

CHAPTER 16

Heart of Algebra

Heart of Algebra questions on the SAT Math Test focus on the mastery of linear equations, systems of linear equations, and linear functions. The ability to analyze and create linear equations, inequalities, and functions is essential for success in college and career, as is the ability to solve linear equations and systems fluently.

Heart of Algebra questions vary significantly in form and appearance. They may be straightforward fluency exercises or pose challenges of strategy or understanding, such as interpreting the relationship between graphical and algebraic representations or solving as a process of reasoning. You'll be required to demonstrate both procedural skill and a deep understanding of concepts.

The questions in Heart of Algebra include both multiple-choice questions and student-produced response questions. The use of a calculator is permitted for some questions in this domain and not permitted for others.

Heart of Algebra is one of the three SAT Math Test subscores, reported on a scale of 1 to 15.

Let's explore the content and skills assessed by Heart of Algebra questions.

Linear Equations, Linear Inequalities, and Linear Functions in Context

When you use algebra to analyze and solve a problem in real life, a key step is to represent the context of the problem algebraically. To do this, you may need to define one or more variables that represent quantities in the context. Then you need to write one or more expressions, equations, inequalities, or functions that represent the relationships described in the context. For example, once you write an equation that represents the context, you solve the equation. Then you interpret the solution to the equation in terms of the context. Questions on the SAT Math Test may assess your ability to accomplish any or all of these steps.



REMEMBER

The SAT Math Test requires you to demonstrate a deep understanding of several core algebra topics, namely linear equations, systems of linear equations, and linear functions. These topics are fundamental to the learning and work often required in college and career.



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Many Heart of Algebra questions such as this one will require you to accomplish the following steps:

1. Define one or more variables that represent quantities in the question.
2. Write one or more equations, expressions, inequalities, or functions that represent the relationships described in the question.
3. Solve the equation.
4. Interpret the solution in terms of what the question is asking.

Ample practice with each of these steps will help you develop your math skills and knowledge.



REMEMBER

There are several different ways you may be tested on the same underlying algebra concepts. Practicing a variety of questions, with different contexts, is a good way to ensure you'll be ready for the questions you'll come across on the SAT.

Example 1

In 2014, County X had 783 miles of paved roads. Starting in 2015, the county has been building 8 miles of new paved roads each year. At this rate, how many miles of paved road will County X have in 2030? (Assume that no paved roads go out of service.)

The first step in answering this question is to decide what variable or variables you need to define. Since the number of miles paved depends on the year, we can define a variable to represent the year. The number of years after 2014 can be represented using the variable n . Then, since the question says that County X had 783 miles of paved road in 2014 and is building 8 miles of new paved roads each year, the expression $783 + 8n$ gives the number of miles of paved roads in County X in the year that is n years after 2014. The year 2030 is $2030 - 2014 = 16$ years after 2014; thus, the year 2030 corresponds to $n = 16$. Hence, to find the number of miles of paved roads in County X in 2030, substitute 16 for n in the expression $783 + 8n$, giving $783 + 8(16) = 783 + 128 = 911$. Therefore, at the given rate of building, County X will have 911 miles of paved roads in 2030.

(Note that this example has no choices. It is a student-produced response question. On the SAT, you would grid your answer in the spaces provided on the answer sheet.)

There are different questions that can be asked about the same context.

Example 2

In 2014, County X had 783 miles of paved roads. Starting in 2015, the county has been building 8 miles of new paved roads each year. At this rate, if n is the number of years after 2014, which of the following functions f gives the number of miles of paved road there will be in County X? (Assume that no paved roads go out of service.)

- A) $f(n) = 8 + 783n$
- B) $f(n) = 2,014 + 783n$
- C) $f(n) = 783 + 8n$
- D) $f(n) = 2,014 + 8n$

This question already defines the variable and asks you to create or identify a function that describes the context. The discussion in Example 1 shows that the correct answer is choice C.

Example 3

In 2014, County X had 783 miles of paved roads. Starting in 2015, the county has been building 8 miles of new paved roads each year. At this rate, in which year will County X first have at least 1,000 miles of paved roads? (Assume that no paved roads go out of service.)

In this question, you must create and solve an inequality. As in Example 1, let n be the number of years after 2014. Then the expression $783 + 8n$ gives the number of miles of paved roads in County X n years after 2014. The question is asking when there will first be at least 1,000 miles of paved roads in County X. This condition can be represented by the inequality $783 + 8n \geq 1,000$. To find the year in which there will first be at least 1,000 miles of paved roads, you solve this inequality for n . Subtracting 783 from each side of $783 + 8n \geq 1,000$ gives $8n \geq 217$. Then dividing each side of $8n \geq 217$ by 8 gives $n \geq 27.125$. Note that an important part of relating the inequality $783 + 8n \geq 1,000$ back to the context is to notice that n is counting calendar years, and so the value of n must be an integer. The least value of n that satisfies $783 + 8n \geq 1,000$ is 27.125, but the year $2014 + 27.125 = 2041.125$ does not make sense as an answer, and in 2041, there would be only $783 + 8(27) = 999$ miles of paved roads in the county. Therefore, the variable n needs to be rounded up to the next integer, and so the least possible value of n is 28. Therefore, the year that County X will first have at least 1,000 miles of paved roads is 28 years after 2014, which is 2042.

In Example 1, once the variable n was defined, you needed to find an expression that represents the number of miles of paved road in terms of n . In other questions, creating the correct expression, equation, or function may require a more insightful understanding of the context.

Example 4

To edit a manuscript, Miguel charges \$50 for the first 2 hours and \$20 per hour after the first 2 hours. Which of the following expresses the amount, C , in dollars, Miguel charges if it takes him x hours to edit a manuscript, where $x > 2$?

- A) $C = 20x$
- B) $C = 20x + 10$
- C) $C = 20x + 50$
- D) $C = 20x + 90$

The question defines the variables C and x and asks you to express C in terms of x . To create the correct equation, you must note that since the \$50 that Miguel charges pays for his first 2 hours of editing, he charges \$20 per hour only *after* the first 2 hours. Thus, if it takes x hours for Miguel to edit a manuscript, he charges \$50 for the first 2 hours and \$20 per hour for the remaining time, which is $x - 2$ hours. Thus, his total charge, C , in dollars, can be written as $C = 50 + 20(x - 2)$, where $x > 2$. This does not match any of the choices. But when the right-hand side of $C = 50 + 20(x - 2)$ is expanded, you get $C = 50 + 20x - 40$, or $C = 20x + 10$, which is choice B.

As with Examples 1 to 3, there are different questions that could be asked about this context. For example, you could be asked to find how long it took Miguel to edit a manuscript if he charged \$370.



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Solving an equation or inequality is often only part of the problem-solving process. You'll also need to interpret the solution in the context of the question, so be sure to remind yourself of the question's context and the meaning of the variables you solved for before selecting your answer.



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When the solution you arrive at doesn't match any of the answer choices, consider if expanding, simplifying, or rearranging your solution will cause it to match an answer choice. Sometimes, this extra step is needed to arrive at the correct answer.

In some questions on the SAT Math Test, you'll be given a function that represents a context and be asked to find the value of the output of the function given an input or the value of the input that corresponds to a given output.

Example 5

A builder uses the function g defined by $g(x) = 80x + 10,000$ to estimate the cost $g(x)$, in dollars, to build a one-story home of planned floor area of x square feet. If the builder estimates that the cost to build a certain one-story home is \$106,000, what is the planned floor area, in square feet, of the home?

This question asks you to find the value of the input of a function when you are given the value of the output and the equation of the function. The estimated cost of the home, in dollars, is the output of the function g for a one-story home of planned floor area of x square feet. That is, the output of the function, $g(x)$, is 106,000, and you need to find the value of the input x that gives an output of 106,000. To do this, substitute 106,000 for $g(x)$ in the equation that defines g : $106,000 = 80x + 10,000$. Now solve for x : First, subtract 10,000 from each side of the equation $106,000 = 80x + 10,000$, which gives $96,000 = 80x$. Then, divide each side of $96,000 = 80x$ by 80, which gives $1,200 = x$. Therefore, a one-story home with an estimated cost of \$106,000 to build has a planned floor area of 1,200 square feet.

Systems of Linear Equations and Inequalities in Context

You may need to define more than one variable and create more than one equation or inequality to represent a context and answer a question. There are questions on the SAT Math Test that require you to create and solve a system of equations or create a system of inequalities.



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You can use either of two approaches—combination or substitution—when solving a system of linear equations. One may get you to the answer more quickly than the other, depending on the equations you're working with and what you're solving for. Practice using both approaches to give you greater flexibility on test day.

Example 6

Maizah bought a pair of pants and a briefcase at a department store. The sum of the prices of the pants and the briefcase before sales tax was \$130.00. There was no sales tax on the pants and a 9% sales tax on the briefcase. The total Maizah paid, including the sales tax, was \$136.75. What was the price, in dollars, of the pants?

To answer the question, you first need to define the variables. The question discusses the prices of a pair of pants and a briefcase and asks you to find the price of the pants. So it's appropriate to let P be the price, in dollars, of the pants and to let B be the price, in dollars, of the briefcase. Since the sum of the prices before sales tax was

\$130.00, the equation $P + B = 130$ is true. A sales tax of 9% was added to the price of the briefcase. Since 9% is equal to 0.09, the price of the briefcase with tax was $B + 0.09B = 1.09B$. There was no sales tax on the pants, and the total Maizah paid, including tax, was \$136.75, so the equation $P + 1.09B = 136.75$ holds.

Now, you need to solve the system

$$\begin{aligned}P + B &= 130 \\P + 1.09B &= 136.75\end{aligned}$$

Subtracting the sides of the first equation from the corresponding sides of the second equation gives you $(P + 1.09B) - (P + B) = 136.75 - 130$, which simplifies to $0.09B = 6.75$. Now you can divide each side of $0.09B = 6.75$ by 0.09. This gives you $B = \frac{6.75}{0.09} = 75$. This is the value of B , the price, in dollars, of the briefcase. The question asks for the price, in dollars, of the pants, which is P . You can substitute 75 for B in the equation $P + B = 130$, which gives you $P + 75 = 130$, or $P = 130 - 75 = 55$, so the pants cost \$55.

Example 7

Each morning, John jogs at 6 miles per hour and rides a bike at 12 miles per hour. His goal is to jog and ride his bike a total of at least 9 miles in no more than 1 hour. If John jogs j miles and rides his bike b miles, which of the following systems of inequalities represents John's goal?

- A) $\begin{aligned} \frac{j}{6} + \frac{b}{12} &\leq 1 \\ j + b &\geq 9 \end{aligned}$
- B) $\begin{aligned} \frac{j}{6} + \frac{b}{12} &\geq 1 \\ j + b &\leq 9 \end{aligned}$
- C) $\begin{aligned} 6j + 12b &\geq 9 \\ j + b &\leq 1 \end{aligned}$
- D) $\begin{aligned} 6j + 12b &\leq 1 \\ j + b &\geq 9 \end{aligned}$

John jogs j miles and rides his bike b miles; his goal to jog and ride his bike a total of at least 9 miles is represented by the inequality $j + b \geq 9$. This eliminates choices B and C.

Since rate \times time = distance, it follows that time is equal to distance divided by rate. John jogs j miles at 6 miles per hour, so the time he jogs is equal to $\frac{j \text{ miles}}{6 \text{ miles/hour}} = \frac{j}{6}$ hours. Similarly, since John rides his bike b miles at 12 miles per hour, the time he rides his bike is $\frac{b}{12}$ hours. Thus, John's goal to complete his jog and his bike ride in no more than 1 hour can be represented by the inequality $\frac{j}{6} + \frac{b}{12} \leq 1$. The system $j + b \geq 9$ and $\frac{j}{6} + \frac{b}{12} \leq 1$ is choice A.



REMEMBER

While this question may seem complex, as it involves numerous steps, solving it requires a strong understanding of the same underlying principles outlined earlier: defining variables, creating equations to represent relationships, solving equations, and interpreting the solution.



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In Example 7, the answer choices each contain two parts. Use this to your advantage by tackling one part at a time and eliminating answers that don't work.



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You should be able to quickly rearrange equations such as distance = rate \times time by solving for any of the variables. Example 7 requires you to solve the equation for time.

Fluency in Solving Linear Equations, Linear Inequalities, and Systems of Linear Equations

Creating linear equations, linear inequalities, and systems of linear equations that represent a context is a key skill for success in college and career. It's also essential to be able to fluently solve linear equations, linear inequalities, and systems of linear equations. Some of the Heart of Algebra questions present equations, inequalities, or systems without a context and directly assess your fluency in solving them.

Some fluency questions permit the use of a calculator; other questions do not permit the use of a calculator and test your ability to solve equations, inequalities, and systems of equations by hand. Even for questions where a calculator is permitted, you may be able to answer the question more quickly without using a calculator, such as in Example 9. Part of what the SAT Math Test assesses is your ability to decide when using a calculator to answer a question is appropriate. Example 8 is an example of a question that could appear on the no-calculator portion of the Math Test.

Example 8

$$3\left(\frac{1}{2} - y\right) = \frac{3}{5} + 15y$$

What is the solution to the given equation?

Using the distributive property to expand the left-hand side of the equation gives $\frac{3}{2} - 3y = \frac{3}{5} + 15y$. Adding $3y$ to both sides of the equation and then subtracting $\frac{3}{5}$ from both sides of the equation gives $\frac{3}{2} - \frac{3}{5} = 18y$. The equation may be easier to solve if it's transformed into an equation without fractions; to do this, multiply each side of $\frac{3}{2} - \frac{3}{5} = 18y$ by 10, which is the least common multiple of the denominators 2 and 5. This gives $\frac{30}{2} - \frac{30}{5} = 180y$, which can be simplified further to $15 - 6 = 180y$, or $9 = 180y$. Therefore, $y = \frac{1}{20}$.



REMEMBER

While a calculator is permitted on one portion of the SAT Math Test, it's important to not over-rely on a calculator. Some questions, such as Example 9, can be solved more efficiently without using a calculator. Your ability to choose when to use and when not to use a calculator is one of the things the SAT Math Test assesses, so be sure to practice this in your studies.

Example 9

$$-2(3x - 2.4) = -3(3x - 2.4)$$

What is the solution to the given equation?

You could solve this in the same way as Example 8, by multiplying everything out and simplifying. But the structure of the equation reveals that -2 times a quantity, $3x - 2.4$, is equal to -3 times the same quantity. This is only possible if the quantity $3x - 2.4$ is equal to zero. Thus, $3x - 2.4 = 0$, or $3x = 2.4$. Therefore, the solution is $x = 0.8$.

Example 10

$$\begin{aligned} -2x &= 4y + 6 \\ 2(2y + 3) &= 3x - 5 \end{aligned}$$

What is the solution (x, y) to the system of equations above?

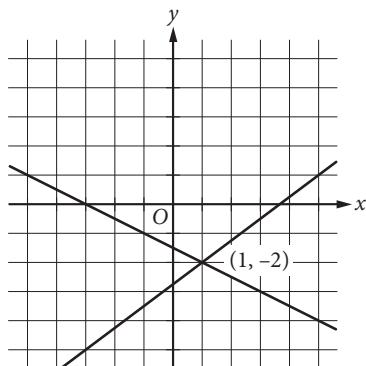
- A) (1, 2)
- B) (1, -2)
- C) (-1, -1)
- D) (-1, 1)

This is an example of a system you can solve more efficiently by substitution. Since $-2x = 4y + 6$, it follows that $-x = 2y + 3$. Now you can substitute $-x$ for $2y + 3$ in the second equation. This gives you $2(-x) = 3x - 5$, which simplifies to $5x = 5$, or $x = 1$. Substituting 1 for x in the first equation gives you $-2 = 4y + 6$, which simplifies to $4y = -8$, or $y = -2$. Therefore, the solution to the system is $(1, -2)$.

In the preceding examples, you have found a unique solution to linear equations and to systems of two linear equations in two variables. But not all such equations and systems have solutions, and some have infinitely many solutions. Some questions on the SAT Math Test assess your ability to determine whether an equation or a system of linear equations has one solution, no solutions, or infinitely many solutions.

The Relationships among Linear Equations, Lines in the Coordinate Plane, and the Contexts They Describe

A system of two linear equations in two variables can be solved by graphing the lines in the coordinate plane. For example, you can graph the equations of the system in the xy -plane in Example 10:



The point of intersection gives the solution to the system.

If the equations in a system of two linear equations in two variables are graphed, each graph will be a line. There are three possibilities:

1. The lines intersect in one point. In this case, the system has a unique solution.



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In Example 6, the elimination method yields an efficient solution to the question. In Example 10, substitution turns out to be an efficient approach. These examples illustrate the benefits of knowing both approaches and thinking critically about which approach may be more efficient on a given question.

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Graphing systems of two linear equations is another effective approach to solving them. Practice arranging linear equations into $y = mx + b$ form and graphing them in the coordinate plane.

**REMEMBER**

When the graphs of a system of two linear equations are parallel lines, as in Example 11, the system has zero solutions. If the question states that a system of two linear equations has an infinite number of solutions, as in Example 12, the equations must be equivalent.

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The equations in the system in Example 11 are in a form that allows you to quickly find both the x -intercept and the y -intercept of the graph of the equation. For example, the graph of $y + 3x = 2$ has an x -intercept of $(\frac{2}{3}, 0)$ because if $y = 0$, then $3x = 2$ and $x = \frac{2}{3}$. Similarly, the graph has a y -intercept of $(0, 2)$ because if $x = 0$, then $y = 2$.

- The lines are parallel. In this case, the system has no solution.
- The lines are identical. In this case, every point on the line is a solution, and so the system has infinitely many solutions.

One way that the second and third cases can be identified is to put the equations of the system in slope-intercept form. If the lines have the same slope and different y -intercepts, they are parallel; if both the slope and the y -intercept are the same, the lines are identical.

How are the second and third cases represented algebraically? Examples 11 and 12 answer this question.

Example 11

$$2y + 6x = 3$$

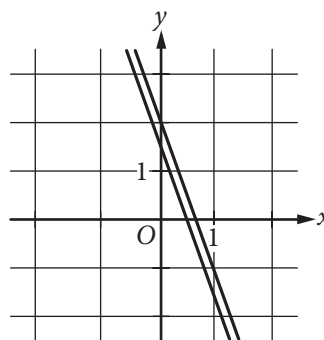
$$y + 3x = 2$$

How many solutions (x, y) does the given system of equations have?

- Zero
- Exactly one
- Exactly two
- Infinitely many

If you multiply each side of $y + 3x = 2$ by 2, you get $2y + 6x = 4$. Then subtracting each side of $2y + 6x = 3$ from the corresponding side of $2y + 6x = 4$ gives $0 = 1$. This is a false statement. Therefore, the system has zero solutions (x, y) .

Alternatively, you could graph the two equations. The graphs are parallel lines, so there are no points of intersection.

**Example 12**

$$3s - 2t = a$$

$$-15s + bt = -7$$

In the system of equations above, a and b are constants. If the system has infinitely many solutions, what is the value of a ?

If a system of two linear equations in two variables has infinitely many solutions, the two equations in the system must be equivalent. Since the two equations are presented in the same form, the second equation must be equal to the first equation multiplied by a constant. Since the coefficient of s in the second equation is -5 times the coefficient of s in the first equation, multiply each side of the first equation by -5 . This gives you the system

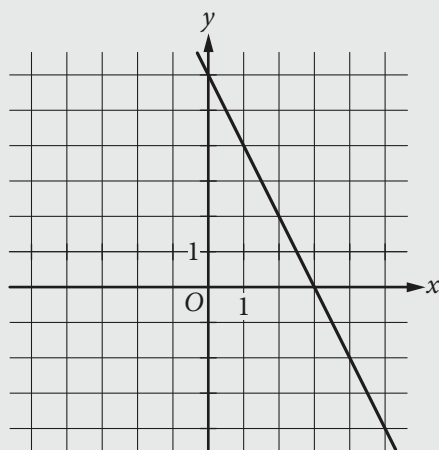
$$\begin{aligned} -15s + 10t &= -5a \\ -15s + bt &= -7 \end{aligned}$$

Since these two equations are equivalent and have the same coefficient of s , the coefficients of t and the constants on the right-hand side must also be the same. Thus, $b = 10$ and $-5a = -7$. Therefore, the value of a is $\frac{7}{5}$.

There will also be questions on the SAT Math Test that assess your knowledge of the relationship between the algebraic and the geometric representations of a line, that is, between an equation of a line and its graph. The key concepts are

- If the slopes of line ℓ and line k are each defined (that is, if neither line is a vertical line), then
 - ♦ Line ℓ and line k are parallel if and only if they have the same slope.
 - ♦ Line ℓ and line k are perpendicular if and only if the product of their slopes is -1 .

Example 13



The graph of line k is shown in the xy -plane above. Which of the following is an equation of a line that is perpendicular to line k ?

- A) $y = -2x + 1$
- B) $y = -\frac{1}{2}x + 2$
- C) $y = \frac{1}{2}x + 3$
- D) $y = 2x + 4$



REMEMBER

The SAT Math Test will further assess your understanding of linear equations by, for instance, asking you to select a linear equation that describes a given graph, select a graph that describes a given linear equation, or determine how a graph may be affected by a change in its equation.



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Example 13 requires a strong understanding of slope as well as the ability to calculate slope: slope is equal to rise over run, or the change in the y -value divided by the change in the x -value. Parallel lines have slopes that are equal. Perpendicular lines have slopes whose product is -1 .

Note that the graph of line k passes through the points $(0, 6)$ and $(3, 0)$. Thus, the slope of line k is $\frac{0-6}{3-0} = -2$. Since the product of the slopes of perpendicular lines is -1 , a line that is perpendicular to line k will have slope $\frac{1}{2}$. All the choices are in slope-intercept form, and so the coefficient of x is the slope of the line represented by the equation. Therefore, choice C, $y = \frac{1}{2}x + 3$, is an equation of a line with slope $\frac{1}{2}$, and thus this line is perpendicular to line k .

As we've noted, some contexts can be described with a linear equation. The graph of a linear equation is a line. A nonvertical line has geometric properties such as its slope and its y -intercept. These geometric properties can often be interpreted in terms of the context. The SAT Math Test has questions that assess your ability to make these interpretations. For example, look back at the contexts in Examples 1 to 3. You created a linear function, $f(n) = 783 + 8n$, that describes the number of miles of paved road County X will have n years after 2014. This equation can be graphed in the coordinate plane, with n on the horizontal axis and $f(n)$ on the vertical axis. The points of this graph lie on a line with slope 8 and y -intercept of $(0, 783)$. The slope, 8, gives the number of miles of new paved roads added each year, and the y -intercept gives the number of miles of paved roads in 2014, the year that corresponds to $n = 0$.

Example 14

A voter registration drive was held in Town Y. The number of voters, V , registered T days after the drive began can be estimated by the equation $V = 3,450 + 65T$. What is the best interpretation of the number 65 in this context?

- A) The number of registered voters at the beginning of the registration drive
- B) The number of registered voters at the end of the registration drive
- C) The total number of voters registered during the drive
- D) The number of voters registered each day during the drive

The correct answer is choice D. For each day that passes, it is the next day of the registration drive, and so T increases by 1. In the given equation, when T , the number of days after the drive began, increases by 1, V , the number of voters registered, becomes $V = 3,450 + 65(T + 1) = 3,450 + 65T + 65$. That is, the number of voters registered increased by 65 for each day of the drive. Therefore, 65 is the number of voters registered each day during the drive.

You should note that choice A describes the number 3,450, and the numbers described by choices B and C can be found only if you know how many days the registration drive lasted; this information is not given in the question.

Mastery of linear equations, systems of linear equations, and linear functions is built upon key skills such as analyzing rates and ratios. Several key skills are discussed in the next domain, Problem Solving and Data Analysis.