

Draft
SYSTEM SCHEMAS

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A later, similar version was published in *The Physics Teacher* magazine in October 2003

In studying Newton's Laws most teachers expect their students to be able to construct a free-body diagram which shows each of the forces that act on an object whose motion they want students to analyze. However, many students frequently cannot identify the correct number of forces that act on the object, or, having decided that a particular force should be added to the diagram, they cannot accurately identify what object exerts that force. In addition, many students have difficulty implementing Newton's Third Law and correctly identifying action-reaction pairs of forces as well as internal and external forces. In general students do not have an organized process for creating an abstract free-body diagram given a concrete physical situation. They make educated guesses without any way of knowing if what they have done is correct. The purpose of this article is to describe a tool that has been found to be valuable in helping students address each of these problems.

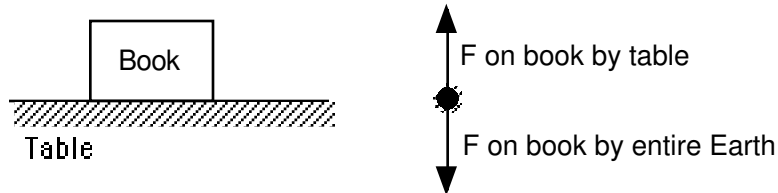


Figure 1

In taking classes through dynamics, at some point we physics teachers commonly ask our students to draw a free-body diagram for simple situations like a book at rest on a table. Nearly all of our students will draw the forces shown in Figure 1, and they will correctly identify the body that exerts each force.

When we ask our students to tell us the reaction force associated with the force that the entire earth exerts on the book, nearly all of our students will incorrectly tell us that the force that the table exerts on the book is the reaction force required by Newton's Third Law. Student reasoning seldom goes beyond noting that it is equal in magnitude and opposite in direction to force on the book by the entire earth.

A tool called a "system schema" has been developed to help students correctly name the reaction force in this situation as well as to solve the additional problems students have in more complicated situations. In order to apply Newton's laws, students must be able to construct free-body diagrams. I and many colleagues find that students who carefully use system schemas are capable of correctly describing and analyzing the structure of a physical system in terms of the objects in the system and the interactions between them and other bodies outside the system.

In an e-mail to me, Glenn Wagner, a physics teacher at Centre Wellington District High School near Toronto, said, "System schemas are probably the most powerful learning tool I have given my students. Before system schemas, I never really taught students how to think about drawing a free-body diagram. By cross-checking between the schema and the free-body diagram, they can KNOW that they have found all of the forces."

Before asking a student to create a system schema for a given physical situation, it is important that the following ideas be discussed.

- 1) The concept of an interaction between two objects, and that, in an interaction, each object exerts a force on the other.
- 2) A discussion of the basic forces that the student will likely encounter in the course (perhaps even having the students create a catalog of forces).
- 3) Most interactions occur only when two bodies touch one another. For such interactions, no contact means no forces. A few interactions can produce forces when there is no contact between bodies. Gravitational and electrical interactions are examples of these forces.
- 4) When a body is on a surface, the surface can exert a maximum of two forces on the body--a normal force that acts perpendicular to the surface and a frictional force that acts tangent to the surface.
- 4) Newton's first law must be discussed. Students need to know that an object in constant velocity must have the vector sum of all forces add to zero. ($\sum F_x = 0$, $\sum F_y = 0$)
- 6) In dynamics, the system is the object or objects whose motion one is interested in analyzing.

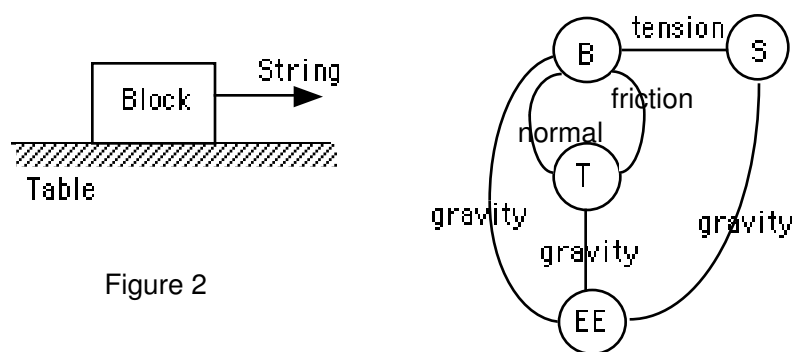


Figure 2

Drawing a circle to represent each of the bodies whose motion the student is interested in analyzing begins a system schema. Additional circles are then added to the schema to represent other bodies that interact with the bodies of interest. The student should name each body in the schema and place an appropriate symbol inside each circle to identify which body it represents. For example, Figure 2 shows a block on a table being pulled at constant speed to the right by a string. The corresponding system schema is shown to the right in figure 2. The lines drawn between two circles represent the fact that these bodies interact with each other. Whenever an interaction line ends on a circle, this means that the body represented by that circle experiences a force that is exerted by the body at the other end of the line. For example, the interaction line between the block (B) and the string (S) means that the string exerts a force on the block. Since this line also touches the circle representing the string, the line also means that the block exerts a force on the string. Hence a schema graphically reinforces the notion that, in an interaction between two objects, there are always two forces. In addition, the two forces associated with an interaction line are an action-reaction pair.

Note that no interaction line is drawn between the circles representing the string and the table. This is because the string does not exert a force on the table. That is, the string and the table do not interact. (Gravitational forces between all laboratory size objects are conveniently ignored because their masses are so small compared to the mass of the Earth.) As indicated in Figure 2, we also ask our students to identify the type of force that each line represents. Arrowheads should be added to the lines where they touch a circle to emphasize that forces are vector quantities.

Since the block moves with constant velocity, in addition to the normal force exerted by the table on the block, the student must be able to use Newton's First Law to recognize that a frictional force must act on the block to balance the force exerted by the string on the block.

The Entire Earth (EE) does not touch the block but it exerts an action-at-a-distance force on it. The word "Entire" is used here to distinguish between the gravitational force exerted by the Earth and the direct contact force exerted by the Earth on any object that touches its surface. If a teacher wishes to emphasize visually the difference between direct contact forces and action-at-a-distance forces, students can use dashed lines to represent gravitational interactions in the system schema.

Since the schema shows four lines connected to the block, the student knows there are four forces acting on the block--three direct contact forces and one action-at-a-distance force. It is also easy to see that one force is exerted on the block by the string, the table exerts two forces, and the entire Earth is responsible for the last force.

Two-body Problems

The next example further illustrates the value of a system schema. Two blocks are on a table, one on top of the other, as shown in Figure 3 below. A string is attached to the bottom block, and a force is applied so that the blocks move with a constant acceleration. The top block does not slide relative to the block on which it rests. The corresponding system schema for this situation is constructed using the same process as before and is shown in Figure 3.

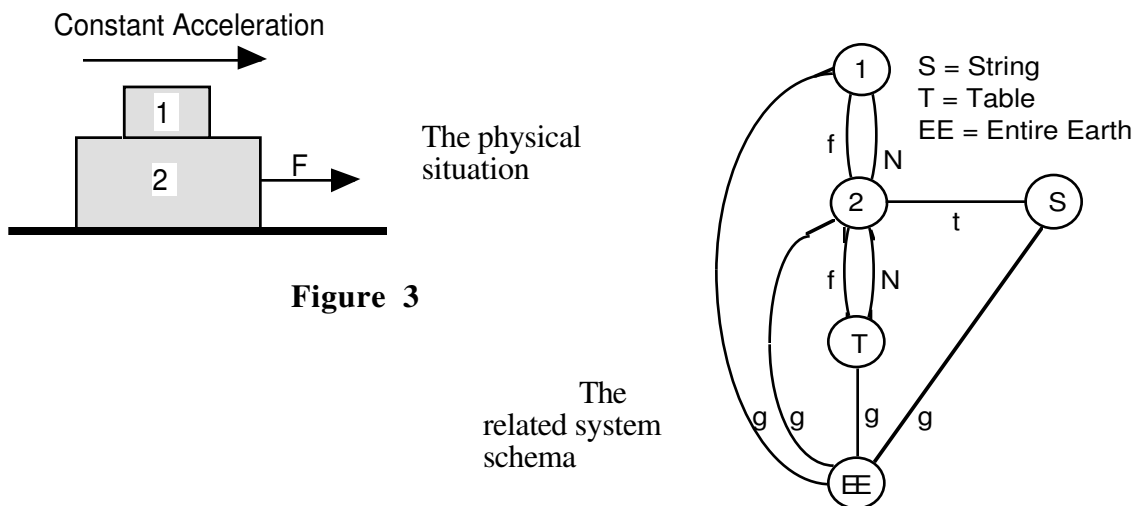
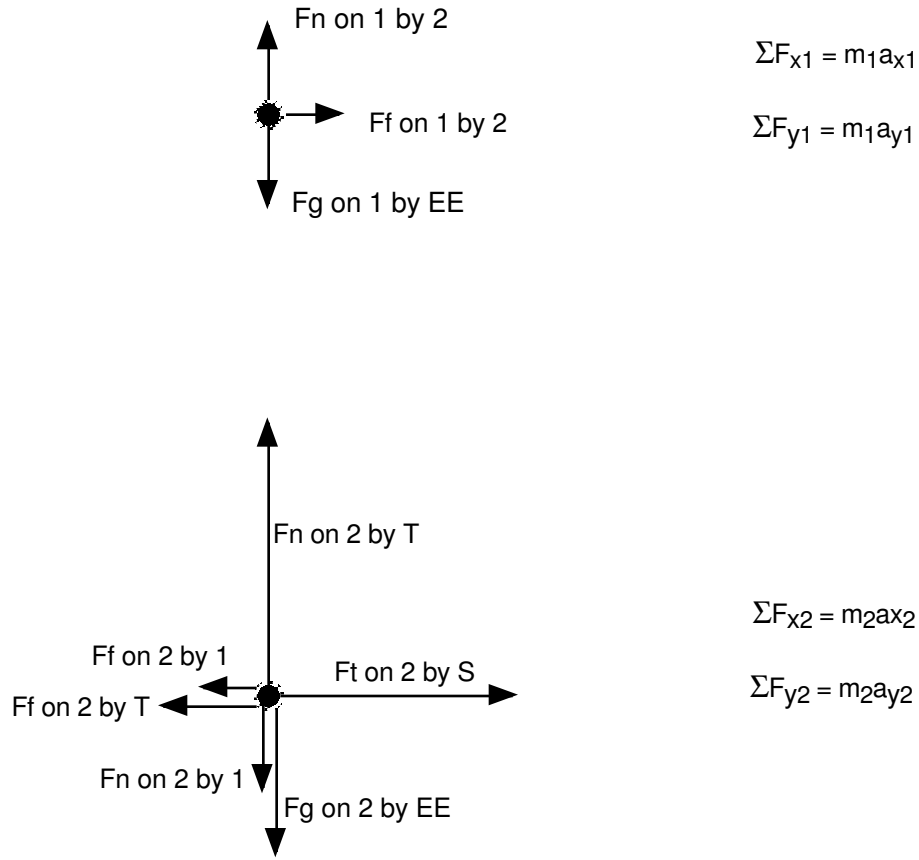


Figure 3

The student needs to determine that the lower block must exert a friction force on the top block if the top block is to move. The schema then clearly shows that the top block has three forces acting on it—two exerted by the table and one by the entire Earth. Similarly, the bottom block must have six forces acting on it assuming there is friction between it and the table. Without a system schema, students are less able to realize that the top block exerts two forces on the bottom block.

Using the system schema, students should be able to construct the free-body diagram shown below in Figure 4. They can then use the free-body diagram to write Newton's second law for each body.



The free-body diagram

Newton's second law

Figure 4

Note that each step in the process takes students to a greater level of abstraction in a way that is designed to minimize errors. A system schema provides a needed bridge linking the concrete physical situation and the abstract free-body diagram. Indeed, system schemas in mechanics may be thought of as the analogy to circuit diagrams in electronics or chemical bond diagrams in chemistry.

The direction of the friction force on body 1 by body 2 can be a problem for many students because they usually remember only that a friction force opposes the motion of an object. They forget that a friction force opposes the motion of an object relative to the surface on which it rests. If students have this problem, ask them to describe the motion of body 1 if there is no friction between it and body 2.

Dr. Michael Politano, Assistant Professor of Physics at Marquette University in Milwaukee, has found that in the more complex situation shown in Figure 5, where students were asked to find the acceleration of the blocks, the only students who achieved a successful solution were those who first drew a system schema.

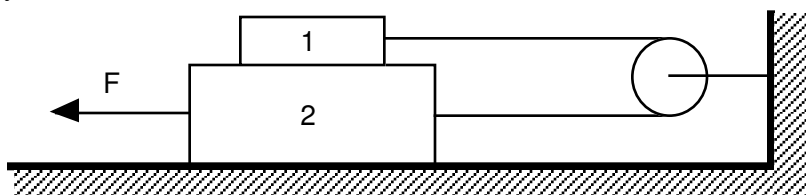


Figure 5. A challenge problem. The two blocks slide in opposite

directions

System schemas also provide clarity when discussing internal and external forces and Newton's third law. Our last example illustrates this point. Figure 6 shows the system schema for the physical situation in Figure 3. A rectangle has been added to define the specific system of objects whose motion we are interested in analyzing. The rectangle divides the objects inside the system from those that are outside the system. (It is a good idea to have students always identify the system with such a rectangle or circle to emphasize the forces that act only on the bodies whose motion they wish to analyze.) The use of a system schema in this case helps make explicit that internal forces are those forces exerted on a body in the system by a body that is also inside the system. They are identified by lines that do not cross the boundary of the system. The schema with the rectangle added also makes visually clear that external forces are exerted on bodies in the system by bodies that are outside the system. They are represented by lines that cross the boundary of the rectangle and are connected to objects outside of the rectangle. Since each line represents pairs of equal, but opposite, forces, the system schema provides a concrete visual representation which reinforces the notion that internal forces cancel in pairs and the net force on the system enclosed by the rectangle is the sum of the external forces acting on the system. This schema shows two internal forces that act on both block 1 and block 2. The schema also shows that block 1 has one external force and that block 2 has four external forces acting on it.

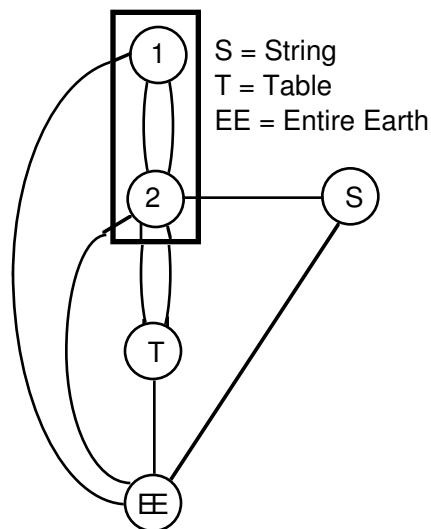


Figure 6. Identifying internal and external forces

Summary

In summary, students have a minimum of difficulty in constructing schemas. They are obviously helpful in complex situations, but they are also helpful in resolving issues raised in simpler situations where student misconceptions frequently produce incorrect numbers of forces, misidentification of the agents of the forces they do list, or an incorrect application of Newton's third law.

How does a system schema minimize the difficulties students have in constructing accurate free-body diagrams?

- By counting the number of interaction lines that end on the body of interest, the student will know the correct number of forces that act on that body.
- By looking at the body at the opposite end of an interaction line, the student can identify the body exerting a given force.

- Given a force on a body of interest, the student can identify its reaction force at the opposite end of its interaction line.
- Internal forces are associated with interaction lines that do not cross the system boundary.
- External forces are associated with interaction lines that cross the system boundary.
- Perhaps most important of all, a system schema provides the student with an easily understood process for creating accurate free-body diagrams.

There are additional benefits to having students constructing system schemas. The schema reinforces the idea that forces on one body are always caused by some other body. The schema also gives a visual reminder that any object also exerts a gravitational force on the entire Earth. With a system schema, the process of constructing a free-body diagram becomes an exercise in analysis instead of memory and/or educated guesswork. When mistakes do occur, good dialogues can occur between teacher and student because together they can examine the process for the source of the error. System schemas ultimately empower the students to select an appropriate system on their own.

Jim Stankevitz, physics teacher at Wheaton Warrenville South High School in Wheaton, Illinois, wrote me in an e-mail, “I insist that my students begin not only force problems with system schemas, but also their energy and momentum problems because it helps them greatly when deciding if any external net force acts to change system energies or momenta.”

The use of system schemas was first suggested by David Hestenes of Arizona State University^{3,4,5}, founder of the Modeling Method of physics instruction, in the belief that the level of student discourse would be raised by having this representational tool available. In conversations with many teachers⁶, they have told him that “system schemas take little time, and are do-able even by less adept students.” In fact, some teachers say “slower students profit MOST by using system schemas.” I echo these statements from conversations I have had with my own students.

In conclusion, we and many others find that, when consistently used, the system schema described in this article provides a coherence previously lacking and builds student confidence in their ability to solve problems.

References

¹ glenn.wagner@ugdsb.on.ca

² jimStanke@comcast.net

³ Wells, Hestenes, and Swackhamer, A modeling method for high school physics instruction, *American Journal of Physics* **67**, 606 (1995)

⁴ Hestenes, in *The Changing Role of Physics Departments in Modern Universities, Proceedings of the International Conference on Undergraduate Physics Education*, Pt. 2, edited by Edward F. Redish and John S. Rigden, AIP, Woodbury, NY, 1997, page 935

⁵ Hestenes, in *Thinking Physics for Teaching*, edited by Carlo Bernardini, et al, (Plenum Press, New York, 1995), Page 25.

⁶ June 23, 1997 talk by David Hestenes to Phase 1 Leadership Modeling Workshop teachers. This talk is available on-line at <http://modeling.asu.edu/modeling/HestenesLectures/5.WhatToTeach.pdf>