Evolving Design

Steam Engines

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Overview

- **A Small Question**
  - History of Thermodynamics
- **Steam Engines**
  - Thomas Newcomen
  - James Watt
- **After Watt**
  - Improvements
  - Steam Cars
  - Steam Locomotives
  - Steamboats
- **Exam 2008**

Which is the Oldest?

- **MIT**

  1861

- **Second Law of Thermodynamics**

  1850 Rudolf Julius Emanuel Clausius (1822-1888)

- **TU Delft**

  1842

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Definition of Mechanical Engineering

- ***"To Build and Run a Steam Engine!"***
  - (Unofficial Version@ME MIT)

History of Thermodynamics

- 1660: Robert Boyle Boyle's Law
- 1712: Thomas Newcomen
- 1741: École Nationale des Ponts et Chaussés
- 1765: James Watt (Only the Idea)
- 1770: Steam Car
- 1776: James Watt (The Engine), Steamboat
- 1794: Ecole Polytechnique
- 1804: Steam Locomotive
- 1824: Sadi Carnot, Carnot Cycle
- 1842: TU Delft

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History of Thermodynamics

- 1843: James Joule, Mechanical Equivalent of Heat
- 1847: Hermann von Helmholtz, Definitive Statement of the First Law of Thermodynamics
- 1849: William John Macquorn Rankine, Saturated Vapor Table (Pressure and Temperature)
- 1850: Rudolf Clausius, The Second Law of Thermodynamics
- 1851: Thomson an Alternative Statement of the Second Law
- 1854: Clausius, Found dQ/T, but Did Not Name It
- 1854: Rankine, Entropy
- 1865: Clausius, Modern Macroscopic Concept of Entropy
- 1876: Josiah Willard Gibbs, the Free Energy as the Driving Force behind Chemical Reactions
- 1877: Boltzmann, the Relationship between Entropy and Probability

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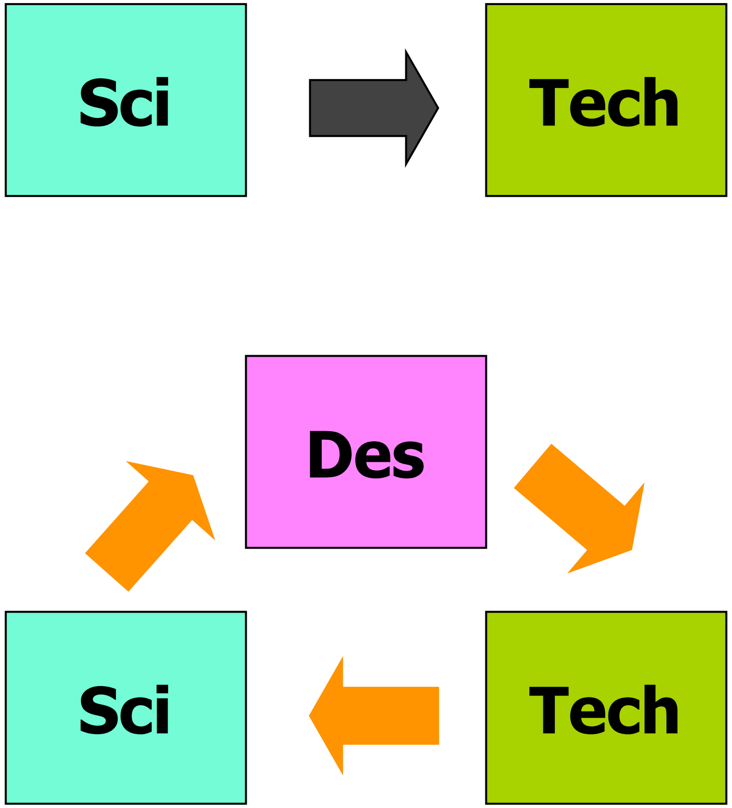
Development of Science

- **Push-Pull Linear Model**
  - Science Pushes
  - Technology (or Society) Pulls
    - Bacteriolysis -> Antibiotics
    - Nuclear Fission -> Atomic Bomb
- **Non-Linear Model**
  - Design Existed First
    - Pumps
    - Steam Engines
    - Machine Tools



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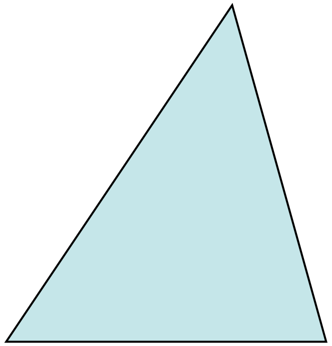
Hero(n) of Alexandria (10-70 AD)

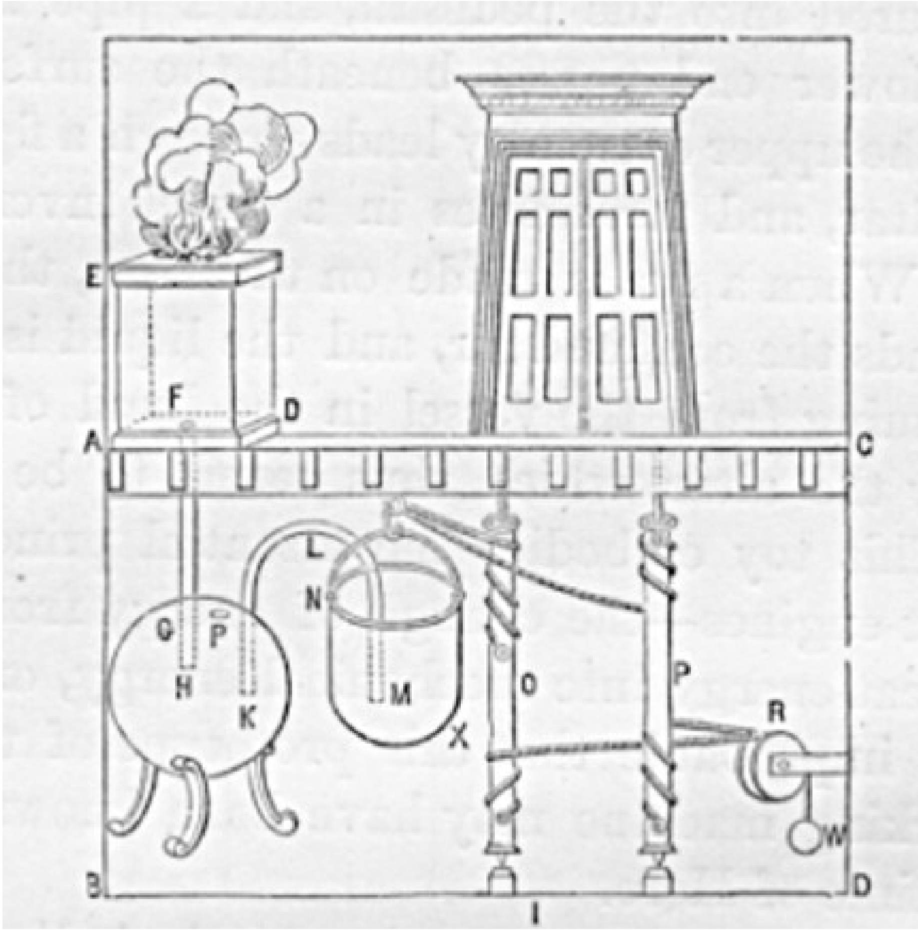
- **Pneumatica, Automata, Mechanica, Metrica, etc.**
- **Aeolipile**
- **Heron's Formula**



$$A = \sqrt{s(s-a)(s-b)(s-c)}$$

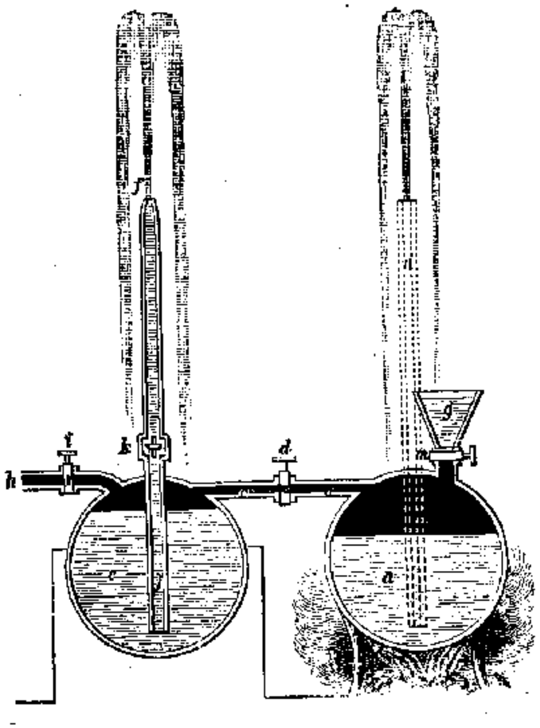
$$s = \frac{a+b+c}{2}$$

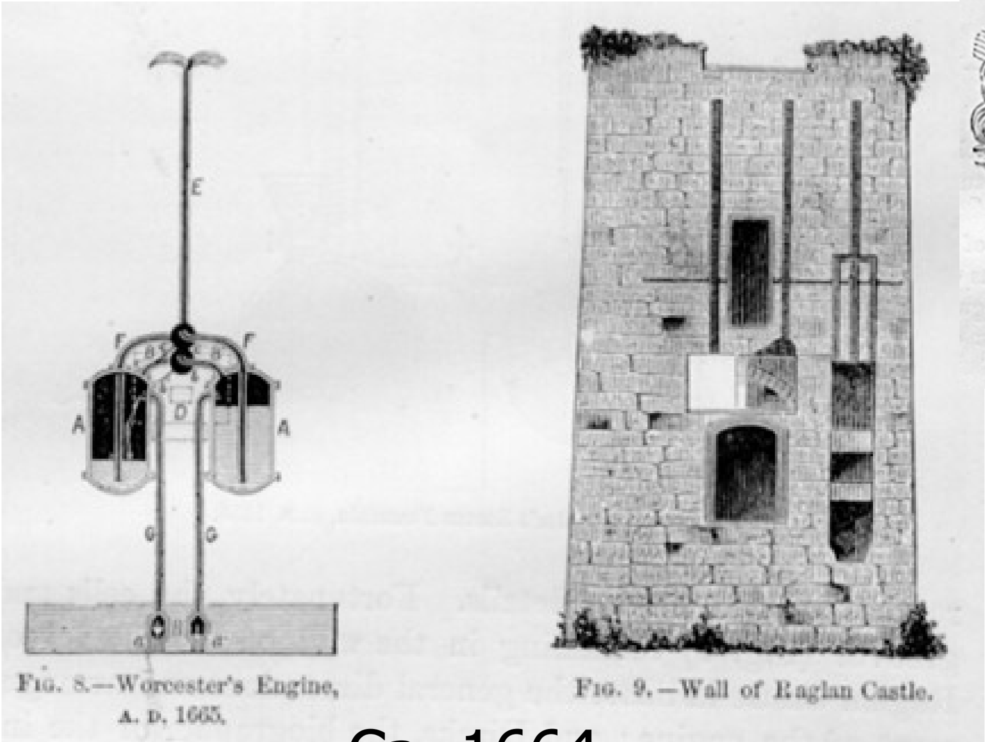
Temple Door Opening Mechanism



Edward Somerset (1601?-1667)

2nd Marquess of Worcester





Ca. 1664

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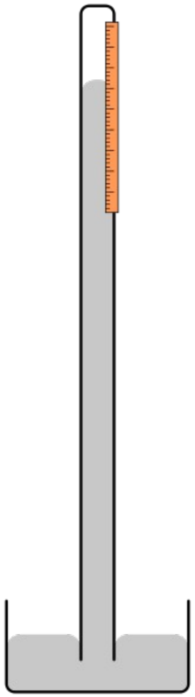
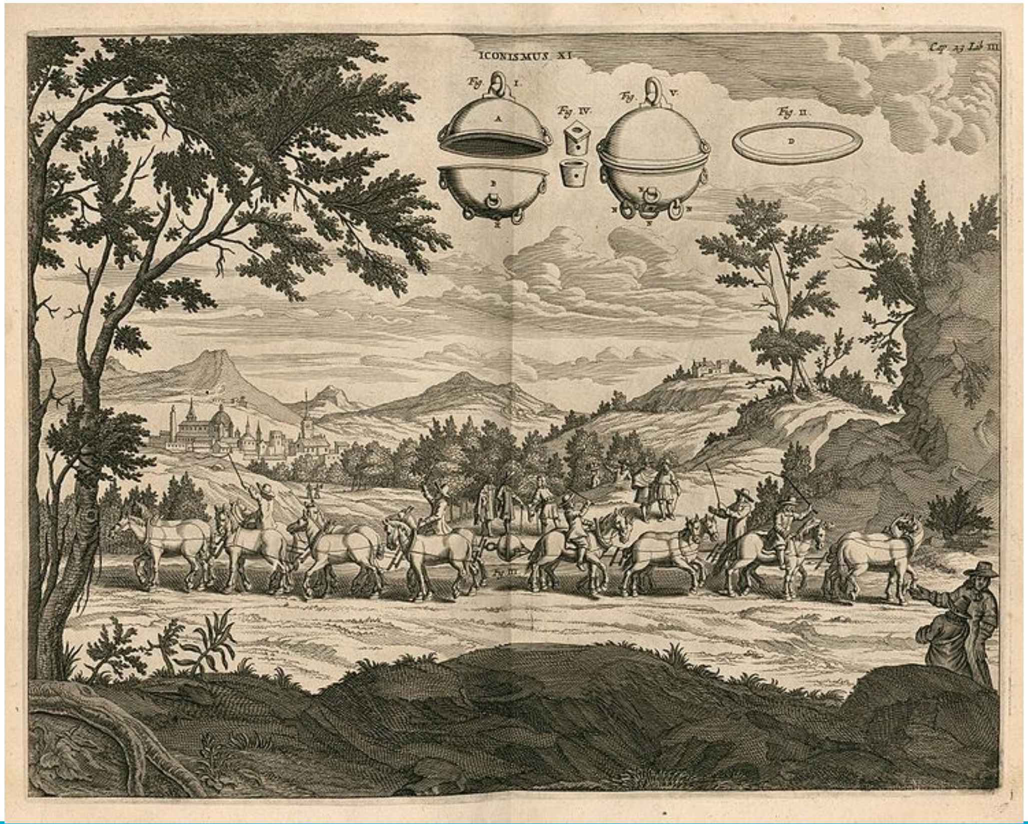
Vacuum around 1640





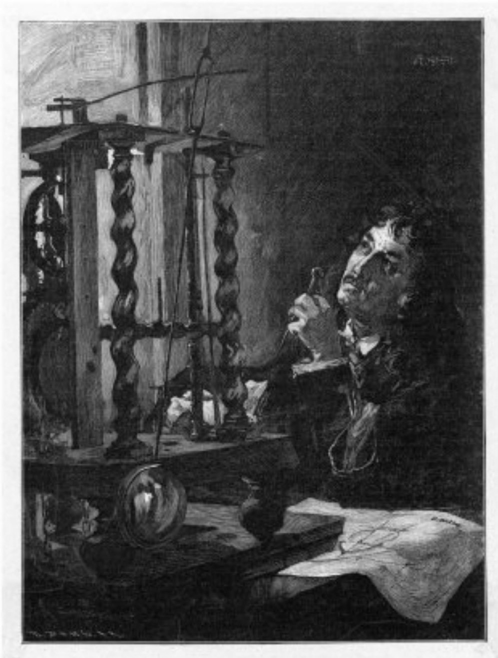
- **Evangelista Torricelli**
  - 1643 Barometer
  - Torr
- **Otto von Guericke**
  - 1654 Magdeburg Hemispheres
- **Robert Boyle**
  - Ca. 1660 Vacuum Pump Made by Robert Hooke

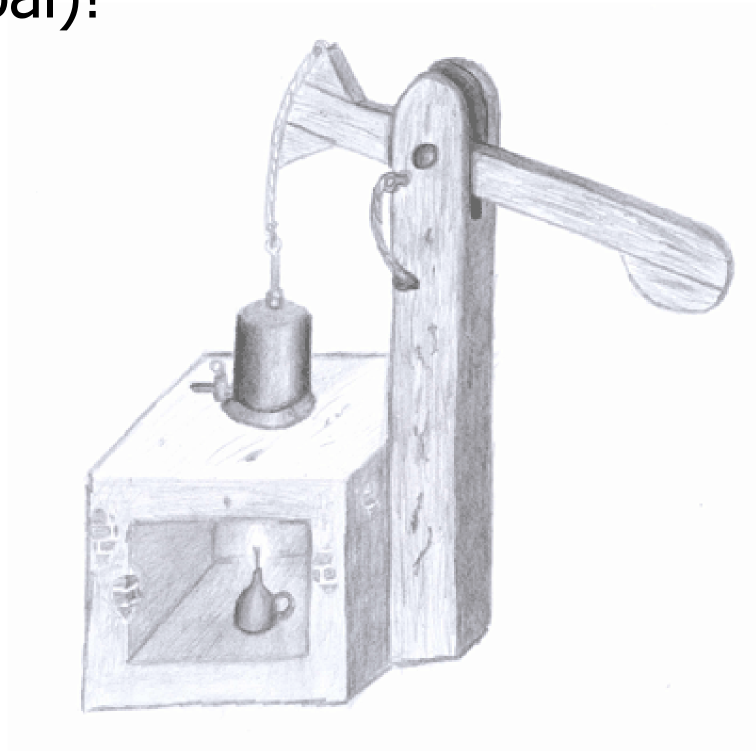
Huygens Family

- **Constantijn, Sr.**
  - 1596-1687
  - Frederik Hendrik
  - William II
- **Constantijn, Jr.**
  - 1627-1698
  - William III
  - Glorious Revolution
- **Christiaan**
  - 1629-1695
  - Full Time Scientist in Paris

Christiaan Huygens (1629-1695)

- **Gun Powder-Based Internal Combustion Engine**
  - Rudolf Diesel Had a Similar Idea (Dust Coal)!





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Denis Papin (1647-ca. 1712, F)

- **Huguenot**
  - Worked for Christiaan Huygens
- **Later Went to England**
  - Connection to Robert Boyle
- **Invented Safety Valve**

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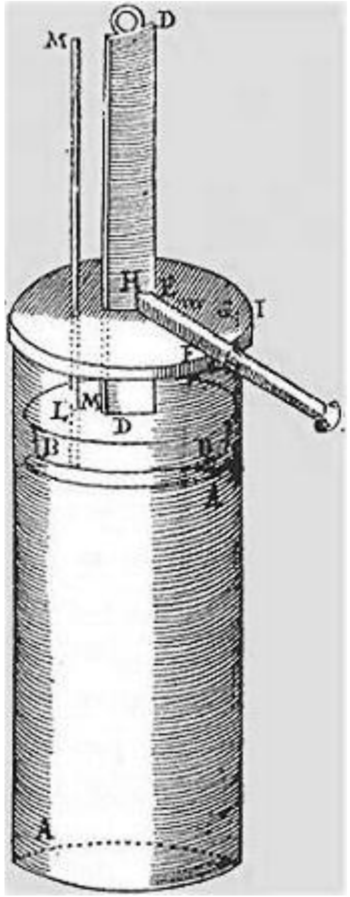
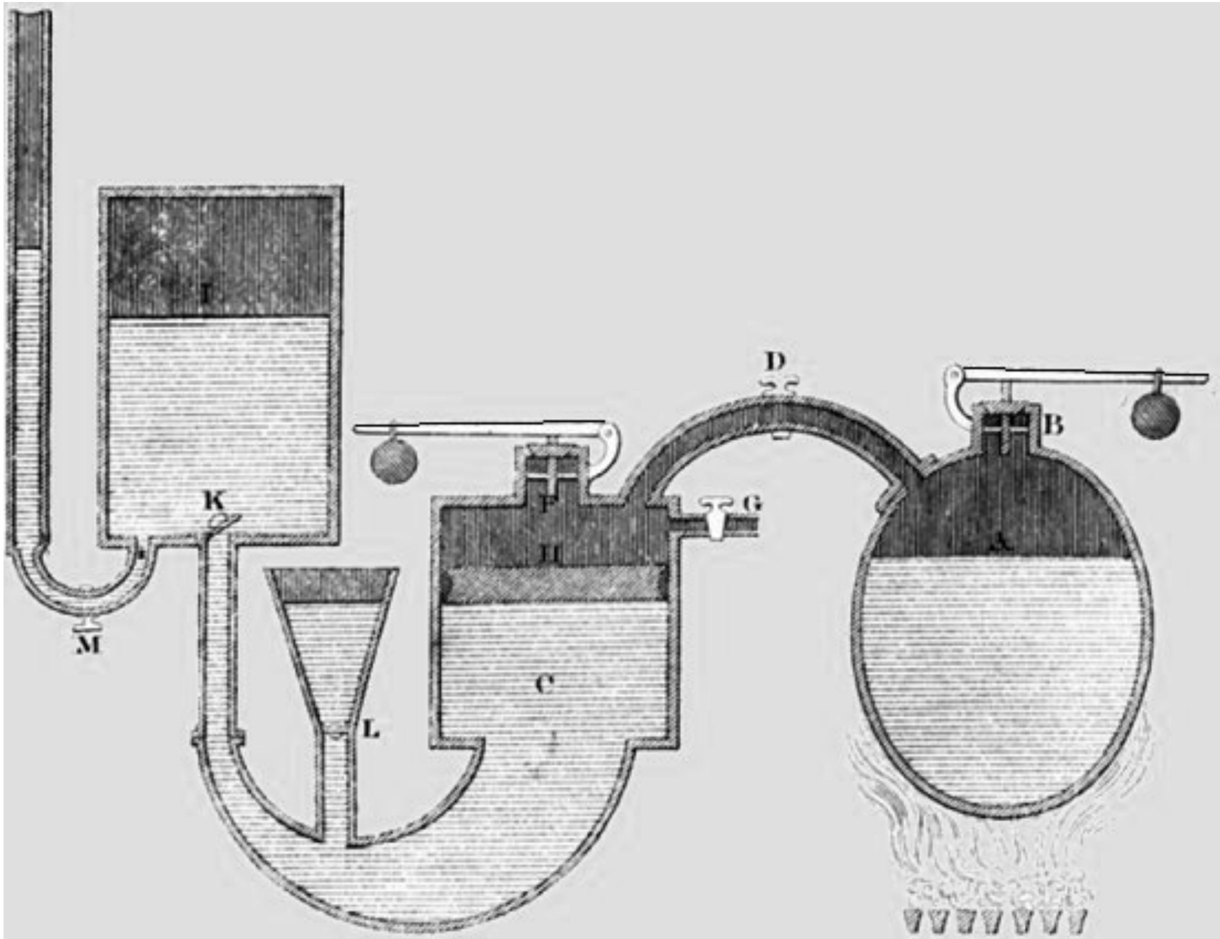
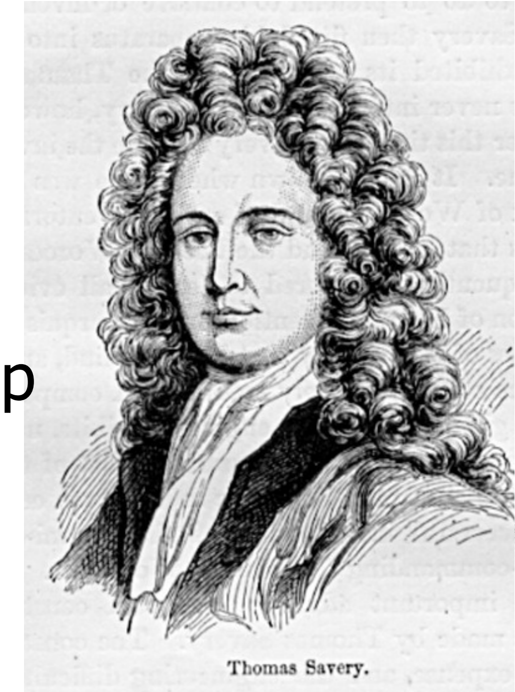
Papin's Digester (1690)

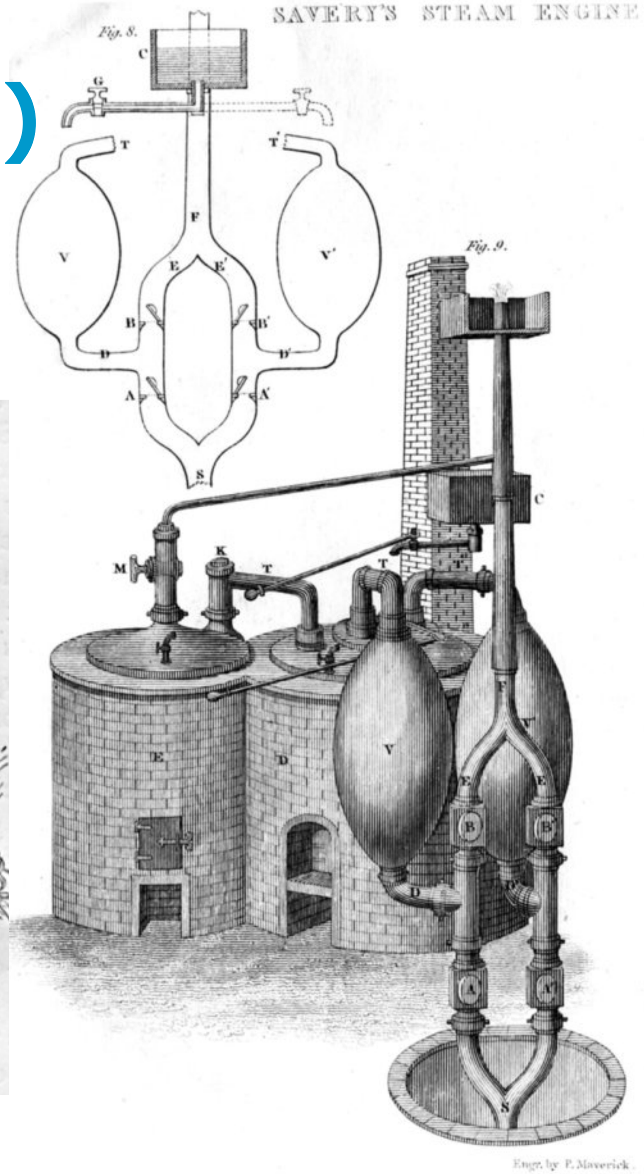




Thomas Savery (ca. 1650- 1715)

- **First Steam Engine**
- **1698 Patented**
- **1699 Demonstration at Royal Society**
  - Atmospheric Engine to Suck Water
  - Positive Pressure to Pump Up Water
  - Miner’s Friend
  - No Piston


Thomas Savery.



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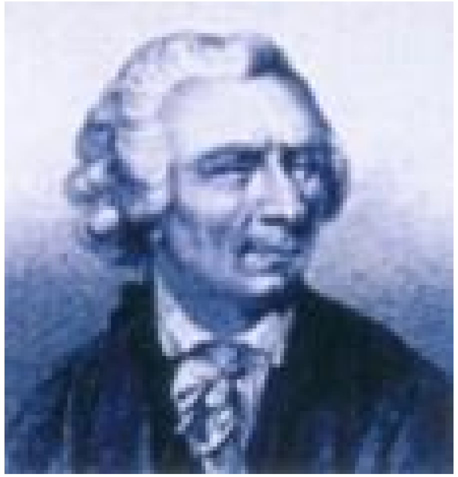
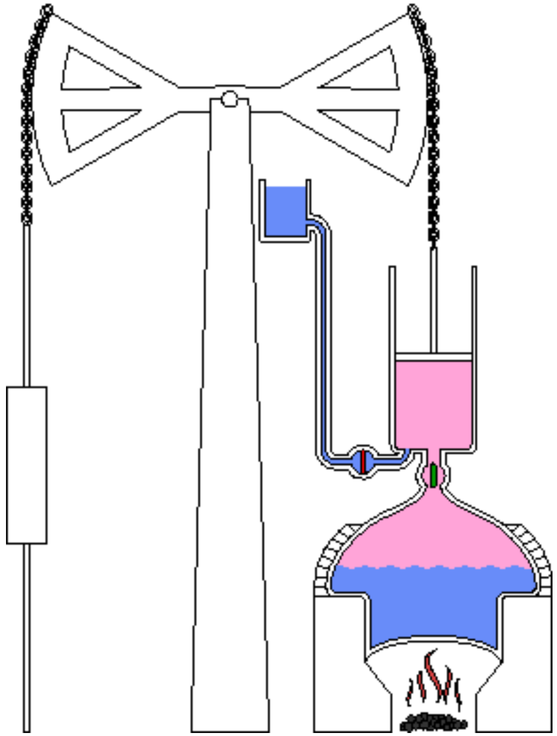
Thomas Newcomen's Atmospheric Engine (1664-1729)

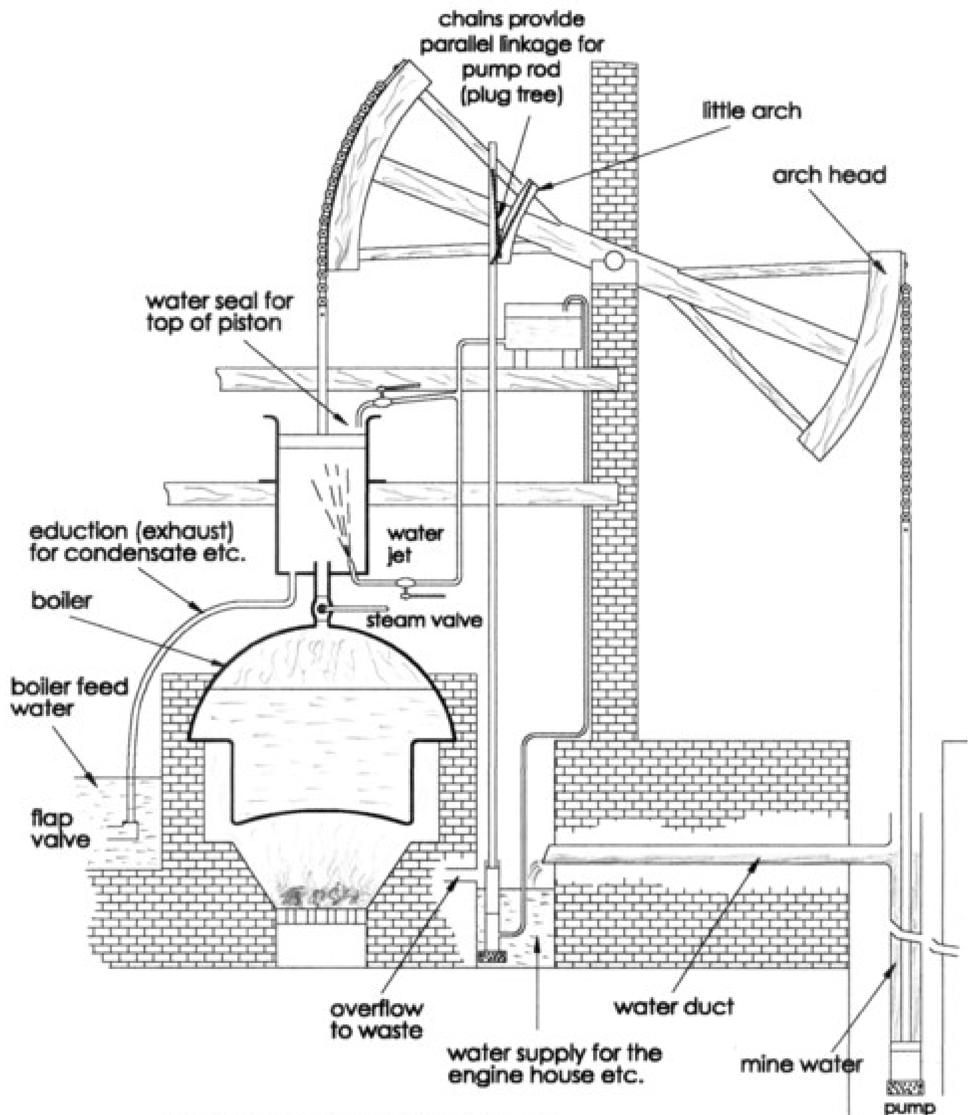




http://www.sciencemuseum.org.uk/on-line/energyhall/theme_See%20the%20engines%20at%20work.asp

Atmospheric Engine (1712): Thomas Newcomen

- **At Most, 1 Bar**
- **Used for Pumping Up Water in Coal Mines**
  - Length 10.5 Feet
  - Diameter 74 Inches
- **Inefficient**
  - Heating Up, Cooling Down
  - Steam Leaks!
  - Brass Boiler
    - Good Conductor and Radiator



Newcomen's Atmospheric Engine

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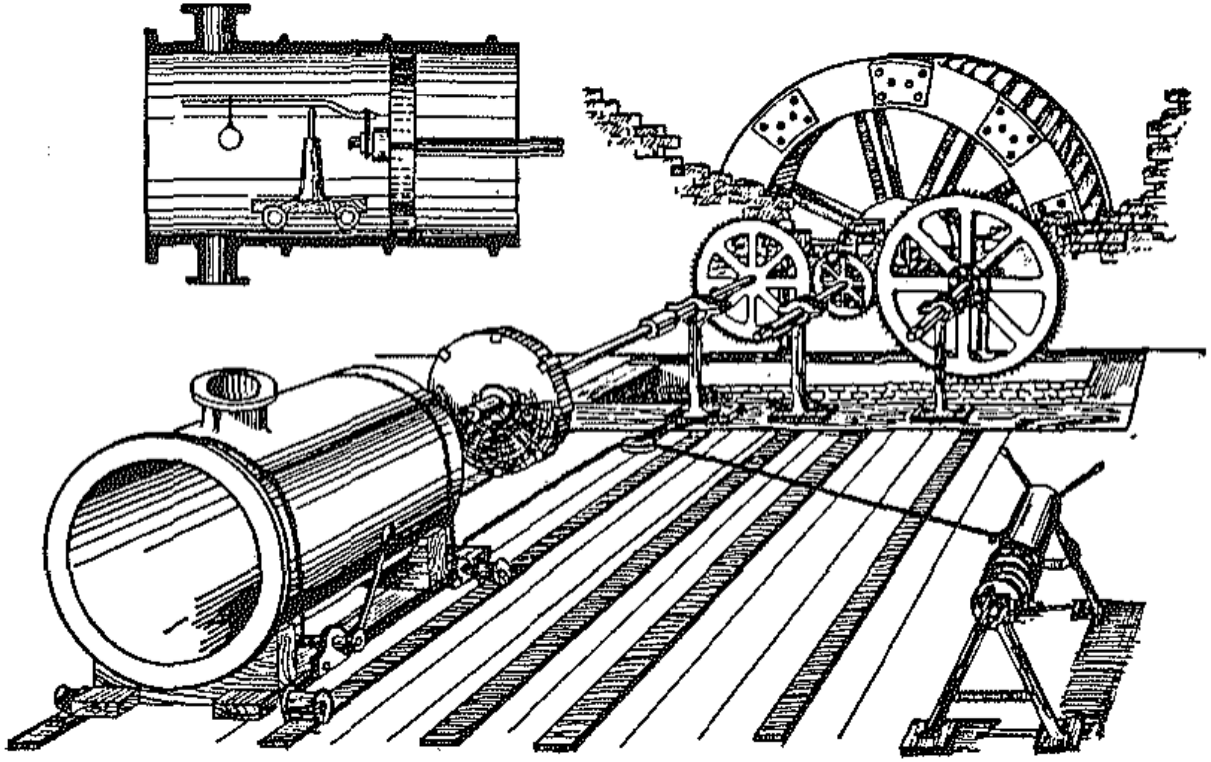
John Smeaton

- **Circularity Error 1/2 Inch for a 28 Inch-Diameter Cylinder**



•Also a Civil Engineer

•Coined the Term "Civil Engineering"

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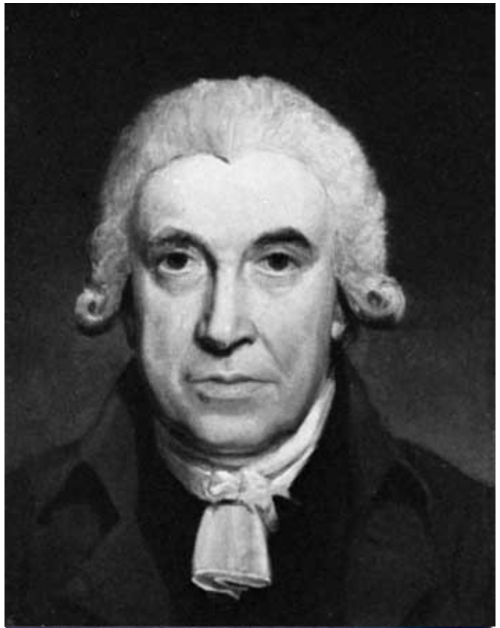
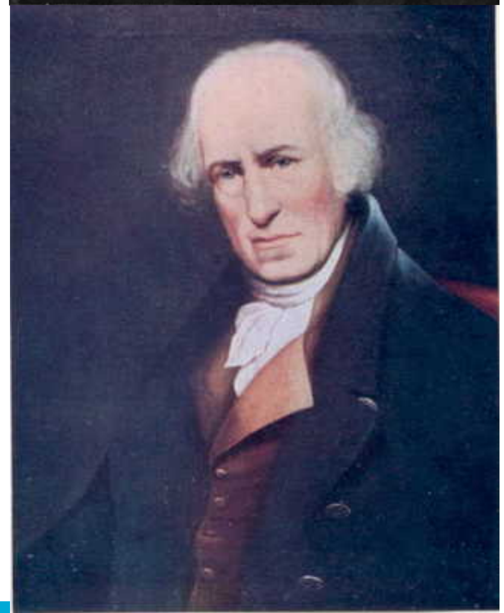
James Watt (1736–1819)





- **Apprentice as Instrument Maker**
- **1756-1764**
  - University of Glasgow
  - Prof. Joseph Black
- **1759**
  - Business Partnership with John Craig
- **1763**
  - Prof. John Anderson
  - A Model of Newcomen Engine
- **1765 Eureka!**
  - External Condenser

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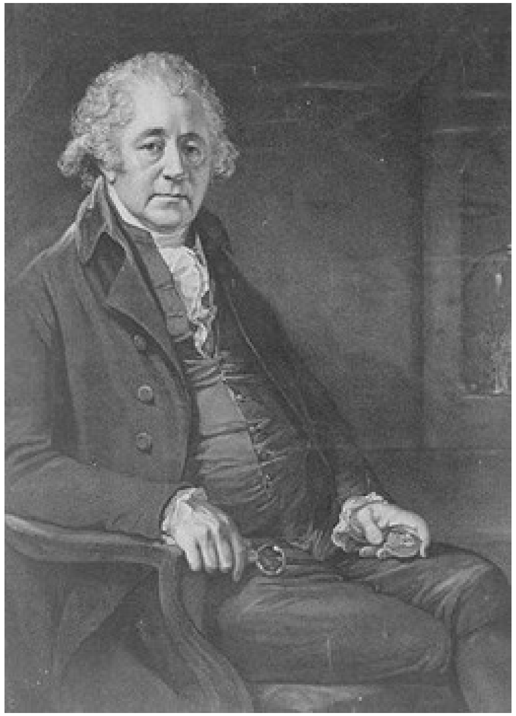
Toward Watt's Steam Engine

- **First Sponsor**
  - John Roebuck, The Founder of Carron Iron Works
  - Patent was Difficult
  - Watt Obliged to Work as a Surveyor for 8 Years
- **Second Sponsor**
  - In 1775 Matthew Boulton, The Owner of Soho Foundry Works Near Birmingham
  - Boulton and Watt, Co. (B&W)



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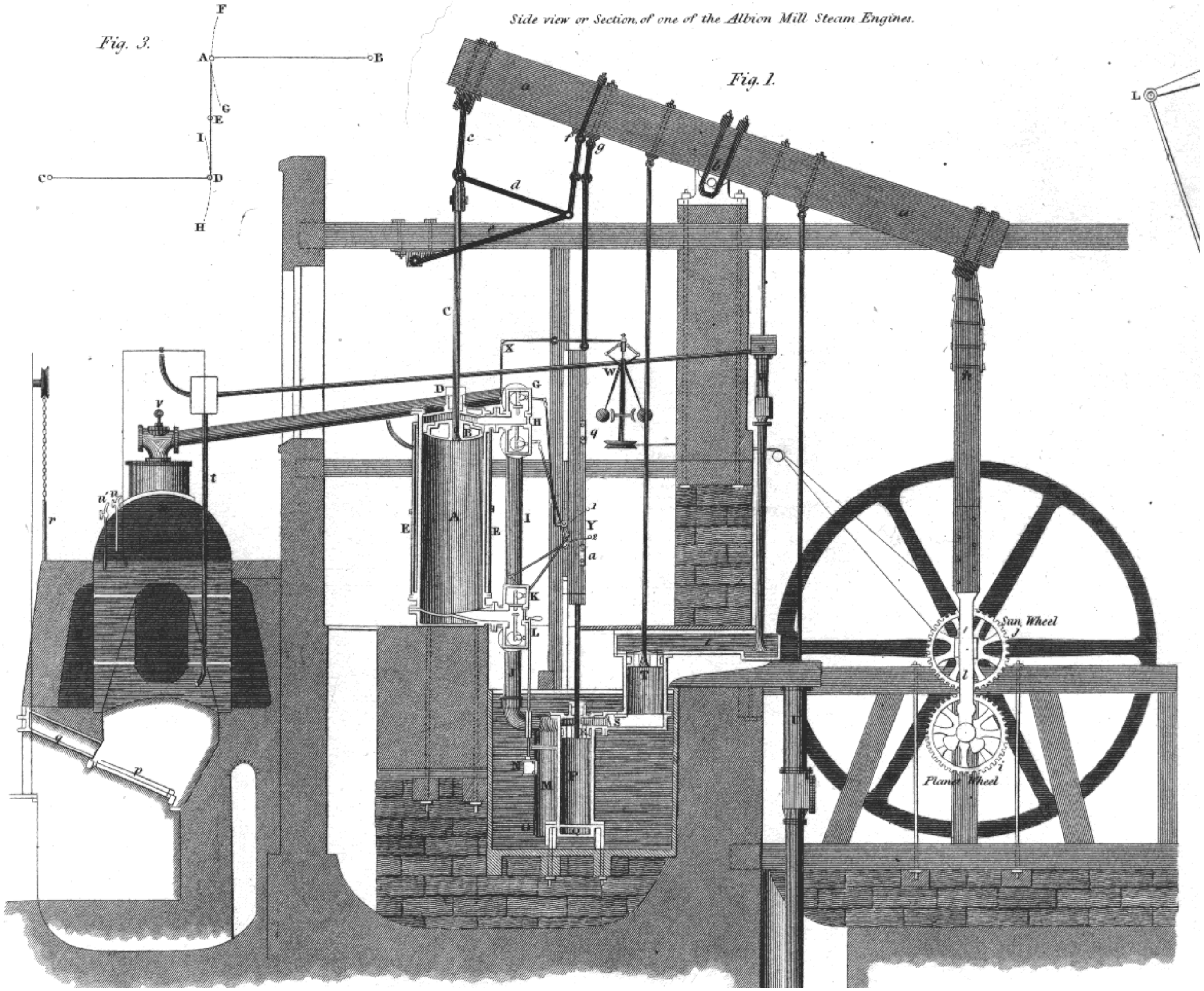
Steam Engine (1776): James Watt

- **Efficient**
  - Higher Pressure
  - External Condenser
  - Cylinder Jacket
  - Insulation
- **Needed Accuracy**
  - John Wilkinson's Boring Machine
  - 72 Inches Diameter
  - "6 Pence Coin" Accuracy



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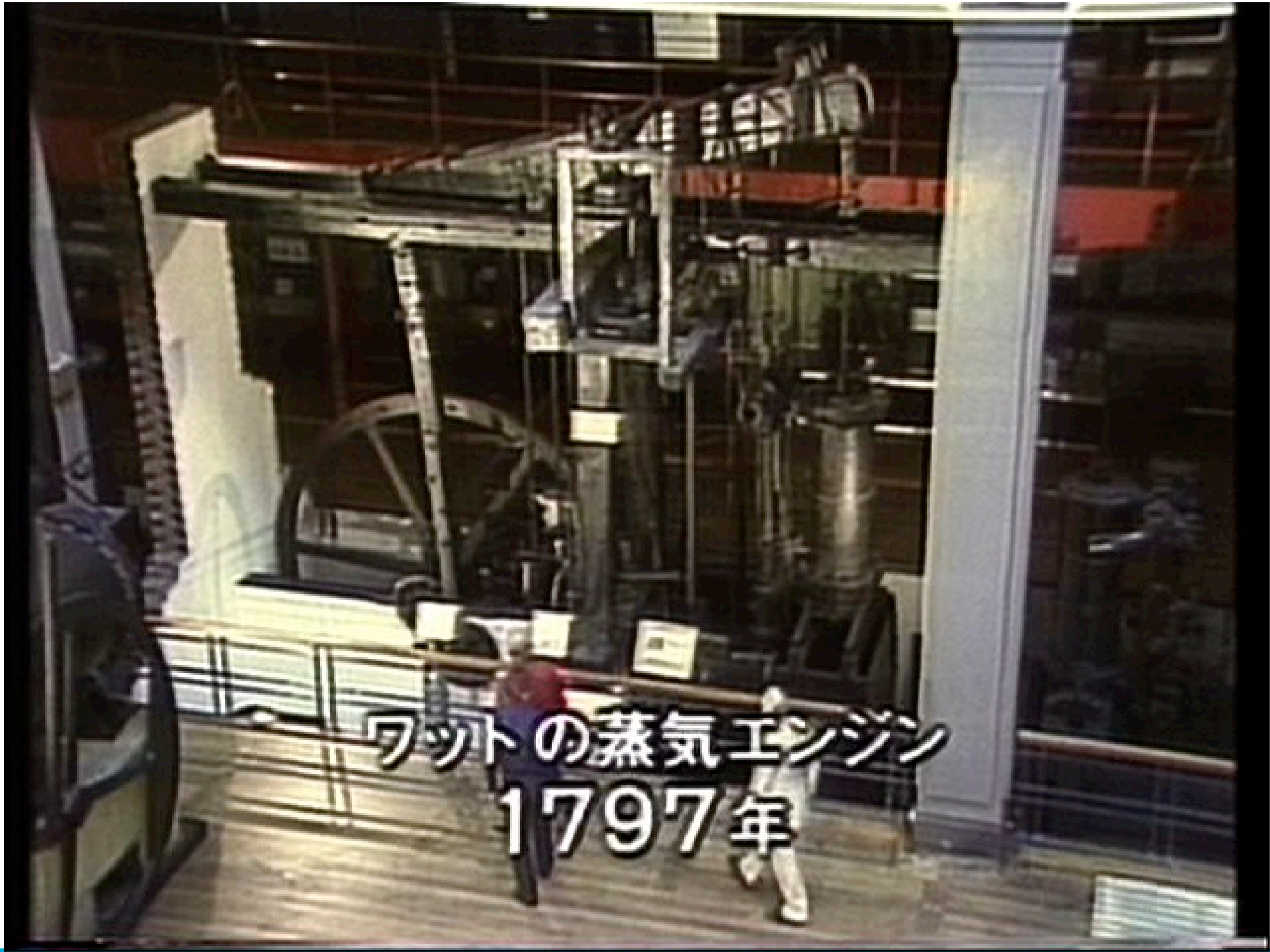
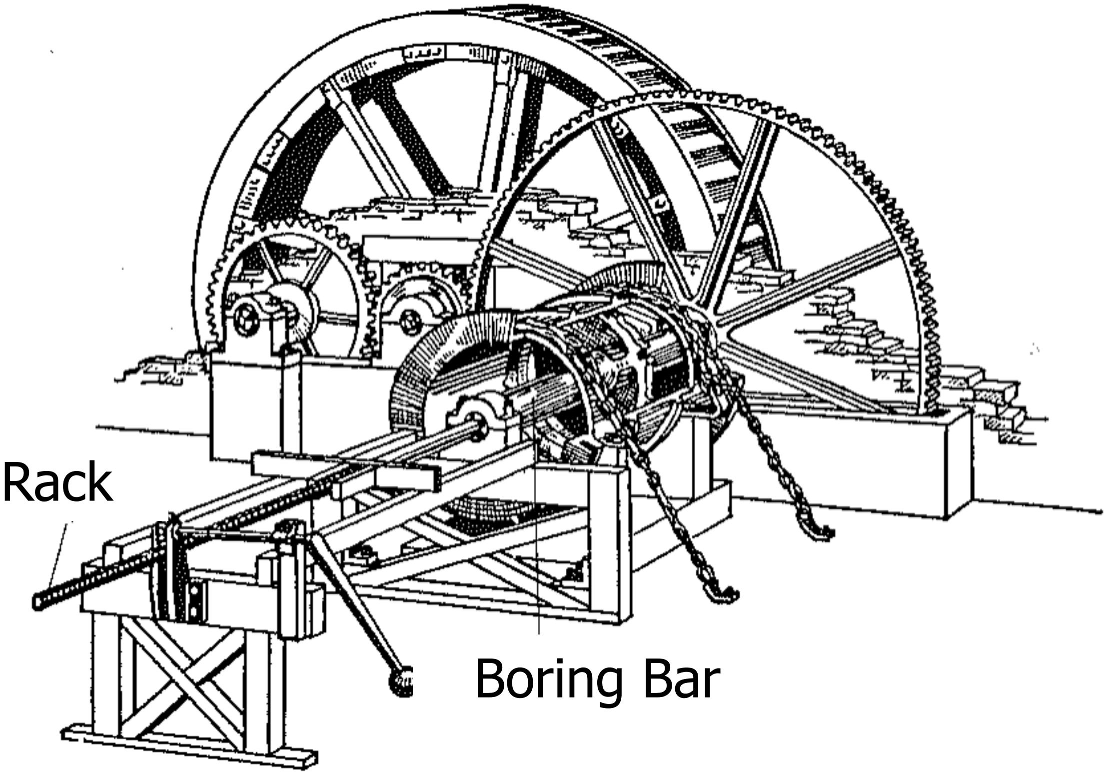

ワットの蒸気エンジン
1797年

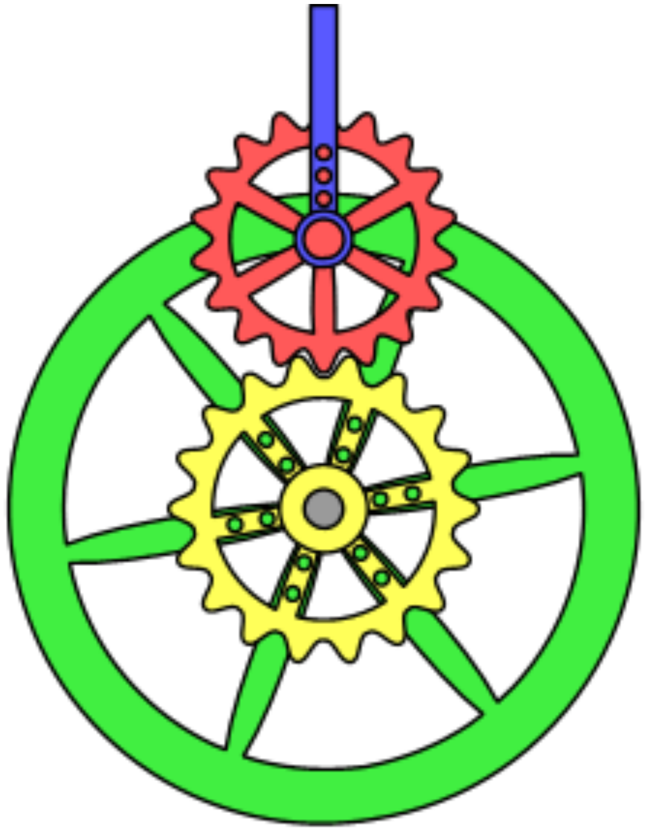
Element 1: Accurate Machining

- **John (Iron-Mad) Wilkinson**
  - Double Supported Rotating Boring Bar
  - Watt was Proud of His Accuracy of 3/8th a Inch (=1cm) from True Cylinders
- **Wilkinson's Machine Could Make 10 Times More True**
  - 4-5 Times More Power (25 to 40 HP Up from 5 to 8)
  - Wilkinson Obtained the Exclusive Rights to Supply Precision Cylinders to B&W



Element 2: Sun and Planetary Gear

- **Need for Rotational Motion**
  - Rather Than Reciprocating Motion
  - James Pickard Had Patented the Crank Mechanism and a Flywheel in 1780
- **James Watt's Workaround**
  - The Same as Pickard, but Less Efficient
  - Only in 1794, B&W Could Use the Crank



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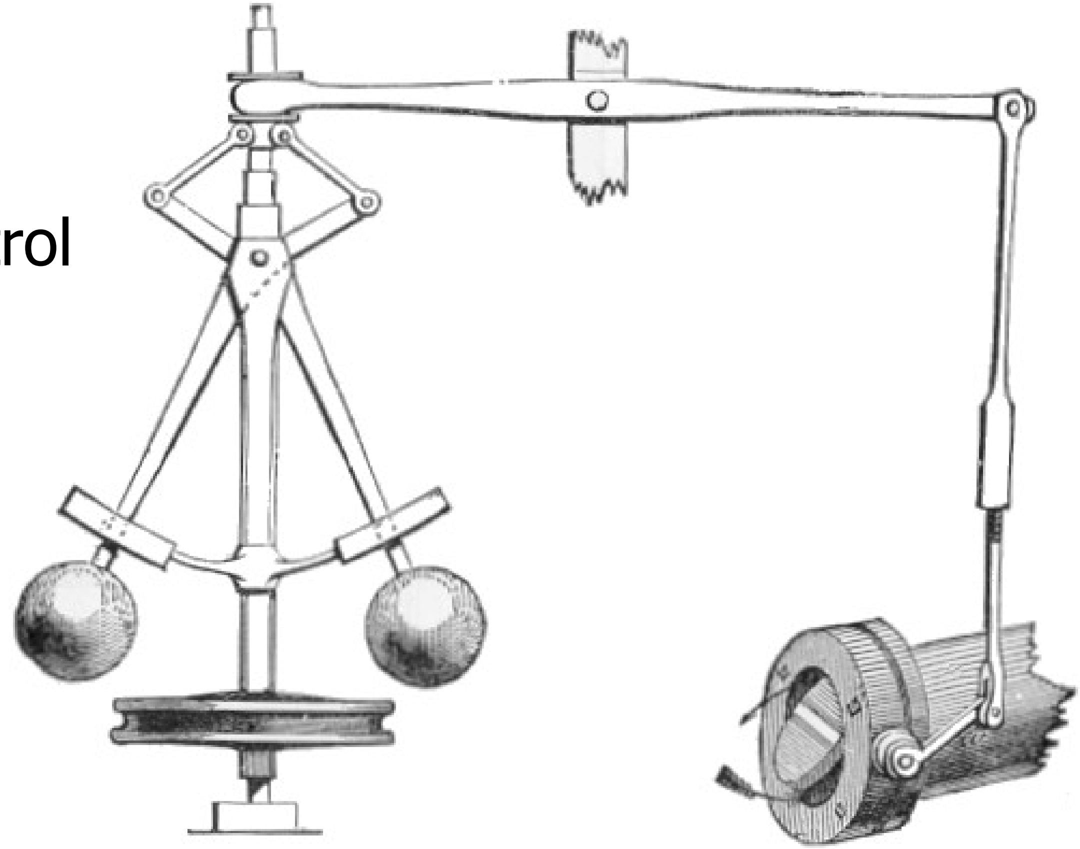
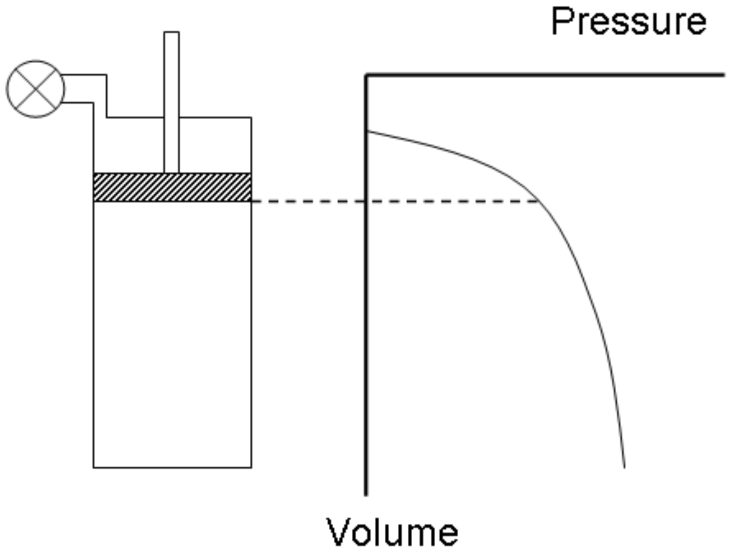
Element 3: Governor

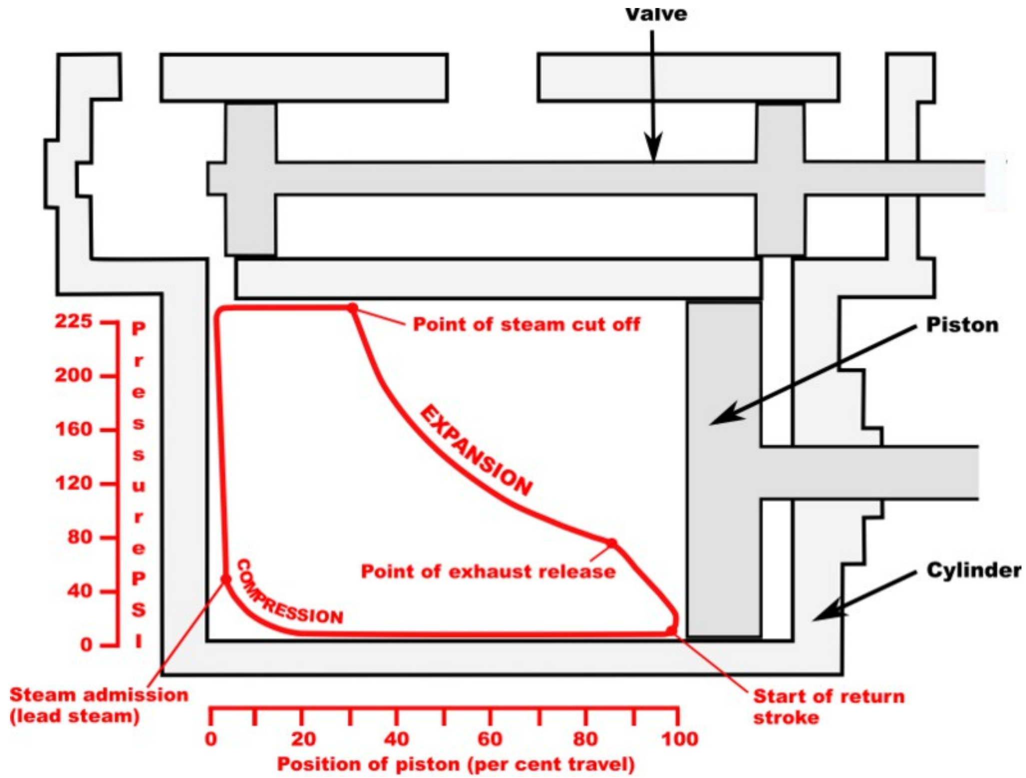
- **Governor**
  - The First Feedback Control
  - "Flyballs"



Element 4: Indicator

- **Kept as "Trade Secret"**





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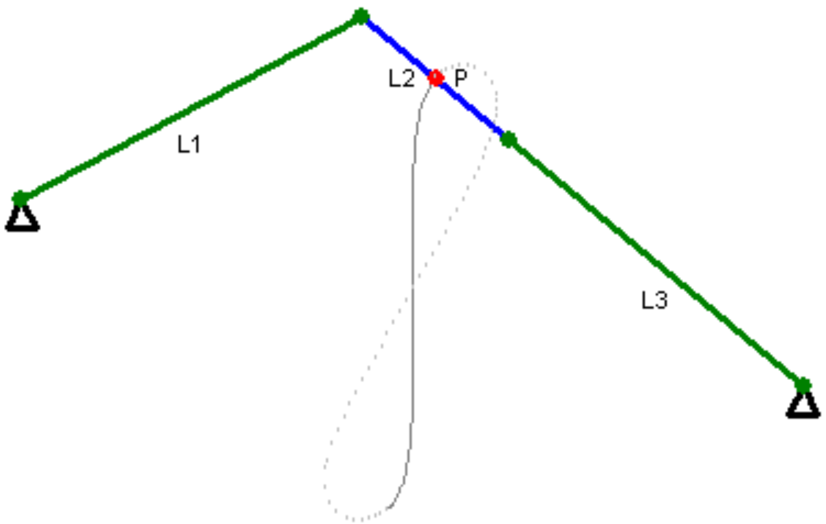
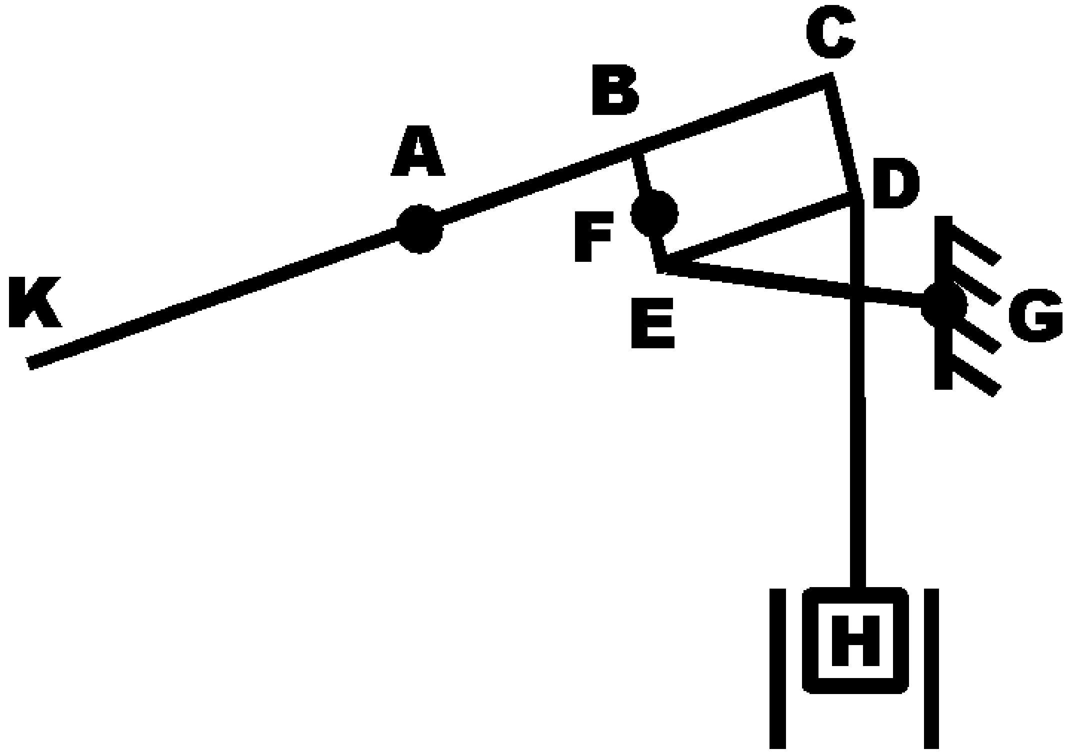
Element 5: Watt’s Parallel Motion





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Element 6: Patent

- **In 1769,**
  - "…in life there is nothing more foolish than inventing, here I work five or more years contriving an engine, and Mr. Moore hears of it, is more evil, gets three patents at once, publishes himself in the newspapers, hires 2,000 men, sets them to work for the whole world in St. George's Fields, gets a fortune at once, and prosecutes me for using my own inventions."
- **Even Disputes with William Mordoch (His Assistant)**
- **Business Expansion**
  - While His Patent was Valid, UK Added about 750 HP/Year
  - After Expiration, 4,000 HP/Year
  - Fuel Efficiency Improved by a Factor of Five between 1810 and 1835

Element 7: Boulton’s Original Business Model (Product Service System)

- **Charge the Customer an Annual Fee based on the Fuel Saved**
  - B&W Asked How Many Horses the Mine Owned
  - Installed a Steam Engine
  - Charge One Third of the Annual Cost of Each Horse It Replaced, Over the Life of the Patent (Until 1800)
- **A Horse Cost about £15/Year**
  - Components for a 4 HP Engine £200-300, a 50 HP Around £1200
  - A 4 HP Engine = £60/Year, the Fee = £20/Year
  - ROI Starts 10 Years
  - A 50 HP Engine Charging £250 Yields Profits Only After 6 Years Over 25 Years!

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Before and After Patent Expiration

- **Before Their Patent Expiration**
  - Trying to Extract Hefty Royalties through Licensing (Main Income)
  - Independent Contractors (e.g., Soho Foundry) Produced Most of the Parts, and B&W Merely Oversaw the Assembly of the Components by the Customer
- **After Patent Expiration**
  - B&W Started to Seriously Manufacture Steam Engines
  - Competitors Principally Aimed at Cheapness Rather than Excellence
  - B&W for Many Years Afterwards Could Keep Up Price and Increase Orders, Emphasizing Manufacturing and Service Activities
- **New Business Model after 1794**
  - Complete Manufacturing of Steam Engines without Depending on Subcontractors
  - Formed New Company: Boulton, Watt & Sons

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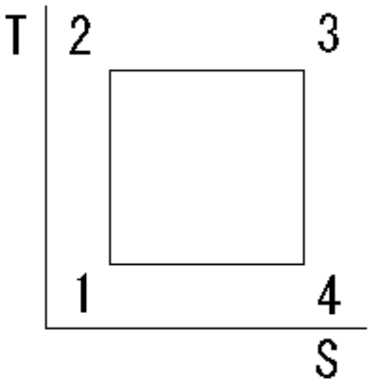
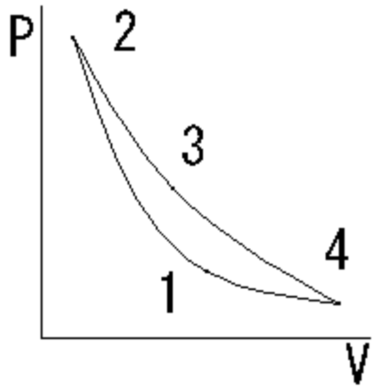
Nicolas Léonard Sadi Carnot (1796-1832)

- **Carnot Cycle (1824)**
  - 1->2: Adiabatic Compression
  - 2->3: Isothermal Expansion
    - Absorbing QH at TH
  - 3->4: Adiabatic Expansion
  - 4->1: Isothermal Compression
    - Radiating QL at TL

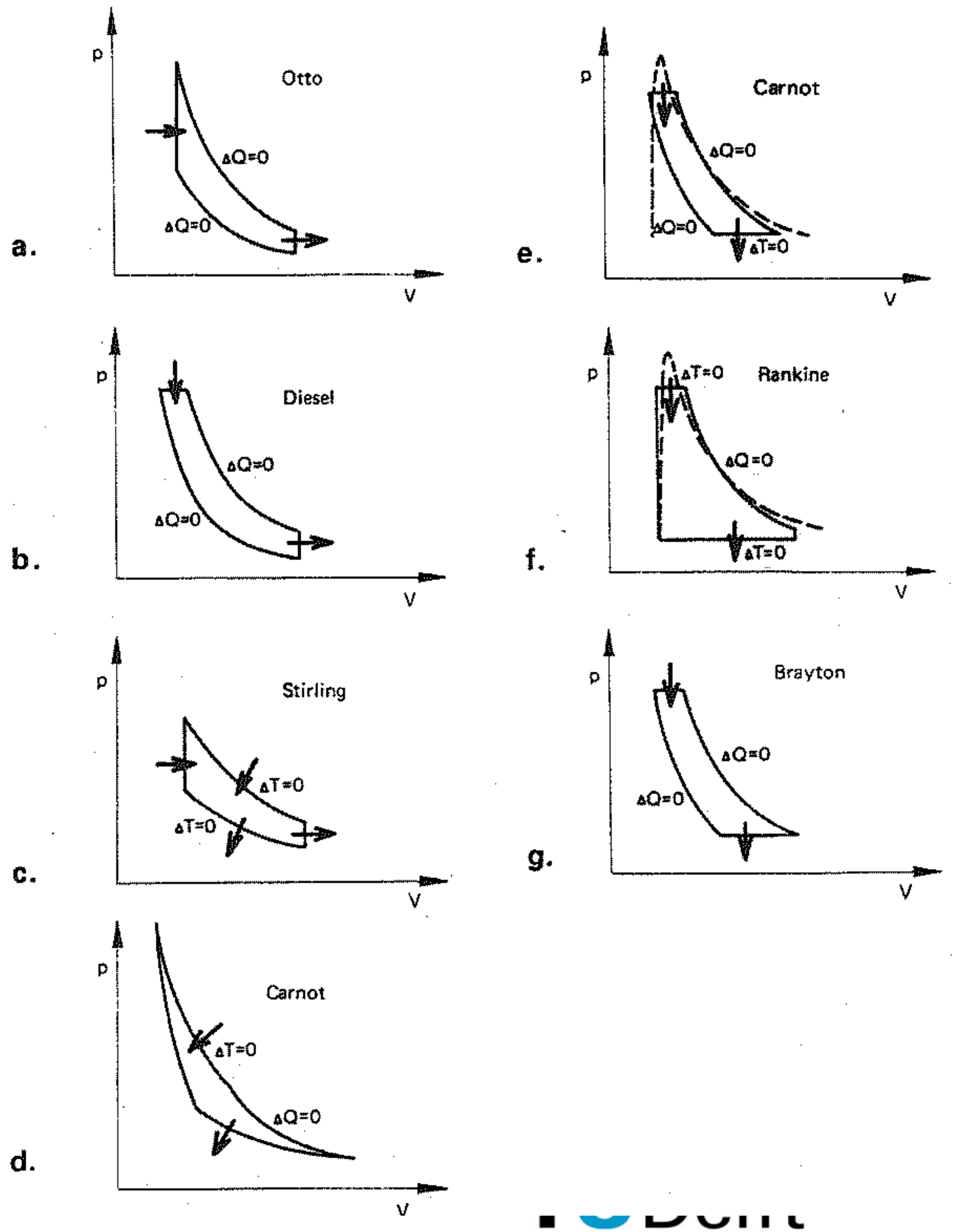




$$\eta = 1 - \frac{T_L}{T_H}$$

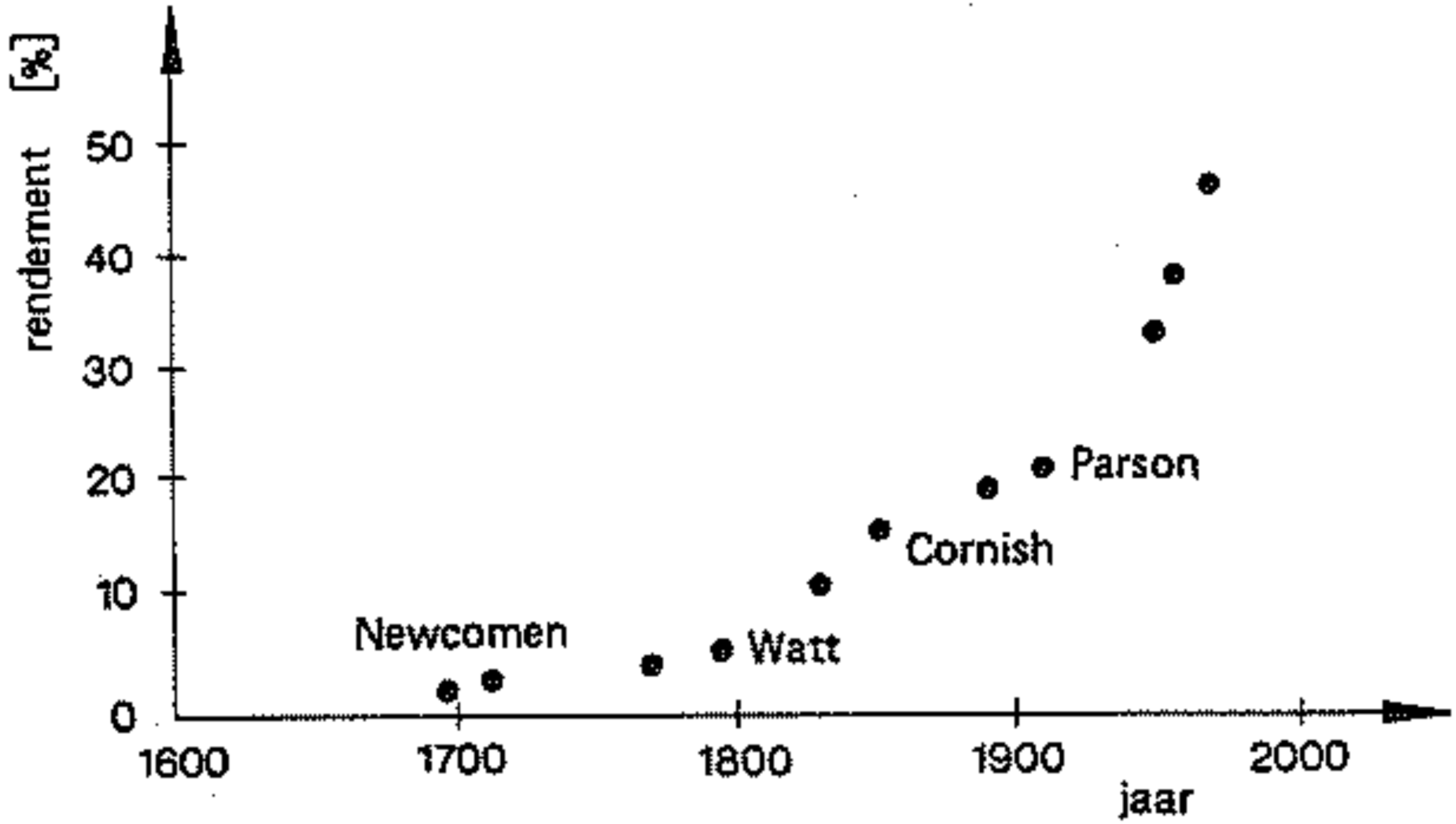
- **Carnot Theorem**
  - No Engine Operating Between Two Heat Reservoirs Can Be More Efficient Than a Carnot Engine Operating Between Those Same Reservoirs.

Indicator Diagrams



Wb3110: Steam Engines

Efficiency



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After Watt

- **Double Action**
- **High Pressure Engine**
  - Watt’s Engine was Effectively an Atmospheric Engine
  - Cornish Engine
    - Cornwall was a Mining Area
  - Crucuius
    - The World’s Biggest (Cornish Type) Steam Engine
- **Steamboat, Steam Locomotives**
- **Reheating**
- **Superheating**

Nicolas-Joseph Cugnot (1725-1804)

- **1770 The First Steam Engine Driven Vehicle**
  - 2.5 tons tare, 4 tons Payload
  - 8 km/h
- **Before Watt!**

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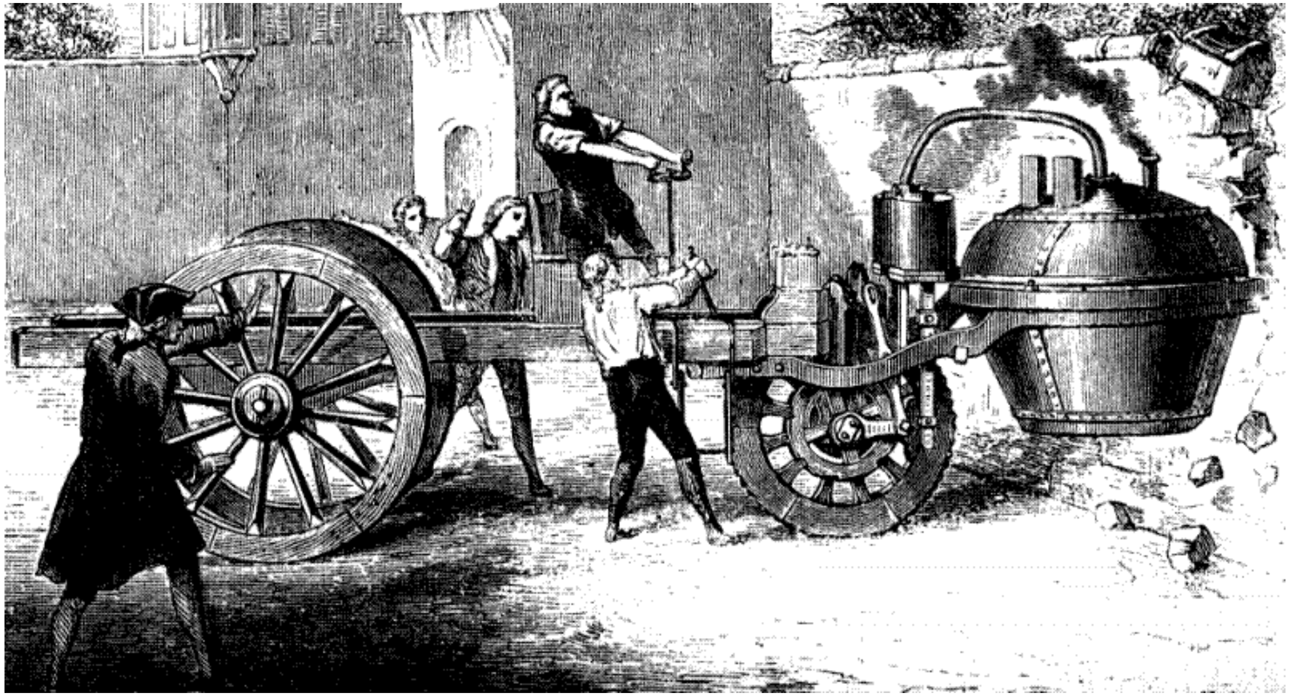

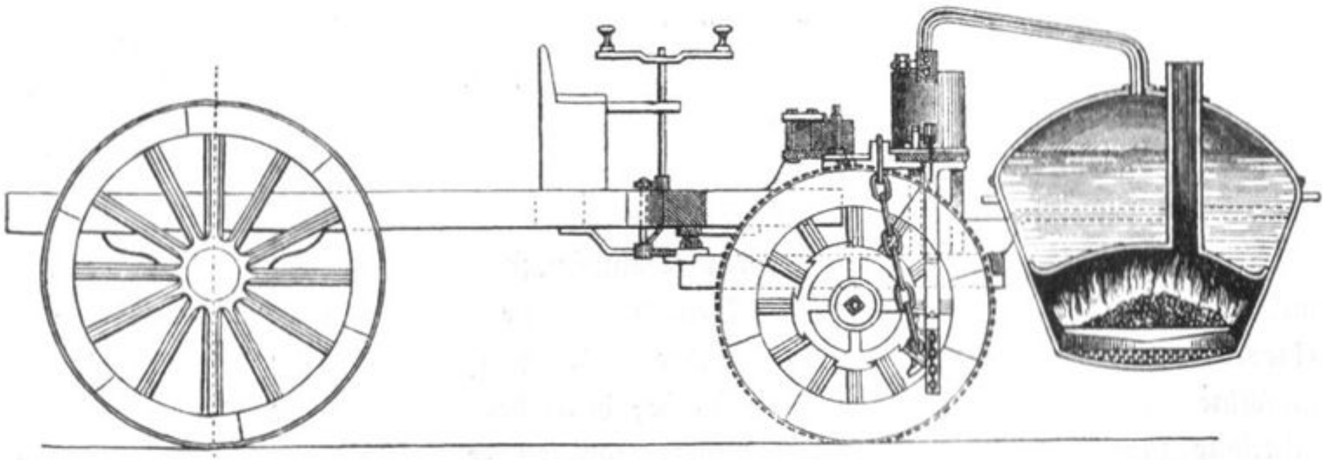

Stanley Steam Car (1923)

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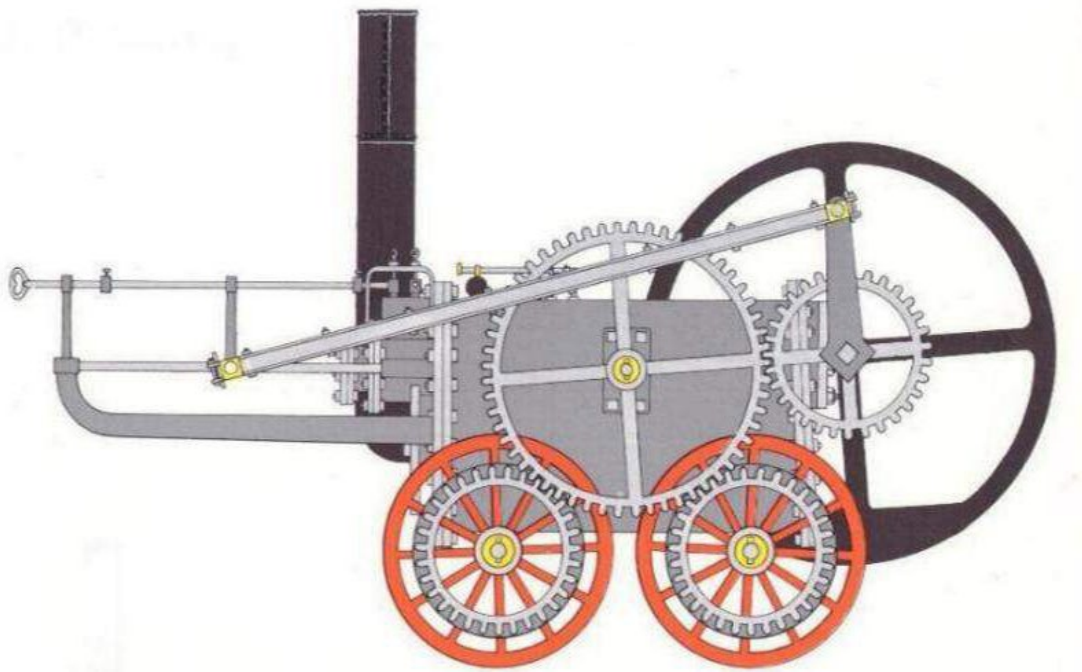
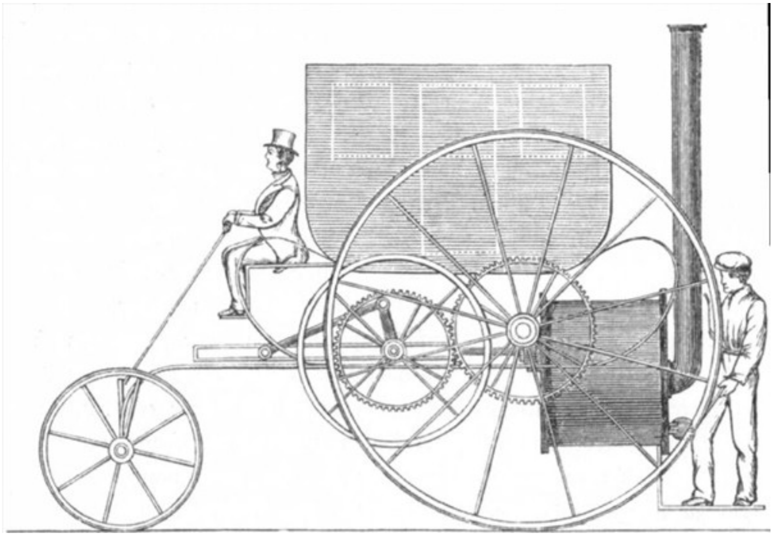
Steam Locomotives

- **1804**
  - Richard Trevithick and Andrew Vivian
  - Penydarren
- **1825**
  - George Stephenson
  - Locomotion
- **1829**
  - George Stephenson
  - Rocket



Richard Trevithick (1771-1833)



- **1801 High Pressure Engine**
  - A Neighbor of William Mordoch (Engineer at Boulton & Watt)
    - No Condenser
  - Watt Never Tried High Pressure
- **1801 Puffing Devil**
  - The First Steam Car
- **1804 Penydarren**
  - The First Steam Locomotive
- **Richard Francis and Francis Henry (His Grandsons) were Invited to Japan to Start Railways**

http://www.sciencemuseum.org.uk/on-line/energyhall/page91.asp

George Stephenson (1781-1848)

- **1825**
    - Locomotion
    - Stockton-Darlington Railway
- **1829**
    - Rocket
    - Liverpool-Manchester Railway

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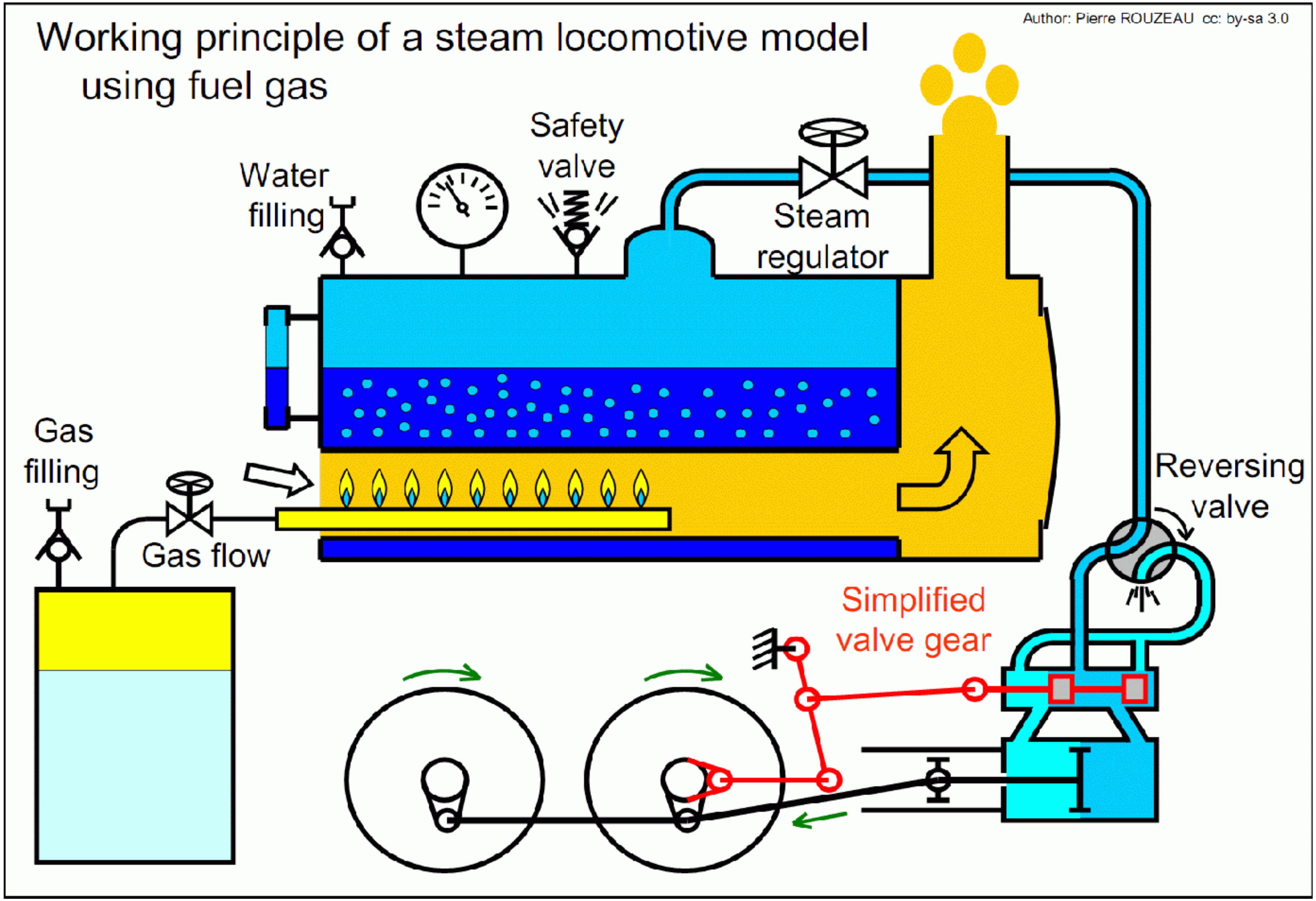
Working principle of a steam locomotive model
using fuel gas
Author: Pierre ROUZEAU cc: by-sa 3.0
Safety
valve
Water
filling
Steam
regulator
Gas
filling
Gas flow
Reversing
valve
Simplified
valve gear

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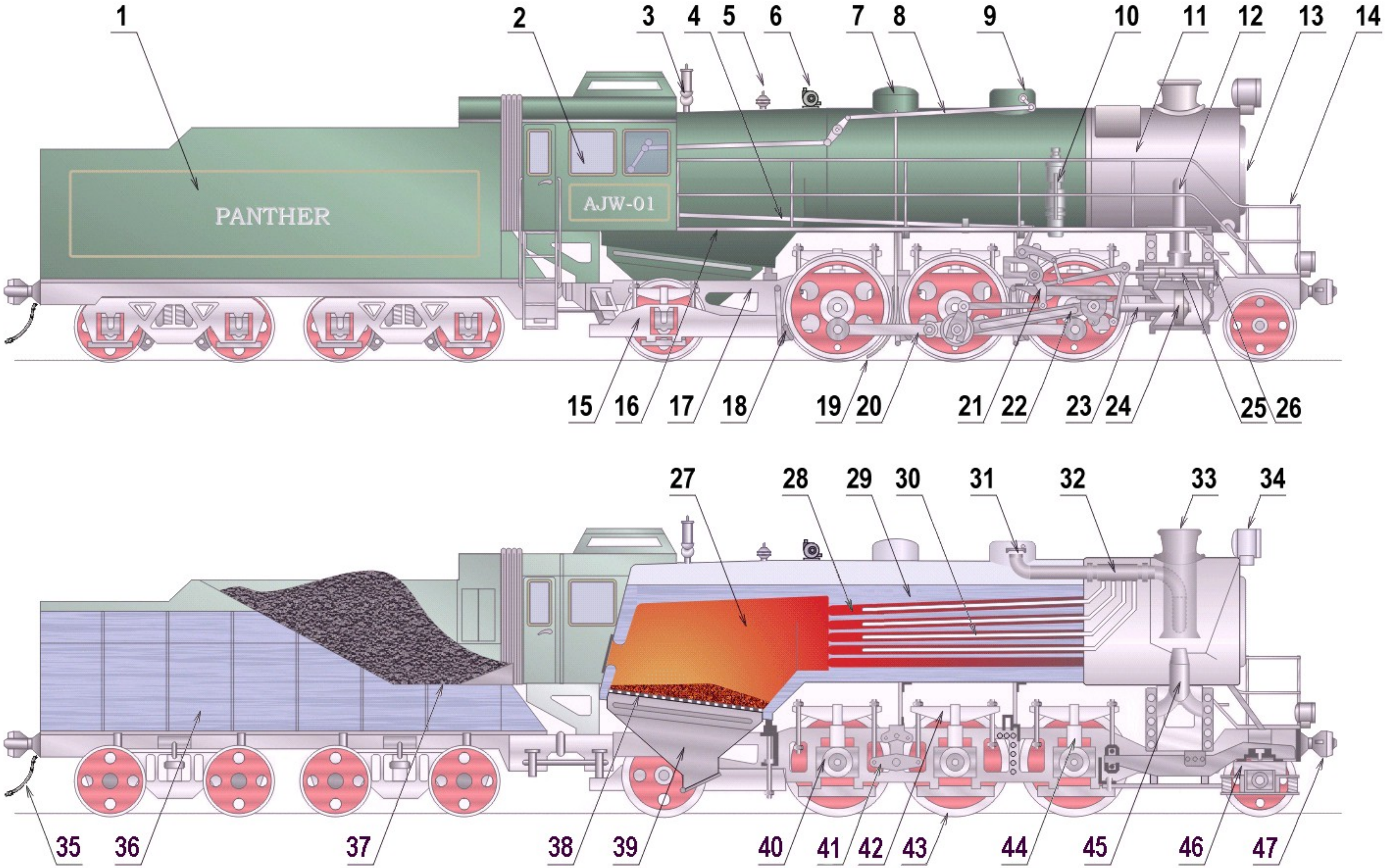

1 2 3 4 5 6 7 8 9 10 11 12 13 14
PANTHER
AJW-01
15 16 17 18 19 20 21 22 23 24 25 26
27 28 29 30 31 32 33 34
35 36 37 38 39 40 41 42 43 44 45 46 47

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Mersey Railway 0-6-4T No.5 "Cecil Raikes"

- **Condenser**
  - For Tunnel Use

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Crucuius

http://www.cruquiusmuseum.nl/framesenglish.htm

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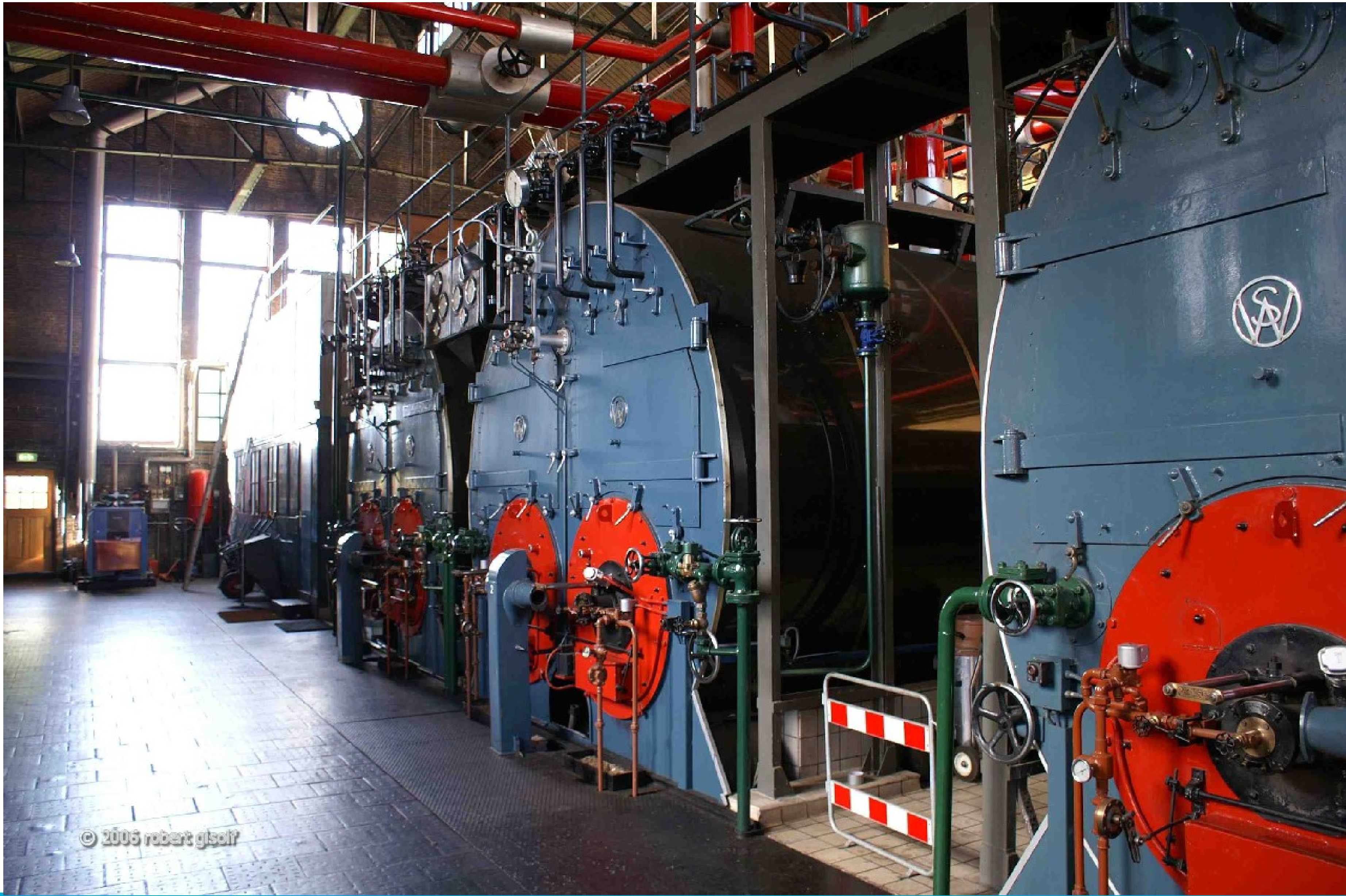
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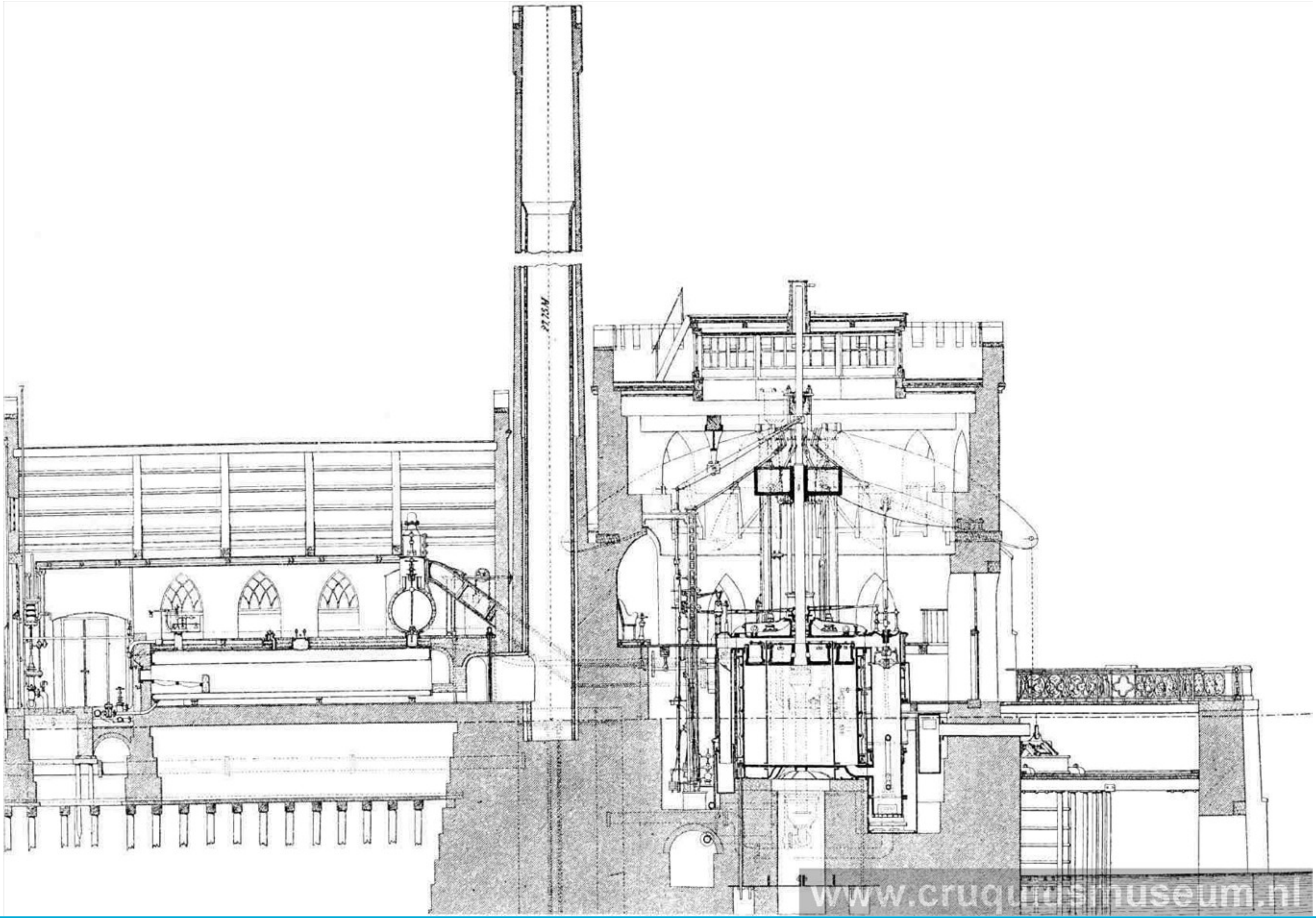

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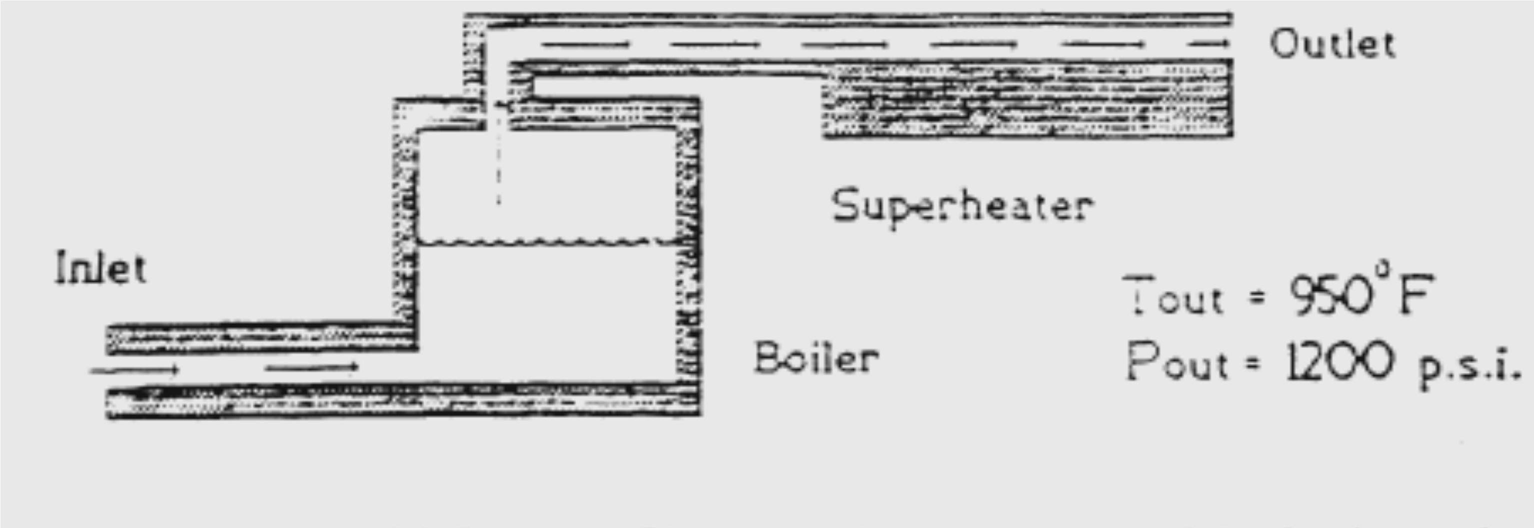
Superheating Steam Turbine



What happens to the temperature of outgoing vapor when the temperature of incoming water increases?

(increases, decreases, remains the same?)

- **Thermodynamical Equations?**

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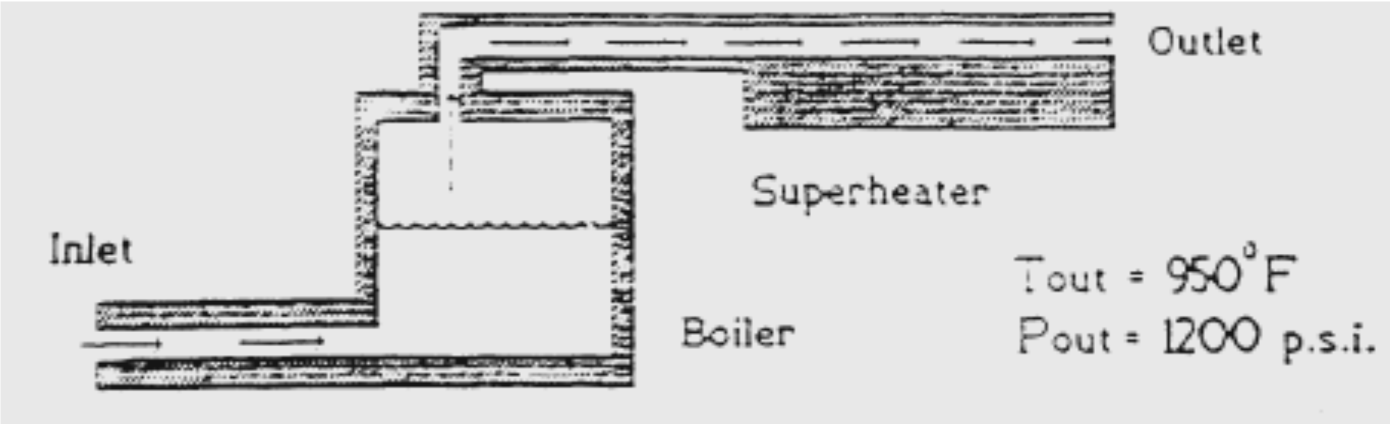
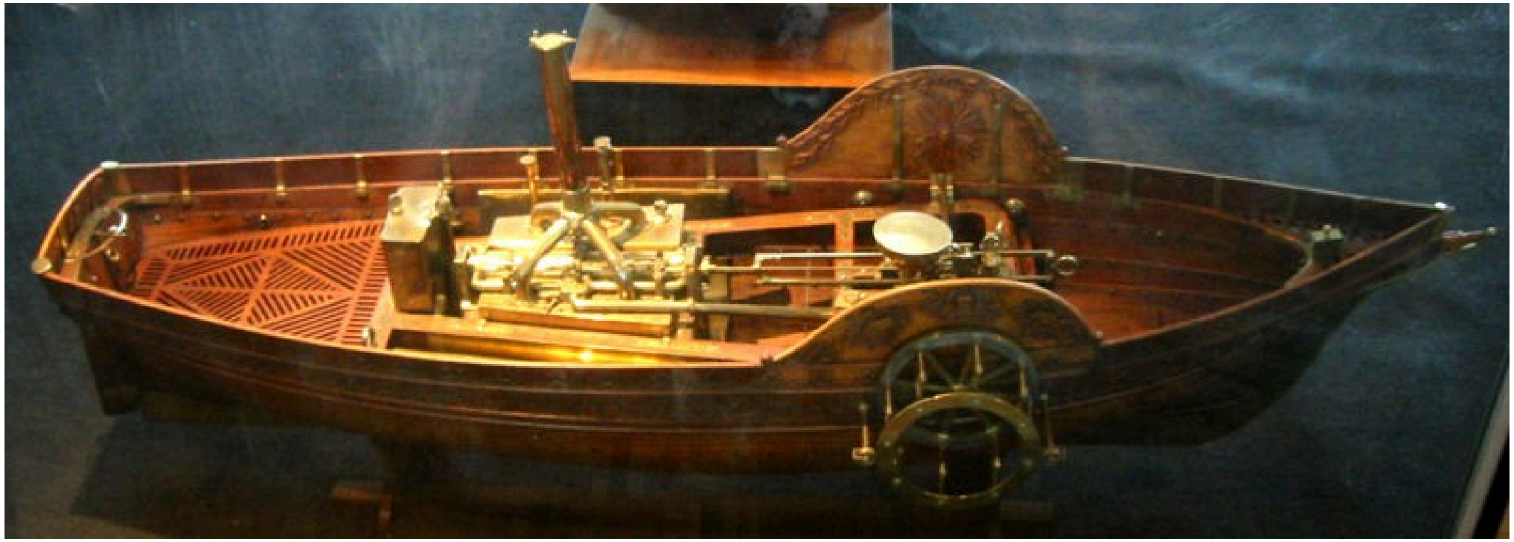
Answer



- **The incoming water →** hotter
- **The amount of heat needed to boil the water →** reduced
- **The water will boil →** sooner
- **The rate of steam production →** increased
- **The time the steam spends in the superheater →** decreased
- **The amount of heat transferred to the steam →** decreased
- **Thus the steam temperature at the outlet →** will decrease

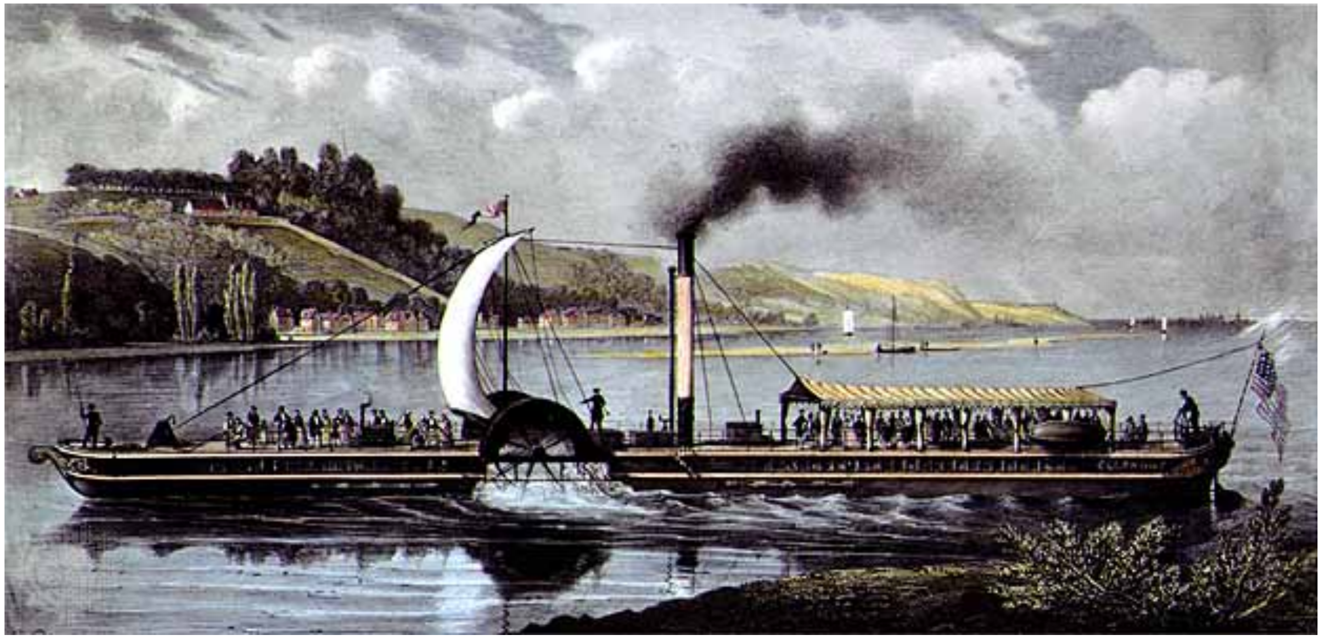
Claude-François-Dorothée, Marquis de Jouffroy d'Abbans (1751–1832)

- **In 1776, Palmipède, the First Paddle-Driven Steamboat**



Robert Fulton (1765-1815, USA)

- **1803**
  - North River Steamboat (Clermont)
  - First Commercial Steamboat between New York and Albany



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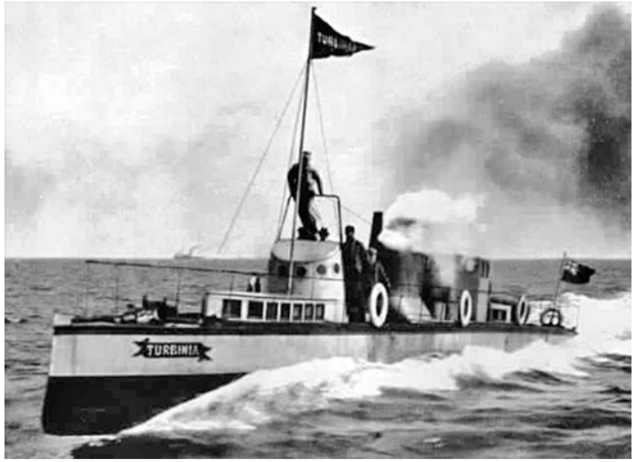
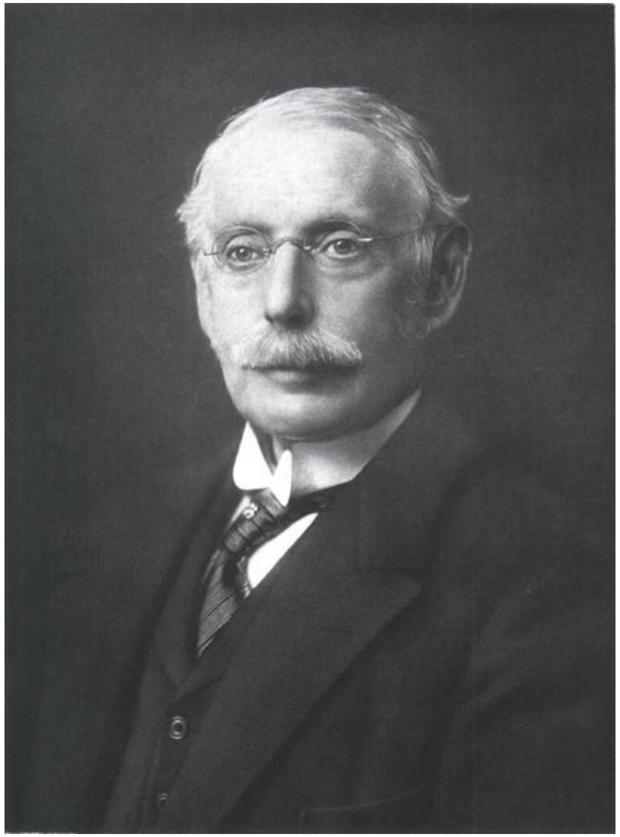
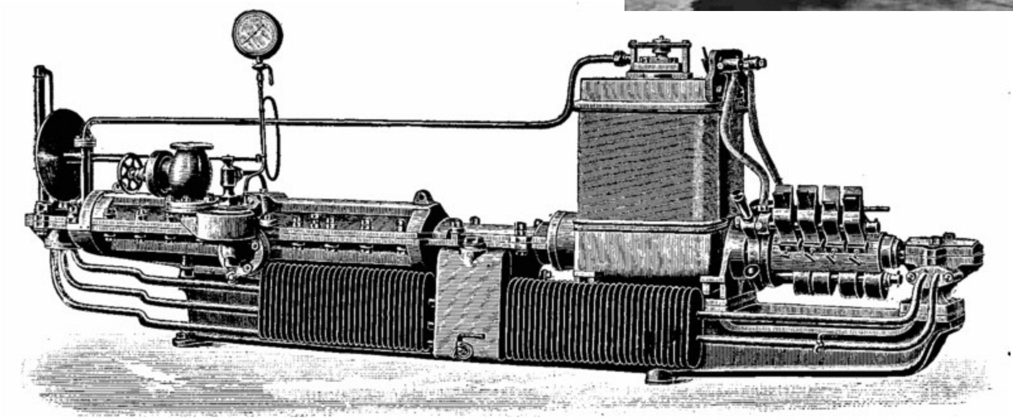
Sir Charles Algernon Parsons (1854-1931)

- **Steam Turbine (1887)**
  - Turbinia: 34 Knots







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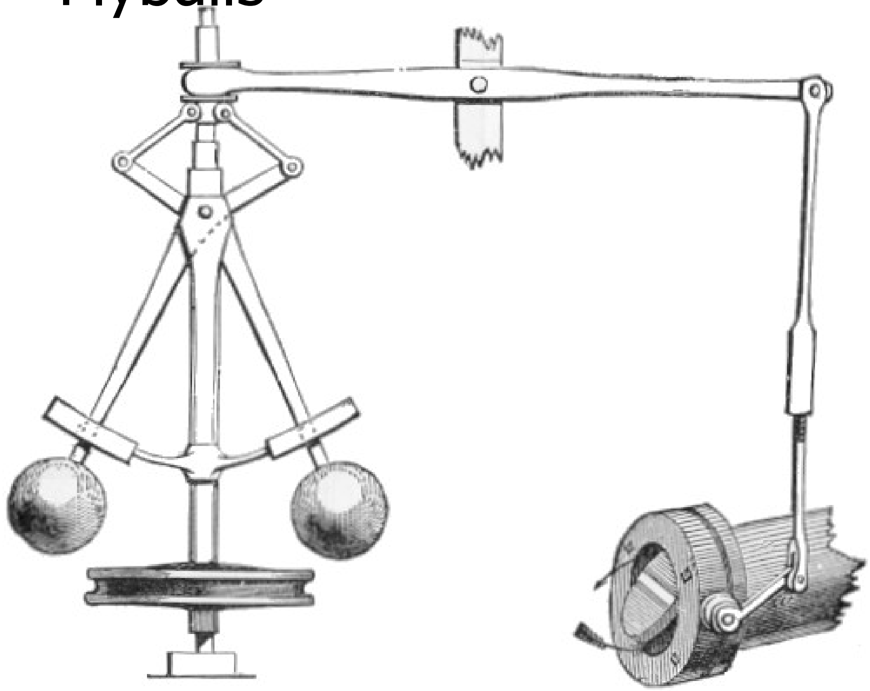
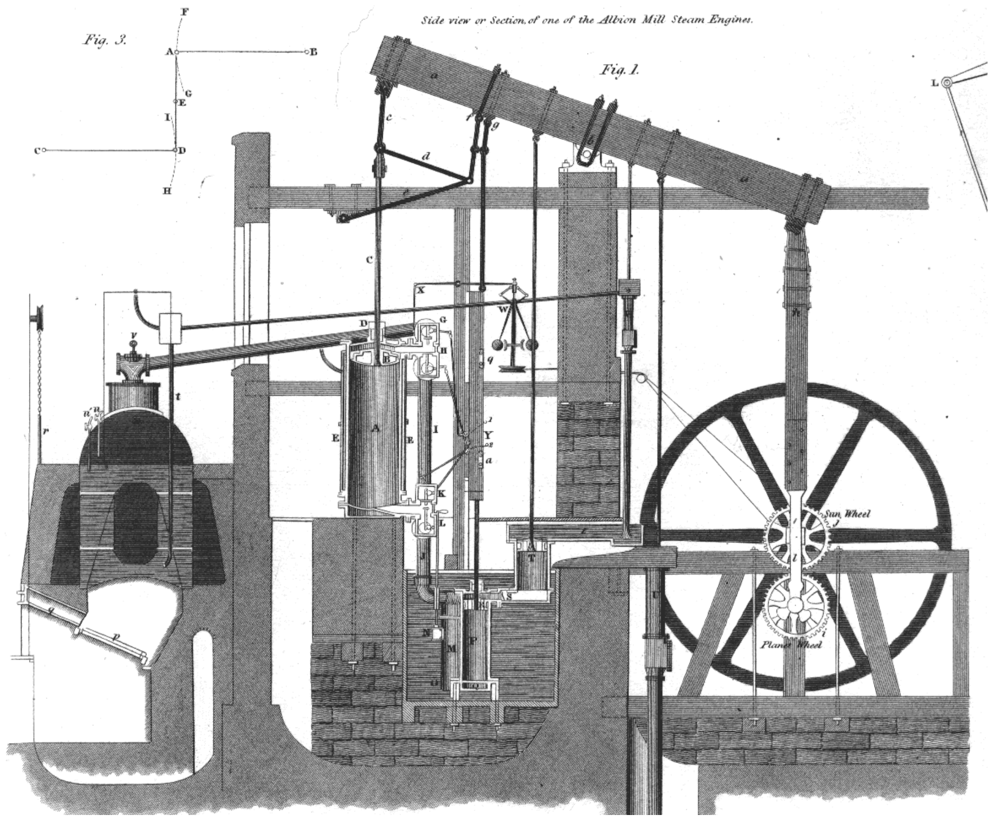
Conclusions

- **First Design, Not First Science**
- **Steam Engine**
  - High Power
  - High Efficiency
  - Lighter
- **Internal Combustion Engines Replaced External Combustion Engines as Power Source for Vehicles**
  - Coming Back?
    - Stirling Engine
    - Environmental Considerations
    - Hybrid, Motor Driven

Exam 2008

- **Governor**
  - The First Feedback Control
  - "Flyballs"





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Consider Only 2 Masses

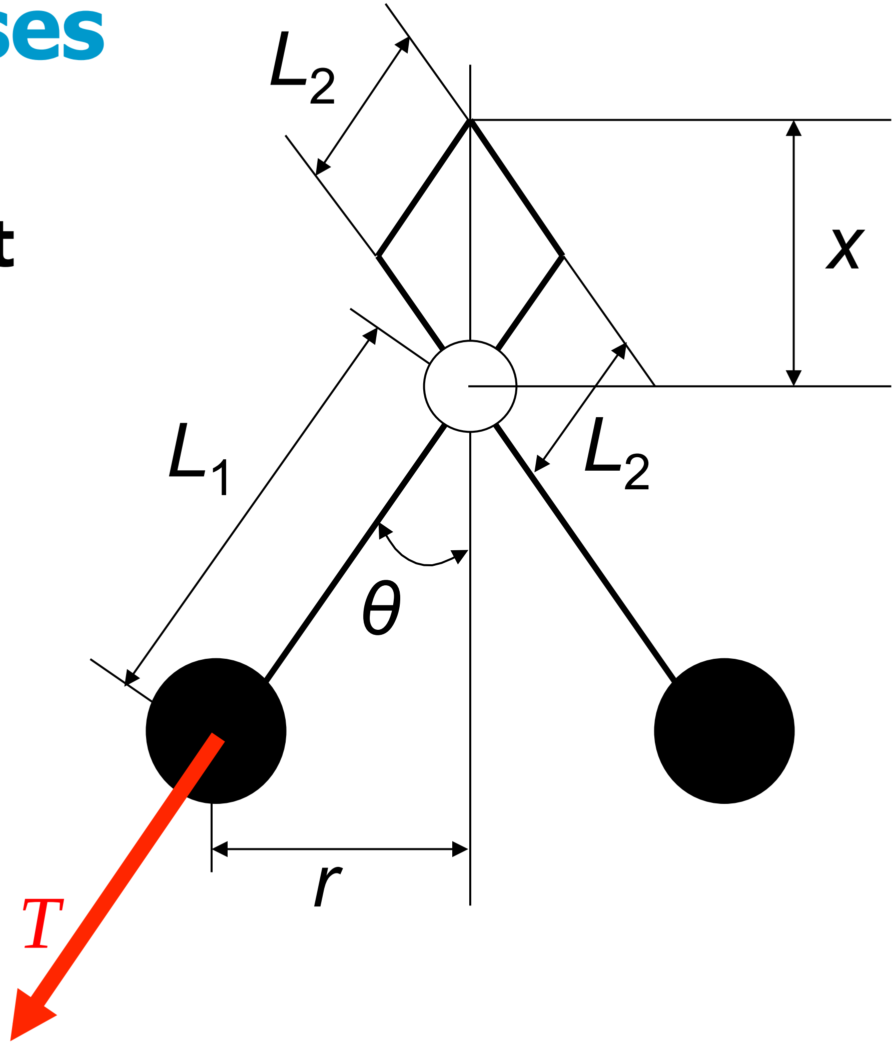
B1. Derive the equations that govern this mechanism focusing only on gravity and centrifugal force. Write your answer in the box below.

Centrifugal Force: $mr\omega^2$

Gravity: mg

$$T\,sin\theta = mr\omega^2$$

$$T\,cos\theta = mg$$



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Solve Equations and Draw Graphs!

B2. Solve the equations and obtain θ and x as a function of ω. Draw rough graphs in the box below that illustrate θ and x as a function of ω.

$$r = L_1 \sin\theta$$

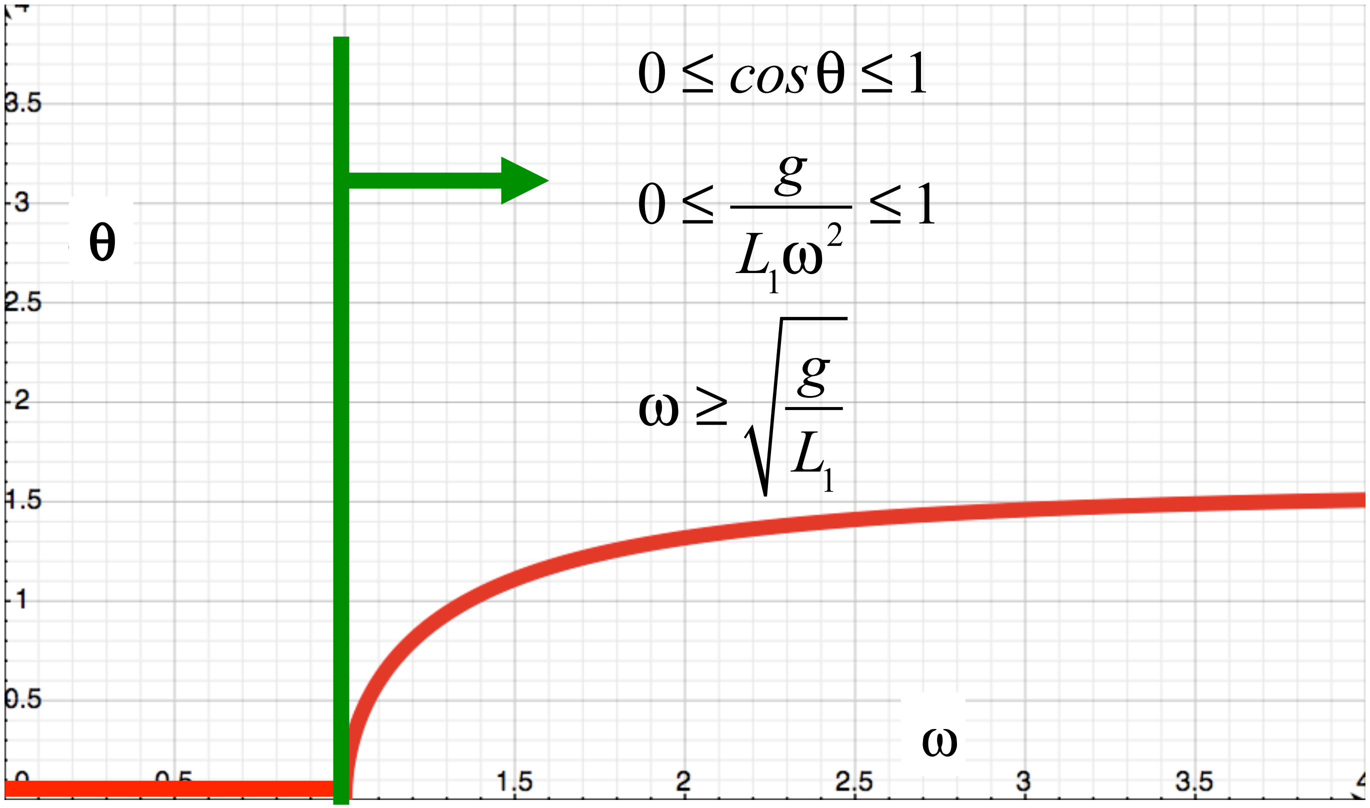
$$T \sin\theta = mL_1 \sin\theta\omega^2$$

$$T \cos\theta = mg$$

$$mL_1\omega^2 \cos\theta = mg$$

$$\theta = \cos^{-1}\left(\frac{g}{L_1\omega^2}\right)$$

$$x = 2L_2 \cos\theta = 2\frac{L_2}{L_1}\bullet\frac{g}{\omega^2}$$



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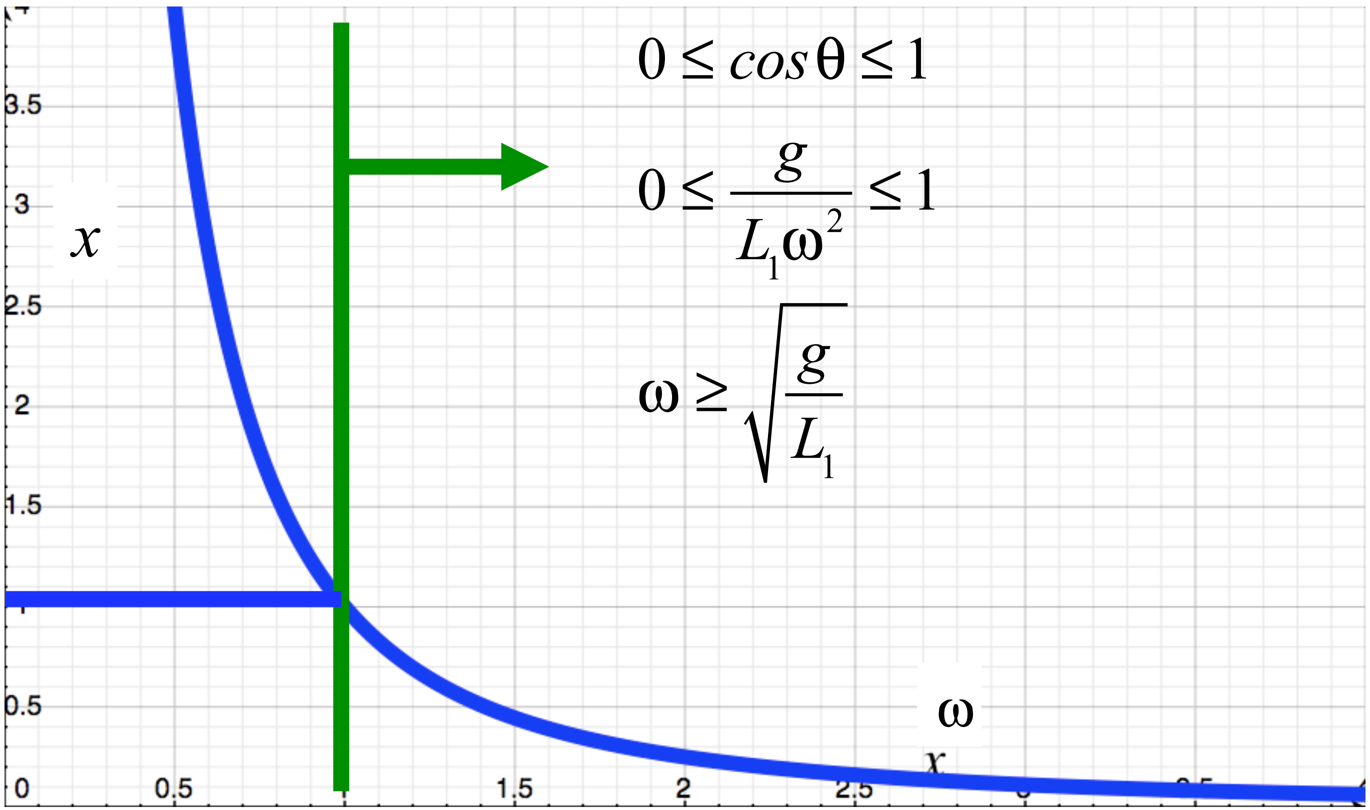

$$0 \le \cos\theta \le 1$$

$$0 \le \frac{g}{L_1\omega^2} \le 1$$

$$\omega \ge \sqrt{\frac{g}{L_1}}$$

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So, What Happens When ω_0 Is Small???

- **Until ω Becomes Bigger Than ω_0**
  - The Mechanism Doesn't Open!
  - Some Fun Fair Machines Have an Offset

$$\theta = cos^{-1}\left(\frac{g}{L_1\omega^2}\right)$$

$$\frac{g}{L_1\omega_0^{\ 2}} = 1$$

$$\omega_0 = \sqrt{\frac{g}{L_1}}$$

Opening of the Mechanism

B3. The governor engages only when the angular velocity ω is faster than a certain speed. For a governor with L1 = 0.2 m, calculate this engaging speed ω_0 and write the answer in the box below. Assume that there is no limiting mechanism.

$$\omega_0 = \sqrt{\frac{g}{L_1}} = \sqrt{\frac{9.8}{0.2}} = \sqrt{49} = 7$$

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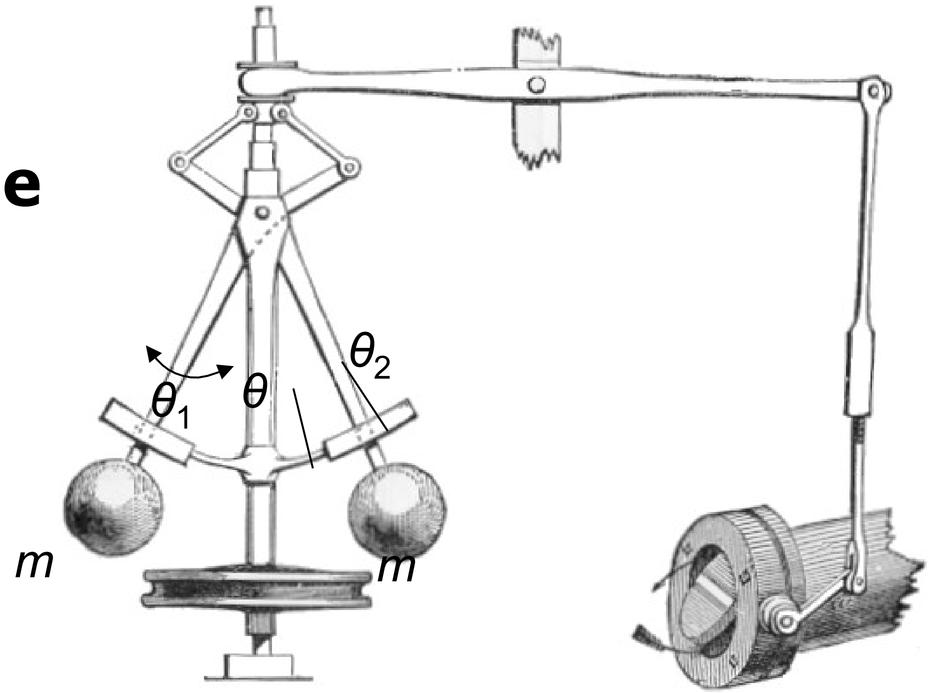
Limiting Mechanism

B4. What are the purposes of the limiting mechanism?

- To Prevent "Sudden" Opening
  - Lower Side θ_1
- To Prevent Complete Closing at Higher Speed
  - Complete Closing = Explosion
  - Higher Side θ_2



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Design Consideration

B5. In order to change the operational characteristics of the governor (e.g., gain, engaging speed, etc.), what kind of design changes can be made? Assume there is a limiting mechanism.

- Change L_1, L_2
- Change θ_1, θ_2
- Add Another Mass
  - Change of m Doesn't Contribute
  - Change of Effective L_1

$$\theta = cos^{-1}\left(\frac{g}{L_1\omega^2}\right)$$

$$x = 2L_2\,cos\,\theta = 2\frac{L_2}{L_1}\bullet\frac{g}{\omega^2}$$

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Complete Analysis

- **In Fact, Watt's Governor is Not Trivial**
  - Initiated "Control Theory" and "Control Engineering"
    - Mathematical Treatment for "Feedback Control"
    - Cybernetics
- **Still Modern Analyses Are Published**