Voyage of the Nitrogen Atom: A Role-playing Activity Illustrating the Biogeochemical Cycle of Nitrogen

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Abstract

In order to derive the nitrogen cycle, each student in the class takes the role of a nitrogen atom, beginning the activity in the form of NO_3^-, amino acid, N_2, etc. Eight stations are set up around the classroom representing different nitrogenous molecules; students travel between stations according to instruction cards drawn randomly at each station. For example, a student acting as NO_3^- may learn that via denitrification, she's been reduced to $1/2N_2$. She would proceed to the N_2 (gas) station, where she may be fixed biologically, reduced abiologically, or remain as N_2 for another turn. After 10 to 12 turns (as time allows), students gather in small groups to compare their unique "voyages." (Instruction cards are included in Appendix I.)

Activity

Invitation for User Feedback. If you have used the activity and would like to provide feedback, please send an e-mail to MicrobeLibrary@asmusa.org. Feedback can include ideas which complement the activity and new approaches for implementing the activity. Your comments will be added to the activity under a separate section labeled "Feedback." Comments may be edited.

Editor's Note (2008): This Curriculum Resource was published prior to establishment of current criteria of submission, and as such, does not contain all criteria required of current publications. However, the Editorial Committee felt that the activity itself remained worthwhile and relevant, and encourages potential users to contact the authors for clarification as needed. If you do update this activity for use with your students, and are interested in updating the resource for distribution in the library, please contact ASM at MicrobeLibrary@asmusa.org.

INTRODUCTION

Time Required.
In class time required: ~20 to 25 minutes for the role-playing itself; ~10 to 30 minutes immediately after the role-play for various follow-up activities.

Learning Objectives.
This activity was designed to allow students to see for themselves that a nitrogen cycle results as nitrogen atoms circulate between various organisms and microenvironments. Within the cycle, some molecular forms may be extremely stable (e.g., the N_2 pool) while others are very biologically active (e.g., NH_4^+). Some instructors may choose to extend these broad concepts in biogeochemical cycling by also having the students match up names of organisms and additional information about the various redox reactions to appropriate parts of the student-derived nitrogen cycle.

Background.
There is a limited amount of matter on the earth. Those atoms that are essential for cellular existence are particularly precious and must be constantly recycled for life to continue. Many of the recycling steps are carried out by bacteria living in specific types of microenvironments. For microbiologists, nitrogen is an especially interesting and precious resource because bacteria uniquely perform several key steps in the recycling process. These bacteria may "get" different things out of the processes; in some cases, they get a source of electrons for energy production, while in other cases they get a sink onto which they can dump spent electrons. Additionally, every bacterium—like all higher organisms on the planet—must assimilate some nitrogen atoms into the proteins and ultrastructure that comprise the fabric of cellular life. In short, forms of nitrogen that are waste products to one organism literally provide "lunch" for another organism.

To illustrate vital principles in nitrogen recycling for *The Voyage of the Nitrogen Atom,* each student in the class will spend several minutes playing a nitrogen atom. Each student will begin the exercise as one specific molecular form of nitrogen (either N_2, NH_4^+, NO_2^-, NO_3^-, plant protein, animal protein, bacterial protein, or ammonia in a bacteroid). Then, by drawing cards, students will "experience" the journey of a nitrogen atom diffusing between organisms and environments. Each card will describe—in general terms—a type of process that acts upon a molecular form of nitrogen, sometimes converting it into a completely different form. At the end of the exercise (after approximately 10 turns), students will gather in small groups to compare their journeys with one another.

The goal of this exercise is to give students a better understanding of naturally occurring processes involving nitrogen atoms. These processes help to illustrate the diversity of bacteria and their critical role in nature. Furthermore, understanding these processes allows a better appreciation for the ways in which human-induced environmental changes have begun to affect natural nitrogen cycling: by providing too much of one form of nitrogen (particularly as concentrated fertilizer and animal manure), the growth of some organisms in the cycle can be increased to the detriment of an entire ecosystem.

In preparation for this in-class exercise, each student should be able to answer the following questions (refer to textbook or other materials, as necessary):

1. What is anaerobic respiration?

   What is the function of a nitrogenous compound in anaerobic respiration?

2. What is lithotrophy?

   What is the function of a nitrogenous compound in lithotrophic processes?

3. What is nitrogen fixation?

   Of what advantage to an organism is the process of nitrogen fixation?

4. Name two examples of organic forms of nitrogen.
   The conversion of organic to inorganic nitrogen is often called:
   The conversion of inorganic to organic nitrogen is often called:

PROCEDURE

Materials.
The following materials are needed for an entire class:

- Eight containers (such as brown paper bags) labeled "Nitrogen gas, N_2"; "ammonium, NH_4^+"; "nitrite, NO_2^-"; "nitrate, NO_3^-"; "plant protein"; "animal protein"; "bacterial protein"; and "bacteroid ammonia" set up in eight different stations around the room
- Instruction cards for each station (See Appendix I.)

Student Version..

1. Go to one of the eight stations as directed by your instructor. Bring a pencil or pen with you. Notice the name of the molecule at this station: this is your starting state.
2. When the class is ready, remove a card at random from the station. Write "1" on the card, to record that this represents the first step in your "journey".
3. Without returning the card to the station, do whatever it says on the card (you may be instructed to go to a different station, or to pause for 10 seconds, then draw from the same station.)
4. Draw a card at random from this station. Write "2" on this card, then follow the instructions on the card. Hold onto both cards as you proceed as instructed.
5. Continue for 10 or more stations as time allows. In each case, record the order in which you drew the card.
6. At the end of the exercise, get together with 2 to 4 other students and arrange your sets of cards sequentially. Compare and contrast the "voyages" that each of you undertook.

Safety Issues. Not applicable.

ASSESSMENT and OUTCOMES

Suggestions for Assessment.
The Voyage of the Nitrogen Atom is an active learning strategy to teach about nutrient cycling, a subject which is often perceived by students to be dry and tedious. By replacing a standard nitrogen cycling lecture with this activity, instructors will find that students are more engaged for learning about the various microbial processes in the nitrogen cycle, other nutrient cycles (carbon, sulfur, etc.), and environmental ramifications such as nitrate pollution and nutrient loading in tidal waters. Special assessment of this activity is not necessarily required; if desired, students may be examined on the

concepts of nitrogen cycling using exam questions similar to those used when teaching nitrogen cycling through non-active means.

In a discussion about the nitrogen cycle following the activity, the instructor (or students) should point out that the frequency of a particular transition for a given molecular form during the role-play was only loosely based on reality. For example, for the N_2 station, the majority of the cards (ten out of fifteen) say "no change" and a minority instruct a reduction to ammonium (three cards via biological fixation and two cards via abiological fixation). For obvious reasons, the card ratio does not really reflect the true conversion ratio (which would be more like a billion cards for "no change," 30 cards for "biological fixation," and 2 cards for "abiological fixation"). As part of the discussion, instructors might help the students to calculate accurate card ratios based on literature values for the global nitrogen reservoir (e.g., see Madigan, M. et al., Brock Biology of Microorganisms, 8th ed., page 572).

In general, the cards have been written in ratios that reflect the high biological activity of the reduced forms of nitrogen (NH_4^+ and amino acids in plants, animals, and bacteria). Most students will spend several turns being interconverted between these molecules. Redox state changes of nitrification and denitrification may not be experienced by every student, but will usually be carried out by at least one student in each group. Still, because the possibility does exist that some groups will derive an incomplete nitrogen cycle based on their cumulative voyages, a class-wide discussion comparing the cycles generated by the different groups is usually beneficial.

Another aspect that should be brought up during class discussion is the limitation of certain portions of the nitrogen cycle to either aerobic environments (in the case of the classical nitrification reactions—i.e., lithotrophic processes other than the recently discovered anammox reactions) or anoxic environments (in the case of denitrification). Students who have already studied nitrogen fixation may point out that nitrogen fixation also requires an oxygen-free environment, although in this case, some nitrogen fixing bacteria are able to generate anoxic micro-environments in the midst of a larger, aerated environment.

In Appendices III, IV, and V, we provide 3 sample worksheets representing different assessment approaches that we have used with students.

- The first one is used as a group worksheet: on this, groups of 3 to 5 students essentially tally their data to derive the entire nitrogen cycle. This worksheet could be handed in for a grade and/or used as the basis of a class-wide summarative discussion about the nitrogen cycle. This worksheet can be adapted for any audience. Instructors may wish to add another step to the instructions for this worksheet: students could be asked to indicate with asterisks or different colored arrows any portions of the nitrogen cycle that occur strictly aerobically or strictly anaerobically.
- The second worksheet is an extension of the first. It requires that—once groups have derived the nitrogen cycle—students add the names of organisms and the specific reactions carried out. It introduces the multi-step nature of nitrification and denitrification. This worksheet is directed toward the biology or microbiology major.
- The third worksheet describes a creative writing assignment. Students hand in a record of their voyage as well as a prose essay describing their journey. This approach is particularly fun for some students who enjoy embellishing their story to give the nitrogen atom a personality. It provides a novel way to support writing within the science curriculum. Instructors can compare each step in the student's essay with their record of conversions in terms of scientific accuracy and completeness. This approach may hold most appeal for the non-majors audience.

Problems and Caveats.
Preparation time for this activity—if using the instruction cards included in Appendix I—requires approximately 30 minutes to print out and photocopy the cards, cut them apart, and put them at the appropriate stations. Alternatively, instructors may choose to modify or completely rewrite instruction cards for the various stations. For convenience, the instructions on the cards are summarized below, with numbers in parenthesis indicating the number of copies per station. For each 5 students in the class, a complete set of 140 cards is recommended (assuming ten to twelve turns for each student).

1. **Fifteen cards for station 1, Nitrogen gas (N_2(g))**

   You've been fixed into ammonium by a free-living, nitrogen-fixing bacterium. Within microseconds, you're converted to an amino acid. Go directly to BACTERIAL PROTEIN (but don't forget that you existed briefly as NH_4^+) (2)

   You've been fixed into ammonium by a symbiotic nitrogen-fixing bacterium. This symbiont (called a "bacteroid") is a nitrogen-fixing slave for the host plant. Go to BACTEROID AMMONIA (1)

   Lightning strike! Now you're reduced to ammonium. Go to NH_4^+ (1)

   Deep within the vats of a fertilizer factory, a lot of money is spent to reduce you to ammonium. Go to NH_4^+ (1)

   You're still atmospheric nitrogen gas, so don't go anywhere. Wait 10 seconds, then draw another card from the NITROGEN GAS station. (10)

2. **Fifteen cards for station 2, Ammonium (NH_4^+)**

   You are oxidized to provide energy to a lithotrophic bacterium as it respires. Go to NITRITE (5)

   You are taken up by a plant root and—within a plant cell—assimilated into an amino acid. Go directly to PLANT PROTEIN (5)

   You are taken up by a bacterial cell and assimilated into an amino acid. Go directly to BACTERIAL PROTEIN (5)

3. **Fifteen cards for station 3, Nitrate (NO_3^{-1})**

You are taken up by a plant root and—within a plant cell—assimilated into an amino acid. Go directly to PLANT PROTEIN (4)

You are taken up by a bacterial cell and are assimilated into an amino acid. Go directly to BACTERIAL PROTEIN (4)

A bacterium has used you as a terminal electron acceptor during respiration. This process reduces you to nitrite. Go to NITRITE. (3)

A bacterium has used you as a terminal electron acceptor during respiration. This process reduces you to nitrogen gas. Go to NITROGEN GAS (2)

You are in an environment without much biological activity, so stay here. Wait 10 seconds, then draw another card from the NITRATE station. (2)

4. **Fifteen cards for station 4, Nitrite (NO_2^{-1})**

   A lithotrophic bacterium has used you as an electron donor during respiration. This process oxidizes you to nitrate. Go to NITRATE (7)

   A bacterium has used you as a terminal electron acceptor during respiration. This process reduces you to nitrogen gas. Go to NITROGEN GAS (6)

   You've diffused into an environment without much biological activity, so stay here. Wait 10 seconds, then draw another card from the NITRITE station (2)

5. **Fifteen cards for station 5, Bacterial Protein**

   Uh, OH! You've just been ingested by some kind of microscopic animal. You're still an amino acid, but now...go to ANIMAL PROTEIN (7)

   Within the bacterial cytoplasm, amino acids are continually recycled. Decomposition of amino acids can liberate free ammonium. Go to NH_4^+ (4)

   Within the bacterial cytoplasm, amino acids are continually recycled as new proteins are needed, so don't go anywhere. Wait 10 seconds, then draw another card from the BACTERIAL PROTEIN station. (4)

6. **Fifteen cards for station 6, Plant Protein**

   Uh, OH! You've just been ingested by some kind of animal. You're still an amino acid, but now...go to ANIMAL PROTEIN (4)

   Uh, OH! The plant in which you reside has just died. Soil microorganisms move in, decompose the plant protein into amino acids, and liberate some ammonium in the process. Go to NH_4^+ (3)

   Uh, OH! The plant in which you reside has just died. Soil microorganisms move in to decompose the plant protein and use the amino acids for themselves. Go to BACTERIAL PROTEIN (4)

   Inside the plant cell, amino acids are continually recycled as new proteins are needed. So stay here, wait 10 seconds, then draw again from PLANT PROTEIN (4)

7. **Fifteen cards for station 7, Animal Protein**

   Animal cell metabolism has converted you into urine molecules, and you're excreted from the animal's body. Soil microorganisms quickly decompose you. Go directly to NH_4^+ (4)

   Uh, OH! The animal in which you reside has just died. Soil microorganisms decompose the dead proteins to amino acids, sometimes liberating ammonium. Go to NH_4^+ (2)

   Uh, OH! The animal in which you reside has just died. Soil microorganisms decompose the dead proteins to valuable amino acids which are quickly taken up by soil bacteria. Go to BACTERIAL PROTEIN (2)

   Uh, OH! The animal in which you reside has just been eaten by a bigger animal! After proteases in the animal's gut degrade you to amino acids, you're taken up by a gut bacterium! Within a few hours you find yourself as part of a smelly pile on the ground. Go to BACTERIAL PROTEIN (4)

   Uh, OH! The animal in which you reside has just been eaten by a bigger animal. Stay here because you're still within animal protein, but wait 10 seconds before drawing another card from ANIMAL PROTEIN. (3)

8. **Fifteen cards for station 8, Bacteroid Ammonia***

   You're quickly passed from the bacteroid to the host plant, where you're assimilated. Go to PLANT PROTEIN (15)

   * Note: The two forms, NH_4^+ (ammonium) and $NH_{3(g)}$ (ammonia gas) exist in equilibrium. If the pH is approximately neutral (or lower), virtually all of the molecule will be protonated, as its pK_a is 9.25. However, the small amount of NH_3 that exists at equilibrium represents a continual source of nitrogen loss for the cell, as $NH_{3(g)}$ readily diffuses through the cell membrane. In *The Voyage of the Nitrogen Atom*, station 8 is referred to as "Bacteroid Ammonia". This is partly to emphasize the diffusion of the fixed nitrogen from the bacteroid to the host

plant. It also is meant to avoid confusion and distinguish "Bacteroid Ammonia" from Station 2, "Ammonium, NH_4^+". However, within the bacteroid, NH_4^+ and NH_3 exist in equilibrium just as they do in any other cell, and station 8 could more accurately be called "Bacteroid NH_4^+".

The instructions on the cards presume that the students have some background knowledge about the processes of anaerobic respiration, lithotrophy, nitrogen fixation, protein synthesis, and decomposition. However, detailed information about each process is not necessary to interpret the cards.

When beginning the exercise, minimal instructions are required, other than pointing out the locations of the various stations. We have usually started the students at random stations, so that they were more or less evenly distributed throughout the room. If an instructor wished to suggest reality, s/he could assign appropriate numbers of students to start at each station according to the size of the natural pool (i.e., most students starting at N_2, several starting at plant, animal, bacterial protein, and bacteroid ammonia, with only a few at the oxidized forms). In this case, it will be necessary to scale up the numbers of cards at the former stations.

Most students enjoy this activity, participate fully, and express satisfaction with their learning of the concepts. Some students will voice frustration at the end of the activity that they spent most of the time as amino acids in one organism or another, or that they "got stuck" in the N_2 pool. Obviously, these frustrations make for eminently "teachable moments", as they provide the perfect springboard for a discussion about biologically active vs. inactive forms of nitrogen.

When using this activity as the basis for a creative writing assignment (see the worksheet example in Appendix V), instructors should be aware that students who happened to experience a journey in which they repeatedly visited the same stations may feel hard-pressed to write a strong essay (the good students can do it, " 'Oh, woe is me' the little di-nitrogen molecule cried, 'if only I could be fixed into ammonium by a nitrogen-fixing bacterium, what a contribution to the biological community I could make!'", etc., but other students will feel stifled by a lack of redox reactions, making the writing exercise very difficult for them). If using *The Voyage of the Nitrogen Atom* as a basis for a writing assignment , we recommend that one or two "idealized journeys" be supplied to the students so that they can choose to use these if their own journey happened to be too boring to write about.

SUPPLEMENTARY MATERIALS

Possible Modification.
Reusing the cards for several classes.
After students have completed the exercise, instructors may wish to have them return all cards for use in future classes. This can be made more expedient if the cards for the different stations are photocopied onto paper of different colors (i.e., all the "NH_4^+ station cards in one color; all the NO_3^- station cards in a second color, etc.). Students should be instructed to cross out any previous writing on the back of the card before recording their number. Lamination of the cards extends their lifetime—if laminated, water-based markers such as Vis-a-Vis pens can be placed near each station for quick numbering of the cards.

References.

1. **Madigan, M. T., J. M. Martinko, and J. Parker**. 1997. Brock Biology of Microorganisms, 8th Edition. Prentice-Hall, Inc. Upper Saddle River, N. J., USA. (chapter 14.4 provides extensive detail about global nitrogen cycling, while chapters 13.12, 13.15, 13.26-13.27, and 16.4 address various specific aspects of the microbiology of nitrogen metabolism.)
2. **Racz, M. Lucia and M. Ligia Carvalhal.** 1998. *Voyage of the Nitrogen Atom*. This Web site describes the *Voyage of the Nitrogen Atom* in Portuguese as used at the University of Sao Paulo, Brazil. Photos show a classroom set up for the activity.
3. **Vitousek, P. M., et.al.** 1997. Human alteration of the global nitrogen cycle: causes and consequences. *Issues in Ecology*, issue 1.

Appendices.

1. Appendix I: a complete set of instruction cards for eight stations (fifteen cards per station). For every five students in the class, photocopy one set.
2. Appendix I in PDF format
3. Appendix II: answers to the pre-activity questions in the students' portion of the write-up
4. Appendix III: a worksheet for groups of students to summarize their "journeys" and generate a nitrogen cycle
5. Appendix IV: a worksheet for groups of students to add names of organisms and reactions to their nitrogen cycle
6. Appendix V: a worksheet for a creative writing assignment based on a student's journey

User Feedback
"I just used the above resource last week in class. It was wonderful! We had gone over carbon and sulfur and neither I nor the students could take another set of cycles. Any chances you would create a similar exercise for carbon and sulfur! I would use them in a heart beat. The directions were very clear and I had no trouble using it in class. Thanks for putting this one together!"
- Beverly J. Brown, Nazareth College of Rochester, Biology Department, Rochester, NY

Appendix I: Fifteen cards for station 1, Nitrogen gas ($N_{2(g)}$)

You've been fixed into ammonium by a free-living, nitrogen-fixing bacterium. Within microseconds, you're converted to an amino acid. Go directly to BACTERIAL PROTEIN (but don't forget that you existed briefly as NH_4^+)	You've been fixed into ammonium by a free-living, nitrogen-fixing bacterium. Within microseconds, you're converted to an amino acid. Go directly to BACTERIAL PROTEIN (but don't forget that you existed briefly as NH_4^+)	You've been fixed into ammonium by a symbiotic nitrogen-fixing bacterium. This symbiont (called a "bacteroid") is a nitrogen-fixing slave for the host plant. Go to BACTEROID AMMONIA
Lightning strike! Now you're reduced to ammonium. Go to NH_4^+	Deep within the vats of a fertilizer factory, a lot of money is spent to reduce you to ammonium. Go to NH_4^+.	You're still atmospheric nitrogen gas, so don't go anywhere. Wait 10 seconds, then draw another card from the NITROGEN GAS station.
You're still atmospheric nitrogen gas, so don't go anywhere. Wait 10 seconds, then draw another card from the NITROGEN GAS station.	You're still atmospheric nitrogen gas, so don't go anywhere. Wait 10 seconds, then draw another card from the NITROGEN GAS station.	You're still atmospheric nitrogen gas, so don't go anywhere. Wait 10 seconds, then draw another card from the NITROGEN GAS station.
You're still atmospheric nitrogen gas, so don't go anywhere. Wait 10 seconds, then draw another card from the NITROGEN GAS station.	You're still atmospheric nitrogen gas, so don't go anywhere. Wait 10 seconds, then draw another card from the NITROGEN GAS station.	You're still atmospheric nitrogen gas, so don't go anywhere. Wait 10 seconds, then draw another card from the NITROGEN GAS station.
You're still atmospheric nitrogen gas, so don't go anywhere. Wait 10 seconds, then draw another card from the NITROGEN GAS station.	You're still atmospheric nitrogen gas, so don't go anywhere. Wait 10 seconds, then draw another card from the NITROGEN GAS station.	You're still atmospheric nitrogen gas, so don't go anywhere. Wait 10 seconds, then draw another card from the NITROGEN GAS station.

for each 5 students in the class, photocopy this page once

Appendix I: Fifteen cards for station 2, Ammonium (NH_4^+)

You are oxidized to provide energy to a lithotrophic bacterium as it respires. Go to NITRITE	You are oxidized to provide energy to a lithotrophic bacterium as it respires. Go to NITRITE	You are oxidized to provide energy to a lithotrophic bacterium as it respires. Go to NITRITE
You are oxidized to provide energy to a lithotrophic bacterium as it respires. Go to NITRITE	You are oxidized to provide energy to a lithotrophic bacterium as it respires. Go to NITRITE	You are taken up by a plant root and— within a plant cell—assimilated into an amino acid. Go directly to PLANT PROTEIN
You are taken up by a plant root and— within a plant cell—assimilated into an amino acid. Go directly to PLANT PROTEIN	You are taken up by a plant root and— within a plant cell—assimilated into an amino acid. Go directly to PLANT PROTEIN	You are taken up by a plant root and— within a plant cell—assimilated into an amino acid. Go directly to PLANT PROTEIN
You are taken up by a plant root and— within a plant cell—assimilated into an amino acid. Go directly to PLANT PROTEIN	You are taken up by a bacterial cell and assimilated into an amino acid. Go directly to BACTERIAL PROTEIN	You are taken up by a bacterial cell and assimilated into an amino acid. Go directly to BACTERIAL PROTEIN
You are taken up by a bacterial cell and assimilated into an amino acid. Go directly to BACTERIAL PROTEIN	You are taken up by a bacterial cell and assimilated into an amino acid. Go directly to BACTERIAL PROTEIN	You are taken up by a bacterial cell and assimilated into an amino acid. Go directly to BACTERIAL PROTEIN

for each 5 students in the class, photocopy this page once

Appendix I: Fifteen cards for station 3, Nitrate (NO_3^{-1})

You are taken up by a plant root and— within a plant cell— assimilated into an amino acid. Go directly to PLANT PROTEIN	You are taken up by a plant root and— within a plant cell— assimilated into an amino acid. Go directly to PLANT PROTEIN	You are taken up by a plant root and— within a plant cell— assimilated into an amino acid. Go directly to PLANT PROTEIN
You are taken up by a plant root and— within a plant cell— assimilated into an amino acid. Go directly to PLANT PROTEIN	You are taken up by a bacterial cell and are assimilated into an amino acid. Go directly to BACTERIAL PROTEIN	You are taken up by a bacterial cell and are assimilated into an amino acid. Go directly to BACTERIAL PROTEIN
You are taken up by a bacterial cell and are assimilated into an amino acid. Go directly to BACTERIAL PROTEIN	You are taken up by a bacterial cell and are assimilated into an amino acid. Go directly to BACTERIAL PROTEIN	A bacterium has used you as a terminal electron acceptor during respiration. This process reduces you to nitrite. Go to NITRITE.
A bacterium has used you as a terminal electron acceptor during respiration. This process reduces you to nitrite. Go to NITRITE.	A bacterium has used you as a terminal electron acceptor during respiration. This process reduces you to nitrite. Go to NITRITE.	A bacterium has used you as a terminal electron acceptor during respiration. This process reduces you to nitrogen gas. Go to NITROGEN GAS
A bacterium has used you as a terminal electron acceptor during respiration. This process reduces you to nitrogen gas. Go to NITROGEN GAS	You are in an environment without much biological activity, so stay here. Wait 10 seconds, then draw another card from the NITRATE station.	You are in an environment without much biological activity, so stay here. Wait 10 seconds, then draw another card from the NITRATE station.

for each 5 students in the class, photocopy this page once

Appendix I: Fifteen cards for station 4, Nitrite (NO_2^{-1})

A lithotrophic bacterium has used you as an electron donor during respiration. This process oxidizes you to nitrate. Go to NITRATE	A lithotrophic bacterium has used you as an electron donor during respiration. This process oxidizes you to nitrate. Go to NITRATE	A lithotrophic bacterium has used you as an electron donor during respiration. This process oxidizes you to nitrate. Go to NITRATE
A lithotrophic bacterium has used you as an electron donor during respiration. This process oxidizes you to nitrate. Go to NITRATE	A lithotrophic bacterium has used you as an electron donor during respiration. This process oxidizes you to nitrate. Go to NITRATE	A lithotrophic bacterium has used you as an electron donor during respiration. This process oxidizes you to nitrate. Go to NITRATE
A lithotrophic bacterium has used you as an electron donor during respiration. This process oxidizes you to nitrate. Go to NITRATE	A bacterium has used you as a terminal electron acceptor during respiration. This process reduces you to nitrogen gas. Go to NITROGEN GAS	A bacterium has used you as a terminal electron acceptor during respiration. This process reduces you to nitrogen gas. Go to NITROGEN GAS
A bacterium has used you as a terminal electron acceptor during respiration. This process reduces you to nitrogen gas. Go to NITROGEN GAS	A bacterium has used you as a terminal electron acceptor during respiration. This process reduces you to nitrogen gas. Go to NITROGEN GAS	A bacterium has used you as a terminal electron acceptor during respiration. This process reduces you to nitrogen gas. Go to NITROGEN GAS
A bacterium has used you as a terminal electron acceptor during respiration. This process reduces you to nitrogen gas. Go to NITROGEN GAS	You've diffused into an environment without much biological activity, so stay here. Wait 10 seconds, then draw another card from the NITRITE station	You've diffused into an environment without much biological activity, so stay here. Wait 10 seconds, then draw another card from the NITRITE station

for each 5 students in the class, photocopy this page once

Appendix I: Fifteen cards for station 5. Bacterial Protein

Uh, OH! You've just been ingested by some kind of microscopic animal. You're still an amino acid, but now...
...go to ANIMAL PROTEIN

Uh, OH! You've just been ingested by some kind of microscopic animal. You're still an amino acid, but now...
...go to ANIMAL PROTEIN

Uh, OH! You've just been ingested by some kind of microscopic animal. You're still an amino acid, but now...
...go to ANIMAL PROTEIN

Uh, OH! You've just been ingested by some kind of microscopic animal. You're still an amino acid, but now...
...go to ANIMAL PROTEIN

Uh, OH! You've just been ingested by some kind of microscopic animal. You're still an amino acid, but now...
...go to ANIMAL PROTEIN

Uh, OH! You've just been ingested by some kind of microscopic animal. You're still an amino acid, but now...
...go to ANIMAL PROTEIN

Uh, OH! You've just been ingested by some kind of microscopic animal. You're still an amino acid, but now...
...go to ANIMAL PROTEIN

Within the bacterial cytoplasm, amino acids are continually recycled. Decomposition of amino acids can liberate free ammonium.
Go to NH_4^+

Within the bacterial cytoplasm, amino acids are continually recycled. Decomposition of amino acids can liberate free ammonium.
Go to NH_4^+

Within the bacterial cytoplasm, amino acids are continually recycled. Decomposition of amino acids can liberate free ammonium.
Go to NH_4^+

Within the bacterial cytoplasm, amino acids are continually recycled. Decomposition of amino acids can liberate free ammonium.
Go to NH_4^+

Within the bacterial cytoplasm, amino acids are continually recycled as new proteins are needed, so don't go anywhere.
Wait 10 seconds, then draw another card from the BACTERIAL PROTEIN

Within the bacterial cytoplasm, amino acids are continually recycled as new proteins are needed, so don't go anywhere.
Wait 10 seconds, then draw another card from the BACTERIAL PROTEIN

Within the bacterial cytoplasm, amino acids are continually recycled as new proteins are needed, so don't go anywhere.
Wait 10 seconds, then draw another card from the BACTERIAL PROTEIN

Within the bacterial cytoplasm, amino acids are continually recycled as new proteins are needed, so don't go anywhere.
Wait 10 seconds, then draw another card from the BACTERIAL PROTEIN

for each 5 students in the class, photocopy this page once

Appendix I: Fifteen cards for station 6, Plant Protein

Uh, OH! You've just been ingested by some kind of animal. You're still an amino acid, but now...
...go to ANIMAL PROTEIN

Uh, OH! You've just been ingested by some kind of animal. You're still an amino acid, but now...
...go to ANIMAL PROTEIN

Uh, OH! You've just been ingested by some kind of animal. You're still an amino acid, but now...
...go to ANIMAL PROTEIN

Uh, OH! You've just been ingested by some kind of animal. You're still an amino acid, but now...
...go to ANIMAL PROTEIN

Uh, OH! The plant in which you reside has just died. Soil microorganisms move in, decompose the plant protein into amino acids, and liberate some ammonium in the process.
Go to NH_4^+

Uh, OH! The plant in which you reside has just died. Soil microorganisms move in, decompose the plant protein into amino acids, and liberate some ammonium in the process.
Go to NH_4^+

Uh, OH! The plant in which you reside has just died. Soil microorganisms move in, decompose the plant protein into amino acids, and liberate some ammonium in the process.
Go to NH_4^+

Uh, OH! The plant in which you reside has just died. Soil microorganisms move in to decompose the plant protein and use the amino acids for themselves.
Go to BACTERIAL PROTEIN

Uh, OH! The plant in which you reside has just died. Soil microorganisms move in to decompose the plant protein and use the amino acids for themselves.
Go to BACTERIAL PROTEIN

Uh, OH! The plant in which you reside has just died. Soil microorganisms move in to decompose the plant protein and use the amino acids for themselves.
Go to BACTERIAL PROTEIN

Uh, OH! The plant in which you reside has just died. Soil microorganisms move in to decompose the plant protein and use the amino acids for themselves.
Go to BACTERIAL PROTEIN

Inside the plant cell, amino acids are continually recycled as new proteins are needed.
So stay here, wait 10 seconds, then draw again from PLANT PROTEIN

Inside the plant cell, amino acids are continually recycled as new proteins are needed.
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Inside the plant cell, amino acids are continually recycled as new proteins are needed.
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Inside the plant cell, amino acids are continually recycled as new proteins are needed.
So stay here, wait 10 seconds, then draw again from PLANT PROTEIN

for each 5 students in the class, photocopy this page once

Appendix I: Fifteen cards for station 7, Animal Protein

Animal cell metabolism has converted you into urine molecules, and you're excreted from the animal's body. Soil microorganisms quickly decompose you. Go directly to NH_4^+	Animal cell metabolism has converted you into urine molecules, and you're excreted from the animal's body. Soil microorganisms quickly decompose you. Go directly to NH_4^+	Animal cell metabolism has converted you into urine molecules, and you're excreted from the animal's body. Soil microorganisms quickly decompose you. Go directly to NH_4^+
Animal cell metabolism has converted you into urine molecules, and you're excreted from the animal's body. Soil microorganisms quickly decompose you. Go directly to NH_4^+	Uh, OH! The animal in which you reside has just died. Soil microorganisms decompose the dead proteins to amino acids, sometimes liberating ammonium. Go to NH_4^+	Uh, OH! The animal in which you reside has just died. Soil microorganisms decompose the dead proteins to amino acids, sometimes liberating ammonium. Go to NH_4^+
Uh, OH! The animal in which you reside has just died. Soil microorganisms decompose the dead proteins to valuable amino acids which are quickly taken up by soil bacteria. Go to BACTERIAL PROTEIN	Uh, OH! The animal in which you reside has just died. Soil microorganisms decompose the dead proteins to valuable amino acids which are quickly taken up by soil bacteria. Go to BACTERIAL PROTEIN	Uh, OH! The animal in which you reside has just been eaten by a bigger animal! After proteases in the animal's gut degrade you to amino acids, you're taken up by a gut bacterium. Within a few hours you find yourself as part of a smelly pile on the ground. Go to BACTERIAL PROTEIN
Uh, OH! The animal in which you reside has just been eaten by a bigger animal! After proteases in the animal's gut degrade you to amino acids, you're taken up by a gut bacterium. Within a few hours you find yourself as part of a smelly pile on the ground. Go to BACTERIAL PROTEIN	Uh, OH! The animal in which you reside has just been eaten by a bigger animal! After proteases in the animal's gut degrade you to amino acids, you're taken up by a gut bacterium. Within a few hours you find yourself as part of a smelly pile on the ground. Go to BACTERIAL PROTEIN	Uh, OH! The animal in which you reside has just been eaten by a bigger animal! After proteases in the animal's gut degrade you to amino acids, you're taken up by a gut bacterium. Within a few hours you find yourself as part of a smelly pile on the ground. Go to BACTERIAL PROTEIN
Uh, OH! The animal in which you reside has just been eaten by a bigger animal. Stay here because you're still within an animal protein but... ...wait 10 seconds before drawing another card from ANIMAL PROTEIN	Uh, OH! The animal in which you reside has just been eaten by a bigger animal. Stay here because you're still within an animal protein but... ...wait 10 seconds before drawing another card from ANIMAL PROTEIN	Uh, OH! The animal in which you reside has just been eaten by a bigger animal. Stay here because you're still within an animal protein but... ...wait 10 seconds before drawing another card from ANIMAL PROTEIN

for each 5 students in the class, photocopy this page once

Curriculum Resources

Appendix II. Voyage of the Nitrogen Atom

Instructors' Answer Key:

- What is anaerobic respiration? *Production of ATP via a proton gradient and membrane-bound ATPase in which the final component in the electron transport chain transfers electrons to an electron acceptor other than oxygen.*

  What is the function of a nitrogenous compound in anaerobic respiration? *Several nitrogenous compounds (most commonly, NO_3^- and NO_2^-) act as electron acceptors.*

- What is lithotrophy? *Production of ATP via a proton gradient and a membrane-bound ATPase in which the source of the electrons is an inorganic molecule.*

  What is the function of a nitrogenous compound in lithotrophic processes? *Several nitrogenous compounds (most commonly, NH_4^+ and NO_2^-) act as electron donors.*

- What is nitrogen fixation? *The reduction of $N_{2(gas)}$ to ammonia that bacteria achieve through an input of ATP and reducing power.*

  Of what advantage to an organism is the process of nitrogen fixation? *Ammonia is necessary for amino acids, which are necessary for protein synthesis. Nitrogen-fixing bacteria have an advantage in natural environments where useful (reduced) nitrogen is limiting.*

- Name two examples of organic forms of nitrogen: *amino acids and bases (purines/pyrimidines of RNA and DNA); also: urea, some phospholipids, some vitamins, and various other biologically active compounds.*

  The conversion of organic to inorganic nitrogen is often called: *decomposition*

  The conversion of inorganic to organic nitrogen is often called: *assimilation*

Curriculum Resources

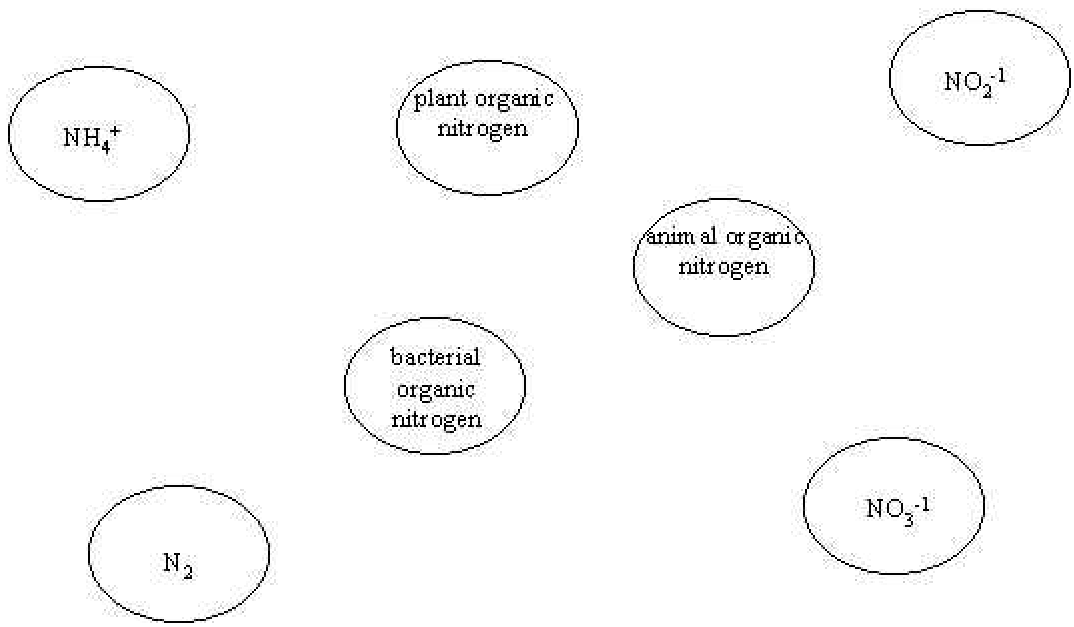
Appendix III: Voyage of the Nitrogen Atom

Nitrogen Cycle Worksheet

Names of group members:

Now that you have experienced the nitrogen cycle first hand and have spent a few minutes comparing your particular "voyage" with those taken by a few other students, answer the questions below:

1) Total the various transformations that people in your group experienced. On the diagram below, draw thick arrows for transformations that occurred frequently, and thin arrows for ones that were less frequent. For example, how many times were group members converted from $N_{2(g)}$ to NH_4^+? From NO_3^- to NO_2^- ? etc.



2) Considering all the group’s information together:

a) Which molecular form was visited most often?

b) Which molecular form(s) were slowest to change?

c) Which molecular form(s) turned over to a different form most rapidly?

d) Were there any molecular forms that no one in the group visited?

If so, what were they?

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Appendix IV: Voyage of the Nitrogen Atom

Nitrogen Cycle Worksheet, Part II

Once you and other group members have compiled a nitrogen cycle, assign each of the following microorganisms to the appropriate part of the cycle:

Process	Organism	From	To
Denitrification	*Pseudomonas* spp.	Nitrate (NO_3^-)	Nitrite (NO_2^-)
Denitrification	*Bacillus licheniformis*	Nitrite (NO_2^-)	Nitrous oxide (N_2O)
Denitrification	*Paracoccus denitrificans*	Nitrous oxide (N_2O)	Nitrogen gas (N_2)
Symbiotic nitrogen fixation	*Rhizobium* spp.	Nitrogen gas (N_2)	Ammonium (NH_4^+)
Symbiotic nitrogen fixation	*Bradyrhizobium* spp.	Nitrogen gas (N_2)	Ammonium (NH_4^+)
Free-living nitrogen fixation	*Beijerinckia* spp.	Nitrogen gas (N_2)	Ammonium (NH_4^+)
Free-living nitrogen fixation	*Cyanobacteria* spp.	Nitrogen gas (N_2)	Ammonium (NH_4^+)
Free-living nitrogen fixation	*Clostridium* spp.	Nitrogen gas (N_2)	Ammonium (NH_4^+)
Nitrification	*Nitrosomonas* spp.	Ammonium (NH_4^+)	Nitrite (NO_2^-)
Nitrification	*Nitrobacter* spp.	Nitrite (NO_2^-)	Nitrate (NO_3^-)
Decomposition	aerobic and anaerobic bacteria and fungi	protein	Ammonium (NH_4^+)

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Appendix V: Voyage of the Nitrogen Atom

Creative Writing and the Nitrogen Cycle

Fill in the chart below based on the information on your cards. Then write a prose story that describes your unique journey more fully (you may use the first person in your writing, if you choose). For full credit, be sure to include credible details such as the names of enzymes involved, specific names of organisms that express these enzymes, the benefit enjoyed by the organism in carrying out each process, where you were in the cell or the organism at the time of the conversion, and a description of the environment (or microenvironment) that the organism was living in at the time. For any given conversion step, some of these specific details will be more relevant than others.

Hand in both your essay and this page on the due date.

turn:	started turn as a molecule of:	what happened to me and by what organism/process during this turn?
1		
2		
3		
4		
5		
6		
7		

8		
9		
10		