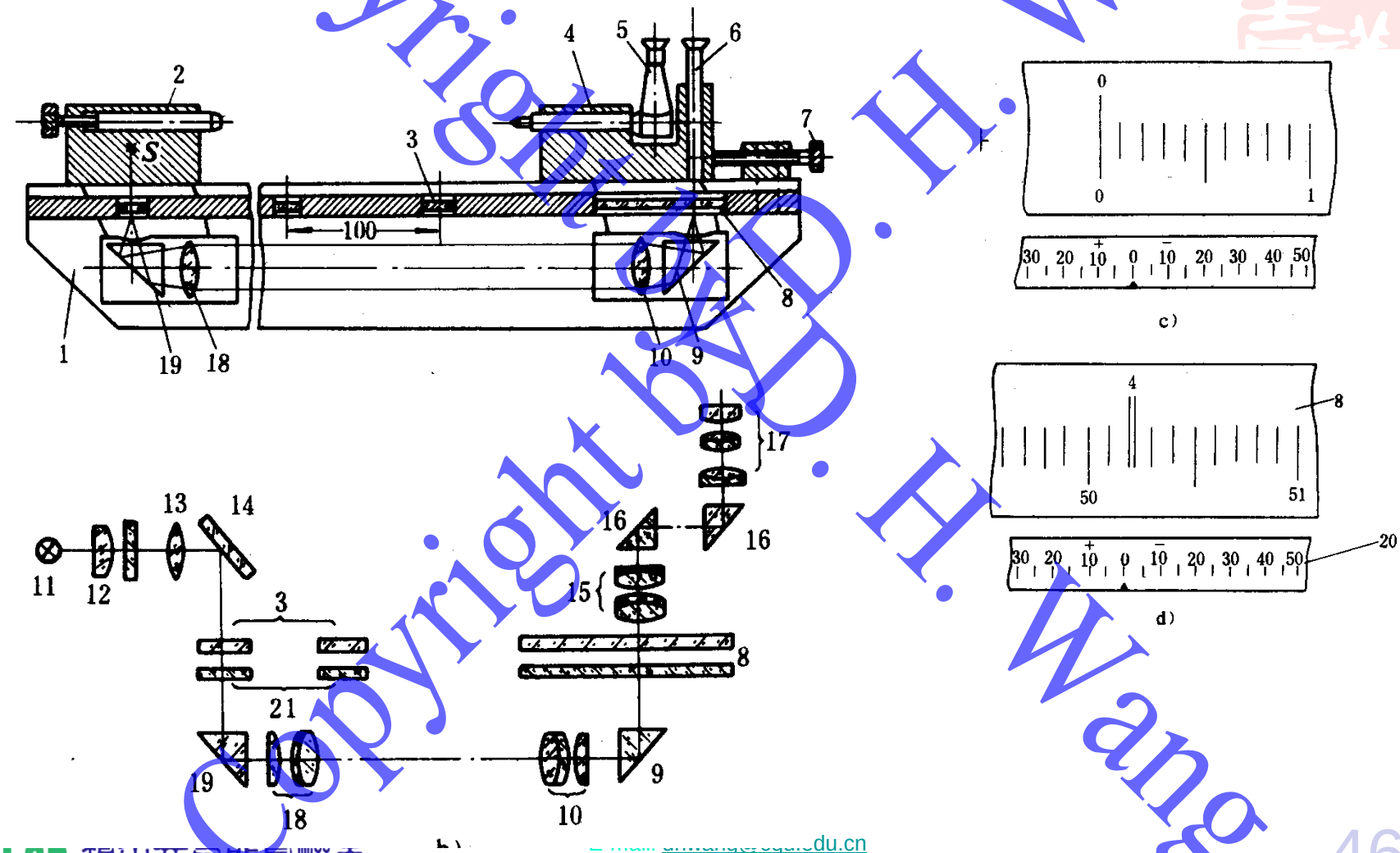
- The functional point is not in line with the measuring line
- Real-time error-corrected the Abbe error with Eppenstein's principle

Optical Micrometer



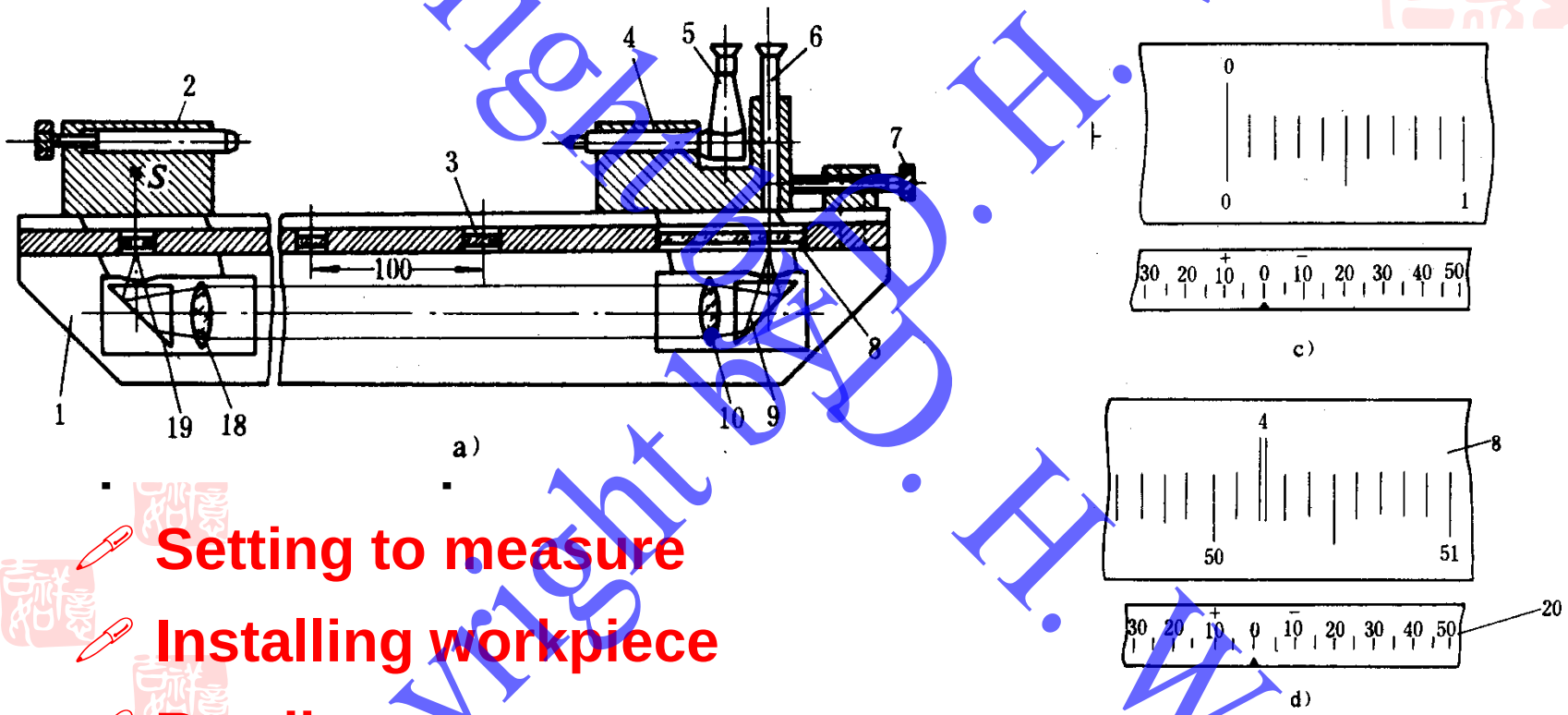
Eppenstein's Principle

❒ 1 m Projection Length Measuring Machine



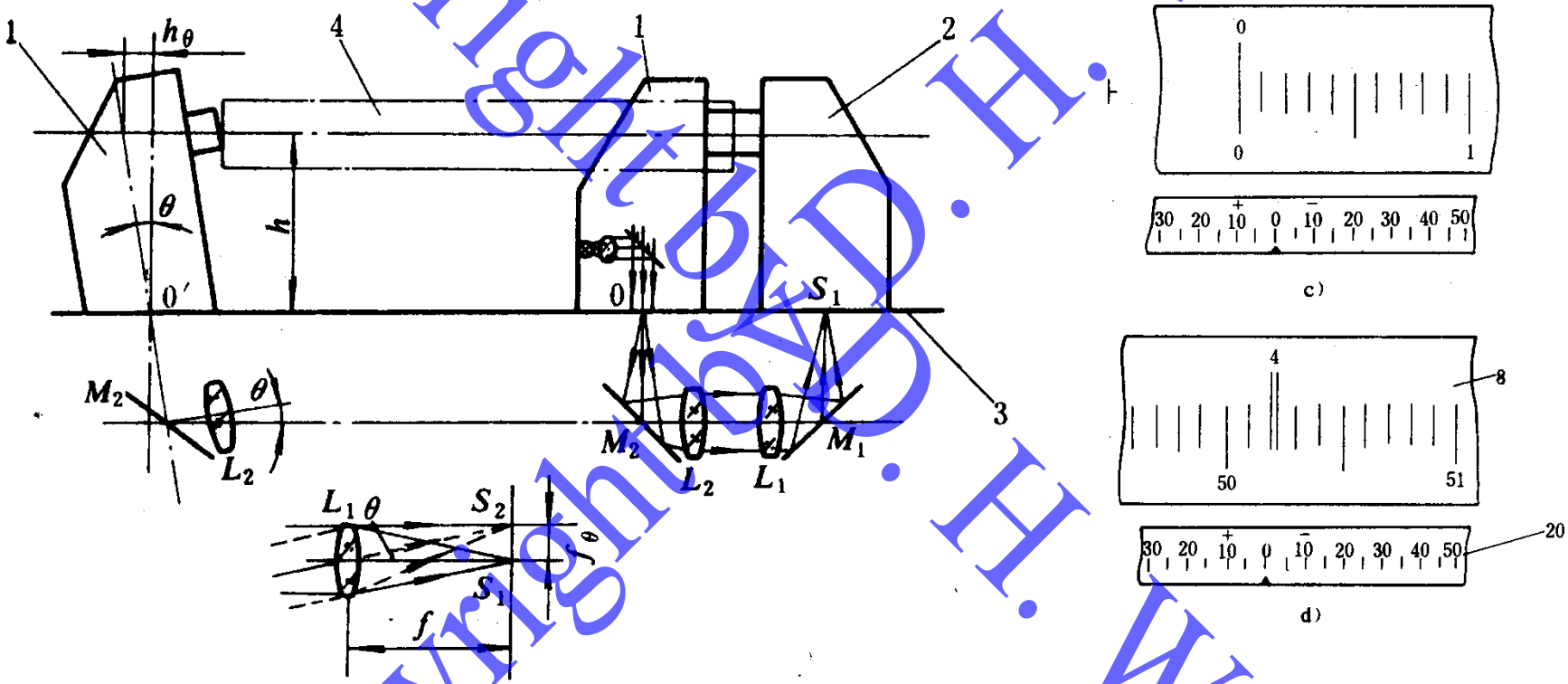
Eppenstein's Principle

❒ 1 m Projection Length Measuring Machine

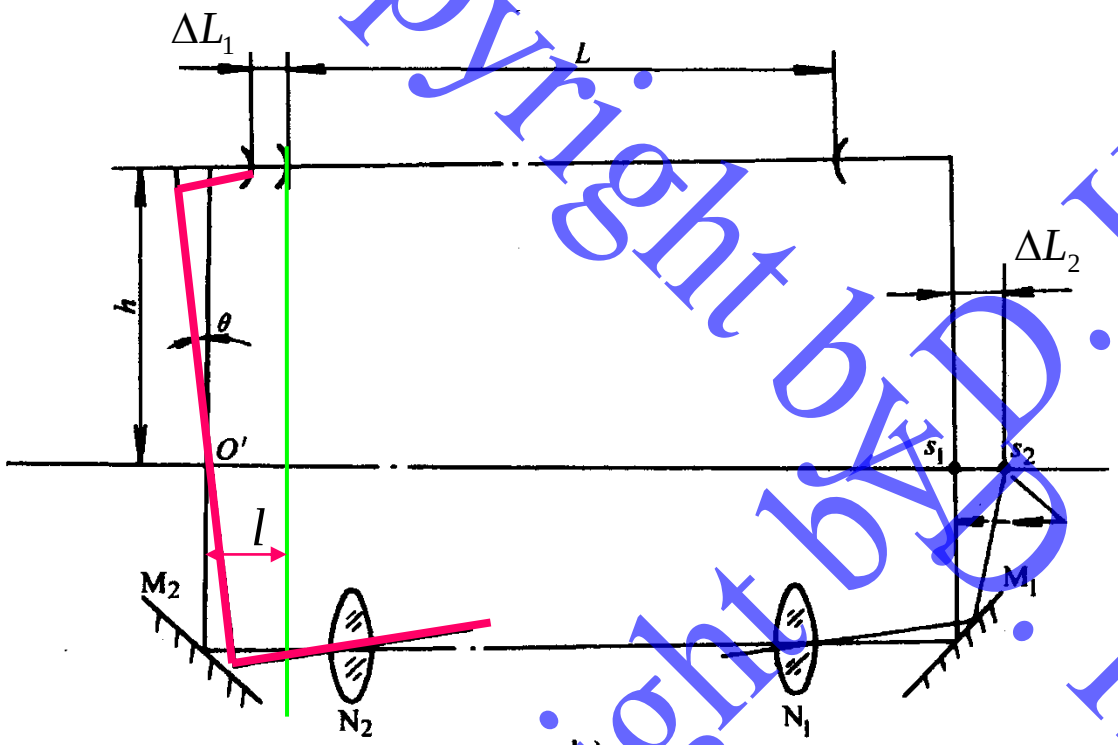


- Setting to measure
- Installing workpiece
- Reading

Eppenstein's Principle



Eppenstein's Principle



❒ 前提条件

对称系统

→

$$\Delta L_1 = l - (l\cos\theta - h\sin\theta)$$

$$\Delta L_2 = \overline{s_1 s_2} = F\tan\theta$$

$$\Delta L = \Delta L_1 - \Delta L_2$$

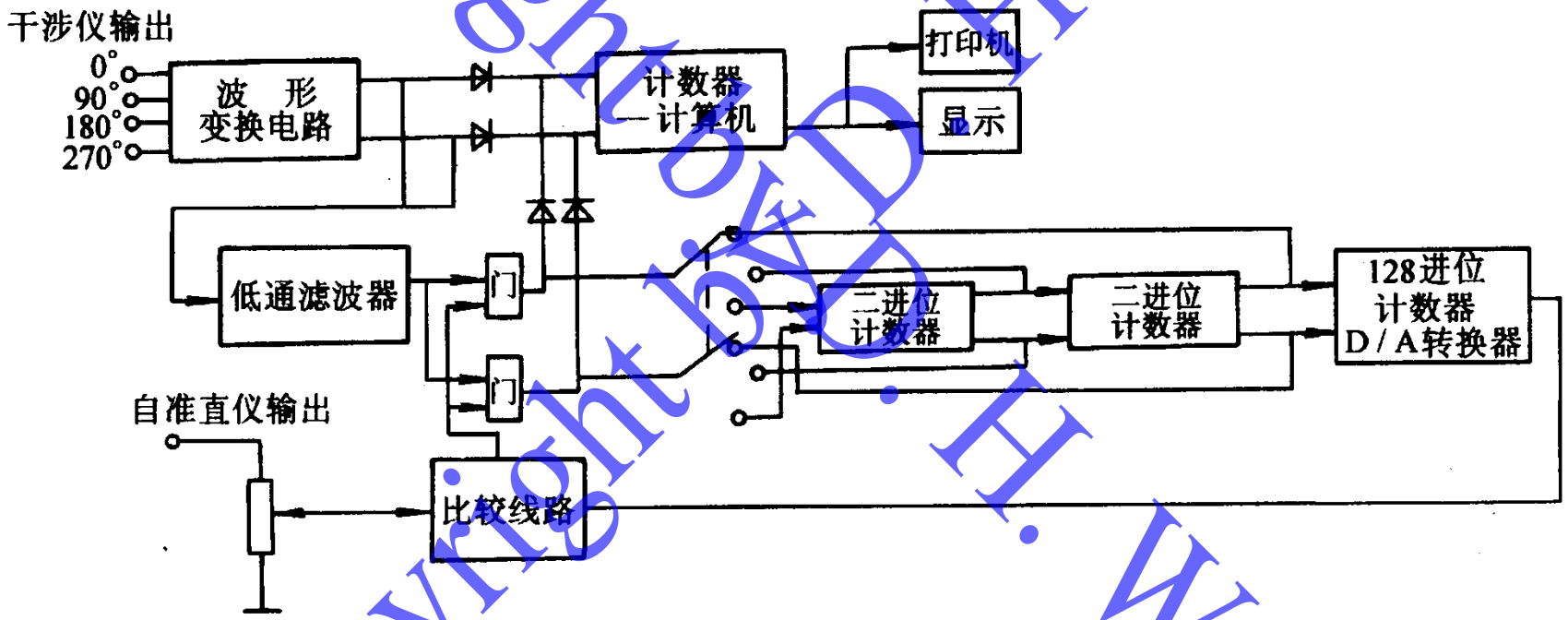
$$= (h - F)\theta + l\frac{\theta^2}{2}$$

$$h = F$$

$$\Delta L \approx l\frac{\theta^2}{2}$$

Compensate Abbe's Error

- Measuring the angular motion and compensating for the sine error



Bryan's Principle

- **Bryan's Principle**
  - **For straightness measuring system**

Bryan's Principle

- Bryan compares the output of an autocollimater (自准直仪) with reflector on the feet of a slide moving over a surface and an electronic displacement indicator indicating between a parallel and a reference surface in various positions with respect to the slide.
- The purpose of the exercise is to measure the straightness of surface and angular motion to demonstrate the effect of several variables of the measurement system on the results.
- Bryan points out people often mistakenly assume that one point on a large mass, like a machine tool, moves in the same manner as other points on the mass.

Bryan's Principle

- A similar mistakes are made for the slideway straightness.
- "*Slide straightness error* is the non-linear movement that an indicator sees when it is either stationary and reading against a perfect straightedge supported on a moving slide or moved by the slide along a perfect straightedge which is stationary."

Bryan's Principle

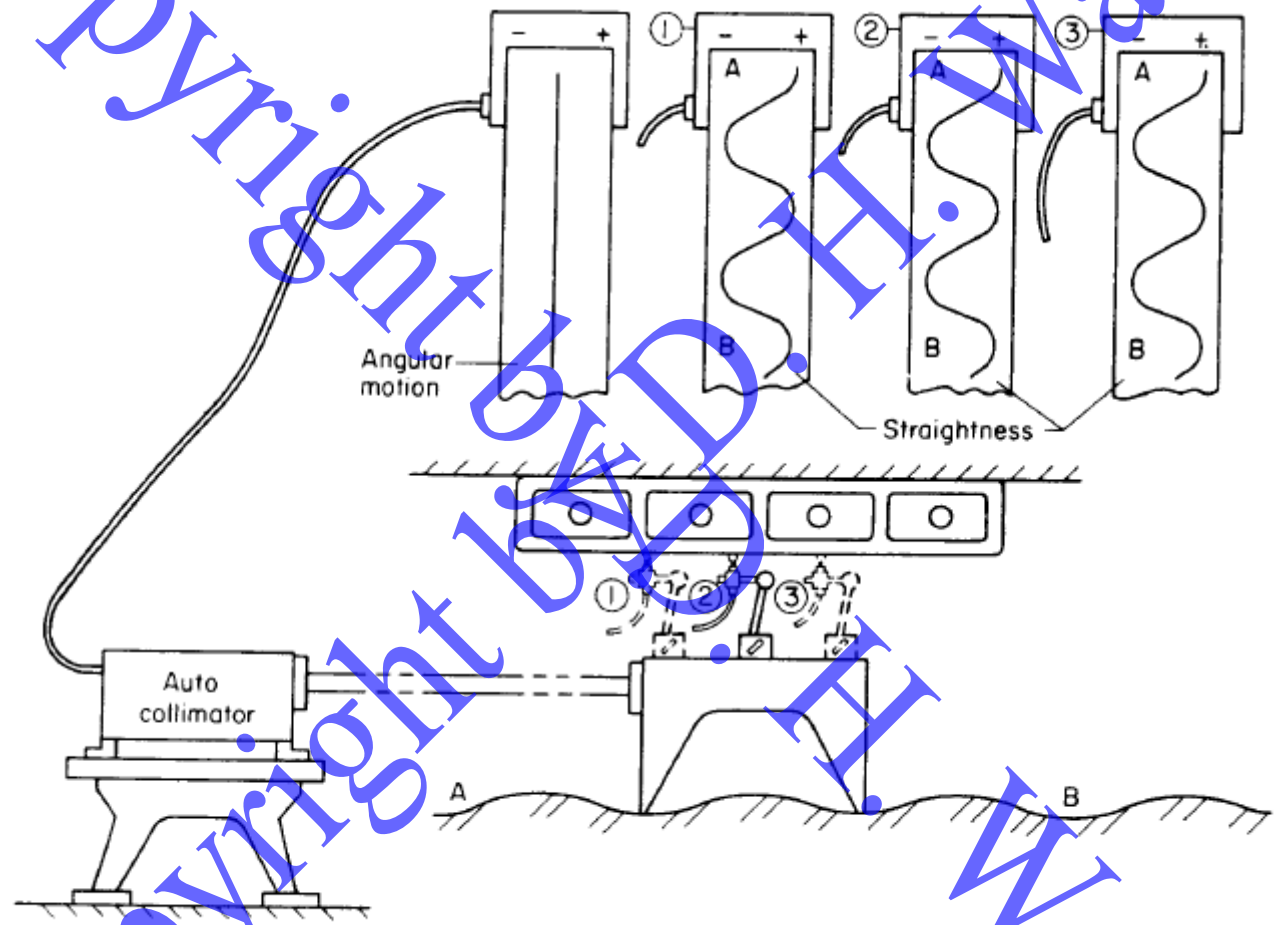
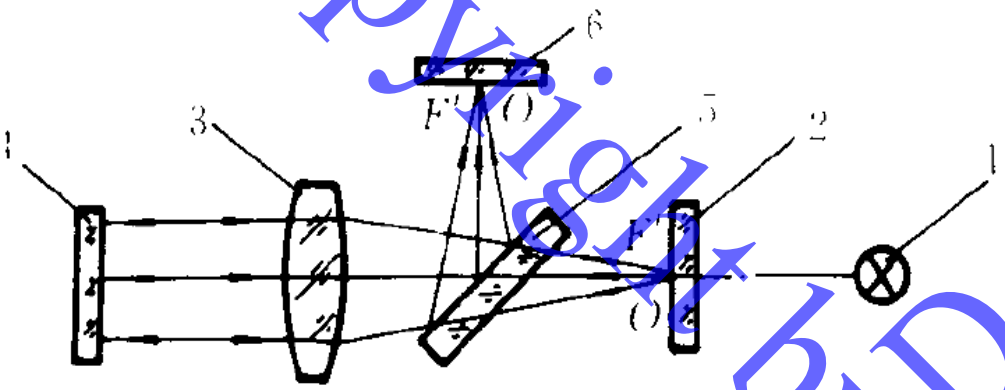
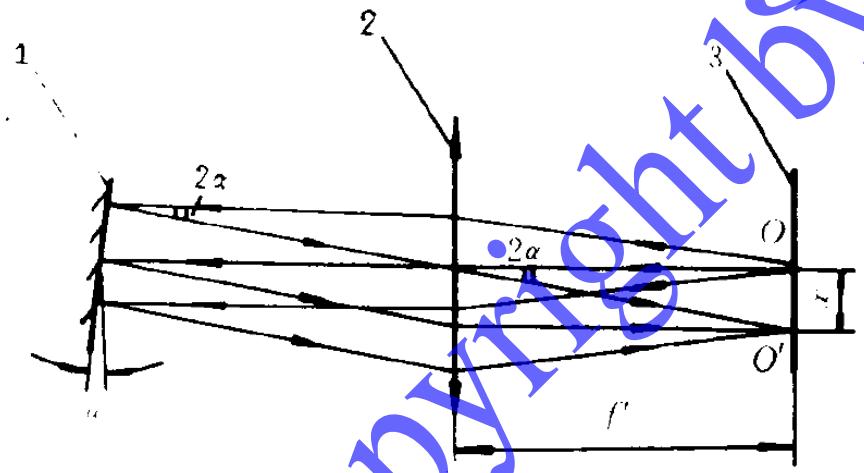


Fig 1 Stationary straightedge; no angular motion

自准直仪: 光学自准直原理

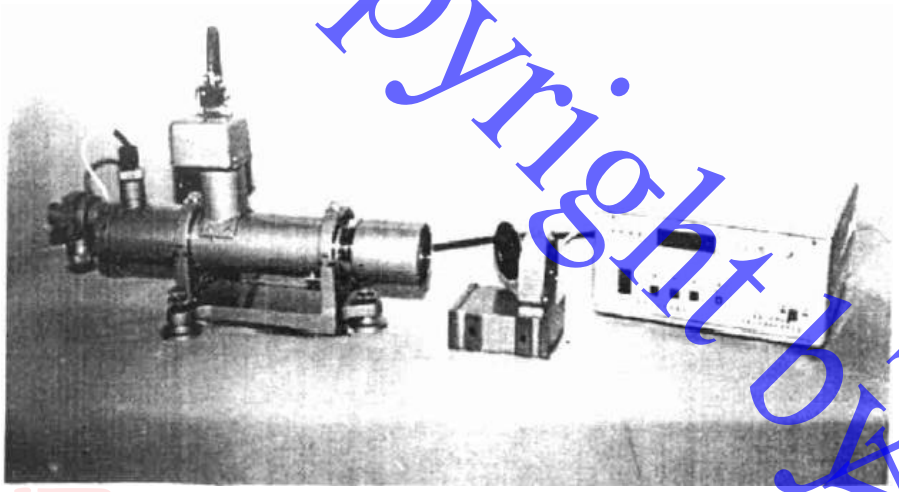


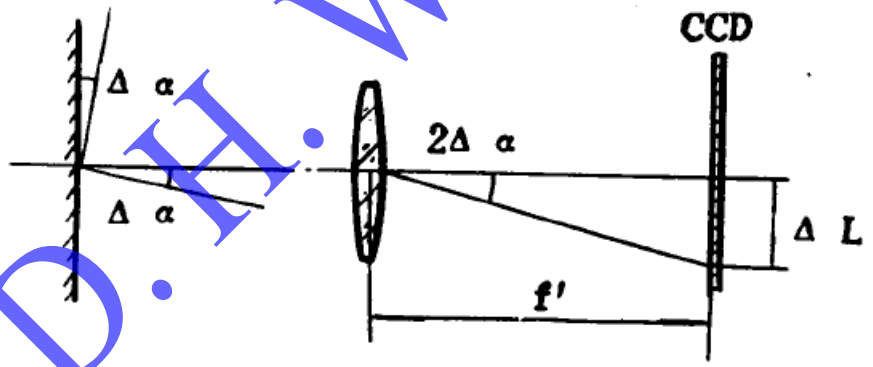


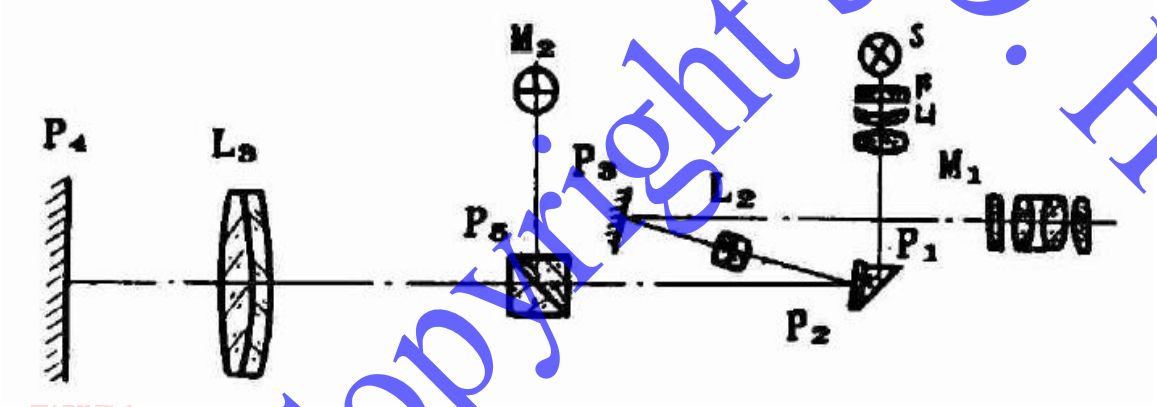
$$x = f\tan 2\alpha$$

$$x \approx 2f\alpha$$

自准直仪: 数字光电自准直仪







Bryan's Principle

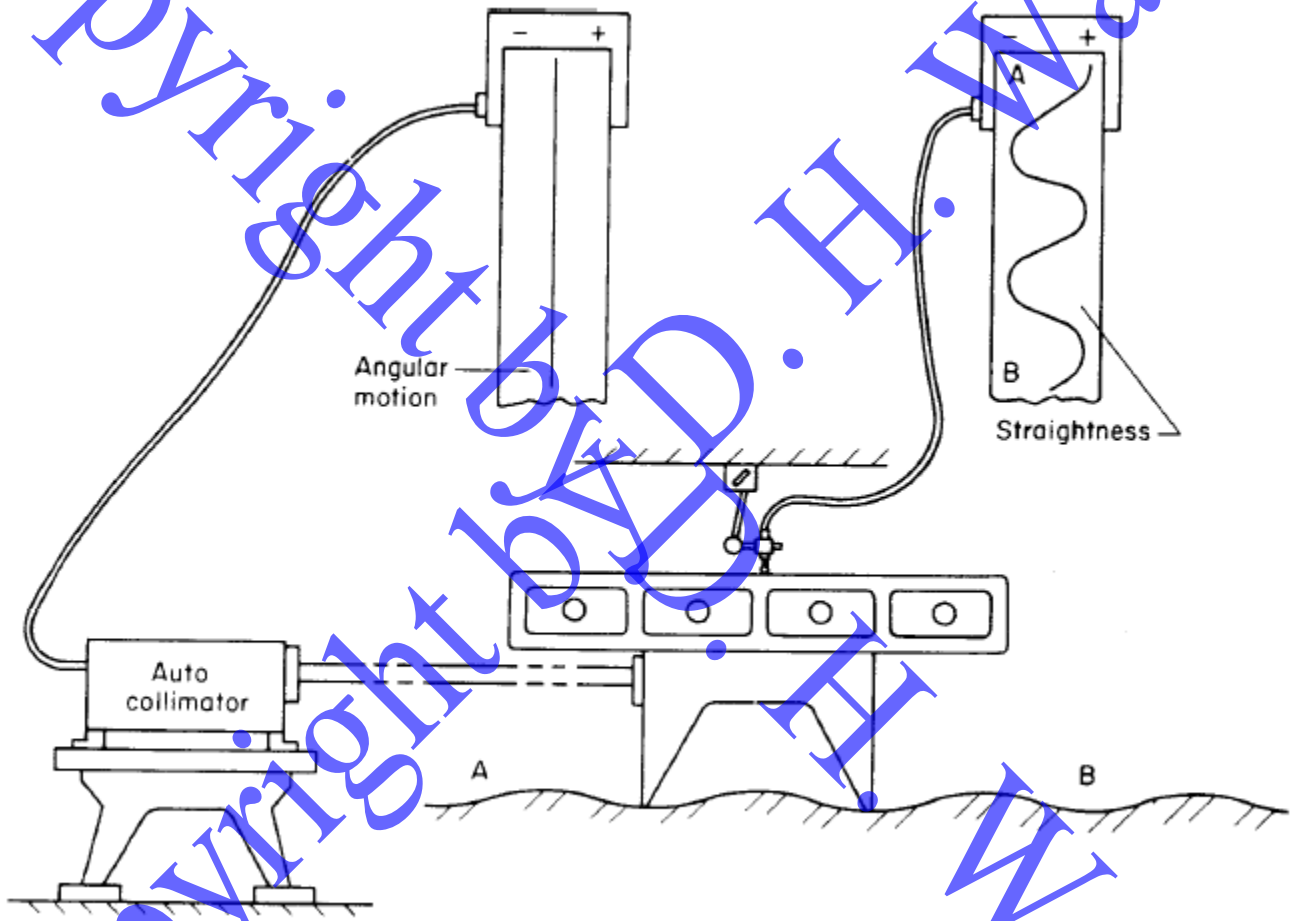


Fig 2 Moving straightedge; no angular motion

Bryan's Principle

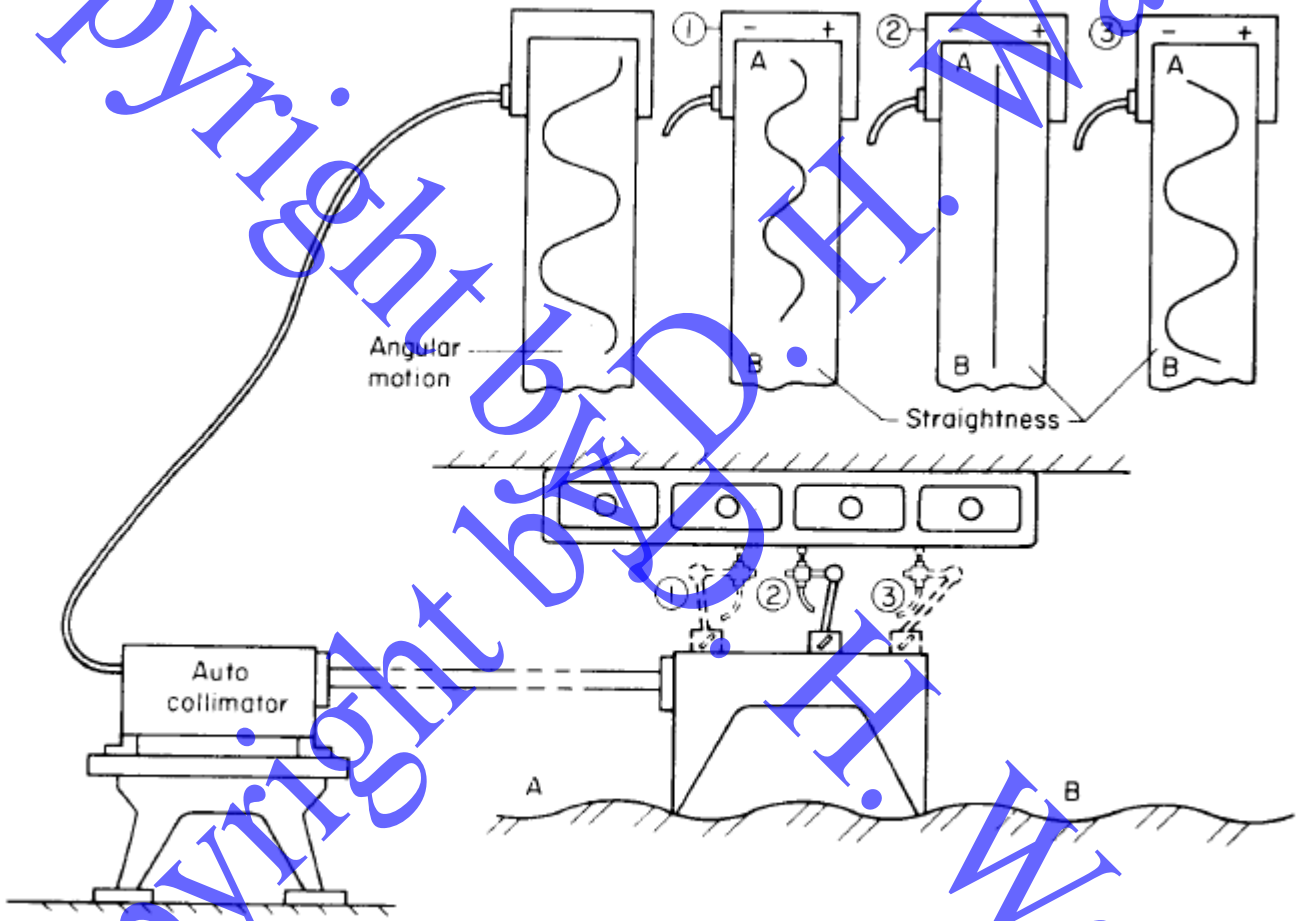


Fig 3 Stationary straightedge; oscillating angular motion

Bryan's Principle

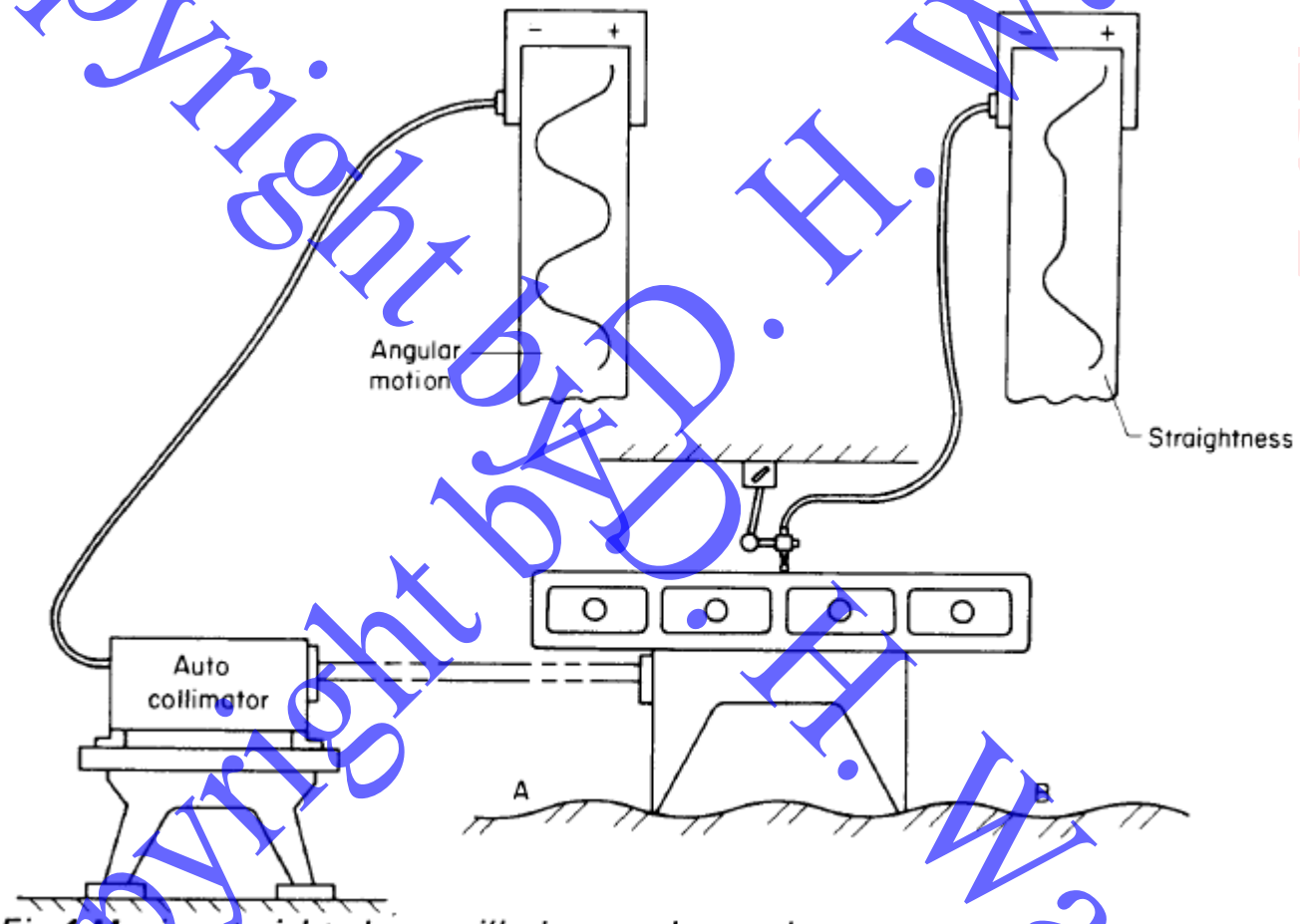


Fig 4 Moving straightedge; oscillating angular motion

Bryan's Principle

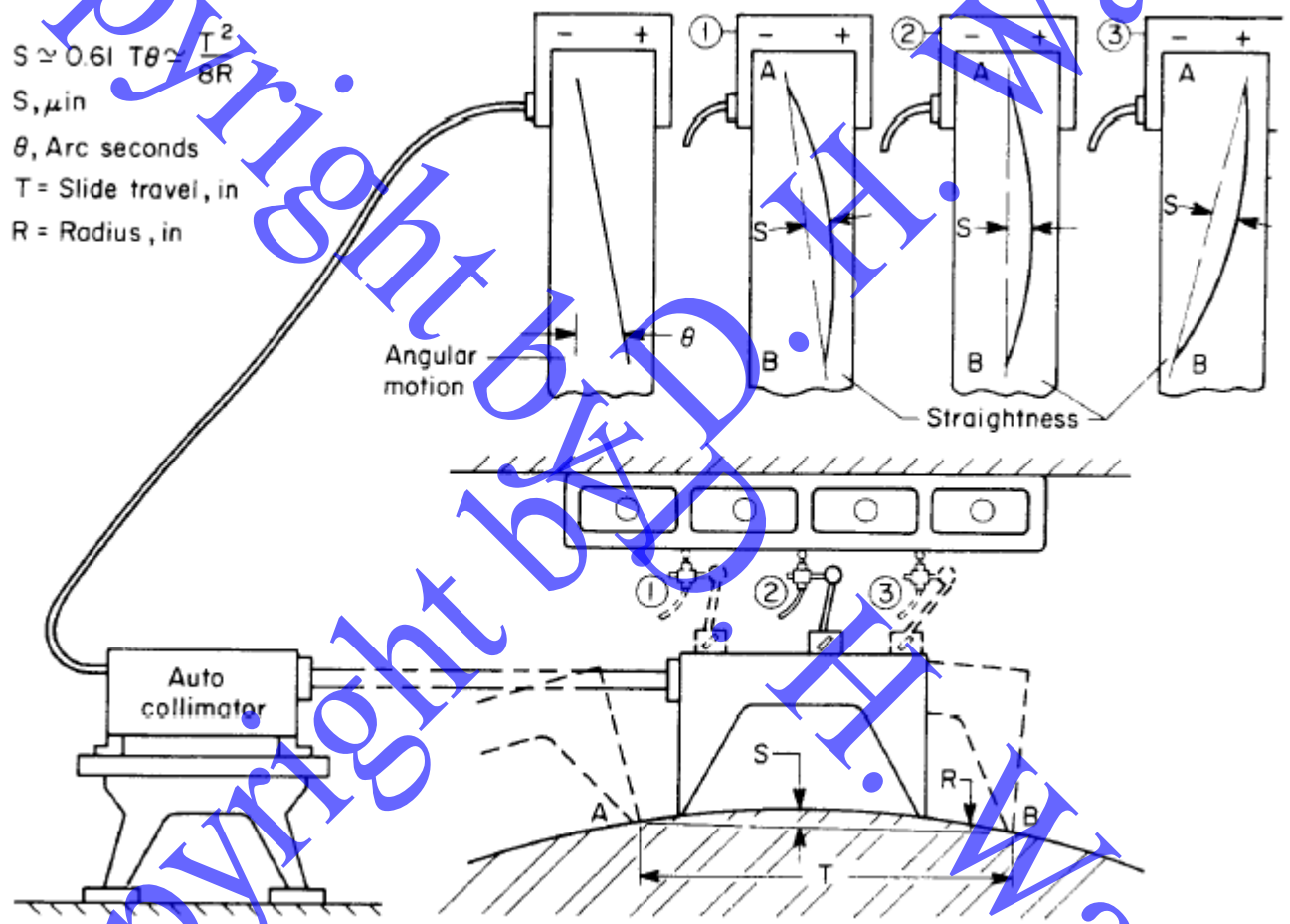


Fig 5 Stationary straightedge; uniform angular motion

Bryan's Principle

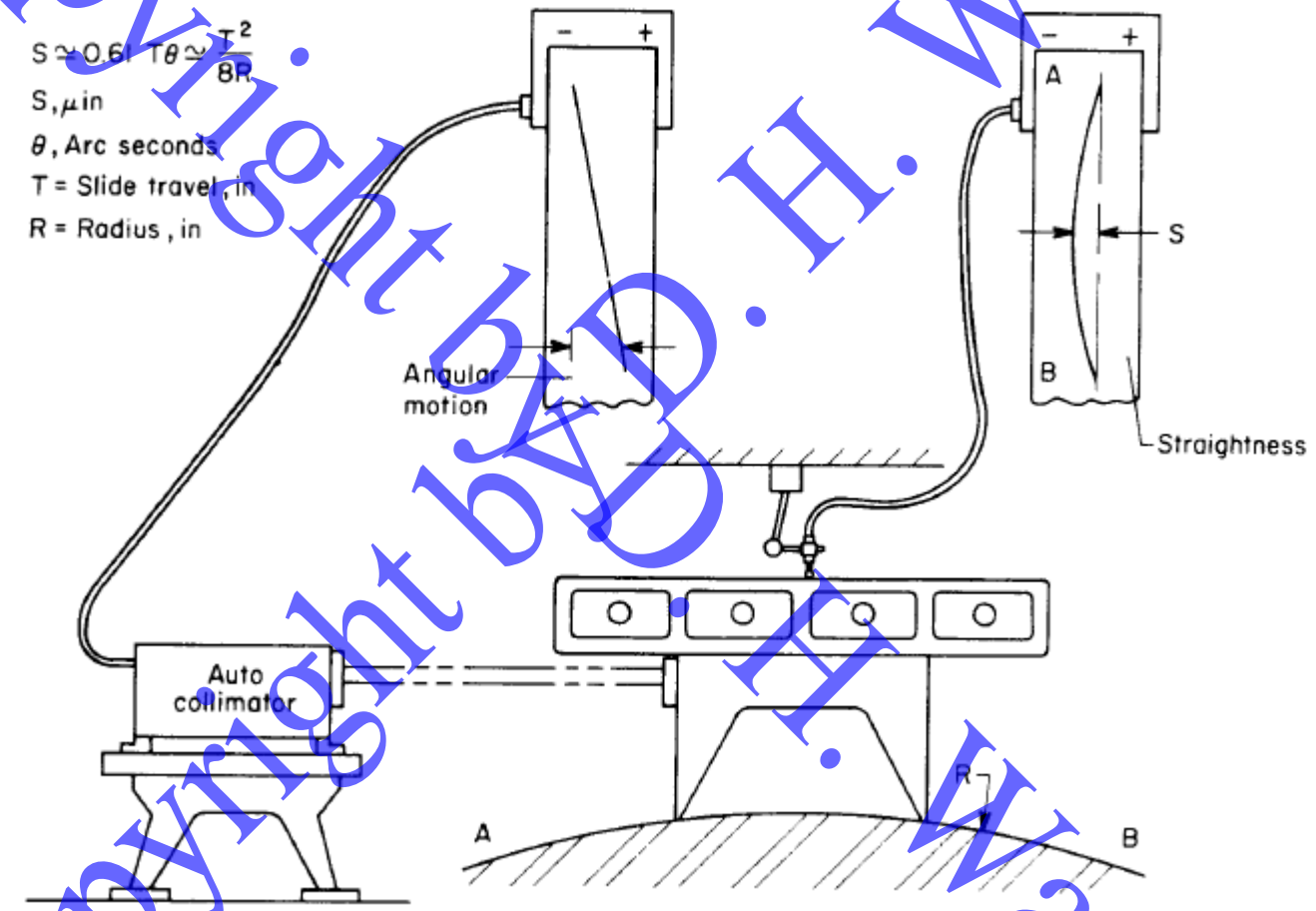


Fig 6 Moving straightedge; uniform angular motion

Bryan's Principle

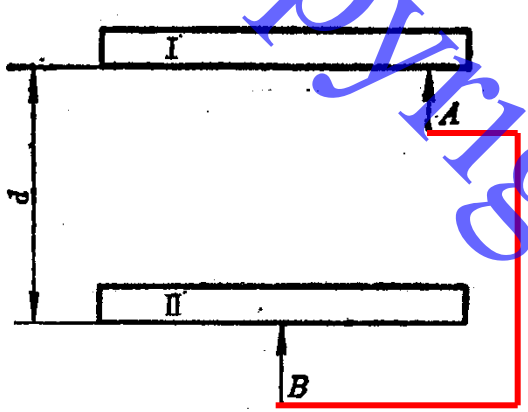
- "The straightness measuring system （平直度测量系统） should be in line with the functional point whose straightness is to be measured*. If this is not possible, either the slideways that transfer the straightness must be free of angular motion or angular motion data must be used to calculate the consequences of the offset."

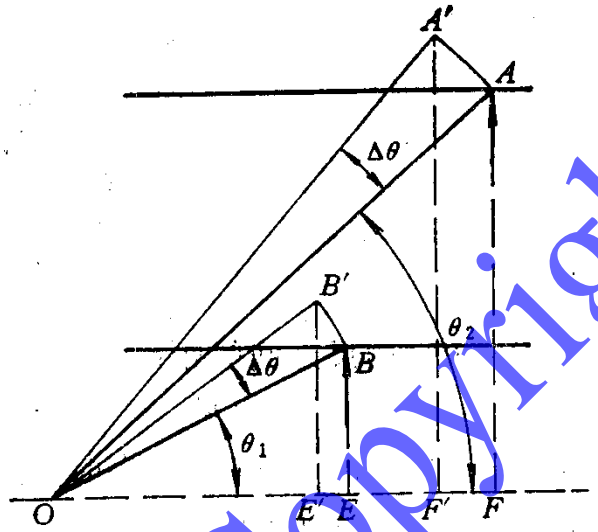
J. B. Bryan, The Abbe Principle Revisited: An Updated Interpretation, *Precision Engineering*, Vol. 1, No. 3, 129-132, 1979.

Bryan's Principle

- The effective point of a straightness measuring system should be along a line which is perpendicular to the direction of slideway travel and passes through the functional point whose straightness is to be measured. If this is not possible, either the slideways that transfer the straightness must be free of angular motion or angular motion data must be used to calculate the consequences of the offset.
- In a machine tool, the *the functional point* is the tool; in a measuring machine, *the functional point* is the sensor (stylus tip, microscope focus point, etc)

Bryan's Principle





$$\Delta B = B'E' - BE$$

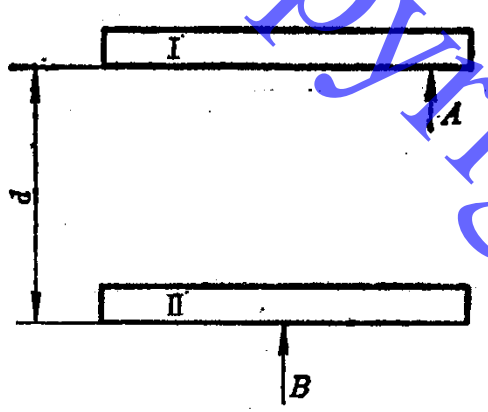
$$= OB'\sin(\theta_1 + \Delta\theta) - OB\sin\theta_1$$

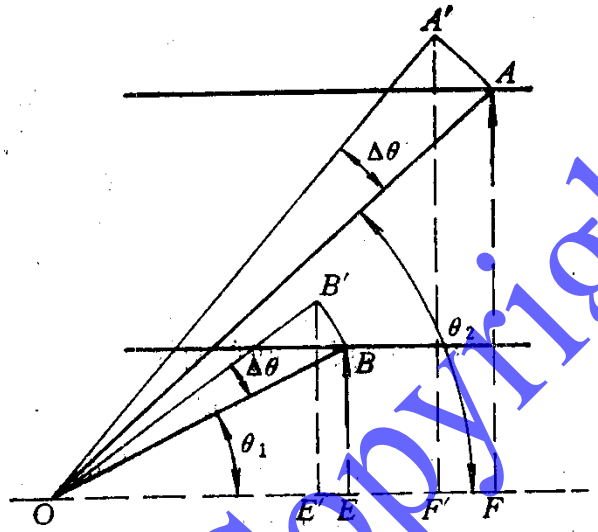
$$OB' = OB$$

$$\Delta B = OB[\sin(\theta_1 + \Delta\theta) - \sin\theta_1]$$

$$\Delta B \approx -BE\frac{\Delta\theta^2}{2} + OE\Delta\theta$$

Bryan's Principle





$$\Delta A = A'F' - AF$$

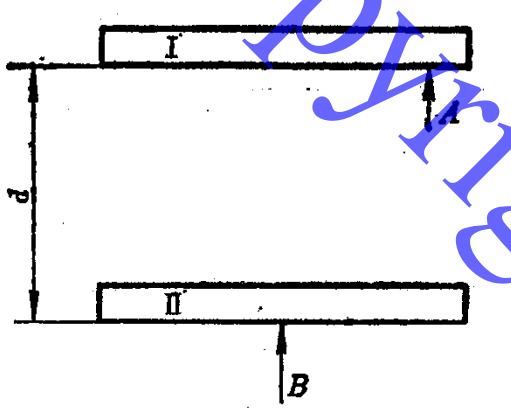
$$= OA'\sin(\theta_2 + \Delta\theta) - OA\sin\theta_2$$

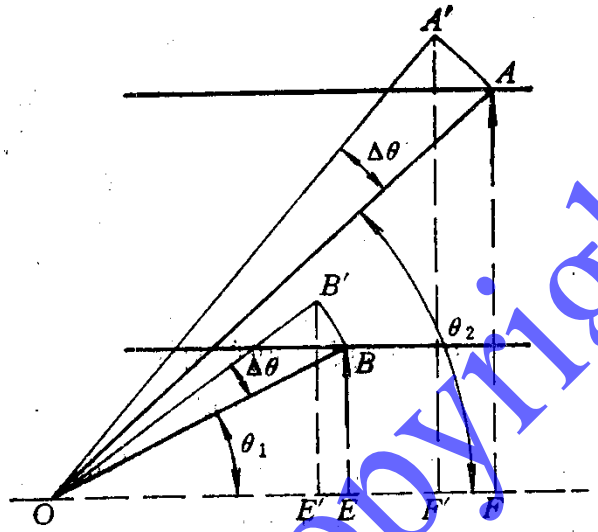
$$OA' = OA$$

$$\Delta A = OA[\sin(\theta_2 + \Delta\theta) - \sin\theta_2]$$

$$\approx -AF\frac{\Delta\theta^2}{2} + OF\Delta\theta$$

Bryan's Principle





J. B. Bryan and D. L. Carter, Design of a new error-corrected co-ordinate measuring machine, *Precision Engineering*, 1979, pp125-128

$$\Delta = \Delta B - \Delta A$$

$$= (AF - BE)\frac{\Delta\theta^2}{2} + (OE - OF)\Delta\theta$$

$$= d\frac{\Delta\theta^2}{2} + (OE - OF)\Delta\theta$$

If $OF = OE$, then

$$\Delta = 0$$

Bryan's Principle

- **The effective point of a straightness measuring system should be along a line which is perpendicular to the direction of slideway travel and passes through the functional point whose straightness is to be measured.**
  If this is not possible, either the slideways that transfer the straightness must be free of angular motion or angular motion data must be used to calculate the consequences of the offset.

J. B. Bryan, The Abbe Principle Revisited: An Updated Interpretation, *Precision Engineering*, Vol. 1, No. 3, 129-132, 1979.

Bryan's Principle

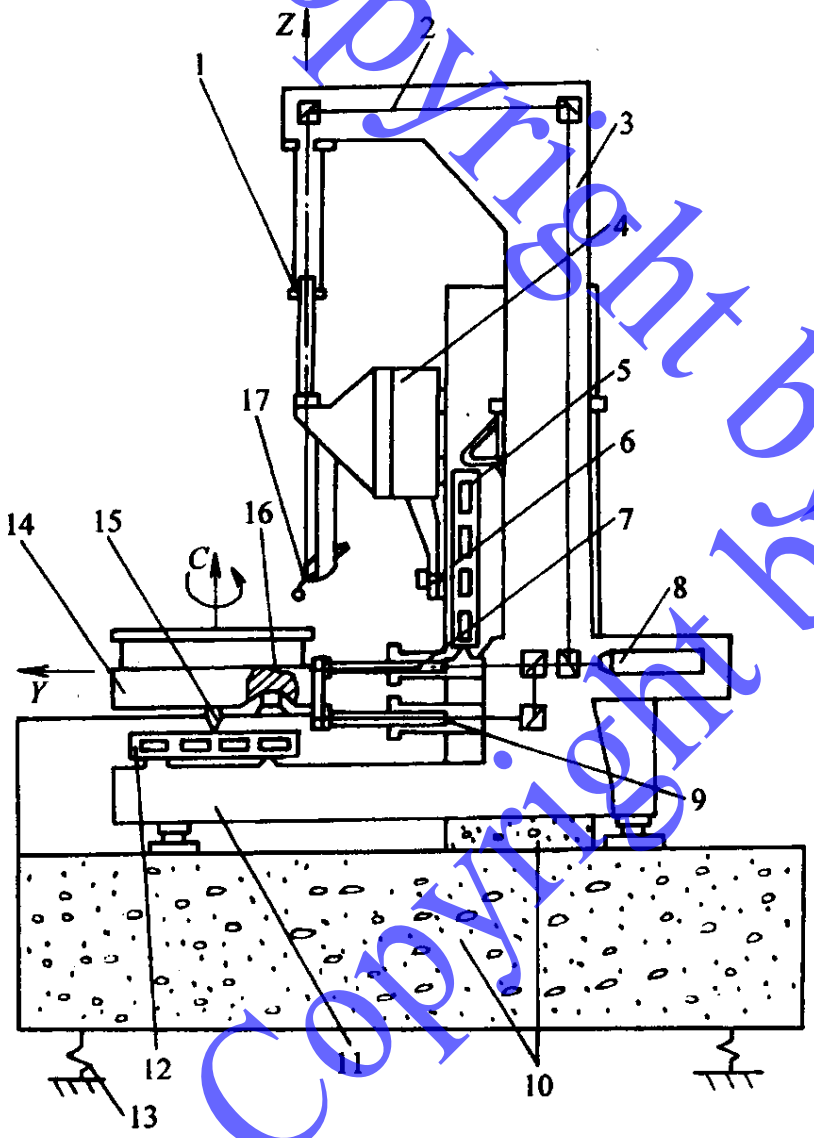
- Bryan's proposal has made the Abbe principle applicable for both displacement and straightness measurement.
- It is his important contribution.

Bryan's Principle

- Schematic of relationship between the functional point and the straightness is to be measured

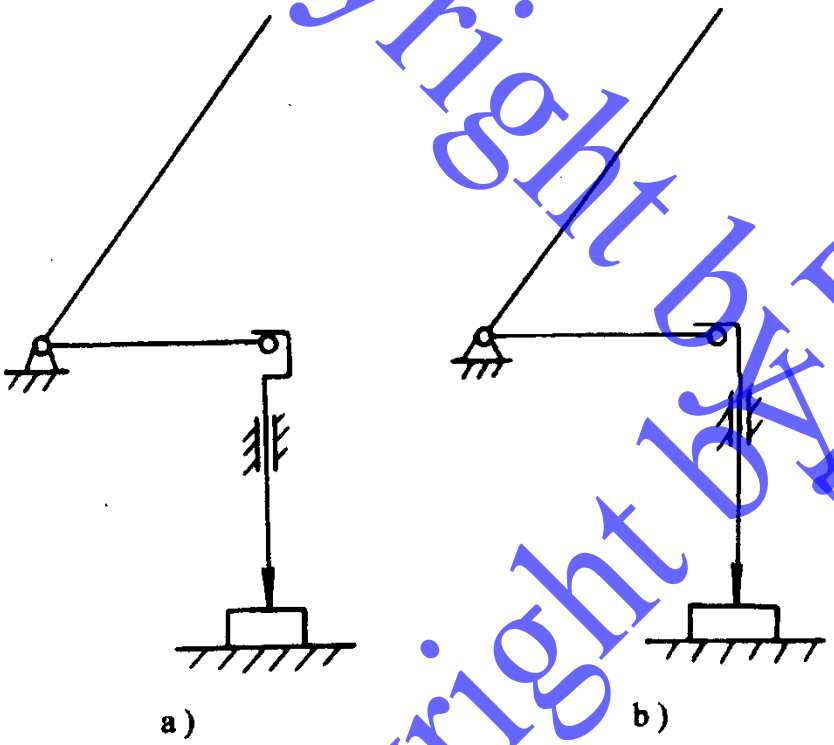
Good Bad

Bryan's Principle



- Straightness Measuring Machine
  - Layout

遵守阿贝原则的传动部件



Good **Bad**

天道酬勤

Acknowledgement

Thank you very much for your attention!