Landmark Lesson Plan:
Climate Change & the Keeling Curve

Grades: 9-12
Subject Areas: Chemistry and History
Based on the National Historic Chemical Landmark on The Keeling Curve: Studies of Atmospheric Carbon Dioxide Measurements at Mauna Loa
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The following inquiry-based student activities are designed for use in high school chemistry lesson planning, but they apply to all science subjects. Some middle school teachers may also find the lesson outline helpful. The lesson plan will help students recognize how scientists came to understand global warming using evidence collected over decades.

The content is designed as a ready-to-go lesson, easily implemented by a teacher or his/her substitute to supplement a unit of study. Students will practice critical reading and writing skills as they develop a deeper understanding of how scientists found evidence for climate change. The final activity in particular integrates writing as students are asked to explain our current understanding of climate change and relate what they have learned to their own lives.

All resources are available online at www.acs.org/LandmarkLessonPlans.

While these activities are thematically linked, each is designed to stand alone as an accompaniment for the handout. Teachers may choose activities based on curricular needs and time considerations.

- Take a few minutes to introduce the lesson with a few conversation starters. What is climate change? What might cause it?
- If you use the Anticipation Guide, do not distribute the handout about climate change and the Keeling Curve until students have indicated their initial opinions or (for the optional engagement exercise) come up with their own ideas. Then distribute the handout for students to check their answers and find the passage that supports or refutes their initial thoughts.
- For the remaining activities, distribute the exercise(s) selected for the class along with the handout about climate change and the Keeling Curve. Make sure students understand the directions for each activity. While students are reading, they should complete the exercise(s).
- For additional information, students may want to refer to information about
    - photosynthesis: http://bit.ly/ACS-photosynthesis
    - combustion: http://bit.ly/ACS-combust and http://bit.ly/ACS-combust2
    - radioactive decay of carbon-14: http://bit.ly/ACS-decay
- Other useful links:
    - NASA's Global Climate Change site: https://climate.nasa.gov
    - Scripps CO_2 Program: http://scrippsco2.ucsd.edu
    - Mauna Loa Observatory: http://www.esrl.noaa.gov/gmd/obop/mlo
    - National Oceanic and Atmospheric Administration's Education and Outreach resources: http://www.esrl.noaa.gov/gmd/education
    - ACS Climate Science Toolkit: https://www.acs.org/content/acs/en/climatescience.html
- After all students have read the handout and completed the exercise(s), use the Answer Guide for student feedback and further discussion.

Student Activities with Objectives

Anticipation Guide and Reading on "Climate Change and the Keeling Curve"
(5 minute introduction, followed by 15-20 min. of reading)

- Students confront their ideas about the greenhouse effect and global warming.

History Exercise: Timeline of events leading to our current understanding of global warming
(10-15 min.)

- Students chronologically order events in the reading.
- Students describe scientists' claims, evidence and reasoning to relate fossil fuel combustion to global warming.

Graphic Organizer: Chemistry and Global Warming
(5-10 min.)

- Students write the equations for processes described in the article, and how each process affects the trends shown by the Keeling Curve.

Why Mauna Loa Observatory?
(5-10 minutes)

- Students describe three advantages and three challenges related to collecting data at Mauna Loa Observatory.

Writing Exercise: The Keeling Curve and You
(20-25 min.)

- Students summarize current understanding of global warming and how this understanding affects their lives.

Climate Change and the Keeling Curve

Climate change is a vital issue that involves many chemical processes, including the "greenhouse effect." In this process, solar radiation reflects off Earth's surface, and greenhouse gases in the atmosphere trap some of that radiation energy, heating the planet.

Many greenhouse gases occur naturally and are critical to supporting life on Earth. Some are also produced by human activities, which further increase atmospheric concentrations of greenhouse gases such as carbon dioxide (CO_2). As a result, average global temperatures are increasing and arctic ice is melting. These changes affect animals such as polar bears that depend on sea ice for hunting, traveling and breeding. They also affect human populations that have to cope with rising sea levels, intensifying weather events and other effects of climate change.

Greenhouse effect

The notion of the greenhouse effect was first proposed in the 1820s by French mathematician and physicist Joseph Fourier. His calculations suggested that Earth should be much cooler than it is, given the amount of energy it receives from the sun.

One explanation he offered was that Earth's atmosphere might provide an insulating effect, retaining heat that would otherwise be re-emitted into space. For the next century and a half, scientists debated the relationship among the composition of the atmosphere, emissions of greenhouse gases and Earth's temperatures.

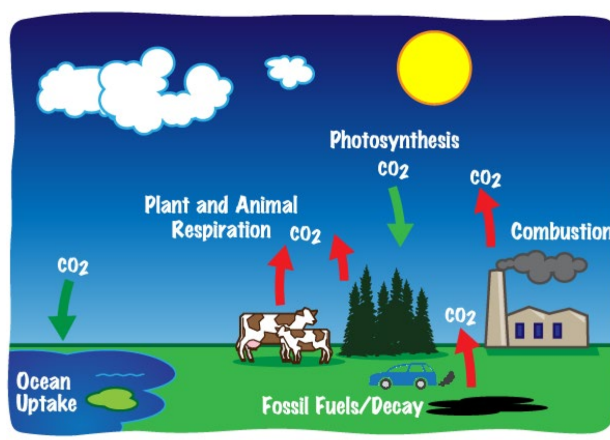
Significant human impact on the atmosphere started in the mid-18th century with the Industrial Revolution, when people began using large quantities of fossil fuels such as coal, oil and natural gas. Burning these fuels released their carbon content into the atmosphere as CO_2, as well as other pollutants and water vapor.

Some scientists believed this growth in CO_2 emissions would cause a small increase in global temperatures. Svante Arrhenius first suggested this connection in 1896. Others argued that natural physical processes such as the absorption of CO_2 by oceans would negate any increases.

Measuring CO_2

Initial attempts to measure atmospheric CO_2 concentrations showed wide variations that were difficult to interpret. So in 1956, the U.S. Weather Bureau (now part of the National Oceanic and Atmospheric Administration, NOAA) began a program to establish a baseline of CO_2 concentrations. Charles David Keeling led the program from the Scripps Institution of Oceanography in La Jolla, California, using measurements of air samples from Hawaii, Antarctica and other remote locations around the world.

The earliest data from the program came from a sample collected at the South Pole in early 1957. In March 1958, an analyzer was installed at the Weather Bureau's Mauna Loa Observatory. The observatory sits at an elevation of 11,135 feet, near the summit of Hawaii's second tallest mountain. An active volcano, Mauna Loa



Adapted from NASA graphic

Keeling's data shed new light on the carbon cycle, shown here. Part of the carbon cycle includes combustion of fossil fuels such as coal, oil and natural gas, which consists primarily of methane. The chemical equation for methane combustion is $CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$.

occasionally emits CO_2, sulfur dioxide and other gases, which can disrupt the open-air data being recorded but are easily detectable. Despite this and other challenges relating to its remote location, the observatory provides researchers with a nearly pristine site for atmospheric observations due to its setting far from human activity, vegetation and dust. A strong inversion layer further suppresses local pollutants from lower elevations.

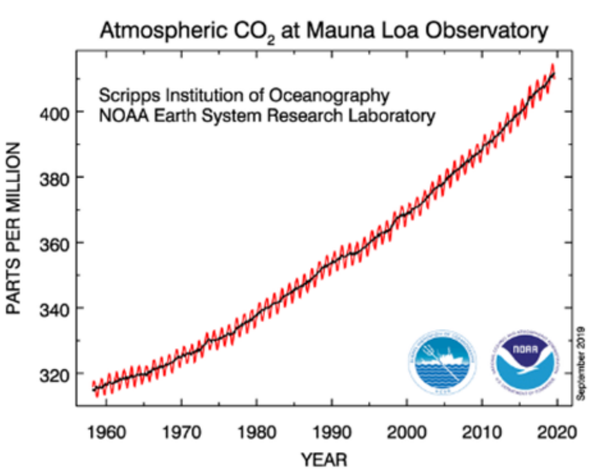
Glossary

Absorption: CO_2 from the atmosphere can dissolve in oceans. This absorption of CO_2 increases ocean acidity, which can harm organisms that live in the water.
Airborne fraction: The amount of CO_2 in the atmosphere, as opposed to the oceans, plants and soil.
Inversion layer: The temperature of the atmosphere normally drops at higher elevations, but when an inversion layer forms, the temperature is warmer at higher elevations. This traps atmospheric pollution at lower elevations.
Isotope: Atoms consist of electrons and a nucleus, which contains protons and neutrons. Different isotopes of a given element — such as ^{12}C and ^{13}C — contain the same number of electrons and protons but a different number of neutrons.
Kyoto Protocol: An international agreement that committed member countries to reductions in emissions of CO_2 and other greenhouse gases.

The first reading from Mauna Loa, on March 29, 1958, measured the atmospheric CO_2 concentration at 313 parts per million (ppm). Daily averages recorded in the following months showed no obvious trend. Keeling later recalled that he was “anxious that the concentration was going to be hopelessly erratic.”

A pattern emerges

Yet after a full year of measurements, a pattern emerged. Seasonal oscillations of CO_2, with peaks in May and lows in November, reflected the impact of vegetation cycles in the northern hemisphere: Plants take in CO_2 during the growing period lasting from April through August via photosynthesis, reducing atmospheric CO_2 levels during these months. The chemical equation for this process is $6CO_2 + 6H_2O \rightarrow C_6H_{12}O_6 + 6O_2$.



Keeling's methods of measuring atmospheric CO_2 revealed clear natural and man-made trends. The jagged red line shows natural annual oscillations caused by plant growth cycles, while the rising black curve shows the increase over time caused by human activities, especially the burning of fossil fuels. The graph of CO_2 data recorded at the Mauna Loa Observatory is known as the Keeling Curve.

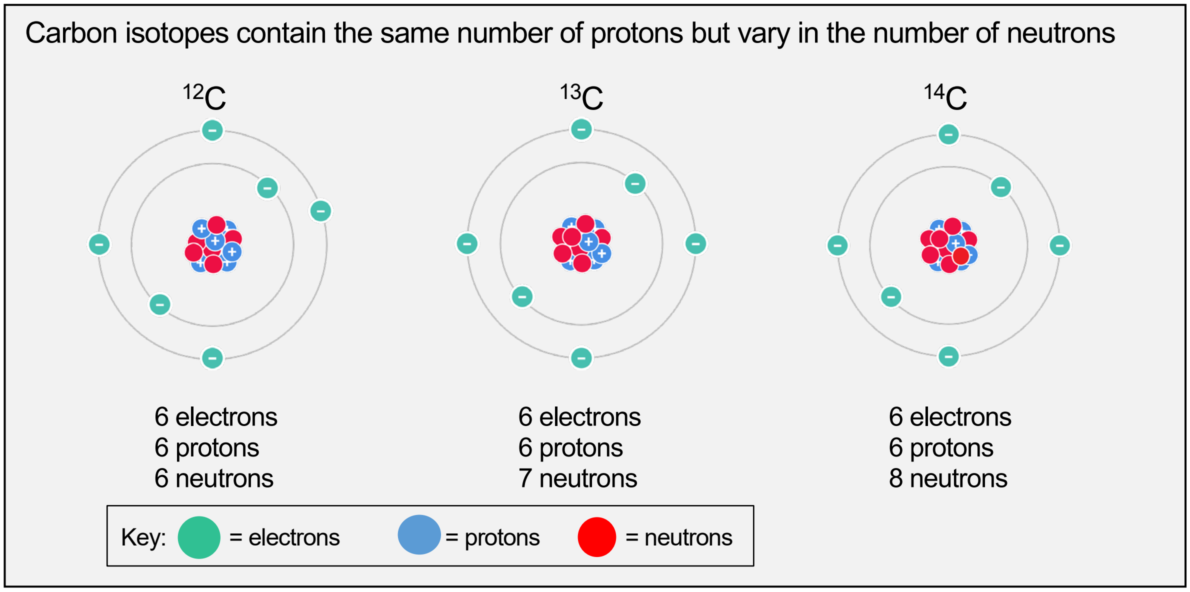
In winter when plants lose their foliage, carbon stored within plant tissues and soils is released to the atmosphere, increasing CO_2 concentrations.

Keeling reported his initial findings, plotted in what became known as the Keeling Curve, in the geophysics journal *Tellus* in 1960. As he amassed additional measurements over a series of years, the annual increase in atmospheric CO_2 became more apparent. Keeling determined that roughly half of all CO_2 released by coal, oil and natural gas was remaining in the atmosphere, thus causing the Keeling Curve’s annual rise. This figure, reported by Keeling and his Scripps colleagues in 1973, is known as the “airborne fraction.” The remainder is dissolved into the oceans, taken up by plants or accumulated in soils.

The observed airborne fraction is critical in developing models that project future climate effects of rising greenhouse gas concentrations, including rising temperatures and sea levels, and ocean acidification. Keeling’s research disproved widely held beliefs in the scientific community that exchanges within the carbon cycle could mitigate rising levels of CO_2.

Isotopic fingerprints and the carbon cycle

In the late 1970s, Keeling’s group looked more closely at sources of the atmospheric CO_2. Carbon can be distinguished by its isotopes — carbon atoms with varying numbers of neutrons. Carbon atoms containing six protons and six neutrons (known as ^{12}C) are the most common



Adapted from American Association of Chemistry Teachers' "Isotopes & Calculating Average Atomic Mass"

isotope and comprise about 99% of all carbon on Earth. Carbon atoms that contain an additional neutron are ^{13}C; they comprise about 1% of all carbon.

Only a trace amount is in the form of ^{14}C, which contains two extra neutrons. This isotope, also known as radiocarbon, is created in nature when a neutron strikes a nitrogen atom (^{14}N) in the atmosphere and forces it to eject a proton. Unlike ^{12}C and ^{13}C, ^{14}C is unstable, so it disappears gradually via radioactive decay, at a predictable rate, by turning back into nitrogen. The equation for this decay is $^{14}C \rightarrow {}^{14}N$ + electron + antineutrino.

Because of that regular disintegration, radiocarbon can be used to determine the age of carbon-based objects like fossilized plants and animals. The less ^{14}C an object contains, the older it must be. In contrast, the amount of ^{12}C and ^{13}C remains unchanged after many thousands of years. Therefore, modern sources of CO_2 such as living organisms have about the same amount of ^{14}C as the atmosphere, whereas ancient sources like fossil fuels have none left. When fossil fuels are burned, they add ^{12}C and ^{13}C to the atmosphere, but no ^{14}C. The result is that the proportion of ^{14}C in the atmosphere goes down.

In 1977, Keeling and researchers at the University of Groningen in the Netherlands began studying the isotopic ratios of carbon in atmospheric samples dating back to 1955. Changes in these ratios provided further evidence that burning of fossil fuels was linked to accumulation of CO_2 in the atmosphere and that seasonal variations were due to annual plant cycles.

Research on air samples trapped within polar ice deposits, conducted in the 1980s, revealed levels of CO_2 dating back hundreds of thousands of years. These data extended the Keeling Curve and showed a startling surge in CO_2 concentrations in recent years.

Action on CO_2 emissions

In 1988 the United Nations (U.N.) created the Intergovernmental Panel on Climate Change to prepare reports and recommendations about climate change. In 1992, the U.N. Framework Convention on Climate Change was ratified, with a goal of stabilizing greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous interference with the climate. Five years later, the Kyoto Protocol emerged, the first international agreement that committed member countries to reductions in CO_2 and other greenhouse gases.

Nearly 40 years after Keeling's data first showed an increase in CO_2 in the atmosphere, significant global action to reduce emissions was finally enacted. Yet disagreements about climate change and ways to address it continue today.

Further reading

Students may wish to refer to additional information about photosynthesis (http://bit.ly/ACS-photosynthesis), combustion (http://bit.ly/ACS-combust and http://bit.ly/ACS-combust2) and radioactive decay of ^{14}C (http://bit.ly/ACS-decay).

NASA's Global Climate Change site also offers many rich resources on the topic (https://climate.nasa.gov).

Student Name: ____________________________ Date: ____________ Period: _________

Anticipation Guide
Climate Change & the Keeling Curve

Anticipation guides help engage students by activating prior knowledge and stimulating student interest before reading. If class time permits, discuss students' responses to each statement ***before*** reading each article. Then, **while** they read, students should look for evidence supporting or refuting their initial responses.

Directions: ***Before reading***, in the first column, write "A" or "D" indicating your agreement or disagreement with each statement. Then, **while** you read, compare your opinions with information from the article. In the space under each statement, cite information from the article that supports or refutes your original ideas.

Me	**Text**	**Statement**
		1. The greenhouse effect was first proposed in the mid-1900s.
		2. Near the end of the 19^{th} century, Arrhenius proposed that the combustion of fossil fuels would lead to an increase in global temperatures.
		3. Keeling discovered that carbon dioxide (CO_2) concentrations decrease over the spring and summer and increase during the winter.
		4. The Keeling Curve is based on measurements of CO_2 from Mauna Loa Observatory in Hawaii.
		5. Vegetation cycles affect the concentration of CO_2 in the atmosphere.
		6. Keeling's data showed that less than 10% of the CO_2 released by fossil fuels remained in the atmosphere.
		7. Carbon-14 (^{14}C) is radioactive, but carbon-12 and carbon-13 are not.
		8. Burning fossil fuels adds large amounts of ^{14}C to the atmosphere.

Student Name: ______________________________ Date: _____________ Period: _________

		9. The concentration of CO_2 in polar ice deposits showed that the current amount of CO_2 in the atmosphere exceeds natural trends.
		10. Mauna Loa is an active volcano.

Optional Engagement Idea

Instead of using the Anticipation Guide, consider this idea to engage your students in reading:

1. Ask students when they think scientists had evidence the Earth is warming.
2. After all students have an opportunity to think about global warming, ask them what scientists think is causing global warming.
3. After this discussion, invite students to read the article to find more details about the claim for global warming, the evidence that supports the claim and the reasons the evidence supports the claim.

Student Name: _____________________________ Date: ____________ Period: _________

Timeline

Challenge students to put the following events in chronological order prior to reading.

While they read, students should re-order the events correctly.

After reading, ask students to write a paragraph describing how scientists became convinced that burning fossil fuels contributes to global warming. Include the scientists' claim(s), the evidence supporting their claim(s) and the reasoning that explains how the evidence supports the claim(s).

A. Charles Keeling published his initial findings on atmospheric levels of carbon dioxide (CO_2).

B. A year of data collection was completed to begin the Keeling Curve.

C. The greenhouse effect was described by a French mathematician.

D. A connection between the emission of CO_2 from burning fossil fuels and an increase in global temperatures was hypothesized.

E. The amount of CO_2 trapped in polar ice deposits was determined.

F. An international agreement, the Kyoto Protocol, was signed by countries committed to reducing CO_2 and other greenhouse gas emissions.

G. Keeling began collecting data at Mauna Loa Observatory.

H. Keeling and a team from the Netherlands began studying the isotopic ratios of carbon samples to identify the source of atmospheric CO_2.

I. The United Nations created the Intergovernmental Panel on Climate change to prepare reports based on scientific information.

J. NOAA founded a program to establish a baseline for CO_2 concentrations in the atmosphere.

Student Name: ______________________________ Date: _____________ Period: _________

Chemistry and Global Warming

Directions: Write the equations for the processes described below, and explain how this relates to the Keeling Curve.

Process	**Equation**	**How does this process affect the amount of carbon dioxide (CO_2) in the atmosphere?**	**Sketch how the Keeling Curve would look if this process <u>did not</u> occur**
Photosynthesis			
Combustion of a fossil fuel			
Radioactive decay of ^{14}C (***Note:*** This is a nuclear equation)			

Student Name: ______________________________ Date: _____________ Period: __________

Mauna Loa Observatory

Describe at least three advantages and three challenges related to collecting data at Mauna Loa Observatory.

Advantages	**Challenges**

Student Name: _____________________________ Date: ____________ Period: _________

The Keeling Curve and You

Write a three-paragraph summary of what you learned from the article.

- In the first paragraph, describe what was hypothesized about the greenhouse effect and global warming prior to Keeling's research.
- In the second paragraph, explain how the work of Keeling and others led to our current understanding of global warming.
- In the last paragraph, relate what you learned from the article to your everyday life. How does knowing this information affect you?

Anticipation Guide
The Keeling Curve

Me	Text	Statement
	D	1. The greenhouse effect was first proposed in the mid-1900s. Correct answer: 1820s; see page 1 of the reading, paragraph 3
	A	2. Near the end of the 19th century, Arrhenius proposed that the combustion of fossil fuels would lead to an increase in global temperatures. 1896; page 1, para. 4
	A	3. Keeling discovered that carbon dioxide (CO_2) concentrations decrease over the spring and summer and increase during the winter. Page 2, para. 3
	A	4. The Keeling Curve is based on measurements of CO_2 from Mauna Loa Observatory in Hawaii. Page 2, para. 5
	A	5. Vegetation cycles affect the concentration of CO_2 in the atmosphere. Page 2, para. 4
	D	6. Keeling's data showed that less than 10% of the CO_2 released by fossil fuels remained in the atmosphere. Correct answer: roughly half; page 2, para. 5
	A	7. Carbon-14 (^{14}C) is radioactive, but carbon-12 and carbon-13 are not. Page 3, para. 2
	D	8. Burning fossil fuels adds large amounts of ^{14}C to the atmosphere. Correct answer: ^{14}C decreases after an organism dies, so fossil fuels contain no ^{14}C; page 3, para. 3
	A	9. The concentration of CO_2 in polar ice deposits showed that the current amount of CO_2 in the atmosphere exceeds natural trends. "startling surge," page 3, para. 5
	A	10. Mauna Loa is an active volcano. Page 1, para. 6

Timeline

Challenge students to put the following events in chronological order prior to reading.

A. Charles Keeling published his initial findings on atmospheric levels of carbon dioxide (CO_2). 1960

B. A year of data collection was completed to begin the Keeling Curve. 1959

C. The greenhouse effect was described by a French mathematician. 1820s

D. A connection between the emission of CO_2 from burning fossil fuels and an increase in global temperatures was hypothesized. 1896

E. The amount of CO_2 trapped in polar ice deposits was determined. 1980s

F. An international agreement, the Kyoto Protocol, was signed by countries committed to reducing CO_2 and other greenhouse gas emissions. 1997

G. Keeling began collecting data at Mauna Loa Observatory. 1958

H. Keeling and a team from the Netherlands began studying the isotopic ratios of carbon samples to identify the source of atmospheric CO_2. 1977

I. The United Nations created the Intergovernmental Panel on Climate change to prepare reports based on scientific information. 1988

J. NOAA founded a program to establish a baseline for CO_2 concentrations in the atmosphere. 1956

Correct order:

C, D, J, G, B, A, H, E, I, F

Chemistry and Global Warming

Directions: Write the equations for the processes described below, and explain how this relates to the Keeling Curve.

Process	**Equation**	**How does this process affect the amount of carbon dioxide (CO_2) in the atmosphere?**	**Sketch how the Keeling Curve would look if this process did not occur**
Photosynthesis	$6CO_2 + 6H_2O \rightarrow C_6H_{12}O_6 + 6O_2$	Reduces CO_2	Sketch should have a steeper slope than Keeling curve; also, it should be a smooth curve that lacks the seasonal fluctuation for each year
Combustion of a fossil fuel	Methane (one example): $CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$; gasoline (another example): $2C_8H_{18} + 25O_2 \rightarrow 16CO_2 + 18H_2O$	Increases CO_2	Sketch should be more horizontal than Keeling curve
Radioactive decay of ^{14}C (***Note:*** This is a nuclear equation)	$^{14}C \rightarrow {}^{14}N$ + electron + antineutrino	No effect	Sketch should show no effect on Keeling curve

Mauna Loa Observatory

Describe at least three advantages and three challenges related to collecting data at Mauna Loa Observatory. Explain why the advantages and disadvantages matter.

Advantages	**Challenges**
Elevation, so above much of the atmosphere	Remote, so difficult to get to
Far from human activity, so less interference from human activities such as driving and growing crops	Active volcano, so care must be taken for scientists to remain safe
Strong inversion layer suppresses pollutants	Emits gases which must be accounted for in the data

Rubric for evaluating student understanding:

Score	Description	Evidence
4	Excellent	Complete; details provided; demonstrates deep understanding of scientific processes and how science relates to everyday life.
3	Good	Complete; few details provided; demonstrates some understanding of scientific processes and the relationship to everyday life.
2	Fair	Incomplete; few details provided; shallow understanding of scientific processes and relationship of findings to everyday life; some misconceptions evident.
1	Poor	Very incomplete; no details provided; many misconceptions evident.
0	Not acceptable	So incomplete that no judgment can be made about student understanding.