Teaching Dynamics Using Modern Tools

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Significant innovations have been made in the teaching of Dynamics at Rose-Hulman Institute of Technology. At Rose-Hulman, Dynamics is the first class that requires mechanical engineering students to solve realistic engineering problems using the basic principles of Newton's Laws, Work-Energy, and Impulse-Momentum. Since these concepts permeate the remainder of the mechanical engineering curriculum, Dynamics is a critical course for students. New tools and pedagogical techniques introduced several years ago include a computer algebra system, the dynamic simulation program Working Model☺ and concept maps. In this paper the details of how these tools and techniques were used will be discussed.

Computer Algebra

All students at Rose-Hulman are taught Calculus I, II and III and Differential Equations I and II using the computer algebra system Maple or Mathematica. Beginning in the 1994-95 academic year, Dynamics was redesigned to exploit the students' expertise in using these tools. In the professor's mind, the emphasis in Dynamics has always been on problem formulation, but in many students' minds, the course seemed to be a collection of mathematical manipulations. To emphasize problem formulation and the derivation of the governing equations, the students were asked to formulate all the necessary equations prior to attempting the mathematical manipulations required to get a numerical answer. After the governing equations were derived, they could then be solved using Mathematica or Maple. In addition to solving the governing equations, the computer algebra system enables students to examine "what-if" scenarios and to plot the result of varying parameters in the problem.

A New Homework Structure

One problem associated with using the computer extensively in solving problems is the danger of students developing a habit of using the computer whenever possible - regardless of whether it is appropriate for the circumstances or not. There is also a risk of students developing a bad habit of trying to formulate a problem while at the computer rather than formulating the problem and then using the computer as a tool to solve the equations. In an effort to avoid these problems and to emphasize that the computer is only a tool to be used in solving problems, a rigid homework structure was required. Every homework assignment in the class was required to have the following sections:

- Problem statement:
- Assumptions:
- Knowns:
- Unknowns/Equations table:
- System:

- Governing equations (principles, constraints, kinematics):
- Solution to equations:
- Check:

The problem statement was required to be clear enough that the student, or someone else, would be able to understand the problem six months in the future. If appropriate, essential features of the problem were to be displayed in a labeled sketch including an appropriate coordinate system. The problem statement section contained two subheadings: Given and Find.

In the two sections titled "Assumptions" and "Knowns", the students were required to list the assumptions made in solving the problem and to extract information given in the problem statement and write that information in terms of parameters needed to solve the problem. An important feature of this format was the section called "Unknowns/Equations table". While solving a problem, the students were required to keep track of both the unknowns in the problem and the equations they had derived that could be used to solve for the unknowns. The students were encouraged to leave the algebra until the end of the problem, that is, until they had derived enough equations to solve for the unknowns.

In the section called "System" the students were asked to identify in words the system or systems to be analyzed. For many problems this section involved drawing a free body diagram and a resultant force diagram (kinetic diagram) with a clearly labeled coordinate system. A critical step in the solution of a problem involves applying the appropriate principles, constraint and kinematic relationships to obtain enough equations so that the unknowns may be determined. This portion of the solution was put in the section called "Governing equations". The final two sections of the homework structure involved solving the governing equations and checking the results for reasonableness. The governing equations were to be solved either by hand or by using a computer algebra system depending on the difficulty of the resulting algebra or calculus.

This structure was intended to emphasize the formulation of the governing equations and to require the students to keep track of the unknowns in a problem. Although this structure worked well for many problems, it was overly cumbersome for some. Many students perceived the structure as "busy work" and felt it was unnecessary for problems that had a small number of unknowns and equations and an obvious path to the answer. Motivating the homework structure as a form of technical communication and as something that would help them solve more difficult problems did not seem to help the students' attitudes. At least one of the professors who teaches statics has subsequently adopted this homework structure for the statics course and the format has been relaxed somewhat for relatively simple problems.

Problem Modifications

Because computer algebra enables students to solve sets of equations in terms of parameters, some of the problems were deliberately modified in order to exploit the capabilities of the computer. An example of the type of problem that can be solved easily using Maple or Mathematica but would be very tedious to solve by hand is shown in Figure 1. In this problem the students are asked to determine the angle of inclination, θ, to maximize the horizontal flight of the ball, d. After applying the necessary principles, which include conservation of energy, conservation of momentum, the coefficient of restitution equation, and the constant acceleration equations required for projectile motion, the distance the ball travels, d, is found to be

$$d = \frac{2v_x v_y}{g} \qquad (1)$$

where

$$v_x = (1+e)\sqrt{2gh}\,\sin(\theta)\cos(\theta) \quad (2)$$

$$v_y = \sqrt{2gh}\left(e\cos\,(\theta) - \sin^2(\theta)\right) \quad (3)$$

Taking the derivative of Eq. (1) with respect to θ, setting it equal to zero and solving for θ is very difficult to do by hand, but is very easy to do using a computer algebra package. The author of the textbook from which this problem came made the incorrect assumption that the ball would leave the incline at 45 degrees with respect to the horizontal in order to solve the equation by hand. A plot of the angle of inclination, θ, required to maximize the distance d shown as a function of the coefficient of restitution can easily be generated by the students.

Another type of problem that was not solved prior to the introduction of computer algebra into the class is shown in Figure 2. In the past, when students were given this type of problem they were asked to determine the velocity and acceleration of point D at a specified angle, θ. After the introduction of computer algebra, the students were asked to determine the velocity and acceleration of point D as a function of θ and to plot the result as shown in Figure 3.

Working Model™

Working Model is a dynamic simulation program produced by Knowledge Revolution. It was used in Dynamics as a way of helping students visualize problems and develop their dynamics intuition. Working Model was used primarily in class, although the students were required to use it on a few homework problems to verify answers obtained analytically. Using Working Model, it is very easy to develop, simulate and animate models. Graphs of velocities, accelerations, and forces are also readily available. This program was especially useful in teaching concepts in 2-D rigid body plane motion such as Chalses' Theorem, instantaneous center of velocity and conservation of energy. It was beneficial for students to see that even though an object is rotating at a constant angular velocity, points on the object are accelerating.

Figure 4 shows an example of a Working Model demonstration used to help students understand the concept of instantaneous center of velocity. This demonstration was projected onto a white board at the front of the room. In Fig. 4, the link on the right is driven with a constant angular velocity. The four-bar linkage was animated and stopped at several different times. The instantaneous center of velocity was found at each time and the students could clearly see how its location moved in space. This demonstration was also used to help the students develop their intuition concerning the velocity and acceleration of different points on rigid bodies. At the instant shown in Fig. 4, the velocities of a number of different points are shown to illustrate that different points on the rigid bodies have different velocities. The students can also see the difference between fixed axis rotation and general plane motion. The students can clearly see that the velocities of points on the link with a constant angular velocity are constant in magnitude, whereas the velocities of points on the other two links change in magnitude indicating that the other two bars have angular accelerations. This demonstration can also be used to show the acceleration of different points on the links.

In addition to its use in illustrating concepts, Working Model was also used to present approximately 40-50% of the example problems solved in class. Animating the problems allowed the students to have a better understanding of what they were trying to determine. Figure 5 shows a Working Model demonstration used to present an example problem worked in class. This demonstration also reinforces the concept of conservation of energy. The collar is released from rest at position C and the students are asked to calculate the velocity of the block at position B. To help the students visualize the problem, the motion of the block is animated and projected onto a screen at the front of the classroom. The velocity of the block is plotted as a function of time and the potential, kinetic and total energy are plotted on a bar graph to illustrate that the total energy of the system remains constant. This problem can also be easily solved using computer algebra and the results compared.

Concept Maps

Concept maps, which are pictorial representations of course material, were introduced to try to help students understand the relationships between the various topics covered in Dynamics and to help them organize the material in their minds. A concept map illustrating the relationship of topics typically covered in the area of particle kinematics is shown in Figure 6. At the top of Fig. 6 are the basic kinematic relationships between position, velocity, and acceleration. The next level of the map illustrates that these relationships can be integrated to obtain algebraic relationships between these quantities and that they are vector quantities that can be represented in different coordinate systems. The last level shows the equations for position, velocity and acceleration in terms of rectangular components, normal-tangential components, and radial-transverse components. While covering this chapter in class, Fig. 6 was projected onto a corner of the classroom's front wall and whenever new material was presented, its location in the concept map was shown to the students so they could see how it was related to topics already covered.

Concept maps were also developed for rigid body kinematics and for particle and rigid body kinetics. The concept map for kinetics is shown in Figure 7 and was designed to help students identify what principles to apply when faced with a new problem. When doing homework, students usually know what principle to apply based on what section in the book immediately precedes the assigned problem. On tests, the problems typically require a variety of different principles to be applied and students have difficulty knowing which ones to apply since they have never had to face a similar situation on the homework. This concept map also gives a brief procedure the students may follow when solving a problem once the required basic principles have been identified.

Student Response

Students were asked to rate on a scale from one to five how lectures, in-class group work, homework, Working Model☺ demonstrations, concept maps, and computer algebra helped the students in five areas. The five areas were 1) problem solving skills, 2) learning and comprehension of Dynamics material, 3) motivation and interest in Dynamics, 4) ability to visualize problems and develop intuition, and 5) enjoyment of Dynamics. A rating of one indicated that the student did not feel that element of the class helped at all and a rating of five indicated that that element helped a great deal. The results are shown in Table 1.

A number of observations can be made from Table 1. The ratings for "Enjoyment of Dynamics" was low for all the elements in the class. This was probably a result of this particular class being primarily electrical engineering students who traditionally are not as interested in dynamics as are mechanical engineering students. The two modifications that received the most positive response were the use of Working Model☺ and the use of concept maps. In the students' opinions, Working Model☺ was particularly effective in helping the students visualize problems and concept maps in helping students' learning/comprehension and problem solving skills. It is interesting to note that lectures were consistently rated very highly by students.

The use of computer algebra was rated poorly in all areas by a significant number of students. This was the first attempt at incorporating computer algebra in Dynamics and it was primarily required to be used as a tool when solving the homework. Many of the homework problems were modified from the textbook to make the use of computer algebra necessary. It was assumed that the students had expertise in using computer algebra from their experience in the calculus sequence and therefore very little class time was devoted to learning the tool. Clearly more time needs to be spent to integrate this tool more effectively into the course. One way to use computer algebra more effectively is to design better, more interesting, and probably fewer, homework problems that require its use and that allow the students to use some of the exploration capabilities afforded by the computer. At Rose-Hulman, this course was originally taught in a classroom equipped with thirty-two, 90 MHz Pentium machines so that class time could be devoted to hands-on use of the computers. Currently all our students are required to own laptop computers and all our classrooms are equipped with power and network connections so we are no longer limited to one classroom. In addition, a pretest may be given the first day of class to assess students' computer algebra skills and students who are found to have insufficient expertise would be required to attend a training session.

Conclusion

A number of new pedagogical techniques and tools have been introduced in Dynamics at Rose-Hulman Institute of Technology. Concept maps and Working Model were perceived by students to be effective in helping them learn dynamics, but more work needs to be done to effectively integrate the use of computer algebra into the course.

Table 1 - Results of the student evaluations in Dynamics. The scale was 1 to 5 where a one indicated that that element of the class did not help at all and a five indicated that that element helped a great deal.

	Element of Class					
Area	Lectures	In-class group work	Homework	Working Model™	Concept Maps	Computer Algebra
Problem Solving Skills	4.2	3.6	4.0	3.8	4.2	2.1
Learning/Comprehension	4.2	3.9	3.7	3.5	4.2	2.2
Motivation/Interest	3.8	3.3	2.2	3.8	3.3	1.8
Problem Visualization and Intuition	4.1	3.9	3.6	4.5	3.6	2.0
Enjoyment	3.8	3.2	1.7	4.1	3.4	1.9

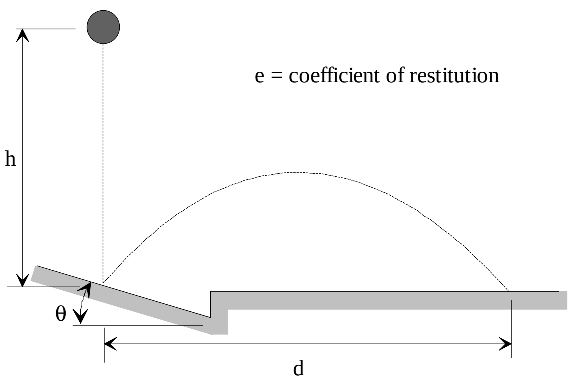

Figure 1 - Example illustrating the use of computer algebra. Students are asked to determine the angle θ to maximize the horizontal flight of the ball, d. This angle will depend on the coefficient of restitution.

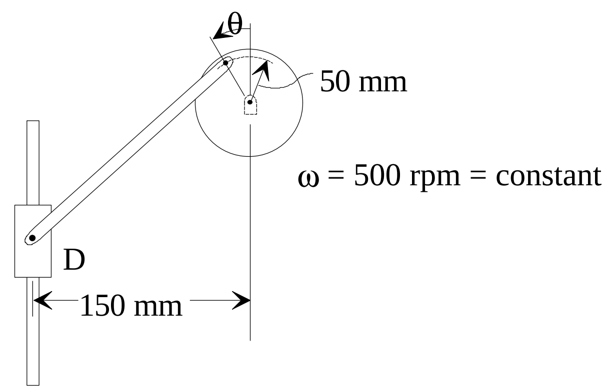

Figure 2 - Example problem illustrating the advantage of using a computer algebra system. Students are asked to plot the acceleration of point D for any angle θ.

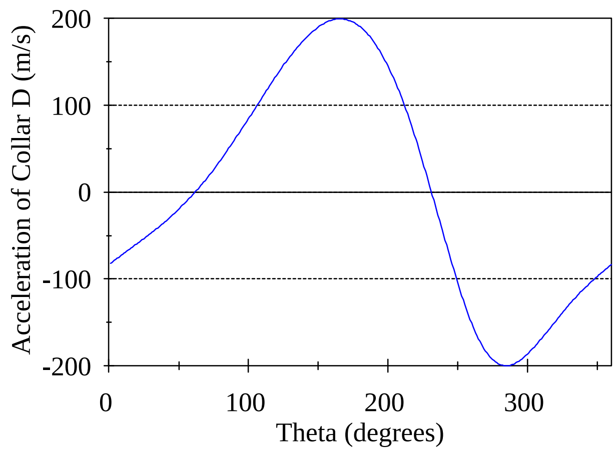

Figure 3 - Acceleration of the collar D shown in Figure 3 for any angle θ. This is the type of problem that is easily solved using a computer algebra system and it is easy to explore the effect of parameter variations.

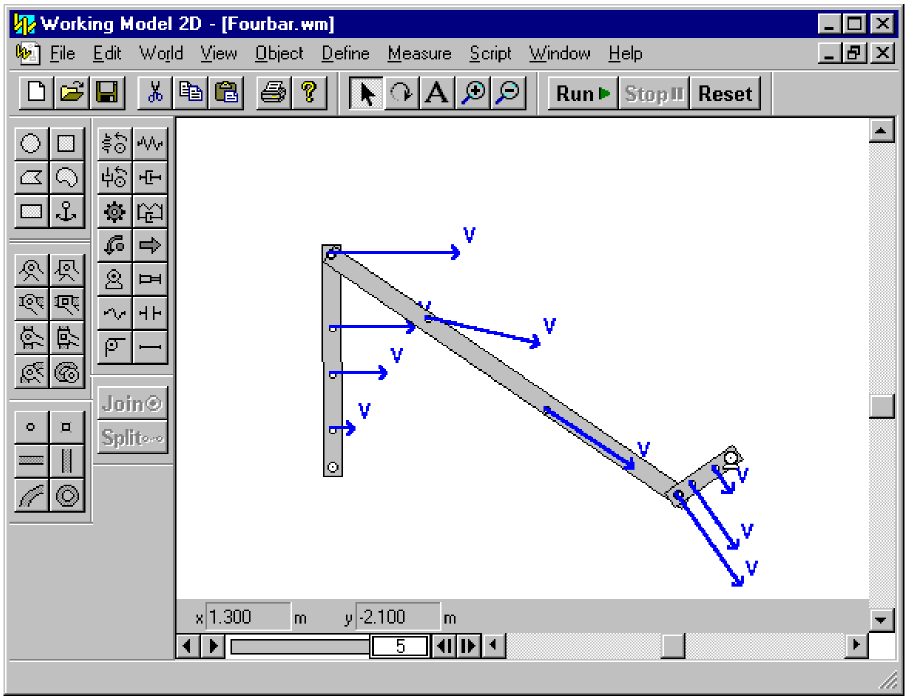

Figure 4 - A snapshot of a Working Model animation used to illustrate the concept of instanteous center of velocity and to show the velocity and acceleration of various points on the rigid body.

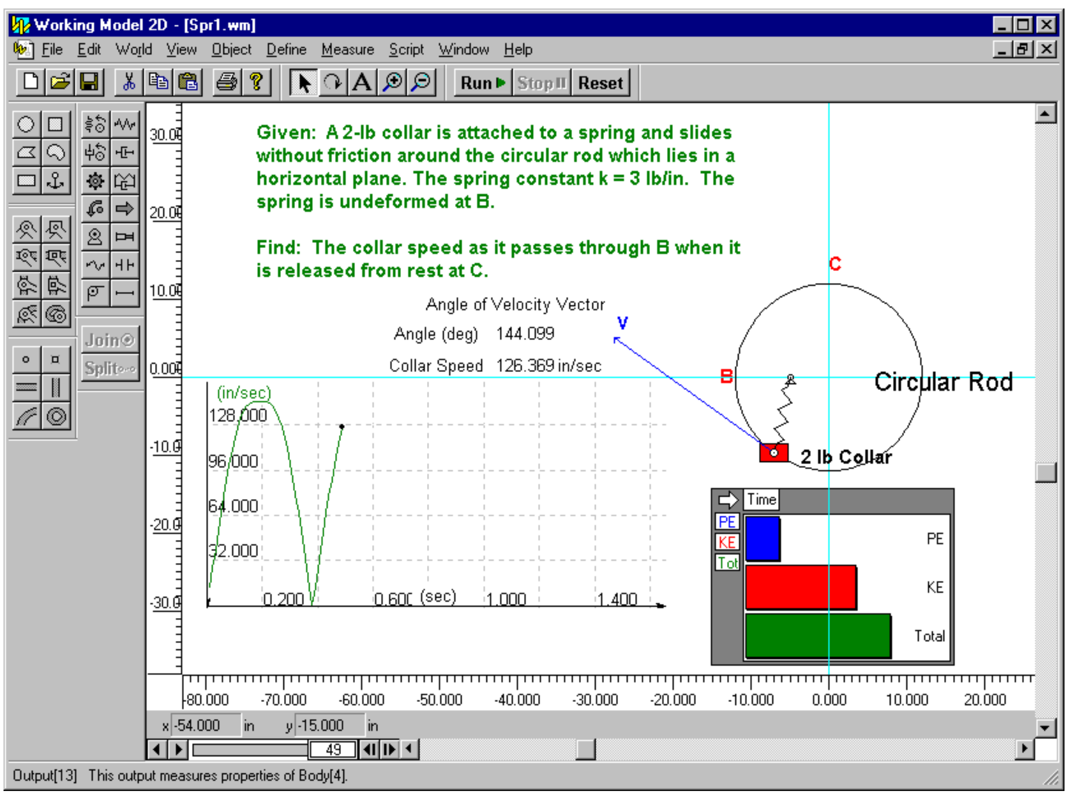

Figure 5 - A snapshot of a Working Model example used to demonstrate conservation of energy

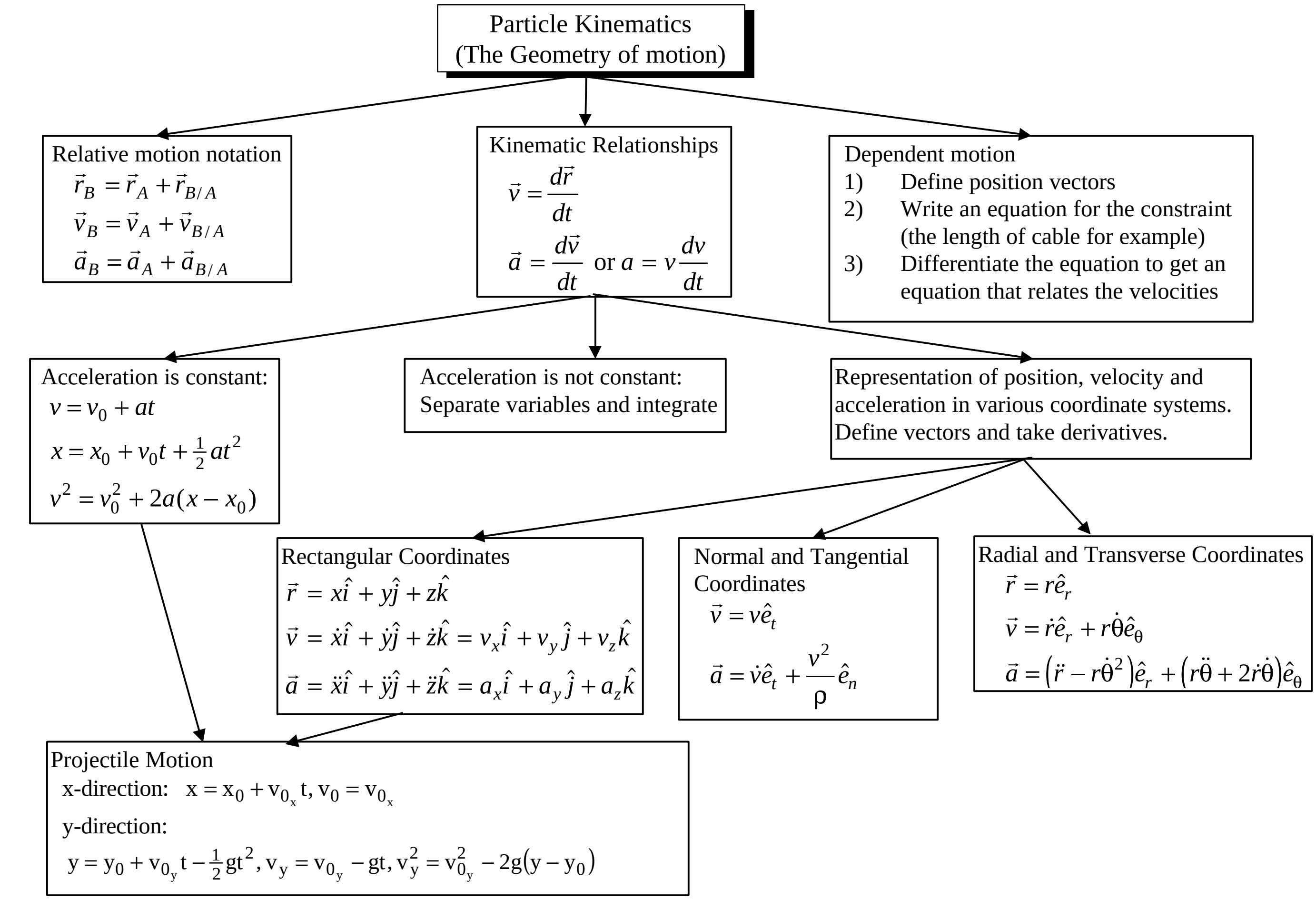

Figure 6 - Concept map for the topic of particle kinematics

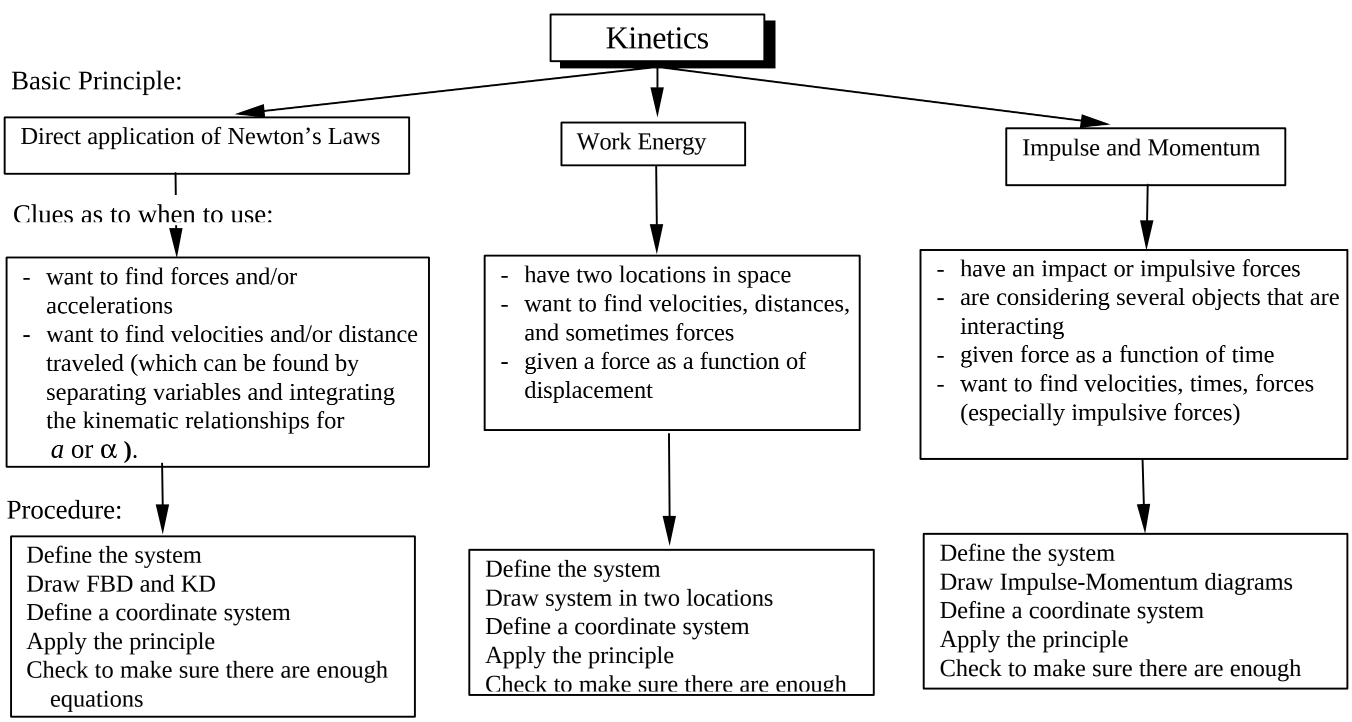

Figure 7 - Concept map for kinetics designed to help students identify the principles to apply when solving problems