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BICYCLE FRAMES: THE DECISION CHALLENGE

Purpose

The purpose of this exercise is to illustrate how science and mathematics can drive an engineering problem, with constraints, for the purposes of a human need.

Problem

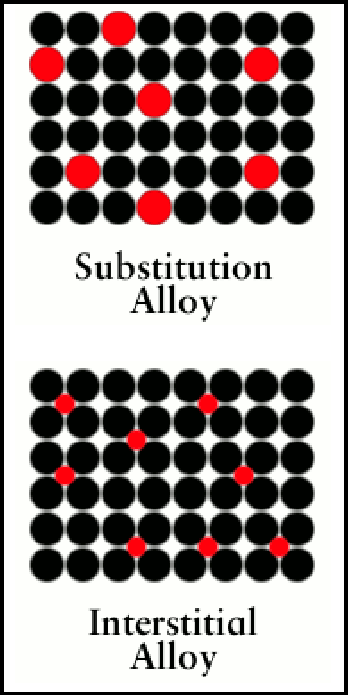
An engineer needs to determine which metal will be most useful for the construction of an unyielding bicycle frame for a tall, heavy rider.

Background

Pure metals are often times incredibly strong, but could be too brittle, bendable, or easily crack under great shear force/pressure when applied during some form of engineering application – such as a bicycle frame. Given a large shear force, using inappropriate material(s) could lead to some type of structural failure. For example, pure aluminum is quite brittle despite how light and durable it may appear. Instead, one would be inclined to prefer a metallic *alloy*, or metals that are combined with other metals to make them stronger, harder, lighter and better for a variety of purposes.

Key Terms

(1) main, based or parent metal
(2) alloying agents
(3) solid solution
(4) substitution alloys
(5) Interstitial alloys
(6) Various properties of metals: bendability, malleability, rigidity, ability to conduct electricity in varying degrees, or varied abilities to conduct heat
(7) powder metallurgy
(8) ion implantation



QUESTION

Which raw material will be most suitable for melting and being combined with another metal for the development of a rigid and durable alloy?

RANK

RANK each numbered sample from:

_____lightest

_____light

_____middle

_____great

_____greatest

PREDICTION:

Based on your ranking, which metal do you believe is a suitable sample for use in a bicycle design for a rider wishing to have the actual bike frame designed to be less than 15 pounds; what about a bike frame greater than 40 pounds?

DATA COLLECTION:

(1) Use the small digital scale to determine the mass of each cube.

(2) Using a ruler, verify the calculated volume as shown in Table 1.

(3) Discuss the qualitative characteristics.

Table 1: Data Collection

Sample metal	Mass (g)	Width (cm)	Length (cm)	Height (cm)	Volume (V) W x L x H = cm3	(D) m ÷ v = g/cm3	Metal
1		2.5	2.5	2.5			
2		2.5	2.5	2.5			
3		2.5	2.5	2.5			
4		2.5	2.5	2.5			
5		2.5	2.5	2.5			

Discussion

1. Explain what is found in the (D) column? What is the significance of having the same "volume" for all samples?

Sample metal	Mass (g)	Width (cm)	Length (cm)	Height (cm)	Volume (V) W x L x H = cm^3	(D) m ÷ v = g/cm^3	Metal
1	*141.90*	2.5	2.5	2.5	15.625	*9.08*	*Copper*
2	*127.60*	2.5	2.5	2.5	15.625	*8.17*	*Iron*
3	*135.00*	2.5	2.5	2.5	15.625	*8.64*	*Brass*
4	*95.50*	2.5	2.5	2.5	15.625	*5.92*	*Zinc*
5	*42.70*	2.5	2.5	2.5	15.625	*2.73*	*Aluminum*

Discussion

1. *Density is mass per unit of volume. In this case that means for every cubic centimeter of volume, there is X amount of matter (mass) found in that particular sample of metal. Density depends on how compacted the material is, given its atomic structure. The significance of having the same volume for all samples is that this variable remains constant, while only the mass changes based on material type. Hence, both mass and volume are extensive properties, whose values can change given size of the sample. On the other hand, density is an intensive property, meaning that regardless of the sample size, the value will remain the same.*

Table 2: Processing Data: 2. Use Table 2 to determine the difference in mass between the metals in their "purest" form from the observed "sample."

Metal	(D) of purest g/cm3	Mass of metal at 15.625 g/cm3 (Purest, g/cm3 * 15.625 g/cm3)	Sample metal	(D) of sample g/cm3	Mass of metal at 15.625 g/cm3 (Sample, g/cm3 * 15.625 g/cm3)	Difference (>mass -< mass)
Copper	8.96	8.96 *15.625 = 140.00g	1	9.08	9.08 *15.625 = 141.88g	141.88 - 140.00 = 1.88g (difference)
Iron*	7.85	7.85 *15.625 = 122.66g	2			
Brass*	8.64	8.64 *15.625 = 135.00g	3			
Zinc*	7.13	7.13 *15.625 = 111.41g	4			
Aluminum	2.70	2.70 *15.625 = 42.19g	5			

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Copper	8.96	8.96 *15.625 = **140.00g**	1	*9.08*	**9.08 *15.625 = 141.88g**	**141.88 - 140.00 = 1.88g (difference)**
Iron*	7.85	7.85 *15.625 = **122.66g**	2	*8.17*	**8.17 *15.625 = 127.66g**	**127.66 - 122.66 = 5.00g (difference)**
Brass*	8.64	8.64 *15.625 = **135.00g**	3	*8.64*	**8.64 *15.625 = 135.00g**	**135.00 -1 35.00 = 0g (difference)**
Zinc*	7.13	7.13 *15.625 = **111.41g**	4	*5.92*	**5.92 *15.625 = 92.50g**	**111.41 - 92.50 = 18.91g (difference)**
Aluminum	2.70	2.70 *15.625 = **42.19g**	5	*2.73*	**2.73 *15.625 = 42.66g**	**42.66 - 42.19 = 0.47g (difference)**

Discussion:

3. Based on your calculated density (D) for all sample the metals, explain possible reasons why the values for your sample do/do not closely match with the values for each metal in its purest form. How can this information be helpful in answering the initial question?

Discussion:

3. ***Masses do not match because the sample metals are impure, meaning that they are a solid solution mixture of two different metals (make up an alloy). We can better evaluate the purity of the sample metals because the density of the alloying agents might affect the overall mass in the positive or negative direction. Sample metals that are close in the range of the pure metals are better samples for applied use in the bike frame.***

Table 3: Fractions, Percentages and Ratios Related to Various Alloys

4. Use Table 3 to calculate various percentages, fractions, and ratios for your "samples" of brass, iron and zinc. Use the mass values you found with the digital scale. **Discuss** the patterns in each of these calculations.

Steps to complete Table 3

- Step 1: Calculate fraction per 100. Percentage of metal in sample in second column goes in the numerators place and 100 goes into denominators place.
- Step 2: Reduce fraction to determine "Fraction of Total."
- Step 3: Determine grams in sample by multiplying total sample in grams X %
- Step 4: Calculate ratio of metal in each row to remaining metals (sum of) as a ratio of 1 to ? For example, for every 1 part of aluminum, are 7.33 parts of iron, nickel and cobalt. To find second number in ratio:
- Step 5: DEN ÷ NUM = 8.33 ; Then, 8.33 – 1 = 7.33
- Step 6: To verify: NUM ÷ DEN = 0.12 ; Then, 8.33 X 0.12 = 1

Alloy	Components	Fraction of Total	Fraction per 100	Grams in 15.625 cm^3 sample	Ratio to remaining metals
Alnico (120.00g) Magnets in loudspeakers and pickups in electric guitars.	Iron (50%)	$\frac{1}{2}$	$\frac{50}{100}$	60.00g	1 : 1 (2*0.5)=1
	Aluminum (12%)	$\frac{3}{25}$	$\frac{12}{100}$	14.40g	1 : 7.33 (8.33*0.12)=1
	Nickel (25%)	$\frac{1}{4}$	$\frac{25}{100}$	30.00g	1 : 3 (4*0.25)=1
	Cobalt (13%)	$\frac{13}{100}$	$\frac{13}{100}$	15.60g	1 : 6.69 (7.69*0.13)=1
	TOTAL	1	1	120.00g	

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	Aluminum (12%)	$\frac{3}{25}$	$\frac{12}{100}$	14.40g	1 : 7.33 (8.33*0.12)=1
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	Cobalt (13%)	$\frac{13}{100}$	$\frac{13}{100}$	15.60g	1 : 6.69 (7.69*0.13)=1
	TOTAL	1	1	120.00g	
Sample Brass* (135.00g) Doors, locks, musical instruments, heating pipes	Copper (75%)	$\frac{3}{4}$	$\frac{75}{100}$	101.25g	1 : .33 (1.33*0.75)=1
	Zinc (25%)	$\frac{1}{4}$	$\frac{25}{100}$	33.75g	1 : 3 (4*0.25)=1
	TOTAL	1	1	135.00g	
Sample Iron* (127.66g) Metal structures and heavy duty cookware	Iron (96%)	$\frac{24}{25}$	$\frac{96}{100}$	122.55g	1 : 0.04 (1.04*0.96)=1
	Carbon, silicon & unknowns (4%)	$\frac{1}{25}$	$\frac{4}{100}$	5.11g	1 : 24 (25*0.04)=1
	TOTAL	1	1	127.66g	
Stainless Steel (128.59g) Metal structures, car and airplane parts, bicycle frames.	Iron (50%)	$\frac{1}{2}$	$\frac{50}{100}$	64.30 g	1 : 1 (2*0.5)=1
	Chromium (25%)	$\frac{1}{4}$	$\frac{25}{100}$	32.15 g	1 : 3 (4*0.25)=1
	Carbon (5%)	$\frac{1}{20}$	$\frac{5}{100}$	6.43 g	1 : 19 (20*0.05)=1
	Nickel (12%)	$\frac{3}{25}$	$\frac{12}{100}$	15.43g	1 : 7.33 (8.33*0.12)=1
	Manganese (8%)	$\frac{2}{25}$	$\frac{8}{100}$	10.29g	1 : 11.50 (12.50*0.08)=1
	TOTAL	1	1	128.59 g	

Duralumin (43.59g) Automobile and aircraft body parts, military equipment.	**Aluminum (94%)**	$\frac{47}{50}$	$\frac{94}{100}$	**40.97g**	**1 : 0.064 (1.064*0.94)=1**
	Copper (4%)	$\frac{1}{25}$	$\frac{4}{100}$	1.74g	1 : 24.05 (25.05*0.04)=1
	Magnesium (1%)	$\frac{1}{100}$	$\frac{1}{100}$	0.44g	1 : 98.07 (99.07*0.01)=1
	Manganese (1%)	$\frac{1}{100}$	$\frac{1}{100}$	0.44g	1 : 98.07 (99.07*0.01)=1
	TOTAL	1	1	43.59g	
Sample Zinc* (<u>92.50g</u>) Die casting products for cars, power tools, or bike parts	Zinc (84%)	$\mathbf{\frac{21}{25}}$	$\mathbf{\frac{84}{100}}$	77.70g	1 : 0.19 (1.19*0.84)=1
	Aluminum (16%)	$\mathbf{\frac{4}{25}}$	$\mathbf{\frac{16}{100}}$	14.8g	1 : 5.25 (6.25*0.16)=1
	TOTAL	1	1	92.50g	

5. **Discussion:** After completing Table 3, explain which metal is most suitable for use in a bicycle design for a rider wishing to have the actual frame designed to be less than 15 pounds or greater than 40 pounds, respectively.

MS.Engineering Design

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Students who demonstrate understanding can:

MS-ETS1-1. **Define the criteria and constraints of a design problem with sufficient precision to ensure a successful solution, taking into account relevant scientific principles and potential impacts on people and the natural environment that may limit possible solutions.**

MS-ETS1-2. **Evaluate competing design solutions using a systematic process to determine how well they meet the criteria and constraints of the problem.**

MS-ETS1-3. **Analyze data from tests to determine similarities and differences among several design solutions to identify the best characteristics of each that can be combined into a new solution to better meet the criteria for success.**

MS-ETS1-4. **Develop a model to generate data for iterative testing and modification of a proposed object, tool, or process such that an optimal design can be achieved.**

The performance expectations above were developed using the following elements from the NRC document *A Framework for K-12 Science Education*:

Science and Engineering Practices

Asking Questions and Defining Problems

Asking questions and defining problems in grades 6–8 builds on grades K–5 experiences and progresses to specifying relationships between variables, and clarifying arguments and models.

- Define a design problem that can be solved through the development of an object, tool, process or system and includes multiple criteria and constraints, including scientific knowledge that may limit possible solutions. (MS-ETS1-1)

Developing and Using Models

Modeling in 6–8 builds on K–5 experiences and progresses to developing, using, and revising models to describe, test, and predict more abstract phenomena and design systems.

- Develop a model to generate data to test ideas about designed systems, including those representing inputs and outputs. (MS-ETS1-4)

Analyzing and Interpreting Data

Analyzing data in 6–8 builds on K–5 experiences and progresses to extending quantitative analysis to investigations, distinguishing between correlation and causation, and basic statistical techniques of data and error analysis.

- Analyze and interpret data to determine similarities and differences in findings. (MS-ETS1-3)

Engaging in Argument from Evidence

Engaging in argument from evidence in 6–8 builds on K–5 experiences and progresses to constructing a convincing argument that supports or refutes claims for either explanations or solutions about the natural and designed world.

- Evaluate competing design solutions based on jointly developed and agreed-upon design criteria. (MS-ETS1-2)

Disciplinary Core Ideas

ETS1.A: Defining and Delimiting Engineering Problems

- The more precisely a design task's criteria and constraints can be defined, the more likely it is that the designed solution will be successful. Specification of constraints includes consideration of scientific principles and other relevant knowledge that are likely to limit possible solutions. (MS-ETS1-1)

ETS1.B: Developing Possible Solutions

- A solution needs to be tested, and then modified on the basis of the test results, in order to improve it. (MS-ETS1-4)
- There are systematic processes for evaluating solutions with respect to how well they meet the criteria and constraints of a problem. (MS-ETS1-2), (MS-ETS1-3)
- Sometimes parts of different solutions can be combined to create a solution that is better than any of its predecessors. (MS-ETS1-3)
- Models of all kinds are important for testing solutions. (MS-ETS1-4)

ETS1.C: Optimizing the Design Solution

- Although one design may not perform the best across all tests, identifying the characteristics of the design that performed the best in each test can provide useful information for the redesign process—that is, some of those characteristics may be incorporated into the new design. (MS-ETS1-3)
- The iterative process of testing the most promising solutions and modifying what is proposed on the basis of the test results leads to greater refinement and ultimately to an optimal solution. (MS-ETS1-4)

Crosscutting Concepts

Influence of Science, Engineering, and Technology on Society and the Natural World

- All human activity draws on natural resources and has both short and long-term consequences, positive as well as negative, for the health of people and the natural environment. (MS-ETS1-1)
- The uses of technologies and limitations on their use are driven by individual or societal needs, desires, and values; by the findings of scientific research; and by differences in such factors as climate, natural resources, and economic conditions. (MS-ETS1-1)

Mathematics –

MP.2 Reason abstractly and quantitatively. *(MS-ETS1-1),(MS-ETS1-2),(MS-ETS1-3),(MS-ETS1-4)*

7.EE.3 Solve multi-step real-life and mathematical problems posed with positive and negative rational numbers in any form (whole numbers, fractions, and decimals), using tools strategically. Apply properties of operations to calculate with numbers in any form; convert between forms as appropriate; and assess the reasonableness of answers using mental computation and estimation strategies. *(MS-ETS1-1),(MS-ETS1-2),(MS-ETS1-3)*

5.Structure and Properties of Matter

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Students who demonstrate understanding can:

5-PS1-1. Develop a model to describe that matter is made of particles too small to be seen. [Clarification Statement: Examples of evidence could include adding air to expand a basketball, compressing air in a syringe, dissolving sugar in water, and evaporating salt water.] [Assessment Boundary: Assessment does not include the atomic-scale mechanism of evaporation and condensation or defining the unseen particles.]

5-PS1-2. Measure and graph quantities to provide evidence that regardless of the type of change that occurs when heating, cooling, or mixing substances, the total weight of matter is conserved. [Clarification Statement: Examples of reactions or changes could include phase changes, dissolving, and mixing that form new substances.] [Assessment Boundary: Assessment does not include distinguishing mass and weight.]

5-PS1-3. Make observations and measurements to identify materials based on their properties. [Clarification Statement: Examples of materials to be identified could include baking soda and other powders, metals, minerals, and liquids. Examples of properties could include color, hardness, reflectivity, electrical conductivity, thermal conductivity, response to magnetic forces, and solubility; density is not intended as an identifiable property.] [Assessment Boundary: Assessment does not include density or distinguishing mass and weight.]

5-PS1-4. Conduct an investigation to determine whether the mixing of two or more substances results in new substances.

The performance expectations above were developed using the following elements from the NRC document *A Framework for K-12 Science Education*:

Science and Engineering Practices

Developing and Using Models
Modeling in 3–5 builds on K–2 experiences and progresses to building and revising simple models and using models to represent events and design solutions.
- Develop a model to describe phenomena. (5-PS1-1)

Planning and Carrying Out Investigations
Planning and carrying out investigations to answer questions or test solutions to problems in 3–5 builds on K–2 experiences and progresses to include investigations that control variables and provide evidence to support explanations or design solutions.
- Conduct an investigation collaboratively to produce data to serve as the basis for evidence, using fair tests in which variables are controlled and the number of trials considered. (5-PS1-4)
- Make observations and measurements to produce data to serve as the basis for evidence for an explanation of a phenomenon. (5-PS1-3)

Using Mathematics and Computational Thinking
Mathematical and computational thinking in 3–5 builds on K–2 experiences and progresses to extending quantitative measurements to a variety of physical properties and using computation and mathematics to analyze data and compare alternative design solutions.
- Measure and graph quantities such as weight to address scientific and engineering questions and problems. (5-PS1-2)

Disciplinary Core Ideas

PS1.A: Structure and Properties of Matter
- Matter of any type can be subdivided into particles that are too small to see, but even then the matter still exists and can be detected by other means. A model showing that gases are made from matter particles that are too small to see and are moving freely around in space can explain many observations, including the inflation and shape of a balloon and the effects of air on larger particles or objects. (5-PS1-1)
- The amount (weight) of matter is conserved when it changes form, even in transitions in which it seems to vanish. (5-PS1-2)
- Measurements of a variety of properties can be used to identify materials. (Boundary: At this grade level, mass and weight are not distinguished, and no attempt is made to define the unseen particles or explain the atomic-scale mechanism of evaporation and condensation.) (5-PS1-3)

PS1.B: Chemical Reactions
- When two or more different substances are mixed, a new substance with different properties may be formed. (5-PS1-4)
- No matter what reaction or change in properties occurs, the total weight of the substances does not change. (Boundary: Mass and weight are not distinguished at this grade level.) (5-PS1-2)

Crosscutting Concepts

Cause and Effect
- Cause and effect relationships are routinely identified, tested, and used to explain change. (5-PS1-4)

Scale, Proportion, and Quantity
- Natural objects exist from the very small to the immensely large. (5-PS1-1)
- Standard units are used to measure and describe physical quantities such as weight, time, temperature, and volume. (5-PS1-2),(5-PS1-3)

Connections to Nature of Science

Scientific Knowledge Assumes an Order and Consistency in Natural Systems
- Science assumes consistent patterns in natural systems. (5-PS1-2)

Graphic Example of Coherence:
Structure and properties of matter (5)

Anchoring Phenomena → ***Making Sense Question: What are properties of matter & how do they apply to the structure of different materials?***

Phenomena-driven Questions	**Make sense of phenomena with science practices**	**What we figured out**
Why do some materials bend, melt, or break more easilv than others?	*Carry out investigation; Ask Questions*	*Some materials are softer than others; which makes them easier to bend. Other materials will melt or break because of what they are made from.*
What are some other properties of matter?	*Carry out investigation; Analyze and interpret data*	*Different materials have different masses even if they are the same size; other properties of matter include color, hardness, solubility, conductivity.*
What evidence is there to distinguish the difference between metal and allovs?	*Analyze and interpret data; argue, construct explanation*	*Alloys are an example of a solid solution; separate metals are heated until thev melt. Then thev are combined.*
How can some solid metals be considered a form of a mixture?	*Analyze and interpret data; argue, construct explanation*	*Different metals can be combined using high heat to form alloys.*
What is density and how is it different from mass or volume?	*Analyze and interpret data; argue, construct explanation*	*Density is ($m \div v$) an intensive property, while mass and volume are extensive properties.*