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# Transforming Technology & Engineering Educator Inputs Into Desired Student Outputs Through Mechanism Analysis and Synthesis

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# transforming technology & engineering educator inputs

## into desired student outputs through mechanism analysis and synthesis

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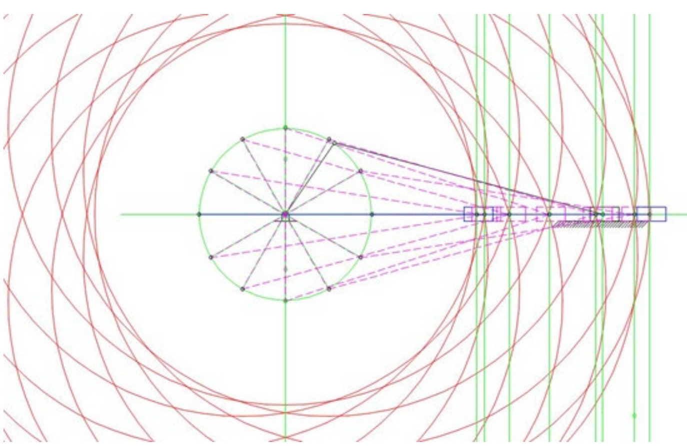

*Applying the instantaneous center method for determining velocities of a mechanism's members during specific instances of the mechanism's motion is based on relatively simple mathematical relationships.*

The intention of this article is to provide middle and high school Technology and Engineering Educators (T&EEs) with a more thorough understanding of an engineering approach to the teaching and learning of mechanics. During the teaching and learning of engineering content, in this case mechanics, the educator should attempt to align pedagogical content knowledge with engineering content knowledge and practices. T&EEs will also need to focus on terminology, structure, and applying theory to practical hands-on learning activities inside and outside of the classroom. T&EEs have the potential to foster middle and high school students' mechanical knowledge and the ability to apply this knowledge during engineering design experiences. As a robust understanding of mechanics is considered a requirement in college-level engineering programs, especially mechanical engineering, T&EEs should consider the development of students' engineering knowledge and ability to apply this knowledge paramount. T&EEs are always looking for new standards-based content focused on improving students' STEM-based skills and hands-on capabilities.

The standards and benchmarks to be utilized in this activity are:

*Standards for Technological and Engineering Literacy* (ITEEA, 2020):

- Standard 2: Core Concepts of Technology and Engineering
  - 2N. Illustrate how systems thinking involves considering relationships between every part.
  - 2T. Demonstrate the use of conceptual, graphical, virtual, mathematical, and physical modeling to identify conflicting considerations before the entire system is developed.
- Standard 6: Influence of Technology on Human Progress
  - 6F. Recognize that technological development has been evolutionary, the result of a series of refinements to basic inventions of technological know-how.
  - 6I. Analyze how the Industrial Revolution resulted in the development of mass production, sophisticated transportation and communication systems, advance construction practices, and improved education and leisure time.
- Standard 7: Design in Technology and Engineering Education
  - 7V. Evaluate and improve their own essential skills necessary to successfully design.
  - 7CC. Apply a broad range of skills to their design process.

*Next Generation Science Standards* (NGSS Lead States, 2013):

- Engineering Design
  - MS-ETS1-4. Develop a model to generate data for iterative testing and modification of a proposed object, tool, or process such that an optimal design can be achieved.
  - HS-ETS1-4. Use a computer simulation to model the impact of proposed solutions to a complex real-world problem with numerous criteria and constraints on interactions within and between systems relevant to the problem.

In the September 2021 issue of *Technology and Engineering Teacher,* Hughes and Merrill (2021) began addressing the basic concepts inherent to mechanics, specifically related to kinematics (i.e., mechanism motion) of a four-bar mechanism. The teaching and learning associated with mechanisms traditionally begins with the study of kinematics and later adds the study of kinetics. This second article will continue to explain the process of educating students about mechanics. In this article, the authors present an introduction to a slider-crank mechanism design using CAD software to produce graphical representations of the mechanism's motion. The explanation of kinematics will be followed by an explanation of kinetics.

The study of Kinematics includes the study of motion, basic geometry of mechanisms, velocity, and acceleration of mechanism components (i.e., members or links) but does not include the forces that cause or affect motion. Kinetics, on the other hand, includes the analysis of forces on a mechanism's components to determine both the internal and external mechanism forces. Due to the inclusion of force analysis in kinetics, students learning about mechanisms more commonly begin by studying kinematics, first focusing on mechanism motion. The authors' favorite aspect of kinematics is that it helps students *conceptually visualize* mechanical motion using *graphical models.* Kinematics consists of both mechanism analysis and synthesis. As the names imply, mechanism analysis is the study of a mechanism's motion and mechanism synthesis is the design of a mechanism to yield desired motion characteristics. In the study of kinematics, it is important to begin by developing an understanding of the motion characteristics for given mechanisms.

## Educating Students about Motion Characteristics

To help students develop an understanding of motion characteristics, teachers can begin by having them use CAD software to draw graphical models for a given mechanism. After students see the mechanism's motion graphically, educators can allow students to 3D print or produce the given mechanism using construction paper and cardboard to help further develop understanding of the mechanism's motion. Then students can modify the given mechanism to change its motion characteristics. There are two common modifications that help students further develop conceptual understanding of a mechanism's motion. The most common is inversion. Inversion is the process of fixing different links in a mechanism and in turn creating different motion characteristics. Another common modification is changing the length of any one member at a time. The next step is educators having students design and produce their own mechanisms. Finally, teachers can add analysis of velocities and accelerations to the understanding of motion using methods like effective component, instant center, relative, difference, calculus, graphical, and or any combination of these methods.

## Graphical Motion of a Mechanism

Figure 1 is a slider-crank mechanism (i.e., slider-crank linkage). Figure 1 is basically a graphical representation of a single cylinder engine. In Figure 1, *Label 1* represents *member 1.* Member 1 is fixed and does not move. Member 1 represents the frame, both the engine block (left side of Figure 1) and the cylinder (right side of Figure 1). *Label 2* represents *member 2* and the engine crankshaft. *Label 3* represents *member 3* and the connecting rod. Finally, *Label 4* represents *member 4,* the slider or piston. The connections between members 1 and 2, 2 and 3, 3 and 4, and 1 and 4 are considered pivots as well as *kinematic pairs,* and more specifically *lower pairs.* Lower pairs have surfaces in contact, for example the surface of member 4, the slider, is in contact with surface 1, the cylinder wall. There are also *higher pairs.* Higher pairs only have one point in contact, for example a cam and follower. Hughes and Merrill (2021) addressed using Gruebler's equation to determine the degrees of freedom for a mechanism. In the case of the slider-crank mechanism, there is one degree of freedom, meaning the mechanism is considered a *constrained kinematic chain.* This basically means that only one member needs to be controlled in order to control the motion of the entire mechanism.

To help students begin graphically visualizing the slider-crank mechanism's motion characteristics, they should use CAD to first draw the slider-crank, and then add drawn layers representing the mechanism motion through every 30 degrees of member 2's rotation (Figure 2). The students can use different layers, line color, and line type to have a colorful, some might say artistic, graphical rep-

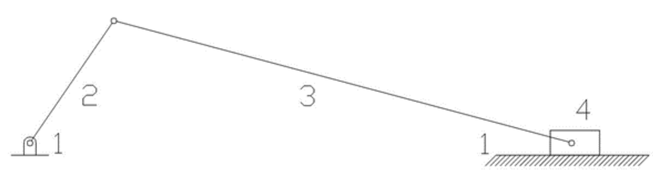


**Figure 1.**
Labeled Slider-crank Mechanism

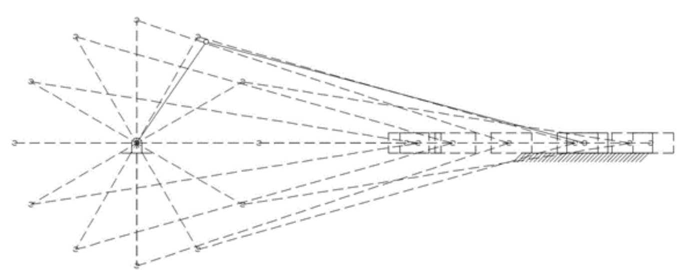

**Figure 2.**
Motion Characteristics

**Figure 3.**
3D Printed Slider-crank Mechanism

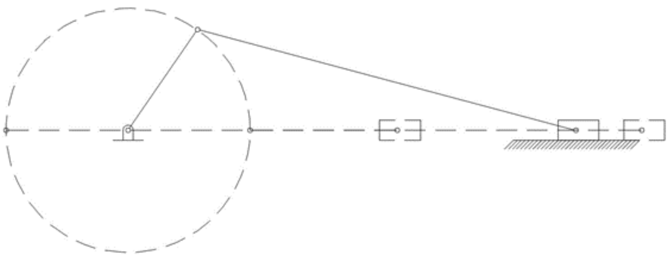

**Figure 4.**
Slider-crank Mechanism Extents

resentation of the slider-crank mechanism's motion (see page 21). At this point students will start to make connections between the graphical representation and the actual motion of a single cylinder engine or similar slider-crank mechanism. This is a good time to show a video of a single cylinder engine with cutaway operating. It is also a good idea for the educator to provide students with some already pre-made slider-crank mechanisms (Figure 3). In Figure 3, the slider (i.e., member 4) is connected to the frame (i.e., member 1) using a sliding dovetail. Figure 4 represents the extents of this slider-crank mechanism's operation. In Figure 4, member 4 is slid as far left and right as possible based on the current mechanism design (i.e., the relationship between members 1, 2, 3, and 4).

## Instantaneous Centers

There are many methods for analyzing the velocities and accelerations of each member in a mechanism, as mentioned above. Arguably the simplest is the instantaneous center method (i.e., instant center method) or velocities by centro method. Hughes and Merrill (2021) addressed how to begin thinking about a mechanism using the instant center method. The goal is to graphically and conceptually visualize a mechanism's motion as rotational motion around an instant center (i.e., point). When visualizing the mechanism's motion, it is important for students to determine how may instant centers exist using this equation; number of instant centers = $\frac{(n\,(n-1)}{2}$ where *n* is the number of members in the mechanism. For the slider-crank mechanism in this article, there are 4 members, which, based on the equation, means there are 6 instant centers.

Hughes and Merrill (2021) explained the use of Kennedy's theorem and the derived circle method to determine the labeling and location of the 6 instant centers. In Figure 5, all instant centers are visible. Kennedy's theorem basically states that any three bodies (i.e., members) having plane motion relative to one another have three instant centers, and these instant centers all lie on a straight line. For example, in Figure 5, you can see that members 1, 2, and 3 have instant centers 12 (said as *instant center one two*), 23, and 13. In Figure 5, you can see that instant centers 12, 23, and 13 all lie on a straight line, this is basically Kennedy's theorem.

Instant center 12 is a fixed instant center because it exists as a fixed center point around which member 2 rotates. Instant center 14 is an example of a unique fixed instant center. Although member 4 reciprocates on a linear path, imagine that member 4 oscillated on a circular path with a center of rotation at instant center 14. As you increased the radius of that circular path, the path would appear to be more of a straight line, especially for a short distance. The instant center 14 exists at infinity because member 4 reciprocates on a linear path. Instant centers 23 and 34 are considered *permanent* instant centers. Member 2 is always connected to member 3 and instant center 23 permanently exists in a circular path (i.e., centrode) defined by the rotation of member 2 and the oscillating motion of member 3. Additionally, member 3 is always connected to member 4, instant center 34 permanently exists along a straight-line path (i.e., centrode), which is defined by linearly sliding motion of member 4. Instant centers 13 and 24 are considered *imaginary* instant centers. Imaginary instant centers exist outside the mechanism at particular instances of the mechanism's operation and have similar characteristics as fixed or permanent instant centers. Instant

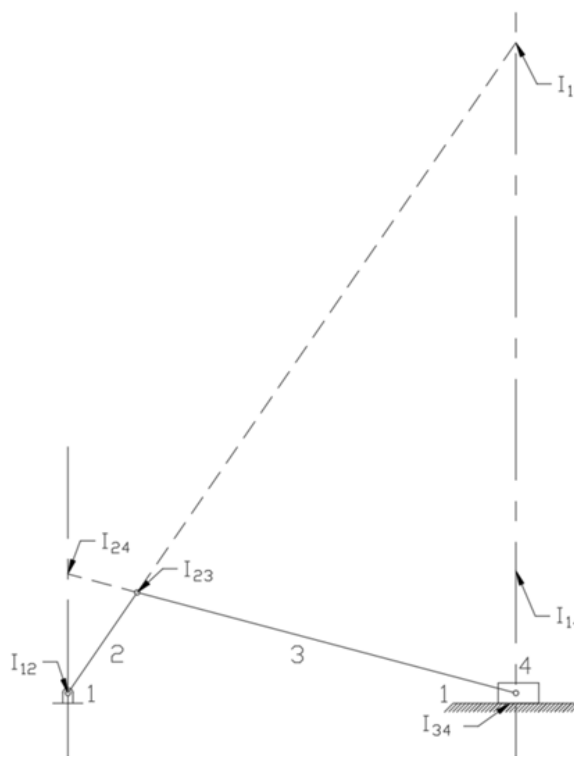


**Figure 5.**
Instant Centers Located

centers 13 and 24 move along the corresponding center lines as the mechanism moves (Figure 5).

## Determining Velocities based on Instantaneous Centers

Applying the instantaneous center method for determining velocities of a mechanism's members during specific instances of the mechanism's motion is based on relatively simple mathematical relationships. The relationships are based on visualizing each member's rotation around an instantaneous center (i.e., point). The ability to determine velocities at any point in terms of pure rotation simplifies the analysis of mechanisms. The velocities of a mechanism's members can be determined through calculation and graphical measurement using CAD. It is a good idea to help students use both calculation and graphical methods when determining velocities.

## Line of Centers Method

The line of centers method is a common method associated with determining velocities using instant centers. The line of centers method uses three links including (1) a known link, (2) an unknown link, and (3) a base link. These three links will also have three instant centers. The instant centers can be determined using the method previously explained. In Figure 6, to determine the velocity ($\nu_{34}$), the three links needed are (1) member 2 (i.e., the know link), (2) member 4 (i.e., the unknown link), and (3) member 1 (i.e., the base link). The three instant centers for these links are 12, 14, and 24. The linear velocity of the point defined by instant center 24 ($\nu_{24}$) is equal to the angular velocity of member 2 ($\omega_2$) multiplied by the radii of rotation for instant center 24 ($\nu_{24} = \omega_2$ (12-24)). The radii of rotation in this example, denoted as 12-24, really means the distance between the center of rotation (i.e., instant center 12) and the point at which the linear velocity ν24 acts (i.e., instant center 24). If member 2 is rotating clockwise at a constant angular velocity of 200 RPM, the linear velocity ν24 is equal to 200 RPM multiplied by 1.46 inches (distance determined in CAD) or 292 in/min. As member 4 translates linear motion into only rotational motion, as in a single cylinder engine, it is known to be in *pure translation.* Additionally, linear velocity $\nu_{24}$ acts at a point (i.e., instant center 24) associated with member 4 with the same orientation as $\nu_{34}$. As such, in Figure 6, this pure translation means that $\nu_{24}$ is the same as $\nu_{34}$.

## Kinetics

The term kinetics was classically used in mechanism analysis to describe the inclusion of force analysis. More recently the term dynamics has replaced the use of the term kinetics. Using the term dynamics makes practical sense considering the inclusion of force analysis in conjunction with mechanism motion. However, it is common for students to begin analyzing forces as if the mechanism is a rigid body. In a single cylinder engine, maximum pressure from combustion happens just after the piston passes through top dead center. In a four-stroke engine, the combustion pressure acts as a force on the piston during the power stroke, which moves the piston through the power, exhaust, intake, and compression strokes. The combustion pressure of an engine can vary based on various engine characteristics. The combustion pressure can be used to determine the force acting on the piston.

In Figure 7, the force from the combustion pressure, F, has been scaled to equal 1.5 lbs. The combustion force F produces a force R in member 3 and a force S in member 2. To determine forces R and S, the rectangular component forces must be used (i.e., $R_x$, $R_y$ $S_x$, and $S_y$). Since force F is the only force introduced and it is directly on the x-axis, $R_x$ must be equal to F. So, $R_x$ equals 1.5 pounds of force. Using the component force equation, $R_x$ = Rcos(9°), we see that R = 1.5 lbs. / .9877 or R = 1.52 lbs. Force $R_y$ is calculated using this component force equation, $R_y$ = Rsin(9°), $R_y$ = 1.52 lbs.(.156) or $R_y$ = .238 lbs. Similarly, force F must be equal $S_x$. So, $S_x$ equals 1.5 pounds of force. Using the component force equation, $S_x$ = Scos(30°), we see that S = 1.5 lbs. / .866 or S = 1.73 lbs. Force $S_y$ is calculated using this component force equation, $S_y$ = Ssin(30°), $S_y$ = 1.73 lbs.(.5) or Sy = .865 lbs.

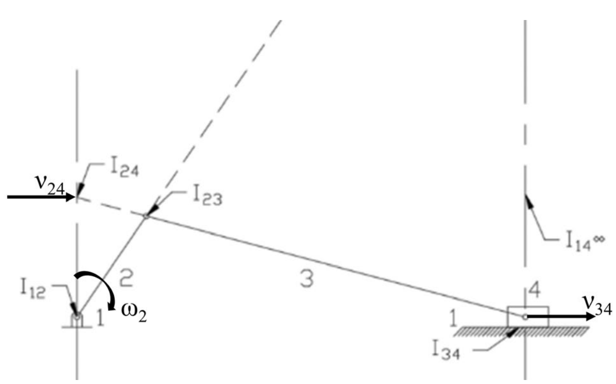


**Figure 6.**
Velocities by Line of Centers Method

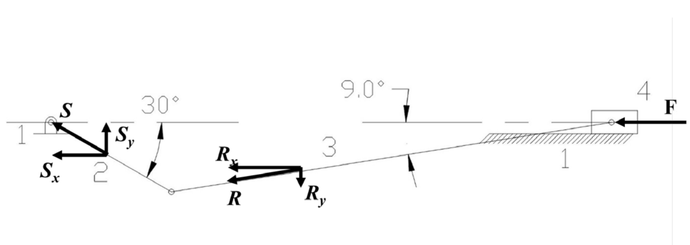


**Figure 7.**
Force Analysis

## Conclusion

This article was a follow-up to a September 2021 *TET* article covering the analysis of a four-bar mechanism. The four-bar and slider-crank mechanisms are the two most common mechanisms for students first learning how to analyze them. The intention of this article was to provide a more thorough understanding of kinematics and kinetics that Technology and Engineering Educators could apply during mechanism design activities in their classrooms. The primary goal is for educators to apply this content to develop students' mechanism knowledge during practical hands-on learning activities in the STEM classroom. Students' ability to analyze and synthesize mechanisms is important for many common activities in Technology and Engineering Education and post-secondary success in engineering programs.

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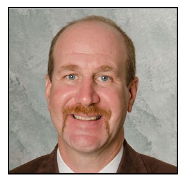


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