Scoring Scheme Manual for the Structure And Motion of Matter (SAMM) Survey

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First, we would like to **thank you** for using the survey in your classrooms. We hope that you find it valuable in your teaching and welcome your feedback.

The goal of the scoring scheme is to evaluate students' implicit assumptions about several concepts tied to the particulate nature of matter model and use these assumptions to characterize students' mental model about diffusion.

INSTRUCTIONS

- **Overall Description**

The scoring scheme evaluates implicit assumptions students rely on when thinking about four fundamental concepts involved in understanding the particulate nature of matter model:

1) Structure of a substance (perfume),
2) Structure of medium (air),
3) Origin of perfume particles' motion, and
4) Trajectories of perfume particles.

For each of these four concepts, we have identified, based on pilot studies and prior research in this area, several levels of assumptions that students may have. For example, the concept of *Structure of a substance* has four levels: not coherent, macroscopic, macro/microscopic, and microscopic. The description of each of these levels in term of students' assumptions and the type of answers they will provide on the SAMM survey (i.e., the holistic version of the scoring scheme) is provided in this manual, starting on page 6 until page 14.

Students' answers are scored according to the presence or absence of indicators that are associated with each level. While these indicators can be found throughout several questions in the survey and are not necessarily associated with one specific question, the programmed Excel® spreadsheet version of the scoring scheme is designed so that you obtain the level describing students' assumptions on each of the four concepts by scoring each question of the survey separately.

For each question on the survey, you will be asked a list of questions for which you answer yes or no by checking the corresponding checkbox. The scoring scheme is programmed to use the answers to each of these yes/no questions to identify the presence or absence of indicators for each concept.

The score for each concept is then depicted at the top of the Excel file. The meaning of these scores is described in this manual, from page 6 to 14.

The Excel® Spreadsheet is then designed to use these scores to identify the potential mental model about diffusion that the student is using while answering the survey. The mental models diagnosed in the spreadsheet have been identified through a rigorous empirical study involving over 400 students from middle school to upper level science courses in college. However, the mental models identified within this population might not reflect all the mental models that students might develop. Therefore, the spreadsheet might give you the following mental model description "Not a model identified in our study". In this case, please look carefully at the student's survey to characterize his/her mental model of diffusion. The description of the five mental model identified is provided in this manual, starting page 16.

- **Using the Excel® file for the scoring scheme**

In order for the Excel® file to work, you will need to enable your macros. If you do not know if your macros are enabled, the file will let you know when you open it: if your macros are disabled, you will get a green screen that explains how to enable macros; if you get a page like Figure 2 below, then your macros are already enabled and you are ready to score.

The scoring scheme contains several sections:

- On the top left corner, **section A** in Figure 1 will present the scores the student has for each of the four concepts.
- **Section B** presents the mental model number and short description that the student is holding.
- **In section C**, "Possible entry problems", a message will let you know if all the data have been entered correctly. If the message as can be seen in Figure 1 section C shows, you will need to double check your data for missed questions or questions in which you checked both checkboxes (yes and no).
- **In section D**, you will be presented with a list of yes/no questions that relates to the student's answers to particular questions in the surveys. For example in Figure 1, we see that we first start scoring question 1a in the survey.

  In each yes/no question, we emphasize important aspects of the question by **bolding the font**; we also emphasize how we expect to see the answers on the surveys by using different verbs (bold and red): for example when we ask if the student "**writes**" a certain word in the answer, we are looking for that exact word; however, if we ask if the student "**explains**" or "**indicates**" an idea, we don't expect the exact words to be in the answer that the student wrote but that the idea is expressed.

  Finally, in order to clarify what we meant by some of the yes/no questions, we showed some examples of students' answers that would qualify as a "yes." In order to see these examples,

you may click on the button called "**Click here to see examples of 'yes' answers**" located on the right side of the question. Once you click this button, a new spreadsheet will open containing examples of "yes" answers (see Figure 2 for an example). Once you have seen the example, you can go back to the scoring scheme by clicking on the link in blue font at the top of the sheet.

- Once you are done scoring a survey, you can easily reset all the checkboxes by clicking the button at the top of the file (under section C) called "**Click here to reset the checkboxes**."

- If you want to save your scores and the way you answered to each question, choose option "print" from the 'File' menu of Excel® and choose "adobe" for the printer (you will need adobe professional for this). Saving it as a PDF document will take less memory. (Note: you could also print to a printer, but we highly recommend saving electronically so that you won't waste paper!)

Figure 1. Screen shot of the programmed Excel® version of the scoring scheme

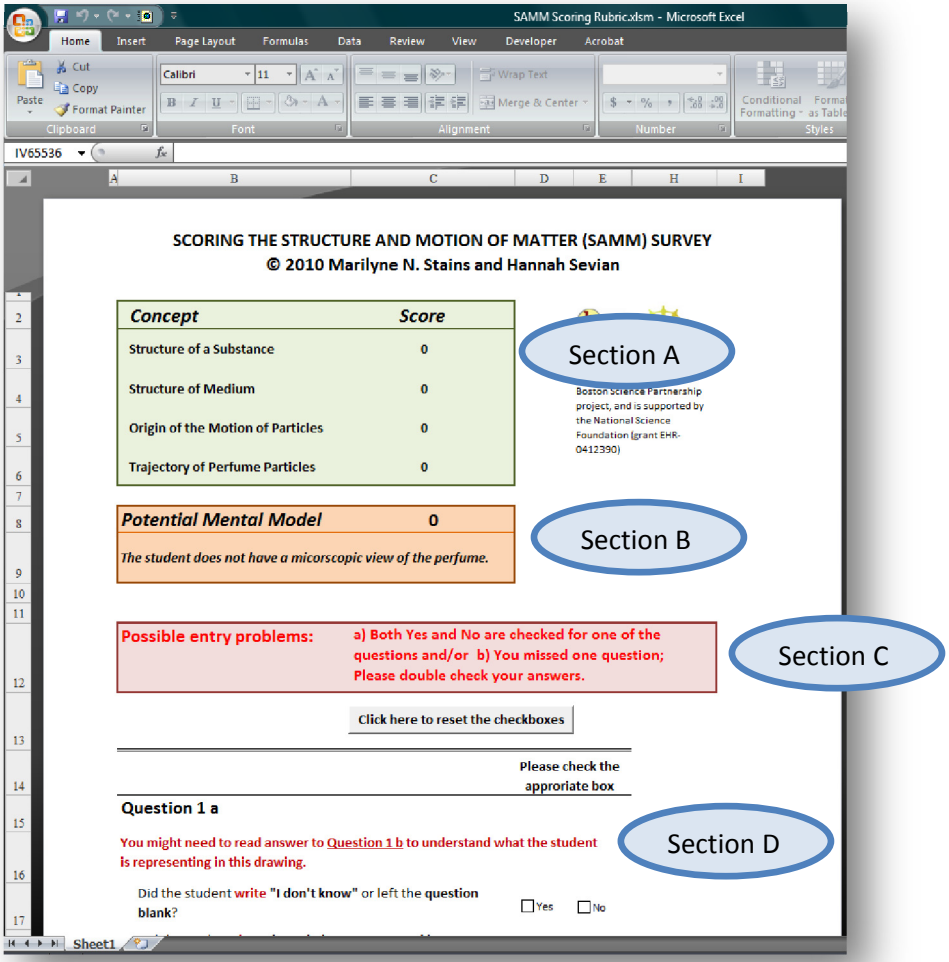
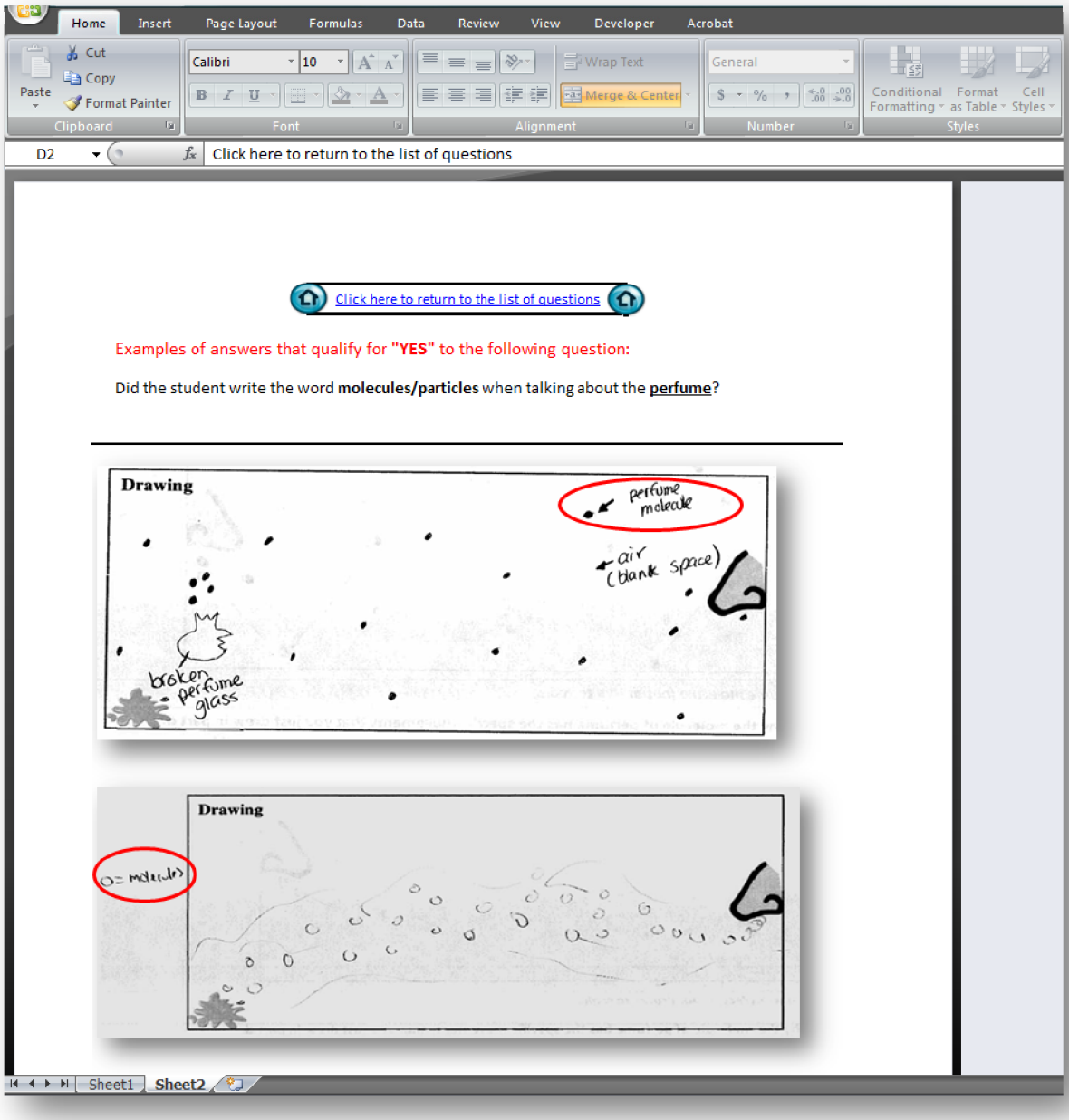


Figure 2. Screenshot of examples of "Yes" answers to the question: "Did the student label any parts of the drawing with the words molecule or particle when talking about the perfume?"



EXPERT ANSWERS

The survey was designed to diagnose a range of student assumptions about the particulate nature of matter. We designed the survey so that that expert chemists (Ph.D. level) score the highest on each concept and secondary students and even freshman science students in college will fall on average in the middle of the scheme, with wide variations from student to student.

A description of expert assumptions of the particulate nature of matter for each of the four concepts is provided below, along with a description of what experts' answers on the survey have been when we have administered the survey with them.

1) **Structure of a substance (perfume):** Matter is made of particles, which have voids between them. Experts draw circles or dots to represent the perfume particles in each drawing of the survey and talk about particles or molecules when describing the perfume's behavior.

2) **Structure of medium (air):** Matter is made of particles, which are separated by voids; air is matter and is thus particulate. Experts draw circles or dots to represent the air particles in each drawing of the survey which asks for a representation of air. They also talk about particles or molecules when describing the air. Some experts label air particles as oxygen (O_2) and nitrogen (N_2).

3) **Origin of the motion of particles:** Particles have kinetic energy and are therefore in constant motion, even in near-vacuum conditions. (The temperature of a sample of matter is a bulk property and is not the same as kinetic energy of individual particles; temperature is related to the average of the individual kinetic energies of all of the particles.) A particle's motion is an intrinsic property of the particle. Experts answer in question 1c that the origin of the perfume particles' motion is kinetic energy which is an intrinsic property of all molecules. Experts also explain that the consequence of this property is that molecules are always in motion. They also recognize the relationship between temperature, kinetic energy and speed of particles in question 2c: higher temperature of the sample corresponds to higher average kinetic energy of the particles due to greater average speed of the molecules.

4) **Trajectories of particles:** A particle moves in a straight line until it collides with another particle. Particle collisions result in the particles changing their directions of straight-line motion. Since the collisions between molecules are random, the trajectory of each molecule is completely random. Air flow does occur in bulk, such as convection currents that arise from temperature differentials in a large room. We don't explicitly ask about any of these, but experts do recognize that they occur and they sometimes write about them in the answer to this question on the survey because they are relevant. However, since this is not explicitly asked for in the survey, we leave it out of the scoring scheme. Experts try to illustrate random movement of the perfume (and air) molecules using random-walk like lines or traces; they do this in most drawings but especially in drawing in 1d. Also in 1d, experts show three types of collisions: between air particles and perfume particles, air-air particle collisions, and occasional perfume-perfume particle collisions. Some experts mention that air flow can influence the trajectories of perfume molecules.

CONCEPT 1: STRUCTURE OF A SUBSTANCE (worth a maximum of 3 pts)

This part of the scoring scheme helps evaluate student's assumptions about the structure of the perfume.

Score	0	1	2	3
Student's Assumption	**Not Coherent**	**Macroscopic:** Student thinks the perfume is continuous	**Macro/Microscopic:** Student inconsistently thinks of the perfume as continuous and as particulate	**Microscopic:** Student thinks of the perfume as particulate
Indicators	Student does not express any relevant information or the expression is so confusing as to be uninterpretable Student writes: "I don't know" Irrelevant answer Incomprehensible answer	Student **does not** draw dots or circles to represent the perfume **AND** **does not** write the word **molecules/particles** when talking about the perfume	Student **at least ONCE** draws dots or circles to represent the perfume **OR** **at least ONCE** writes the word "molecules" or "particles" when talking about the perfume	Student **at least ONCE** draws dots or circles to represent the perfume **AND** **at least ONCE** writes the word "molecules" or "particles" when talking about the perfume

CONCEPT 2: STRUCTURE OF MEDIUM (worth a maximum of 4 pts)

This part of the scoring scheme evaluates student's assumptions about the structure of the air in the room (i.e., the medium the perfume is in).

Score	0	1	2	3	4
Student's Assumption	**Not Coherent**	**Ignored/Absent:** Student never mentions or draws air	**Macroscopic:** Student assumes that the air is continuous	**Macro/Microscopic:** Student assumes that air is continuous sometimes and particulate at other times	**Microscopic:** Student assumes that air is particulate
Indicators	Student does not express any relevant information or the expression is so confusing as to be uninterpretable Student writes: "I don't know" Irrelevant answer Incomprehensible answer	Student **does not** draw air **AND** **does not** write any of the following words: air, air molecules, oxygen molecules	Student **does not** draw dots or circles to represent air (S/he might write air or N_2 or O_2 in the drawings) **AND** **does not** write any of the following words: air **molecules**, oxygen **molecules** **BUT** Writes/draws **air, oxygen, wind or breeze**.	Student **at least ONCE** draws dots or circles to represent air **OR** **at least ONCE** writes the words air **molecules**, oxygen **molecules**. **OR** **at least ONCE** implicitly refers to air as particulate using expressions such as **"other molecules"**, "other particles".	Student **at least ONCE** draws dots or circles to represent air **AND** **at least ONCE** writes the words air **molecules**, oxygen **molecules**. **OR** **at least ONCE** implicitly refers to air as particulate using expressions such as **"other molecules"**, "other particles".

CONCEPT 3: ORIGIN OF THE MOTION OF PARTICLES (worth a maximum of 5 pts)

This part of the scoring scheme assesses student's assumptions about the origin of the perfume particles' motion (i.e., why do the perfume molecules move?).

Score	0	1
Student's Assumption	**Not Coherent**	**Motion of molecules is caused by external forces:** Student assumes that external forces are the cause of particles movement
Indicators	Student does not express any relevant information or the expression is so confusing as to be uninterpretable Student writes: "I don't know" Irrelevant answer Incomprehensible answer	Student explains through drawings and/or words that **external forces/agents outside of the perfume molecules cause the perfume molecules to move.** *Possible types of external forces (*any of the following; *this list is not inclusive) - usually found in answers to question 1c*: - **air current, wind**: student draws fans, windows, circular motion in the room, and/or writes that temperature makes the AIR molecules go faster and therefore the perfume moves faster - **inhaling/breathing:** student explains that inhaling air through the nose attracts the molecules and thus makes them move toward the nose - **diffusion**: diffusion is considered as a force that pushes molecules from one area of the room to another - **difference in concentration**: student writes that molecules need/have to go from an area of higher concentration to an area of lower concentration - **lack of containment AND external forces involvement**: student writes that since perfume molecules are not confined to the perfume bottle they can move because they are picked up by the air - **Heat is considered as a force:** student writes that heat puts pressure on the molecules *Types of agents (*any of the following; *this list is not inclusive) - usually found in answers to question 1c*: - **Other molecules:** collisions with other molecules push the perfume molecules (similar to Air Hockey where the air molecules are your hand) **OR** collisions with other molecules give energy to the perfume molecules to move **OR** Student writes in 1c that motion comes from kinetic energy but fails to explicitly recognize the relationship between kinetic energy and speed of molecules

Descriptions of scores 2 and 3 on the next page

Score	2	3
Student's Assumption	**Molecules' motion is conditioned by certain properties or features of the substance but external forces are the main agent of movement:** Student recognizes implicitly that molecules move but still mentions an external force as the cause of movement	**Molecules' motion is conditioned by certain properties or features of the substance**: Student expresses the idea that molecules move by themselves but does not explicitly say that they are in constant motion
Indicators	Student states **explicitly** that **external forces/agents outside of the perfume molecules cause them to move** (see score 1 for examples of external forces) **AND** **implicitly** recognizes that the **molecules of perfume move by themselves** by (any of the following; *this list is not inclusive*): - writing in 2c that an **increase in temperature or higher temperatures** results in <u>higher kinetic energy</u> and/or increase in the <u>speed of the perfume molecules</u> - saying that molecules takes longer to go through <u>dense air.</u> - writing in 3c that molecules <u>with less mass</u> move faster **OR** explains (usually in question 1c) that molecules move **because** of some **properties/ features** of the substance. <u>*Possible Features*</u> *(*any of the following; *this list is not inclusive):* - molecules are in the **gas phase** - molecules have certain **atoms** that allows them to move - molecules have something **within/about themselves** that makes them move (size, electrons, weight, size, etc.) - molecules have a **natural tendency/want** to move - phase change (vaporization) causes the molecules to move **AND** **does not explicitly** say that molecules are in constant motion	Student **explicitly** recognizes that the **molecules of perfume move by themselves** by *(*any of the following; *this list is not inclusive):* - writing that **perfume molecules move** in several questions - writing in 2c that an **increase in temperature or higher temperatures** results in <u>higher kinetic energy</u> and/or increase in the <u>speed of the perfume molecules</u> - writing in 3c that molecules <u>with less mass</u> move faster **AND** explains (usually in question 1c) that molecules move **because** of some **properties/ features** of the substance (see score 2 for examples of features). **AND** **does not explicitly** say that molecules are in **constant motion**.

Descriptions of scores 4 and 5 on the next page

CONCEPT 3: ORIGIN OF THE MOTION OF PARTICLES (worth a maximum of 5 pts)

Score	4	5
Student's Assumption	**Molecules' motion is conditioned by certain properties or features of the substance** **AND** **Molecules are always in motion**	**Molecules are always in motion**: Student explicitly recognizes that molecules' motion is an intrinsic property of the molecules
Indicators	Student **explicitly** recognizes that the **molecules of perfume move by themselves** by *(*any of the following; *this list is not inclusive):* - writing that **perfume molecules move** in several questions - writing in 2c that an **increase in temperature or higher temperatures** results in <u>higher kinetic energy</u> and/or increase in the <u>speed of the perfume molecules</u> - writing in 3c that molecules <u>with less mass</u> move faster **AND** explains (usually in question 1c) that molecules move **because** of some **properties/ features** of the substance (see score 2 for examples of features). **AND** **explicitly** says that molecules are in **constant motion**.	Student **explicitly** recognizes that the **molecules of perfume move by themselves** by (any of the following; *this list is not inclusive*): - writing in 2c that an **increase in temperature or higher temperatures** results in <u>higher kinetic energy</u> and/or increase in the <u>speed of the perfume molecules</u> - writing in 3c that molecules <u>with less mass</u> move faster **AND** **explicitly** says that molecules are in **<u>constant motion</u>** **BUT** **<u>does not</u>** think that molecules move **because** of some **properties/ features** of the substance (see score 2 for examples of features).

CONCEPT 4: TRAJECTORY OF PERFUME PARTICLES (worth a maximum of 9 pts)

This scoring scheme assesses students' assumptions about the trajectory the perfume particles follow (i.e., how do the molecules move?).

Score	0	1	2	3
Student's Assumption	**Not Coherent**	**Perfume particles <u>do not move</u> by themselves;** **The air <u>controls</u> their trajectory**	**Perfume particles <u>move</u>;** **The air <u>controls</u> their trajectory**	**Perfume particles <u>move</u> but it's not clear how;** **The air might <u>influence</u> the trajectory**
Indicators	Student does not express any relevant information or the expression is so confusing as to be uninterpretable Student writes: "I don't know" Irrelevant answer Incomprehensible answer Student writes indicators that fall both in level 1 or 2 and level 9	Student states that **without air or external forces** perfume **molecules would not move**. **AND/OR** student **does not say anywhere** that the perfume **molecules move** (in 2c for example, does not say that higher temperature will make the <u>perfume</u> molecules move faster) **AND/OR** **only** talks about the **movement of perfume molecules <u>in terms of air movement</u>** (any of the following; *this list is not inclusive*): - perfume molecules **<u>bond to air</u>** molecules which then carry them around the room - **<u>air molecules are warmer</u>** so they move faster and thus move the perfume particles faster	Student **explicitly** recognizes that the **molecules of perfume move by themselves** (see Origin of motion (Concept 3) score 2 for indicators) **AND** says that the **air or outside forces <u>controls</u> where the perfume molecules go** (any of the following; *this list is not inclusive*): - writes that wind, breeze or air current **<u>controls/ guides</u>** the trajectory of the perfume molecules to the nose - writes that perfume **<u>molecules float in/on air</u>** - mentions that **<u>inhaling</u>** attract molecules	Student **explicitly** recognizes that the **molecules of perfume move by themselves** (see Origin of motion (Concept 3) score 2 for indicators) **AND** **does not explain clearly <u>HOW</u>** the perfume molecules move (any of the following; *this list is not inclusive*): - draws **straight line**(s) from spill to nose - **does not clearly draw** collisions with molecules or objects, random motion, radiation outward - writes the molecules of perfume go **from high to low concentration areas** - shows molecules **moving along the floor** and rise once close to the nose - write that molecules **goes in all directions but provides no indication of how**. **AND MIGHT** mention that **air, air current, breeze, or wind <u>influences</u>** (not controls; e.g. "helps") the **trajectory** of the perfume particles

Descriptions of scores 4, 5, 6 and 7 on the next page

Disclaimer: the questions only ask about particles that successfully arrive at the nose so it is not possible to tell if students understand that some particles do not get to the nose.

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CONCEPT 4: TRAJECTORY OF PERFUME PARTICLES (worth a maximum of 9 pts)

Score	4	5	6	7
Student's Assumption	**Perfume particles collide or avoid macroscopic obstacles ;** **The air might influence the trajectory**	**The perfume radiates outward from the spill;** **The air might influence the trajectory**	**The perfume molecules collide with other molecules** **BUT** **The air controls the trajectory**	**The trajectory is random;** **The air might influence the trajectory**
Indicators	Student draws/writes about (any of the following; *this list is not inclusive*): - different **density of air** in question 2c and perfume molecules moving around the air "mass", or - collisions with **walls or other macroscopic objects** **AND MIGHT** mention that **air, air current, breeze, or wind influences** (not controls) the **trajectory** of the perfume particles.	Student draws molecules **radiating outward in all directions** (straight lines going in all directions like sun rays) **AND MIGHT** mention that **air, air current, breeze, or wind influences** (not controls) the **trajectory** of the perfume particles.	Student **draws or writes about collisions** with other perfume and/or air **molecules in the context of explaining where/ how** the molecules move around the room **AND** says that the **air or outside forces controls where the perfume molecules go** (any of the following; *this list is not inclusive*): - writes that wind, breeze or air current **controls/ guides** the trajectory of the perfume molecules to the nose - writes that perfume **molecules float in/on air** - mentions that **inhaling** attract molecules	Student draws molecules moving randomly **without collisions with air or other particles** (any of the following; *this list is not inclusive*): - draws **wiggly,** random-walk lines (**NO** straight lines) - draws perfume molecules moving **randomly around air molecules** - writes that there is **no specific destination/ direction** - writes that the molecules **eventually** make it to the nose **AND MIGHT** mention that **air, air current, breeze, or wind influences** (not controls) the **trajectory** of the perfume particles

Descriptions of scores 8 and 9 on the next page

Disclaimer: the questions only ask about particles that successfully arrive at the nose so it is not possible to tell if students understand that some particles do not get to the nose.

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CONCEPT 4: TRAJECTORY OF PERFUME PARTICLES (worth a maximum of 9 pts)

Score	8	9
Student's Assumption	**The trajectory is based on collisions with air molecules; however the <u>air molecules provide the force/energy</u> for the perfume molecules to move**	**The trajectory is based on <u>random collisions with other microscopic objects</u>;** **The air might <u>influence</u> the trajectory**
Indicators	Student **draws or writes about collisions** with **air molecules** **AND** write that the **air molecules push the perfume molecules** (similar to Air Hockey where the air molecules are your hand) **OR** write that **perfume molecules get energy from air molecules** when they touch or collide with them	Student **draws or writes about collisions** with other perfume and/or air **molecules in the context of explaining where/ how** the molecules move around the room (*<u>not only</u> in the context of the hot room*) **AND MIGHT** mention that **air, air current, breeze, or wind <u>influences</u>** (not controls) the **trajectory** of the perfume particles

Disclaimer: the questions only ask about particles that successfully arrive at the nose so it is not possible to tell if students understand that some particles do not get to the nose.

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SCORING SUMMARY FOR THE SAMM SURVEY

Student's Name: _____ **Score:** _____/21

Concept	Student's Assumption	Score	Comments
1 Structure of a Substance	Not Coherent	**0**	
	Macroscopic	**1**	
	Macro/Microscopic	**2**	
	Microscopic	**3**	
2 Structure of Medium	Not Coherent	**0**	
	Ignored/Absent	**1**	
	Macroscopic	**2**	
	Macro/Microscopic	**3**	
	Microscopic	**4**	
3 Origin of the Motion of Particles	Not Coherent	**0**	
	Motion of molecules is caused by external forces	**1**	
	Molecules' motion is conditioned by certain properties or features of the substance but external forces are the main agent of movement	**2**	
	Molecules' motion is conditioned by certain properties or features of the substance	**3**	
	Molecules' motion is conditioned by certain properties or features of the substance AND molecules are always in motion	**4**	
	Molecules are always in motion	**5**	
4 Trajectories of Perfume Particles	Not Coherent	**0**	
	Perfume particles do not move by themselves; The air controls their trajectory	**1**	
	Perfume particles move; The air controls their trajectory	**2**	
	Perfume particles move but it's not clear how; The air might influence the trajectory	**3**	
	Perfume particles collide or avoid macroscopic obstacles; The air might influence the trajectory	**4**	
	The perfume radiates outward from the spill; The air might influence the trajectory	**5**	
	The perfume molecules collide with other molecules BUT the air controls the trajectory	**6**	
	The trajectory is random; The air might influence the trajectory	**7**	
	The trajectory is based on collisions with air molecules; however the air molecules provide the force/energy for the perfume molecules to move	**8**	
	The trajectory is based on random collisions with other microscopic objects; The air might influence the trajectory	**9**	

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Mental Model 1: The process of diffusion is unclear.

Students holding this mental model seem to view particles of perfume as immersed in the air and are confused about the dynamics taking place during diffusion. The majority of these students describe air macroscopically. Most students holding this mental model are unable to explain the origin of motion of perfume particles and the trajectory that the perfume molecules follow.

Mental Model 2: Diffusion is a direct process, in which air causes and controls perfume molecules' movement.

Students holding this mental model describe diffusion as a direct process, in which air is the active agent and perfume particles are passive, inanimate agents. Air can be considered as continuous and consistently or inconsistently as particulate. Regardless of their assumption about air, the majority of students who built this model assume that air causes and controls the movement of the perfume molecules. Analysis of answers to the surveys collected showed that students conceptualize this causation in different ways. The majority of students attributed the cause of movement to wind, air circulation, or air current. Few others thought that the perfume molecules formed bond(s) with air molecules and subsequently traveled with the air molecules. It is important to note that questions in the survey do not address the issue of air circulation in the room. Students are provided with the following scenario: "Imagine that someone breaks a glass of perfume on one side of a room and that you are standing on the other side of the room." The questions ask students to describe "how the molecules move from the spill to your nose"; in questions 1d, 2 and 3, we ask them to "Please make sure to also represent the AIR in the room". Students' assumption of air movement is thus part of their mental model.

Mental model 3: Diffusion is a direct process, in which air controls perfume molecules' movement.

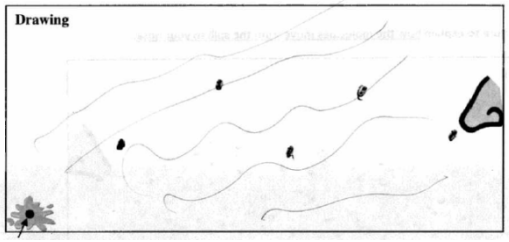
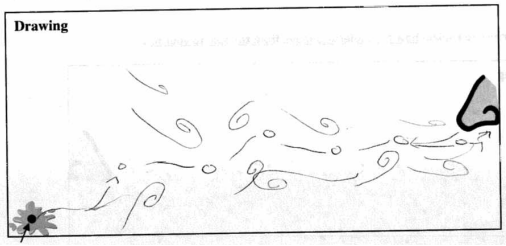
Students holding this mental model explain diffusion as a direct process in which the force of air overcomes the independent movement of perfume molecules and enables their dispersion through the room. Indeed, students' explanations still show air, which is thought by the majority of students as macroscopic, as the main agent of the diffusion process. Air is seen as a controlling factor, a facilitator ("molecules are pushed") rather than a cause of motion as in Mental Model 2 ("[air] movement will carry perfume molecules"). Indeed, all students recognize the independent movement of perfume molecules contrary to students holding Mental Model 2. Some students explain that molecules of perfume can move by themselves because of some characteristics of the molecules such as electrons, state of matter, or the presence of certain atoms. Other students implicitly recognize particles' independent motion by describing changes in the perfume molecules' speed based on the temperature of the environment. However, each of these students attributes air as the cause of the diffusion process.

Mental model 4: Diffusion occurs through random motion.

Students holding this model seem to recognize the randomness of the process but have difficulty explaining its origin. Students, in general, describe air at the particulate level. In our study, almost half of the students describe the origin of motion in a variety of ways, while over a third cannot explain it. For example, one of the high school chemistry honor students assumes that the state of matter of the perfume is the cause of motion, while one of the middle school students cannot provide a clear reason. However, most of the students holding this model describe the trajectory of the perfume particles through the room as random.

Mental model 5: Diffusion is an emergent process.

This is the most scientifically sound model that was identified in our study. Students holding this model recognize that diffusion occurs through random collisions between perfume and air molecules. Over two-third of the students holding this model describes air at the particulate level; none describe it at the macroscopic level consistently. Students explain that diffusion occurs through random collisions between air and perfume particles and thus recognize the emergent nature of the process. However, students holding this model still do not recognize motion as an intrinsic property of molecules, i.e. molecules are always in motion due to their kinetic energy. For example, a middle school student attributed the cause of motion to collisions with other molecules: molecules move because they are being propelled when colliding with other molecules.

Mental Model	Description	Cognitive Constraints		Example
		Structure	Dynamics	
1	The process of diffusion is unclear	Embedding	Unclear	 "The molecules move around" AP-CHEM-O-14
2	Diffusion is a direct process, in which air pushes perfume molecules	Embedding or Vacuum	Causal-dynamic	 "The molecules' ability to move comes from the air moving; The molecule has those specific movements because of the direction the air is traveling" HS CHEM O F P5 2

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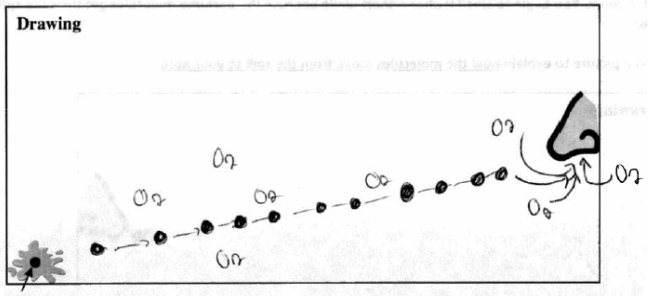
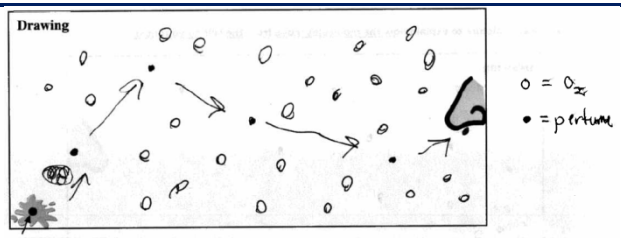
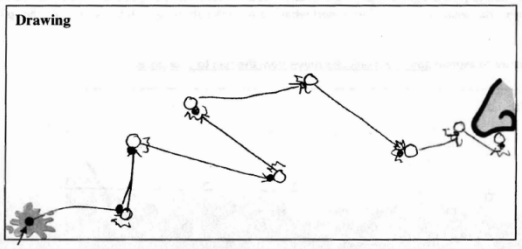
3	Diffusion is a direct process, in which air controls perfume molecules' movement	Embedding	Causal-dynamic and contingent-dynamic	**c. Use words to explain where the molecules' ability to move comes from.** The ability for the molecule to move comes from gravity and the atoms that make up the perfume  *One perfume molecule (not drawn to scale)* **e. Explain why the molecule of perfume has the specific movements that you just drew in part d.** because oxygen is being sucked up by my nose in that direction. if there were a fan blowing the molecule the opposite way then the molecule wouldn't get to my nose
4	Diffusion occurs through random motion	Embedding or vacuum	Causal-dynamic or contingent-dynamic	 *One perfume molecule (not drawn to scale)* "Potential energy within the molecule [cause the molecules to move]; The movement of the molecules is random" UMB-BIO338-8

5	Diffusion is an emergent process	Vacuum	Causal-dynamic or Contingent-dynamic	**c. Use words to explain where the molecules' ability to move comes from.** The movement of the molecules rest in the "bouncing off" of air molecules **Drawing**  *One perfume molecule (not drawn to scale)* "The scent molecules bounce off the air molecules" MS-BLA-6