PHYS12 CH:9.3 How Ancient Humans Moved Mountains

The Six Tools That Built Civilization

Mr. Gullo

December 2025

Outline

How did ancient humans move

20-ton stone blocks

without engines or electricity?

How did ancient humans move

20-ton stone blocks

without engines or electricity?

They discovered six simple machines that multiply force.

The Mystery

How did ancient humans move
20-ton stone blocks
without engines or electricity?

They discovered six simple machines that multiply force.

Same tools built the pyramids and launch rockets today.

Learning Objectives

By the end of this lesson, you will be able to:

- **9.3:** Describe simple and complex machines

Learning Objectives

By the end of this lesson, you will be able to:

- **9.3:** Describe simple and complex machines
- **9.3:** Calculate mechanical advantage of simple machines

Learning Objectives

By the end of this lesson, you will be able to:

- **9.3:** Describe simple and complex machines
- **9.3:** Calculate mechanical advantage of simple machines
- **9.3:** Calculate efficiency of simple and complex machines

9.3 The Conservation Trade-Off

Nature's Accounting System

In closed systems, total energy is conserved.
Machines cannot create energy.

9.3 The Conservation Trade-Off

Nature's Accounting System

In closed systems, total energy is conserved.
Machines cannot create energy.

What simple machines DO:

- Reduce force required

9.3 The Conservation Trade-Off

Nature's Accounting System

In closed systems, total energy is conserved.
Machines cannot create energy.

What simple machines DO:

- Reduce force required
- Increase distance over which force acts

9.3 The Conservation Trade-Off

Nature's Accounting System

In closed systems, total energy is conserved.
Machines cannot create energy.

What simple machines DO:

- Reduce force required
- Increase distance over which force acts
- Product $f \times d$ stays constant

9.3 The Conservation Trade-Off

Nature's Accounting System

In closed systems, total energy is conserved.
Machines cannot create energy.

What simple machines DO:

- Reduce force required
- Increase distance over which force acts
- Product $f \times d$ stays constant

The Illusion

Machines make work "easier" but don't reduce total work.

9.3 The Trade-Off Equation

Universal Law of Simple Machines

$$\boxed{W_i = W_o}$$

Work input equals work output (in ideal case)

9.3 The Trade-Off Equation

Universal Law of Simple Machines

$$\boxed{W_i = W_o}$$

Work input equals work output (in ideal case)

Expanding this:

$$F_e \times d_e = F_r \times d_r$$

9.3 The Trade-Off Equation

Universal Law of Simple Machines

$$\boxed{W_i = W_o}$$

Work input equals work output (in ideal case)

Expanding this:

$$F_e \times d_e = F_r \times d_r$$

The Mental Model

If effort force F_e is less than resistance force F_r,
then effort distance d_e must be greater than resistance distance d_r.

9.3 The Lever: Humanity's First Force Multiplier

9.3 The Lever: Humanity's First Force Multiplier

Components:

- Fulcrum: the pivot point
- Effort arm L_e: distance from fulcrum to effort force
- Resistance arm L_r: distance from fulcrum to load

9.3 Mechanical Advantage

Definition: Ideal Mechanical Advantage (IMA)

The number of times a machine multiplies the effort force.

Definition: Ideal Mechanical Advantage (IMA)

The number of times a machine multiplies the effort force.

For a lever:

$$IMA = \frac{L_e}{L_r}$$

9.3 Mechanical Advantage

Definition: Ideal Mechanical Advantage (IMA)

The number of times a machine multiplies the effort force.

For a lever:

$$IMA = \frac{L_e}{L_r}$$

General formula:

$$IMA = \frac{F_r}{F_e} = \frac{d_e}{d_r}$$

9.3 Mechanical Advantage

Definition: Ideal Mechanical Advantage (IMA)

The number of times a machine multiplies the effort force.

For a lever:

$$IMA = \frac{L_e}{L_r}$$

General formula:

$$IMA = \frac{F_r}{F_e} = \frac{d_e}{d_r}$$

The Mental Model

IMA of 4 means you lift 400 N with only 100 N effort.

The catch: you pull 4 times the distance.

Three classes based on fulcrum position:

9.3 Lever Classes

Three classes based on fulcrum position:

- **Class 1:** Fulcrum between effort and load
  Examples: seesaw, pry bar, scissors

9.3 Lever Classes

Three classes based on fulcrum position:

- **Class 1:** Fulcrum between effort and load
  Examples: seesaw, pry bar, scissors
- **Class 2:** Load between fulcrum and effort
  Examples: wheelbarrow, bottle opener, nutcracker

Three classes based on fulcrum position:

- **Class 1:** Fulcrum between effort and load
  Examples: seesaw, pry bar, scissors
- **Class 2:** Load between fulcrum and effort
  Examples: wheelbarrow, bottle opener, nutcracker
- **Class 3:** Effort between fulcrum and load
  Examples: baseball bat, hammer, golf club

Three classes based on fulcrum position:

- **Class 1:** Fulcrum between effort and load
  Examples: seesaw, pry bar, scissors
- **Class 2:** Load between fulcrum and effort
  Examples: wheelbarrow, bottle opener, nutcracker
- **Class 3:** Effort between fulcrum and load
  Examples: baseball bat, hammer, golf club

The Paradox

Class 3 levers have IMA less than 1. They reduce force but increase speed!

9.3 Wheel and Axle

IMA formula:

$$IMA = \frac{r_{wheel}}{r_{axle}}$$

9.3 Wheel and Axle

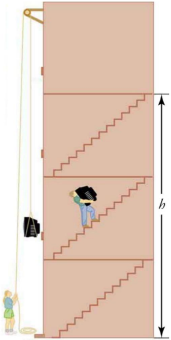
IMA formula:

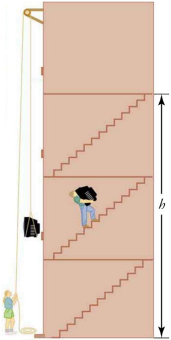
$$IMA = \frac{r_{wheel}}{r_{axle}}$$

Real-World Examples

Steering wheel, door knob, windlass, screwdriver handle

9.3 Inclined Plane



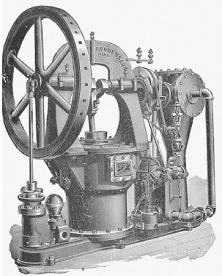


IMA formula:

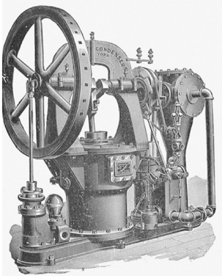
$$IMA = \frac{L}{h}$$

where L is length of ramp and h is height

9.3 The Wedge

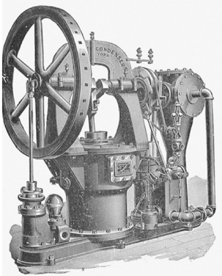


9.3 The Wedge



What it is: Two inclined planes back to back

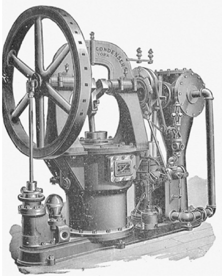
9.3 The Wedge



What it is: Two inclined planes back to back

IMA formula:

$$IMA = \frac{L}{h}$$



What it is: Two inclined planes back to back

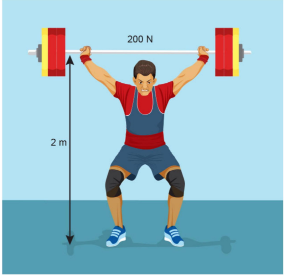
IMA formula:

$$IMA = \frac{L}{h}$$

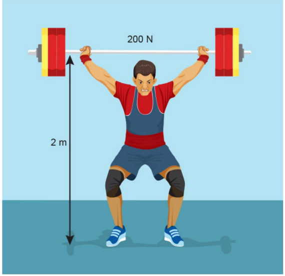
Real-World Examples

Knife, axe, chisel, nail, zipper teeth

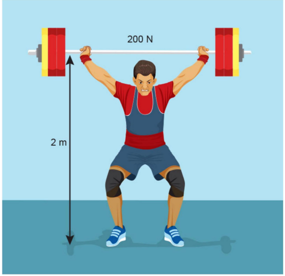
9.3 The Screw



9.3 The Screw



What it is: An inclined plane wrapped around a cylinder



What it is: An inclined plane wrapped around a cylinder

IMA formula:

$$IMA = \frac{2\pi L}{P}$$

where L is handle length and P is pitch (distance between threads)

9.3 The Pulley

9.3 The Pulley

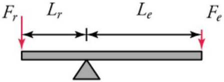
IMA formula (easiest!):

$$IMA = N$$

where N is number of ropes supporting the load

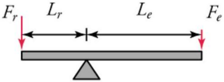
9.3 Complex Machines

$$IMA = \frac{L_e}{L_r}$$



9.3 Complex Machines

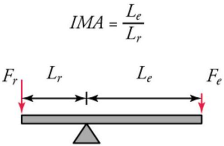
$$IMA = \frac{L_e}{L_r}$$



Definition: Complex Machine

A combination of two or more simple machines

9.3 Complex Machines

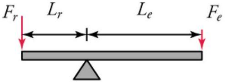


Definition: Complex Machine

A combination of two or more simple machines

Wire cutters combine:

- Two levers
- Two wedges



Definition: Complex Machine

A combination of two or more simple machines

Wire cutters combine:

- Two levers
- Two wedges

More Examples

Bicycle: wheel and axle, levers, screws, pulleys
Car: hundreds of simple machines combined

9.3 The Reality of Friction

Civilian View vs. Reality

Ideal machine: $W_i = W_o$ (100% efficiency)
Real machine: $W_o < W_i$ (always less than 100%)

Civilian View vs. Reality

Ideal machine: $W_i = W_o$ (100% efficiency)
Real machine: $W_o < W_i$ (always less than 100%)

Why the difference?

- Friction between moving parts

9.3 The Reality of Friction

Civilian View vs. Reality

Ideal machine: $W_i = W_o$ (100% efficiency)
Real machine: $W_o < W_i$ (always less than 100%)

Why the difference?

- Friction between moving parts
- Air resistance

9.3 The Reality of Friction

Civilian View vs. Reality

Ideal machine: $W_i = W_o$ (100% efficiency)
Real machine: $W_o < W_i$ (always less than 100%)

Why the difference?

- Friction between moving parts
- Air resistance
- Heat generation

9.3 The Reality of Friction

Civilian View vs. Reality

Ideal machine: $W_i = W_o$ (100% efficiency)
Real machine: $W_o < W_i$ (always less than 100%)

Why the difference?

- Friction between moving parts
- Air resistance
- Heat generation
- Deformation of materials

Civilian View vs. Reality

Ideal machine: $W_i = W_o$ (100% efficiency)
Real machine: $W_o < W_i$ (always less than 100%)

Why the difference?

- Friction between moving parts
- Air resistance
- Heat generation
- Deformation of materials

Energy is conserved, but some becomes unavailable heat.

9.3 Calculating Efficiency

Definition: Efficiency

The ratio of output work to input work, expressed as percentage

9.3 Calculating Efficiency

Definition: Efficiency

The ratio of output work to input work, expressed as percentage

Efficiency formula:

$$\text{Efficiency} = \frac{W_o}{W_i} \times 100\%$$

9.3 Calculating Efficiency

Definition: Efficiency

The ratio of output work to input work, expressed as percentage

Efficiency formula:

$$\text{Efficiency} = \frac{W_o}{W_i} \times 100\%$$

Since $W = F \times d$:

$$\text{Efficiency} = \frac{F_o \times d_o}{F_i \times d_i} \times 100\%$$

9.3 Which Machines Are Most Efficient?

Think about friction:

9.3 Which Machines Are Most Efficient?

Think about friction:

- Depends on smoothness of surfaces

9.3 Which Machines Are Most Efficient?

Think about friction:

- Depends on smoothness of surfaces
- Depends on area of surfaces in contact

9.3 Which Machines Are Most Efficient?

Think about friction:

- Depends on smoothness of surfaces
- Depends on area of surfaces in contact
- Depends on types of materials

9.3 Which Machines Are Most Efficient?

Think about friction:

- Depends on smoothness of surfaces
- Depends on area of surfaces in contact
- Depends on types of materials

Ranking by Efficiency (typical)

1. Pulleys (95-98%)
2. Wheel and axle (90-95%)
3. Levers (90-95%)
4. Inclined plane (60-90%)
5. Wedge (50-80%)
6. Screw (30-70%)

Attempt: Lever Efficiency

The Challenge (3 min, silent)

An input force of 11 N acting on the effort arm of a lever moves 0.4 m. This lifts a 40 N weight on the resistance arm a distance of 0.1 m.

Given:

- $F_i = 11$ N, $d_i = 0.4$ m
- $F_o = 40$ N, $d_o = 0.1$ m

Find: Efficiency of the lever

Can you calculate how much work is lost to friction?

Compare: Efficiency Strategy

Turn and talk (2 min):

1. What equation did you use for efficiency?
2. Did you calculate W_i and W_o separately?
3. What units should efficiency have?

Compare: Efficiency Strategy

Turn and talk (2 min):

1. What equation did you use for efficiency?
2. Did you calculate W_i and W_o separately?
3. What units should efficiency have?

Name wheel: One pair share your approach (not your answer).

Reveal: Lever Efficiency Solution

Self-correct in a different color:

Step 1: Calculate input work

$$W_i = F_i \times d_i = 11 \times 0.4 = 4.4 \text{ J}$$

Reveal: Lever Efficiency Solution

Self-correct in a different color:

Step 1: Calculate input work

$$W_i = F_i \times d_i = 11 \times 0.4 = 4.4 \text{ J}$$

Step 2: Calculate output work

$$W_o = F_o \times d_o = 40 \times 0.1 = 4.0 \text{ J}$$

Reveal: Lever Efficiency Solution

Self-correct in a different color:

Step 1: Calculate input work

$$W_i = F_i \times d_i = 11 \times 0.4 = 4.4 \text{ J}$$

Step 2: Calculate output work

$$W_o = F_o \times d_o = 40 \times 0.1 = 4.0 \text{ J}$$

Step 3: Calculate efficiency

$$\text{Efficiency} = \frac{W_o}{W_i} \times 100\% = \frac{4.0}{4.4} \times 100\% = \boxed{91\%}$$

Reveal: Lever Efficiency Solution

Self-correct in a different color:

Step 1: Calculate input work

$$W_i = F_i \times d_i = 11 \times 0.4 = 4.4 \text{ J}$$

Step 2: Calculate output work

$$W_o = F_o \times d_o = 40 \times 0.1 = 4.0 \text{ J}$$

Step 3: Calculate efficiency

$$\text{Efficiency} = \frac{W_o}{W_i} \times 100\% = \frac{4.0}{4.4} \times 100\% = \boxed{91\%}$$

Check: 0.4 J lost to friction out of 4.4 J input - reasonable!

Attempt: Inclined Plane IMA

The Challenge (3 min, silent)

An inclined plane is 5.0 m long and 2.0 m high.

Given:

- Length $L = 5.0$ m
- Height $h = 2.0$ m

Find: Ideal mechanical advantage (IMA)

How much does this ramp multiply your force?

Compare: IMA Formula

Turn and talk (2 min):

1. What is the formula for IMA of an inclined plane?
2. Which value goes in numerator and which in denominator?
3. Should IMA have units?

Compare: IMA Formula

Turn and talk (2 min):

1. What is the formula for IMA of an inclined plane?
2. Which value goes in numerator and which in denominator?
3. Should IMA have units?

Name wheel: One pair share your reasoning.

Reveal: Inclined Plane IMA Solution

Self-correct in a different color:

Formula for inclined plane:

$$IMA = \frac{L}{h}$$

Reveal: Inclined Plane IMA Solution

Self-correct in a different color:

Formula for inclined plane:

$$IMA = \frac{L}{h}$$

Substitute values:

$$IMA = \frac{5.0\ \text{m}}{2.0\ \text{m}} = \boxed{2.5}$$

Reveal: Inclined Plane IMA Solution

Self-correct in a different color:

Formula for inclined plane:

$$IMA = \frac{L}{h}$$

Substitute values:

$$IMA = \frac{5.0\text{ m}}{2.0\text{ m}} = \boxed{2.5}$$

Interpretation: This ramp multiplies your force by 2.5.
You can push a 250 N load with only 100 N effort.
The trade-off: you push 2.5 times the distance.

Attempt: Pulley System

The Challenge (3 min, silent)

A pulley system lifts a 200 N load with an effort force of 52 N. The system has an efficiency of almost 100%.

Given:

- $F_r = 200$ N (load)
- $F_e = 52$ N (effort)
- Efficiency $\approx 100\%$

Find: Number of ropes supporting the load

How many ropes does this system need?

Compare: Pulley Logic

Turn and talk (2 min):

1. What is mechanical advantage for pulleys?
2. How do you find actual MA from given forces?
3. For pulleys, what does IMA equal?

Compare: Pulley Logic

Turn and talk (2 min):

1. What is mechanical advantage for pulleys?
2. How do you find actual MA from given forces?
3. For pulleys, what does IMA equal?

Name wheel: One pair share your reasoning.

Reveal: Pulley System Solution

Self-correct in a different color:

Step 1: Calculate actual mechanical advantage

$$MA = \frac{F_r}{F_e} = \frac{200\ \text{N}}{52\ \text{N}} = 3.85$$

Reveal: Pulley System Solution

Self-correct in a different color:

Step 1: Calculate actual mechanical advantage

$$MA = \frac{F_r}{F_e} = \frac{200\text{ N}}{52\text{ N}} = 3.85$$

Step 2: For pulleys, $IMA = N$ (number of ropes)

Reveal: Pulley System Solution

Self-correct in a different color:

Step 1: Calculate actual mechanical advantage

$$MA = \frac{F_r}{F_e} = \frac{200 \text{ N}}{52 \text{ N}} = 3.85$$

Step 2: For pulleys, $IMA = N$ (number of ropes)
Step 3: Since efficiency $\approx$ 100%, actual MA $\approx$ IMA

$$N \approx 3.85 \approx \boxed{\text{4 ropes}}$$

Reveal: Pulley System Solution

Self-correct in a different color:

Step 1: Calculate actual mechanical advantage

$$MA = \frac{F_r}{F_e} = \frac{200\text{ N}}{52\text{ N}} = 3.85$$

Step 2: For pulleys, $IMA = N$ (number of ropes)
Step 3: Since efficiency $\approx$ 100%, actual MA $\approx$ IMA

$$N \approx 3.85 \approx \boxed{4\text{ ropes}}$$

Check: 4 ropes supporting load makes sense.
Each rope carries roughly $200/4 = 50$ N.

The Six Force Multipliers

Simple Machines Summary

1. **Lever:** $IMA = \frac{L_e}{L_r}$

The Six Force Multipliers

Simple Machines Summary

1. **Lever:** $IMA = \frac{L_e}{L_r}$
2. **Wheel and Axle:** $IMA = \frac{r_{wheel}}{r_{axle}}$

The Six Force Multipliers

Simple Machines Summary

1. **Lever:** $IMA = \frac{L_e}{L_r}$
2. **Wheel and Axle:** $IMA = \frac{r_{wheel}}{r_{axle}}$
3. **Inclined Plane:** $IMA = \frac{L}{h}$

The Six Force Multipliers

Simple Machines Summary

1. **Lever:** $IMA = \frac{L_e}{L_r}$
2. **Wheel and Axle:** $IMA = \frac{r_{wheel}}{r_{axle}}$
3. **Inclined Plane:** $IMA = \frac{L}{h}$
4. **Wedge:** $IMA = \frac{L}{h}$

The Six Force Multipliers

Simple Machines Summary

1. **Lever:** $IMA = \frac{L_e}{L_r}$
2. **Wheel and Axle:** $IMA = \frac{r_{wheel}}{r_{axle}}$
3. **Inclined Plane:** $IMA = \frac{L}{h}$
4. **Wedge:** $IMA = \frac{L}{h}$
5. **Screw:** $IMA = \frac{2\pi L}{P}$

The Six Force Multipliers

Simple Machines Summary

1. **Lever:** $IMA = \frac{L_e}{L_r}$
2. **Wheel and Axle:** $IMA = \frac{r_{wheel}}{r_{axle}}$
3. **Inclined Plane:** $IMA = \frac{L}{h}$
4. **Wedge:** $IMA = \frac{L}{h}$
5. **Screw:** $IMA = \frac{2\pi L}{P}$
6. **Pulley:** $IMA = N$ (number of ropes)

Key Equations

$$IMA = \frac{F_r}{F_e} = \frac{d_e}{d_r} \tag{1}$$

$$W_i = W_o \quad \text{(ideal machine)} \tag{2}$$

$$F_e \times d_e = F_r \times d_r \tag{3}$$

$$\text{Efficiency} = \frac{W_o}{W_i} \times 100\% \tag{4}$$

What You Now Know

The Revelations

1. Simple machines trade force for distance

What You Now Know

The Revelations

1. Simple machines trade force for distance
2. Machines cannot create energy - conservation rules

What You Now Know

The Revelations

1. Simple machines trade force for distance
2. Machines cannot create energy - conservation rules
3. Six types: lever, wheel-axle, incline, wedge, screw, pulley

What You Now Know

The Revelations

1. Simple machines trade force for distance
2. Machines cannot create energy - conservation rules
3. Six types: lever, wheel-axle, incline, wedge, screw, pulley
4. IMA tells you how much force is multiplied

What You Now Know

The Revelations

1. Simple machines trade force for distance
2. Machines cannot create energy - conservation rules
3. Six types: lever, wheel-axle, incline, wedge, screw, pulley
4. IMA tells you how much force is multiplied
5. Efficiency measures work lost to friction

What You Now Know

The Revelations

1. Simple machines trade force for distance
2. Machines cannot create energy - conservation rules
3. Six types: lever, wheel-axle, incline, wedge, screw, pulley
4. IMA tells you how much force is multiplied
5. Efficiency measures work lost to friction
6. Complex machines combine simple machines

Complete the assigned problems

posted on the LMS

Temporary page!

LaTeX was unable to guess the total number of pages correctly. A
was some unprocessed data that should have been added to the
this extra page has been added to receive it.

If you rerun the document (without altering it) this surplus page
away, because LaTeX now knows how many pages to expect for t
document.