Word Problems: Interest, Growth/Decay, and Half-Life

*Applying logarithms and exponential functions*

Topics include simple and compound interest, $e$, depreciation, rule of 72, exponential vs. linear models, and more.
Simple vs. Compound Interest

Observe the difference:

Simple Interest...
You deposit 10,000 into a bank that pays simple interest at a 10% interest rate

<table>
<thead>
<tr>
<th>t (years)</th>
<th>Home</th>
<th>Bank</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>(bank deposit)</td>
<td>10,000</td>
<td>0</td>
<td>10,000</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>10,000</td>
<td>10,000</td>
</tr>
<tr>
<td>1</td>
<td>1000</td>
<td>10,000</td>
<td>11,000</td>
</tr>
<tr>
<td>2</td>
<td>2000</td>
<td>10,000</td>
<td>12,000</td>
</tr>
<tr>
<td>3</td>
<td>3000</td>
<td>10,000</td>
<td>13,000</td>
</tr>
<tr>
<td>4</td>
<td>4000</td>
<td>10,000</td>
<td>14,000</td>
</tr>
</tbody>
</table>

$1000 interest payments every year are sent home

Total 10,000 Bank 10,000 Home 10,000 t (years) 4

Compound Interest...
You deposit $10,000 into a bank that earns 10% interest compounded annually.

<table>
<thead>
<tr>
<th>Total</th>
<th>Bank</th>
<th>Home</th>
<th>t (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10,000</td>
<td>10,000</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>11,000</td>
<td>11,000</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>12,100</td>
<td>12,100</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>13,310</td>
<td>13,310</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>14,641</td>
<td>14,641</td>
<td>0</td>
<td>4</td>
</tr>
</tbody>
</table>

The 10% interest payments every year stay in the bank!

Interest Formulas

Simple Interest

\[
A = P + Pr t \\
A = \text{future amount} \\
P = \text{principal amount} \\
r = \text{annual interest rate} \\
t = \text{time (years)} \\
I = Pr t \\
I = \text{simple interest earned}
\]

Compound interest

\[
A = P \left(1 + \frac{r}{n}\right)^{nt} \\
A = \text{future amount} \\
P = \text{principal amount} \\
r = \text{(nominal) annual interest rate} \\
n = \text{number of times of compounding} \\
t = \text{years} \\
\]

note: \(nt = \text{number of times the amount is compounded} \)

\[
\frac{r}{n} = \text{the rate that is paid at each compounding time.}
\]

Compound Interest comparisons

Assume 12% annual interest rate: $1000 deposit....

<table>
<thead>
<tr>
<th>compounded</th>
<th>annually</th>
<th>semi-annually</th>
<th>Quarterly</th>
<th>Monthly</th>
<th>Daily</th>
<th>Continuously</th>
</tr>
</thead>
<tbody>
<tr>
<td># of payments</td>
<td>1</td>
<td>2</td>
<td>4</td>
<td>12</td>
<td>365</td>
<td>----</td>
</tr>
<tr>
<td>rate of each payment</td>
<td>12%</td>
<td>6%</td>
<td>3%</td>
<td>1%</td>
<td>.0328%</td>
<td>(A = Pe^{rt})</td>
</tr>
<tr>
<td>Future amount</td>
<td>1120</td>
<td>1123.60</td>
<td>1124.86</td>
<td>1126.83</td>
<td>1127.47</td>
<td>1127.50</td>
</tr>
<tr>
<td>1 year earnings</td>
<td>120</td>
<td>123.60</td>
<td>124.86</td>
<td>126.83</td>
<td>127.47</td>
<td>127.50</td>
</tr>
</tbody>
</table>

**The more times the principal (and interest) compounds, the more the amount grows!!**
"The Rule of 72"

What is it? If a sum is compounding at \(X\)% per year, that sum will double in approximately \(\frac{72}{X}\) cycles.

Example:

Suppose you deposit $100 in a bank that earns 10% interest per year. How many years will it take to double your money?

<table>
<thead>
<tr>
<th>time</th>
<th>balance</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>100 (initial deposit)</td>
</tr>
<tr>
<td>1</td>
<td>110 ((100 + 10))</td>
</tr>
<tr>
<td>2</td>
<td>121 ((110 + 11))</td>
</tr>
<tr>
<td>3</td>
<td>133.10 ((121 + 12.10))</td>
</tr>
<tr>
<td>4</td>
<td>146.41 ((133.1 + 13.31))</td>
</tr>
<tr>
<td>5</td>
<td>161.05 ((146.41 + 10% of 146.41))</td>
</tr>
<tr>
<td>6</td>
<td>177.15 ((161.05 + \text{interest payment}))</td>
</tr>
<tr>
<td>7</td>
<td>194.86 ((177.15 + \text{interest on 177.15}))</td>
</tr>
<tr>
<td>8</td>
<td>212.57</td>
</tr>
</tbody>
</table>

Account doubles from 100 to 200 shortly after 7 years...

Using the "rule of 72"

\[
\frac{72}{10} = 7.2
\]

So, a little over 7 years...

Formula for compounding interest

\[\text{Amount} = P \left(1 + \text{interest rate}\right)^t \] (where \(P\) is the principle and \(t\) is the time it compounds)

Using our example:

\[
200 = 100 \left(1 + .10\right)^t
\]

\[
\frac{200}{100} = \left(1.10\right)^t
\]

\[
t = \frac{\log 2}{\log (1.10)} \approx 7.27
\]

**If you're earning 10% interest, it will take approximately 7.27 years for you to double your money!**
Exponential Growth Applications

**Example:** A cell population \( t \) days from now is modeled by \( A(t) = 8e^{0.5t} \)

1) What is the current cell population?
   
   The current population is when time \( t = 0 \) \( A(0) = 8e^{0.5(0)} = 8 \) (also, the initial amount)

2) Determine the cell population 5 days from now.
   
   And, the cell population 5 days from now, occurs when \( t = 5 \) \( A(5) = 8e^{0.5(5)} = 8 \cdot 12.18 = 97.46 \)

3) When will the cell population exceed 200?
   
   Let the amount = 200... then solve (using logarithms)
   
   \[
   200 = 8e^{0.5t} \\
   \ln 200 = \ln (8e^{0.5t}) \\
   \ln 200 = \ln 8 + 0.5t \ln e \\
   3.219 = 0.5t \\
   t = 6.44 \text{ days}
   \]

**Example.** Stan invests $10,000 in an account that earns 7% compounded annually.
Eric invests $8,000 in an account that earns 9% compounded annually.

How many years will it take before Eric has more money in his account?

\[
A = P(1 + r)^t
\]

Stan's account: \( A = 10,000(1 + .07)^t \)
Eric's account: \( A = 8,000(1 + .09)^t \)

Since Eric's account is increasing at a faster rate, eventually it'll exceed Stan's...
So, let's find when they are equal...

\[
10,000(1 + .07)^t = 8,000(1 + .09)^t
\]

\[
\frac{5}{4} (1.07)^t = (1.09)^t
\]

\[
\frac{5}{4} = (1.09)^t (1.07)^{-t}
\]

\[
\log \frac{5}{4} = t \cdot \log \left( \frac{1.09}{1.07} \right)
\]

\[
t = \frac{\log \frac{5}{4}}{\log \left( \frac{1.09}{1.07} \right)} = \frac{.0969}{.0080} = 12.05 \text{ years}
\]

Check:

12 years (Stan)
\[10,000(1.07)^{12.1} = 22,674.81\]
12 years (Eric)
\[8,000(1.09)^{12.1} = 22,696.07\]
Example: Ian Apple has $750 in his savings account that earns 2.5% compounded continuously. The cost of a phone he likes costs $500. But, the price of the phone is increasing continuously at a rate of 7%.

When will Mr. Apple no longer have enough savings to buy the phone?

\[
\text{Savings} = 750 \, e^{0.025t} \\
\text{phone cost} = 500 \, e^{0.07t}
\]

set them equal to determine year they match...

\[
750 \, e^{0.025t} = 500 \, e^{0.07t}
\]

\[
\frac{3}{2} \, e^{0.025t} = e^{0.07t}
\]

\[
1.5 = e^{0.045t}
\]

\[
\ln(1.5) = \ln e^{0.045t}
\]

\[
\ln(1.5) = 0.045t
\]

\[
9.01 \text{ years...}
\]

Interest Growth, Decay, and Half-Life

Example: $20,000 is deposited into an investment account that offers a 6% interest rate.

How much will the account have after 6 1/2 years compounded

a) semi-annually?  
b) monthly?  
c) continuously?

\[
\text{Amount} = \text{Principal} \left(1 + \frac{\text{rate}}{n}\right)^{nt}
\]

\[
n = \# \text{ of payments per year.} \\
t = \# \text{ of years}
\]

\[
\text{Amount} = Pe^{rt}
\]

a) Amount = 20,000 \left(1 + \frac{0.06}{2}\right)^{13} 
= 20,000(1.03)^{13} 
= 29,370.67

b) Amount = 20,000 \left(1 + \frac{0.06}{12}\right)^{78} 
= 20,000(1.005)^{78} 
= 29,519.92

c) Amount = 20,000e^{-0.06 \times 6.5} 
= 29,559.62

Example: Ancient paintings are discovered in a remote cave.
To estimate the age, scientists take a sampling and measure the carbon count, knowing that the decay of carbon is

\[
A = A_o e^{-0.001201 t}
\]

If the sample contains 15% of the original carbon-14, estimate how old the painting is.

we'll suppose the original sample was 100...

If 15% remains, then

\[
15 = 100 e^{-0.001201 t}
\]

\[
.15 = e^{-0.001201 t}
\]

\[
\ln(.15) = -0.001201 t \cdot (\ln e)
\]

\[
\ln(.15) = -0.001201 t
\]

\[
t \approx 15,796 \text{ years...}
\]

(Note: without rounding, the time will be closer to approx. 15,678 years.)

Example: RC Adams has $2500 in a savings account that earns 3.5% compounded continuously. The current price of a screen TV he likes costs $6000. But, the cost of the TV is decreasing continuously at a rate of 7%.

When will RC A. be able to afford the television?

RCA's savings will increase... Meanwhile, the television will decrease...
At some point, they will be equal (and RCA will be able to buy the TV!)

\[
\text{RCA money} = 2500e^{0.035t} \\
\text{TV cost} = 6000e^{-0.07t}
\]

set them equal...

\[
2500e^{0.035t} = 6000e^{-0.07t}
\]

\[
e^{0.035t} = 2.4e^{-0.07t}
\]

\[
e^{0.105t} = 2.4
\]

\[
\ln(2.4) = .105t
\]

\[
t = \frac{\ln(2.4)}{-0.105} 
= 8.34 \text{ years...}
\]

mathplane.com
Example: Given the coordinates (0, 100) and (2, 400)

Find a linear equation that passes through the coordinates.

Find an exponential equation that goes through the coordinates.

Graph both functions.

To find a linear equation, you need the slope and a point.

Slope:

\[
\text{"rise" \over \text{"run"}} = \frac{y_1 - y_2}{x_1 - x_2} = \frac{400 - 100}{2 - 0} = 150
\]

A point: (0, 100)

Equation of the line: \( y - 100 = 150(x - 0) \)

or \( y = 150x + 100 \)

To find the exponential equation, use the general form \( y = ab^x \)

Substitute (0, 100): \( 100 = ab^0 \)

\( 100 = a(1) \)

\( a = 100 \)

Substitute (2, 400): \( 400 = ab^2 \)

\( 400 = (100)b^2 \)

\( b^2 = 4 \)

\( b = 2 \)

Equation of the exponential curve: \( y = 100(2)^x \)
Example:

In January 1923, 79,000 residents lived in Emigration City, USA. Each year, 1/3 of the population would leave. (Assuming there are no births, deaths, or immigrants,) what year did the population eventually fall to under 100 residents?

If 1/3 leave each year, then 2/3 remain...

We can model the population of Emigration City.

\[
79,000 \left(\frac{2}{3}\right)^n = \text{Population}
\]

where \(n\) = number of years after 1923

\[
\left(\frac{2}{3}\right)^n = \frac{100}{79,000}
\]

\[
n \log\left(\frac{2}{3}\right) = \log\left(\frac{100}{79,000}\right)
\]

\[
n = \frac{\log\left(\frac{100}{79,000}\right)}{\log\left(\frac{2}{3}\right)} = \frac{-2.898}{-0.176} = 16.46 \text{ (approximately)}
\]

Therefore, in the 17th year, the population will fall under 100.

<table>
<thead>
<tr>
<th>Year</th>
<th>Population at the beginning of each year</th>
</tr>
</thead>
<tbody>
<tr>
<td>1923</td>
<td>79,000</td>
</tr>
<tr>
<td>1924</td>
<td>52667</td>
</tr>
<tr>
<td>1925</td>
<td>35111</td>
</tr>
<tr>
<td>1926</td>
<td>23408</td>
</tr>
<tr>
<td>1927</td>
<td>15605</td>
</tr>
<tr>
<td>1928</td>
<td>10402</td>
</tr>
<tr>
<td>1929</td>
<td>6934</td>
</tr>
<tr>
<td>1930</td>
<td>4622</td>
</tr>
<tr>
<td>1931</td>
<td>3081</td>
</tr>
<tr>
<td>1932</td>
<td>2054</td>
</tr>
<tr>
<td>1933</td>
<td>1369</td>
</tr>
<tr>
<td>1934</td>
<td>912</td>
</tr>
<tr>
<td>1935</td>
<td>608</td>
</tr>
<tr>
<td>1936</td>
<td>405</td>
</tr>
<tr>
<td>1937</td>
<td>270</td>
</tr>
<tr>
<td>1938</td>
<td>180</td>
</tr>
<tr>
<td>1939</td>
<td>120</td>
</tr>
<tr>
<td>1940</td>
<td>80</td>
</tr>
</tbody>
</table>

(first column is rounding up, second column is rounding down...)

Practice Questions (and Answers) →
1) A bank offers 4.25% interest rate compounded daily. What is the annual yield?

2) A bacteria grows exponentially. The initial amount was 10,000. After 1 hour, the amount grew to 25,000.
   a) Find the doubling period. (How long does it take the bacteria to double?)
   b) What is the amount after 3 hours?

3) A special element has a half-life of 5 days. The initial amount is 500 grams.
   a) How many grams will remain after 15 days?
   b) What is the daily rate of decay?
   c) How many grams will remain after 12 days?
4) A radioactive element has a half-life of 1000 years. What percentage of the sample remains after 250 years?

5) If 250 mg of a radioactive material decays to 200 mg in 48 hours, what is the 1/2 life of the material?

6) Jim deposits $1000 into a bank that pays 8% annual interest, compounded continuously. Carol deposits $250 at the beginning of each quarter (Jan., Apr., July, Oct.) into the same bank. At the end of the year, how much more will Jim have in his account?
7) Compounding and Investing...

A) Scenario #1: invest $5,000 at age 25... 8% interest compounded annually
   Scenario #2: invest $20,000 at age 45... 8% interest compounded annually
   Which will have more money at age 65?

B) Scenario #3: invest $1000 per year from age 21 to age 30 (10 years)
   Scenario #4: invest $1000 per year from age 31 to age 65 (35 years)
   assume 8% interest compounded annually
   Which will have more money at age 65? Explain..

8) Depreciating.... A car cost $43,500. The car's value depreciates at a rate of 4%.

A) How much is the car worth after 7 years if the rate decreases
   a) annually?
   b) quarterly?
   c) continuously?

B) How much was the car worth 5 years ago, if the depreciation occurred
   a) quarterly?
   b) continuously?
"Today's lesson is half-life..."

\[ \frac{1}{2} = e^{kt} \]

Algebra II Honors
Mr. DeKay

"And, here is a formula for the rate of change, where \( t \) is the number of seconds..."

\[ \frac{1}{2} = e^{kt} \]

\[ MC = MC_0 e^{-0.069t} \]

"For example, the half-life of this math comic is 10 seconds..."

"Every 10 seconds, the Math Comic loses 50%... But, don't worry..."

"...the Comic will never go away completely!"
1) A bank offers 4.25% interest rate compounded daily. What is the annual yield?

Suppose we deposit $10000. What is the amount one year later?

\[ A = P \left(1 + \frac{r}{n}\right)^{nt} \]

<table>
<thead>
<tr>
<th>A</th>
<th>= future amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>= principal amount</td>
</tr>
<tr>
<td>r</td>
<td>= interest rate</td>
</tr>
<tr>
<td>n</td>
<td>= number of times the amount is compounded per year</td>
</tr>
<tr>
<td>t</td>
<td>= number of years</td>
</tr>
</tbody>
</table>

\[ A = 10000 \left(1 + \frac{0.0425}{365}\right)^{365(1)} = 10000 \times 1.00011644^{365} = 10,434.13 \]

So, $10,000 to $10,434 is an increase of $434 in one year.

\[ \frac{434}{10,000} = 0.0434 \]

Annual yield...

2) A bacteria grows exponentially. The initial amount was 10,000. After 1 hour, the amount grew to 25,000.

a) Find the doubling period. (How long does it take the bacteria to double?)

b) What is the amount after 3 hours?

We are given 2 points of measurement: (0, 10,000) and (1, 25,000)

Use substitution: \( y = ab^x \)

\( (10,000) = ab^0 \)

\( 10,000 = a(1) \)

\( a = 10,000 \)

\( 25,000 = 10,000b \)

\( b = 2.5 \)

The bacteria equation is \( y = 10000(2.5)^x \)

a) At the end of the doubling period, the bacteria amount will be 20,000...

\[ 20,000 = 10,000(2.5)^x \]

\[ 2 = (2.5)^x \]

\[ \log 2 = \log (2.5)^x \]

\[ .301 = x \log (2.5) \]

\[ x = \frac{.301}{\log (2.5)} \]

\[ x = .756 \text{ hours or 45.4 minutes} \]

b) After 3 hours,

\[ y = 10000(2.5)^3 = 156,250 \]

3) A special element has a half-life of 5 days. The initial amount is 500 grams.

a) How many grams will remain after 15 days?

b) What is the daily rate of decay?

c) How many grams will remain after 12 days?

\[ \text{Finding Half life formula:} \]

\[ A = Pe^{rt} \]

\[ A = \text{final amount} \]

\[ e = \text{euler's number} \]

\[ r = \text{rate} \]

\[ t = \text{time} \]

\[ \frac{1}{2}P = Pe^{rt} \]

\[ \frac{1}{2} = e^{rt} \]

\[ \ln \frac{1}{2} = \ln e^{rt} \]

\[ -.693 = 5r(\ln e) \]

\[ -.693 = 5r(1) \]

\[ r = -.1386 \]

daily rate: -13.86%

<table>
<thead>
<tr>
<th>Days</th>
<th>amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>500</td>
</tr>
<tr>
<td>5</td>
<td>250</td>
</tr>
<tr>
<td>10</td>
<td>125</td>
</tr>
<tr>
<td>15</td>
<td>62.5</td>
</tr>
<tr>
<td>20</td>
<td>31.25</td>
</tr>
</tbody>
</table>

62.5 grams
Growth, Decay, and Interest Rate Questions

4) A radioactive element has a half-life of 1000 years. What percentage of the sample remains after 250 years?

Part 1: Find the rate
\[ \frac{1}{2} = e^{rt} \]
\[ \frac{1}{2} = e^{1000r} \]
\[ \ln \frac{1}{2} = \ln e^{1000r} \]
\[ -.693 = 1000r \]
\[ r = -.000693 \]

Part 2: Apply formula
\[ A = Pe^{rt} \]
\[ A = P \left( e^{250(-.000693)} \right) \]
\[ A = P \left( 1e^{250(-.000693)} \right) \]
\[ A = P \cdot .841 \]
Approximately 84.1% remains

5) If 250 mg of a radioactive material decays to 200 mg in 48 hours, what is the 1/2 life of the material?

first, find the rate of decay...
\[ A = Pe^{rt} \]
200 = 250e^{.48}\]
\[ .8 = e^{.48r} \]
\[ r = -.0046 \]

then, find the 1/2 life
\[ 125 = 250e^{-0.0046t} \]
\[ .5 = e^{-0.0046t} \]
\[ t = 149 \text{ hours} \]

6) Jim deposits $1000 into a bank that pays 8% annual interest, compounded continuously. Carol deposits $250 at the beginning of each quarter (Jan., Apr., July, Oct.) into the same bank.

At the end of the year, how much more will Jim have in his account?

Jim: \[ A = 1000(e^{.08(1)}) = 1083.287 \]
Carol: \[ A = 250(e^{.08(1)}) = 270.822 \]

Total: \$1083.29
first deposit
\[ A = 250(e^{.08(.75)}) = 265.459 \]
second deposit (compounds for 9 months)
\[ A = 250(e^{.08(.50)}) = 260.203 \]
third deposit (compounds for 6 months)
\[ A = 250(e^{.08(.25)}) = 255.050 \]
fourth deposit (compounds for 3 months)

Jim will have \$31.76 more at the end of the year...

Total: \$1051.53
7) Compounding and Investing...

A) Scenario #1: invest $5,000 at age 25... 8% interest compounded annually

Scenario #2: invest $20,000 at age 45... 8% interest compounded annually

Which will have more money at age 65?

\[
\text{Amount 1} = 5,000(1 + .08)^{10} = \$108,622
\]
\[
\text{Amount 2} = 20,000(1 + .08)^{20} = \$93,219
\]

Note the power of compounding interest! (Also, notice how investing early is important!)

then, recognize the “rule of 72” ---- at 8%, you would expect your money to roughly double every \( \frac{72}{8} = 9 \) years

Scenario #1 would double the money almost 4 1/2 times...
5K, 10K, 20K, 40K, 80K, 120K (doubling 5 times)
Scenario #2 would double the money twice and a bit more...
20K, 40K, 80K (doubling twice)

B) Scenario #3: invest $1000 per year from age 21 to age 30 (10 years)

Scenario #4: invest $1000 per year from age 31 to age 65 (35 years) assume 8% interest compounded annually

Which will have more money at age 65? Explain...

Scenario #3 segments
\[
\text{Amount} = 1000(1.08)^{10} = 29,555 \quad \text{(age 21 deposit)}
\]
\[
\text{Amount} = 1000(1.08)^{40} = 21,724 \quad \text{(age 25 deposit)}
\]
\[
\text{Amount} = 1000(1.08)^{35} = 14,785 \quad \text{(age 30 deposit)}
\]

Apparently, Scenario #3 will have more money...

Using a rough estimate, Scenario #3 will end up with about 200K;
and, Scenario #4 will end up with about 175K...

Scenario #4 segments
\[
\text{Amount} = 1000(1.08)^{34} = 13,690 \quad \text{(age 31 deposit)}
\]
\[
\text{Amount} = 1000(1.08)^{17} = 3,700 \quad \text{(age 48 deposit)}
\]
\[
\text{Amount} = 1000(1.08)^{1} = 1,080 \quad \text{(age 64 deposit)}
\]

8) Depreciating... A car cost $43,500. The car's value depreciates at a rate of 4%.

A) How much is the car worth after 7 years if the rate decreases

\[
\text{a) annually?} \quad V = 43,500(1 - .04)^7 = \$32,688
\]
\[
\text{b) quarterly?} \quad V = 43,500(1 - \frac{.04}{4})^{7(4)} = 43,500(1 - .01)^{28} \quad \text{or} \quad \$32,830
\]
\[
\text{c) continuously?} \quad V = 43,500e^{-0.04(7)} = \$32,876
\]

Notice: when you increase the number of depreciations, the depreciation/decay slows!
EX: taking 1% each quarter will decrease LESS than taking 4% at the end of the year!

B) How much was the car worth 5 years ago, if the depreciation occurred

\[
\text{a) quarterly?} \quad V = 43,500(1 - \frac{.04}{4})^{-5(4)} = 43,500(0.99)^{-20} = \$53,184
\]
\[
\text{b) continuously?} \quad V = 43,500e^{-0.04(-5)} = \$53,131
\]
Thanks for visiting. (Hope it helped!)

If you have questions, suggestions, or requests, let us know.

Cheers

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