THE USE OF PHYSICAL AND VIRTUAL MANIPULATIVES IN AN UNDERGRADUATE MECHANICAL ENGINEERING (DYNAMICS) COURSE

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ABSTRACT

Science, technology, engineering, and mathematics (STEM) education is a national focus. Engineering education, as part of STEM education, needs to adapt to meet the needs of the nation in a rapidly changing world. Using computer-based visualization tools and corresponding 3D printed physical objects may help nontraditional students succeed in engineering classes. This dissertation investigated how adding physical or virtual learning objects (called *manipulatives*) to courses that require mental visualization of mechanical systems can aid student performance. Dynamics is one such course, and tends to be taught using lecture and textbooks with static diagrams of moving systems. Students often fail to solve the problems correctly and an inability to mentally visualize the system can contribute to student difficulties.

This study found no differences between treatment groups on quantitative measures of spatial ability and conceptual knowledge. There were differences between treatments on measures of mechanical reasoning ability, in favor of the use of physical and virtual manipulatives over static diagrams alone. There were no major differences in student performance between the use of physical and virtual manipulatives. Students used the physical and virtual manipulatives to test their theories about how the machines worked, however their actual time handling the manipulatives was extremely limited relative to the amount of time they spent working on the problems. Students used the physical and virtual manipulatives as visual aids when communicating about the problem with their partners, and this behavior was also seen with Traditional group students who had to use the static diagrams and gesture instead. The explanations students gave for how the machines worked provided evidence of mental simulation; however, their causal

chain analyses were often flawed, probably due to attempts to decrease cognitive load. Student opinions about the static diagrams and dynamic models varied by type of model (static, physical, virtual), but were generally favorable. The Traditional group students, however, indicated that the lack of adequate representation of motion in the static diagrams was a problem, and wished they had access to the physical and virtual models.

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APPROVAL OF THE DISSERTATION

This dissertation, *The Use of Physical and Virtual Manipulatives in an Undergraduate Mechanical Engineering (Dynamics) Course*, has been approved by the Graduate Faculty of the Curry School of Education in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

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Dedication

This dissertation is dedicated to
my wife, Karen,
whose patience, encouragement, and help
made it all possible

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CHAPTER 1

INTRODUCTION

Science, technology, engineering, and mathematics (STEM) education is a national focus (The White House, Office of the Press Secretary, 2010). President Obama has described the success of the United States in terms of “leading the world in developing the technologies, businesses, and industries of the future” (The White House, Office of the Press Secretary, 2010, para. 10) and that success is contingent on the nation’s ability to invest in STEM education. America needs to identify students with the “talent and inclination” for STEM, and “give them the tools that they need so that they can succeed” (The White House, Office of the Press Secretary, 2010, para. 12).

Engineering education, as part of STEM education, must adapt to meet the needs of the nation in a rapidly changing world. Not only is technology changing, but also our own population is changing. According to *The Engineer of 2020*, “the engineering profession will need to develop solutions that are acceptable to an increasingly diverse population and will need to draw more students from sectors that traditionally have not been well represented in the engineering workforce” (National Academy of Engineering, 2004, p. 28). Students who have traditionally been in the minority in engineering include women and those from low socio-economic status (SES); these nontraditional students typically have worse spatial skills than their male or higher SES counterparts (Levine, Vasilyeva, Lourenco, Newcombe, & Huttenlocher, 2005). To help diversify and grow the engineering workforce, engineering educators can investigate different modes of instruction to help nontraditional students succeed. One approach is to try to bridge the spatial ability gap through the use of instructional technology that can help students develop their spatial visualization ability, such as making abstract ideas concrete through the use of physical objects, or using virtual environments that allow exploration in three dimensions. Additionally, engineering education must also incorporate the skills that engineers need to function in today's changing world (National Academy of Engineering, 2004). This means that engineering education should incorporate aspects of authentic engineering practice (such as the use of computer-aided design and rapid prototyping) wherever possible.

Advances in fabrication technologies (such as laser cutting and 3D printing) and educational technologies (such as computer-based virtual learning tools) have the potential to help engage engineering students in authentic practices. Additionally, engineering programs need to produce students who are competent in the use of computer and information technology (National Academy of Engineering, 2004). Authentic engineering practice involves the use of computer-based virtual tools and physical objects. Many engineers in industry use computer-aided design (CAD) software not only to create designs but also to test them with computer simulations prior to creating physical models (if the ultimate product is physical). Engineers also engage in *reverse-engineering*, a process of disassembling physical artifacts in order to ascertain its properties and functions (Dalrymple, Sears, & Evangelou, 2011). Some practicing engineers also use 3D printers to rapidly prototype designs or products.

Using computer-based visualization tools and corresponding physical objects (created via rapid prototyping methods such as laser cutting or 3D printing) may also help nontraditional students succeed in engineering classes. Spatial visualization skills are important for success in engineering (Field, 1999; Sorby & Baartmans, 2000; Onyancha, Derov, & Kinsey, 2009), however, students enter engineering with spatial skills that are comparable to the university population as a whole (Field, 1999), with many at a deficient level (Field, 1999; Sorby & Baartmans, 2000). Yet engineering students must commonly be able to visualize three-dimensional objects from two-dimensional representations. Tools like CAD simulations can help students develop spatial visualization skills (Bhatt, Tang, Lee, & Krovi, 2008). This can help students who may not otherwise have succeeded in engineering.

Educational research demonstrates the effectiveness of virtual environments or simulations on learning in a variety of domains (Honey & Hilton, 2011; Höffler & Leutner, 2007; Zacharia & Olympiou, 2011; Klahr, Triona, & Williams, 2007). Much research also points to the benefits of learning with physical objects (e.g., Zacharia & Olympiou, 2011; Manches, O'Malley, & Benford, 2010). Additionally, end goals for many engineering disciplines are for students to design and prototype physical objects as well as virtual objects.

This dissertation investigated how physical objects and virtual environments (or objects) can be used in engineering education to help students succeed. Specifically, I investigated how adding physical or virtual learning objects (called *manipulatives*) to courses that require mental visualization of mechanical systems can aid student performance (i.e., spatial visualization ability, conceptual knowledge, and mechanical reasoning).

Dynamics is one such course. Dynamics is a foundational Mechanical Engineering course and the second part of a study of a larger topic known as engineering mechanics. The first part of engineering mechanics is the topic of statics, which is the study of stationary bodies or bodies moving at constant velocity. Dynamics is the study of bodies undergoing accelerated motion (Hibbeler, 1992). Dynamics can be broken down into four major topics: particle kinematics, particle kinetics, rigid body kinematics, and rigid body kinetics. Particle kinematics describes the geometric motion of a particle of negligible size and shape. This includes bodies whose motion can be reduced to that of a particle, such as the motion of its center of mass. Particle kinetics describes the effect of unbalanced forces acting on a particle. Typical scenarios described by particle kinematics, and kinetics, are ballistic motion (like the motion of balls falling) and circular motion (such as a vehicle traveling along an arc). Rigid body kinematics describes the geometric motion of rigid bodies, which are bodies whose motion cannot be reduced to a description of a particle, such as objects that are rotating. Rigid body kinetics describes the effect of unbalanced forces acting on rigid bodies.

Although the nature of the material of the course is inherently dynamic, classes tend to be taught using lecture and textbooks with static diagrams of moving systems. Students are given word problems with associated diagrams (which together supply initial conditions of the problem to solve) of mechanical systems and asked to solve for the value of some property of the system (such as the velocity of a component, or the behavior of a component as a result of an interaction between various components in the system). Students often fail to solve the problems correctly and an inability to mentally visualize the system can contribute to student difficulties. Adding opportunities to help students visualize these systems, through access to virtual or physical objects, may be potentially powerful for struggling students.

Purpose of the Study

Spatial-visualization ability is important in for success in engineering (Field, 1999; Sorby & Baartmans, 2000; Onyancha, Derov, & Kinsey, 2009). Specifically in classes like Dynamics, students have to mentally visualize and animate complex mechanical systems. Difficulties in visualizing mechanical systems can contribute to students making incorrect inferences about the operation of those systems, and thus hinder student performance. This study investigated whether the use of multiple representations of dynamic mechanical systems help students visualize and analyze such systems. More specifically, this study investigated whether students using physical or virtual models of mechanical systems outperform students using the traditional method of static diagrams and text descriptions of systems typically found in textbooks. In particular, this dissertation addresses the following research questions:

1. How does student performance compare for students with instruction supplemented with physical manipulatives, instruction supplemented with virtual manipulatives, and traditional methods of instruction?
2. How do students use static diagrams, physical manipulatives, and virtual manipulatives when learning rigid body kinematics?
    a. What kinds of mental models of mechanical systems do students develop using static diagrams, physical manipulatives, and virtual manipulatives?
3. What do students think about static diagrams, physical manipulatives, and virtual manipulatives as learning aids?

CHAPTER 2

REVIEW OF LITERATURE

In order to understand how students learn with physical and virtual manipulatives in dynamics courses, I present an overview of relevant theoretical frameworks for learning. To understand how students develop and use mechanistic mental models and mechanical reasoning in solving dynamics problems, I review various perspectives on mental models as well as past studies exploring the effectiveness of physical and virtual materials used in instruction. To build upon best practices in dynamics, I also review effective instructional approaches in dynamics.

Theoretical Framework

How People Learn

The landmark report, *How People Learn*, from the National Research Council (Bransford, Brown, & Cocking, 2000) describes a framework for cognition and learning. People construct knowledge based on their prior knowledge, and all learning involves transfer of prior knowledge to new situations. Prior knowledge influences what people notice and learn. Experts notice things that novices do not, and this affects their ability to perform (e.g., solve problems) and learn in any given context. Bransford, Brown, and Cocking (2000) write, "one dimension of acquiring greater competence appears to be the increased ability to segment the perceptual field (learning how to see). Research on expertise suggests the importance of providing students with learning experiences that specifically enhance their abilities to recognize meaningful patterns of information" (p.36), and "it would be a mistake simply to expose novices to expert models and assume that the novices will learn effectively; what they will learn depends on how much they know already" (p.50). In other words, we need to give novices experiences to help build their fund of background knowledge so that they can learn to see and think like experts (who already have extensive background knowledge). This process takes time and practice, and learning with multiple representations can help people think flexibly.

Embodied Cognition

Embodied cognition is a movement in cognitive science that promotes an integral role of the body (or the body's presence in the environment) in cognition and not merely a vessel or input/output device for the brain. Wilson (2002) examines six claims of embodied cognition: cognition is situated in the real world and involves perception and action; cognition is time pressured; people offload cognitive work to the environment; the environment is part of the cognitive system and must be taken into consideration; the function of the mind is to guide action; and cognitive activity is based on mechanisms of sensory processing and motor control. The last of these claims is relevant to this study.

Wilson (2002) describes evidence in support of the notion that cognition has roots in sensorimotor functions. She describes an evolutionary process of counting on fingers, progressing to counting by tapping fingers, to performing the same function as what is basically a mental simulation of the same activity. She describes how mental imagery, including auditory and kinesthetic imagery as well as visual imagery, consists of representations that are analogous to their real-world counterparts (evidence of a cognitive link to visual, auditory, and kinesthetic functioning).

Evidence for embodied cognition can be seen in brain scans. Garbarini and Adenzato (2004) describe the neurophysiological support for embodied cognition. Certain neurons fire when a person observes an object, as if the observer was interacting with it. Other neurons fire when people observe other people interacting with objects, as if the observer himself were interacting with the object. These neurons are not, however, activated during motion that does not imply interaction with an object. According to Garbarini and Adenzato, "the existence of a mechanism coupling the execution and observation of actions decidedly confirms the role of the premotor area, not only in the planning of movements, but also in the representation of action in the abstract terms of its underlying purpose" (p.102).

There is further evidence for embodied cognition. *Subvocalization*, also known as *covert speech*, is the human process of translating print to sounds (Daneman & Newson, 1992) and has been shown to play a role in auditory imagery (Smith, Wilson, Reisberg, 1995). Processing of verbal information can be disrupted by keeping the "relevant articulatory muscles" busy repeating a nonsense word (Wilson, 2002, p. 633). Wilson (2002) also cites episodic memory, where events are relived "with all attendant visual, kinesthetic, and spatial impressions" (p.633) as further evidence of a sensorimotor link with cognition.

Gesturing while thinking is a common phenomenon. People making mechanical inferences often gesture while running mental simulations of mechanical systems (Hegarty, 2004; Hegarty, Mayer, Kriz, & Keehner, 2005). Hegarty, Mayer, Kriz, and

Keehner (2005) found that some people will even gesture with their heads when they are not able to gesture with their hands. Thomas and Lleras (2009) investigated the effect of directed actions on problem solving, and found that participants who were directed to move in a manner that suggested the solution to a problem were more likely to solve the problem than those who were directed to move in a manner contrary to the solution. This also suggests a link between kinesthetic functioning and cognition. If human cognition is rooted in sensorimotor functions as embodied cognition proposes, then physical manipulatives tap into cognition at a very primal level and may provide a more unconscious understanding of rigid body kinematics problems.

Cognitive Load Theory

Cognitive load theory (CLT) was initially developed in the 1980s and provides guidelines for instructional design based on human cognitive architecture (Paas, Renkl, & Sweller, 2003; Sweller, van Merrienboer, & Paas, 1998). CLT is based on the assumption that humans have a limited amount of working memory, which is short-term memory that is used to process information. Working memory can be thought of having simultaneous processors, a visual-spatial sketchpad that manages visual information as well as a phonological loop that manages auditory or verbal information (Baddeley, 1992). CLT asserts that instructional design must take into account the limitations of working memory and work to maximize efficiency of cognitive load on the learner, or aspects of a task that requires resources from working memory.

CLT specifies three types of cognitive loads: *intrinsic*, *extraneous* (or *ineffective*), and *germane* (or *effective*). Intrinsic cognitive load is dependent upon the *interactivity of* the elements of a task. A task that is said to have low-element interactivity, or low intrinsic load is one that can be reduced to a set of elements that do not depend on each other. An example of a task with low intrinsic load is transcribing the letters of a word in reverse order. In order to accomplish this task a person only needs to consider one letter at a time, beginning with the end of the word and working towards the beginning. The letters do not depend on each other and the task would be the same even if the "word" was a nonsensical jumble of random letters. If a task has inherently high-element interactivity then it causes a person to experience high intrinsic cognitive load. A task that is said to have high-element interactivity is one whose elements depend on each other and therefore need to be considered simultaneously in order to be understood. For example, finding all the possible words from a string of letters is a task with high intrinsic load. Such a task requires a person to consider what letters are available, which have been used already, whether a certain combination and sequence of letters actually makes a word, and also requires an extensive knowledge of vocabulary in order to be exhaustive. All the letters selected must be processed simultaneously and compared against a word bank of vocabulary.

Extraneous cognitive load comes from the way a task is presented. In education, this means that extraneous cognitive load comes from the instructional method. According to Paas, Renkl, and Sweller (2003), information stored in long-term memory is organized into *schemas*, which are cognitive structures that link related ideas into a grouping that serves a specific function. They describe extraneous load as unnecessary aspects of task presentation that "interferes with schema acquisition and automation" (p. 2). That is, extraneous load gets in the way of a person successfully retrieving relevant schemas from long-term memory into working memory. An example of a task that induces high extraneous load is solving a word problem that is written in unnecessarily complex, obscure, flowery, or otherwise difficult language, such that it causes the reader to have to determine what the word problem is even asking before working on the actual problem. An example of a task has low extraneous load is reading a stop sign—its presentation is simple and unambiguous.

Germane cognitive load also comes from the way a task is presented. Whereas extraneous load is unnecessary and impedes understanding, germane load (also known as effective load) aids in understanding. A task with high germane load is determining the orientation of an airplane relative to the ground (known as attitude) from an airplane attitude indicator (also known as an *artificial horizon*). This device is designed with lines resembling the cross-section of an airplane in the middle, and a floating background that is split horizontally such that the top portion is colored blue to resemble the sky and the bottom is colored brown to resemble the ground (see Figure 1). If the airplane cross-section is in the blue area the plane is heading up towards the sky. If the cross-section is in the brown area, the plane is heading toward the ground. The design decision to color code the background so that it resembles the real world increases germane cognitive load. On the other hand, a display that just shows numbers for the angle of inclination/declination and pitch of the plane would impart less germane load because, although it conveys the same information, a pilot would not have the visual cues to aid in understanding.

Figure 1. Airplane attitude indicator. The top portion of the background is blue and the bottom portion is brown. Lines in the middle of the display are fixed in the foreground and resemble the cross-section of an airplane. When the airplane cross-section is in the blue part of the background, the airplane is heading up into the sky. When it is in the brown part, the airplane is heading towards the ground. (Photo source: WikiMedia Commons: http://en.wikipedia.org/wiki/File:VMS_Artificial_Horizon.jpg)

Extraneous and germane load are not dependent upon each other. That is, reducing extraneous load does not necessarily increase germane load (although it might) or vice versa. Imagine a person running on a flat surface. Wind blowing in the opposite direction the person is running (a headwind) will work to hinder the runner and is like extraneous load impeding understanding. Wind blowing in the same direction as the person is running (a tailwind) will help the runner and is like germane load aiding understanding. The absence of the headwind does not indicate the presence of a tailwind, and likewise the absence of extraneous load does not indicate the presence of germane load. However, according to CLT, the sum of intrinsic load, extraneous load, and germane load cannot exceed the capacity of working memory. Therefore, after working memory resources are allocated to intrinsic load (which is inherent in the task and cannot be reduced), a reduction in extraneous load results in more working memory resources available for germane load (Paas, Renkl, Sweller, 2003). There appears to be a priority of working memory resource allocation in CLT between the loads, with intrinsic load taking first priority, then extraneous load, and finally germane load taking what is left over (if anything). CLT provides a basis for understanding how visualizations and physical objects can help students develop mental models of dynamic systems.

Mental Models

This study focused on how physical and virtual objects can help students visualize mechanical systems when solving dynamics problems. Thus, this dissertation was concerned with what is going on in the student's head: how a person represents knowledge, and how they operate with that knowledge. These mental representations are often described as *mental models* (Gentner & Stevens, 1983).

Breaking apart the term into its constituent words, one definition from Merriam-Webster (2012) is "occurring or experienced in the mind." *Model* is defined in many ways, two that are relevant to this study are "a description or analogy used to help visualize something (as an atom) that cannot be directly observed," and "a system of postulates, data, and inferences presented as a mathematical description of an entity or state of affairs" (Merriam-Webster, 2012). Although the second definition presented here for a model refers to mathematical models, the idea of a model being made up of "postulates, data, and inferences" is relevant to the concept of mental models.

Gentner and Stevens (1983) describe mental models research as "fundamentally concerned with understanding human knowledge about the world" (p.1). Norman (1988) defines mental models as "the models people have of themselves, others, the environment, and the things with which they interact," and says that people "form mental models through experience, training, and instruction" (p. 17). According to Norman (1983), people's mental models "provide predictive and explanatory power for understanding" (p. 7) their interactions with the environment, other people, artifacts, and technology.

From the definitions of the constituent words in the term, and the descriptions of mental models research and Norman's (1988) somewhat self-referential definition of mental models, I define a *mental model* to be a representation in a person's mind of knowledge, which is used to make predictions and generate explanations for some domain. Many researchers have various theories of mental models (Gentner & Stevens, 1983). The following sections describe major constructs of mental models from the literature and discuss how each informs the conceptualization of mental models in this study.

General Characteristics of Mental Models

According to Norman (1983), mental models are evolving constructs, and are formed through a person's interaction with a system. People's mental models are usually incomplete, unclear, and "unscientific" (people's "superstitious" beliefs about a system are part of their mental model of that system). He says that people's mental models are "parsimonious," that people will often trade more physical work for a smaller or less complex mental model (presumably because it saves mental effort). Furthermore, he says that people's abilities to *run* their mental models are "severely limited" (p. 8). The idea of *running* a mental model comes up often in mental models literature, and refers to a person's ability to insert some initial information into the model to produce some kind of outcome, which is then used to make a prediction or explanation.

Phenomenological Primitives

diSessa's (1983) version of a mental model is a collection of "recognizable phenomena" with which people see the world and explain how it works. These packets of recognizable phenomena are the basic building blocks of understanding, and are not broken down into smaller pieces. Each of these packets is called a *phenomenological primitive*, or *p-prim*. P-prims are typically generated as a result of a person's everyday experiences. An example of a p-prim is an explanatory phenomena that diSessa calls *Ohm's P-prim*, wherein an impetus acts through a resistance to produce a result. An increase in the impetus results in an increase in the result, and an increase in the resistance results in a decrease in the result. An example of this would be a ball that rolls on a flat surface and then goes up a hill (increased resistance) and slows down as a result. Other examples of p-prims include the *Dying Away* p-prim (things naturally decrease over time), and the *Force as Mover* p-prim (force causes motion in the direction of the force). According to diSessa, people notice certain salient features of a situation (such as a problem to solve) and these features cue specific p-prims. Appropriate application of p-prims to the situation results in successful inferences about the situation, but inappropriate application of p-prims to the situation results in faulty inferences.

diSessa (1983) describes how Ohm's P-prim is a good match as a mental model for understanding Ohm's Law in electricity, because voltage (the impetus) is affected by resistance to produce current, such that an increase in resistance results in a decrease in current, and an increase in voltage results in an increase in current. However Ohm's P-prim is also incorrectly invoked to make predictions (and generate explanations) for what happens to the sound a vacuum cleaner makes when the nozzle of gets blocked. Inappropriate use of Ohm's P-prim in this case leads some people to predict that an increase in resistance (the blockage) results in a decrease in the sound produced by the vacuum cleaner.

A p-prim perspective provides insight into how intuitive or everyday knowledge can play a role in the development of mental models. Instead of students holding coherent models or theories, mental models are often fragmented and inconsistent (diSessa, 1983, diSessa & Sherin, 1998). Slight changes in contexts can produce dramatically different results from students, depending on what p-prim, or intuitive knowledge, is invoked in the situation. Some cognitive perspectives on how people learn in STEM fields view students' alternative ideas (or misconceptions) as destructive, resistant to change and interfering with instruction (Carey, 1999; Strike & Posner, 1992). Instructional efforts are thus aimed to replace misconceptions with correct answers. However, recent research in how people learn view student conceptions as productive rather than destructive roles in the acquisition of expertise (Bransford, Brown & Cocking, 2000). That is, instruction should help students build upon existing ideas and provide ways to sort and refine ideas and connections (Linn & Eylon, 2006). Building upon a p-prim perspective in terms of mental models of dynamics systems, students may have intuitive ideas about how systems work based upon their interactions with the everyday world, and instruction should help students to connect, refine and revise mental models.

Mappings

Young (1983) describes a form of mental model that is a mapping between a task and the actions required to perform the task. These are simplistic models that are basically lookup tables that someone uses to determine how to do something (algorithmically) in order to accomplish the task. An example of this might be someone who is new to electronic mail and wants to send a message. That person might have a procedure to accomplish the task of sending a message which might consist of finding a message in the inbox from the person the new message is for, opening the message, then clicking the reply button, writing the new message body, and clicking the send button. This individual does not have any more knowledge of the electronic mail system and how it works beyond a set of routines to accomplish such tasks.

This type of mental model describes how students may develop simplistic, procedural knowledge to solve problems in Dynamics. Instead of understanding underlying concepts and principles, students may develop particular strategies for solving particular types of problems within kinematics or kinetics. This is often seen in novice physics students, who learn particular procedures to solve problems without understanding of the underlying mechanics principles. For example, Larkin (1983) describes how novices often solve physics problems by using a *means-ends* strategy where they begin with mathematical equations representing physics principles and then try to transform them into an equation that will solve the problem, without analyzing the physics of the problem scenario and applying theory. Thus, students' mental models of a mechanical system may simply be an algorithmic view of how to solve superficial groups of problems.

Structure-Mapping Theory of Analogical Thinking

Gentner and Gentner (1983) describe how people use analogies of familiar systems to understand, explain, and predict the behavior of unfamiliar systems. Their structure-mapping theory describes how the relations and objects of one domain map to the relations and objects of another domain. There are two structural rules. The first rule, called *Preservation of Relationships*, specifies that relationships in the base domain exist in the target domain between corresponding objects. The second rule, called *Systematicity*, specifies that a relationship in the base domain is more likely to exist in the target domain if it is part of a cohesive system of relationships in the base domain that is also valid in the target domain. An example of analogical thinking is the water analogy for understanding electricity, in which the electrical system is modeled as a plumbing system. An inference drawn from this analogy is that electric current is analogous to water flow rate, and voltage is analogous to water pressure.

Research demonstrates that analogies can be powerful tools to help students develop understanding of unfamiliar systems (Duit, 1991; Vosniadou & Ortony, 1989). However, similar to the p-prim perspective, research demonstrates that many students may make faulty mappings between base and targeted domains (Dagher, 1995). Students can draw incorrect inferences based on known characteristics of the base domain that do not map onto the targeted domain. In the water example, many students make incorrect assumptions about electricity based on properties of water. Thus, it is important to consider analogical thinking in the development of mental models.

Mechanistic Mental Models

Certain mental model theories specifically relate to how a person reasons about a physical system. de Kleer and Brown (1983) call these *mechanistic mental models*. I define mechanistic mental models to be those in which a physical system is represented by a corresponding visual mental model of the device, and this model can be *run* in one's mind in order to make inferences about how the physical system operates. This definition is similar to Young's (1983) *surrogate model*, which is a mental model that stands-in for an actual physical device in making predictions about the behavior of the device. However, while a surrogate model will allow someone to determine outputs of a mechanism based on inputs, it does not aid in understanding how the mechanism actually produces outputs. In effect, a surrogate model is Young's mapping theory applied to mechanical reasoning. A surrogate or mechanistic mental model can be at varying levels of abstraction, depending on the prior knowledge and expertise of the person, as well as the complexity of the physical system.

Other researchers further conceptualize mental models in terms of prior knowledge. Larkin (1983) describes mental models as *naïve* and *physical* representations; with particular attention to the role these models play in the reasoning of novices and experts within a domain (in this case, physics). According to Larkin, novices have a *naïve representation* of physics problems, which is composed of objects that exist in the real world (such as blocks, pulleys, and springs). Experts use the naïve representation also, but also construct a *physical representation* (also a mental construct) that is basically the naïve representation with the addition of "imagined entities such as forces and momenta" (p.75). The naïve representation can be run, explicitly involves time, and is animated in real time. The problem context influences inferences made using the naïve representation. In contrast to the naïve representation, the physical representation (used by experts) does not involve time, and inferences are context-free. Experts are able to connect their conceptual understanding of topics such as energy and force to the naïve representation to build a more sophisticated mechanistic mental model. The inability of novices to construct the "physical" representation, or to make connections to underlying concepts, leads to their inability to solve problems that experts can solve. This theory is relevant to this study in that it explains how students who struggle to solve dynamics problems may be experiencing difficulty constructing the "physical" representation, or may be attempting to rely entirely on running their naïve representation.

Williams, Hollan, and Stevens (1983), in their research on human reasoning about physical systems, define a mental model as a collection of connected mental objects, each with "an explicit representation of state, an explicit representation of its topological connections to other objects, […] a set of internal parameters," and "a set of rules which modify its parameters and thus specify its behavior" (p. 133). Furthermore, they say that a mental model can be run by "modifying the parameters of the model by propagating information using the internal rules and specified topology" (Williams, Hollan, & Stevens, 1983, p. 133). Williams, Hollan, and Stevens note that people use multiple mental models to understand the same system, switching between them when one or the other fails to produce satisfactory inferences. Thus, students may not have just naïve or just physical representations of dynamics problems, but may use naïve representations in some cases and physical representations in some cases, and even have particular parameters to govern when certain kinds of mental models are employed.

de Kleer and Brown (1983) describe a theory of *qualitative simulations*, which derive from "the common intuition of 'simulating the machine in the mind's eye'" (p.155). The authors make the distinction between constructing the qualitative simulation (called *envisioning*), and *running* the simulation (actually, running the results of the envisioning process). This is a fairly complicated theory that seems to focus on identifying and naming parts of the qualitative simulation, as well as steps and products in the process of creating and running the simulation. Like Williams, Hollan, and Stevens' model, this is a direct representation of a mechanical system. It is also similar in that respect to Larkin's representations (the running part is similar to Larkin's naïve representation in that they are both run, but the complexity of this model is more descriptive than Larkin's "physical" model). One of the key ideas in deKleer and Brown's theory is that the model is made up of components (the component model) whose interacting behaviors constitute a causal chain. This is directly relevant to the kind of thinking that students need to engage in for solving rigid body kinematics problems.

Similar to *qualitative simulations, mental simulation* refers to trying to determine how a mechanical system will move by creating and running a mental model (simulation) of the mechanical system (Hegarty, 2004). The mental simulation is not a holistic representation of the machine, however, but rather a piecemeal one that may or may not connect to a coherent whole. For example, a mental simulation of a pulley system is not analyzed as an entire machine with all of its parts operating simultaneously, but as a stepwise causal chain. If a person is asked what happens to a bucket attached to a pulley, connected to the end of a rope that is wound through a series of pulleys, that person analyzes the behavior of the system one pulley at a time, stepping down the causal chain, rather than running the whole system simultaneously and immediately *seeing* what happens to the bucket. This analysis behavior can be understood in terms of cognitive load theory, where the problem space is reduced from the entire pulley system to what happens between two pulleys, in an attempt to reduce intrinsic cognitive load and thereby not overwhelm working memory.

The mental simulation is not merely a visual representation of the machine. It also incorporates non-visible entities and properties, like force (Hegarty, 2004), similar to the physical representation described by Larkin (1983). When people run their mental simulations to make inferences about the behavior of the machine, they often use gestures that simulate the motion of objects, such as using their fingers to trace the direction of rotation of gears in a system of gears (Hegarty, 2004). This also suggests that there may be motor representations in mental simulations, and how embodied perspectives may contribute to how people learn and understand mechanistic systems.

Hegarty's framing of mental simulation builds upon previous mental model frameworks (e.g. Young's surrogates; the collection of autonomous objects described by Williams, Hollan, and Stevens; and deKleer and Brown's qualitative simulations). It articulates how students may think of rigid body kinematics as sequences of causal steps and incorporates gestures or physical movement into mental models.

Mental Model Frameworks for this Study

Each of these perspectives provides insight into the kinds of mental models of dynamic systems that students may have or develop during instruction. This study builds from these frameworks to explore what kinds of mental models students use while solving kinematics problems.

Background

Visualizations

Visualizations have the potential to improve understanding of dynamic systems by helping students develop robust mechanistic mental models. *Visualizations* in education are external graphical representations (Chiu, 2010). They can be static (such as diagrams in a textbook) or dynamic (video and animations), and they can be interactive or non-interactive (Honey & Hilton, 2011). CAD software programs in engineering provide static (such as mechanical drawings) and dynamic visualizations (such as three dimensional mechanical assembly simulations) that are both interactive and non-interactive. Dynamic visualizations such as animations provide the learner with the obvious advantage over static graphics of depicting motion in a more direct way. Animations also offer other affordances, such as the ability to add and remove objects, and change properties of objects (Lowe, 2004). Research has shown that learning with animations tends to be better than learning with static pictures (Höffler & Leutner, 2007).

For example, Boucheix and Schneider (2009) investigated the effect of static versus animated presentations on student learning of pulley systems. Specifically, they compared learning from a single static diagram; multiple static diagrams depicting a time sequence of the operation of the pulley system, simultaneously presented side-by-side (called *integrated sequential static frames*); the same time sequence presented one (and only one) diagram at a time (called *sequential independent static frames*); and an animation of the pulley system operating. They found that student performance on a comprehension test was similar for those exposed to integrated sequential static frames (simply called *integrated sequential*) as those exposed to the animation. Student performance for integrated sequential and animated was higher than for students exposed to the sequential independent static frames or the single static frame. Students of both high and low spatial reasoning abilities benefitted from the integrated sequential static frames and animation, but those of low spatial reasoning ability benefitted more. Students of low ability benefitted from being able to control the animation, whereas there was evidence of a negative effect on the comprehension of students of high ability. The effect of user control on comprehension (positive for low ability, negative for high ability) was attributed to time spent studying the animation. Low ability students spent more time studying the animation than students of high ability, and this was correlated with performance on the comprehension test.

Höffler and Leutner (2011) investigated the role of spatial ability in learning from animations. They found that students with high spatial-visualization ability are able to learn from static diagrams better than students with low spatial-visualization ability. Animations appeared to be better suited for students with low spatial-visualization ability. They say that the construction of mental animations from static diagrams requires spatial ability, whereas animated materials do not require the learner to have high spatial ability.

However, merely interacting with visualizations does not guarantee learning. Linn, Chang, Chiu, Zhang, and McElhaney (2010) describe a phenomenon of *deceptive clarity* of visualizations. This occurs when students “become convinced they understand complex processes when they can recall only superficial features of what they have seen” (p.237). Deceptive clarity can especially be a problem in cases where a learner is passively observing visualizations depicting phenomena that they would otherwise not be able to see. Linn et al. (2010) describe how a student may just see a bunch of bouncing balls instead of aspects of molecular theory from an animated visualization. Rozenblit and Keil (2002) describe a similar phenomenon, called *illusion of explanatory depth*. They say that people tend to think they understand complex phenomena better than they actually do. People are not aware that their understanding is deficient until they are challenged to actually explain their understanding. Regarding mechanical systems, illusion of explanatory depth appears to be related to the visibility of the mechanical system. The more apparent the operation of the system seems, the greater the illusion of understanding.

Physical and Virtual Manipulatives

Although visualizations can help students develop mental models of mechanical systems, interacting with physical objects has particular benefit to students. Hands-on learning with physical objects (known as *physical manipulatives*) is often seen as a superior way of learning (Sarama & Clements, 2009) and has a long history in education (Manches, O’Malley, & Benford, 2010). Physical manipulatives such as blocks and sticks have been used to teach topics in math, such as numbers and counting (Sarama &

Clements, 2009). Science lab experiments with physical apparatuses are also a form of physical manipulatives. The advent of computer technology has, however, introduced the concept of *virtual manipulatives*: computer-based versions of traditional physical manipulatives. Since the use of virtual manipulatives is newer than the use physical manipulatives much of the research tends to focus on what virtual manipulatives offer, or a comparison of virtual and physical manipulatives (Zacharia & Olympiou, 2011).

As with all computer software, virtual manipulatives enjoy certain benefits, such as a high degree of control by the designer, ease of replication, flexibility in representation, and minimal physical space requirements (a computer workstation as opposed to, say, a hallway or large floor space for some physical experiments) for use as well as storage. Virtual laboratories also offer the advantage of safety and cost-effectiveness that may not be present in a physical laboratory environment where there may be chemical or physical hazards and expensive materials might need to be consumed. According to Sarama and Clements (2009), virtual manipulatives also mirror mental actions on objects better than physical manipulatives, whereas physical manipulatives can actually hamper learning by allowing children to attend to different details, processes, and perspectives than intended by instruction. In her study of students learning about work and energy in simple machines, Chini (2010) found improved student learning when a virtual experiment precedes a physical experiment.

Different affordances and constraints of physical and virtual manipulatives can affect learners' problem-solving strategies. Manches, O'Malley, and Benford (2010) studied young children who used physical and virtual manipulatives to describe the ways a number can be decomposed into two numbers (for instance, the number three can be decomposed as 0+3, 1+2, 2+1, and 3+0). They found that children using physical manipulatives, with the affordance of moving entire groups of blocks at a time, would tend to distribute the blocks evenly (the idea of fair sharing that is commonly taught in early schooling), whereas children using virtual manipulatives tended to just move one block at a time (because the software operated in that manner).

Prior knowledge may play a role in the effectiveness of virtual and physical manipulatives. In their study of learning math with virtual manipulatives Moyer-Packenham and Suh (in press) only observed significant gains for low-achieving students (as opposed to average- and high-achieving students). The interesting finding from their study was that nature of interaction for each of the achievement groups differed. The low-achieving students tended to rely more on the pictorial representations of the virtual manipulatives than the other groups, and engaged in more trial-and-error interactions with the virtual manipulatives.

Some research, however, has found no difference in student outcomes between the use of physical and virtual manipulatives. Triona and Klahr (2003) found no difference between the use of physical equipment and virtual equipment for students learning to design science experiments. Students who learned using virtual equipment were also able to perform equally well as students who used physical equipment on a transfer task involving designing another experiment using physical equipment. They suggest that the virtual experience incorporated the relevant aspects of the learning task, and therefore physicality was not necessary. Physical manipulatives would be more suited if the development of a motor skill is the learning objective. Similarly, Klahr, Triona, and Williams (2007) found no difference in student learning or confidence when learning how to design mousetrap cars using physical or virtual manipulatives. The mousetrap car study differed from the experimental design study in that it investigated the use of physical and virtual manipulatives in the context of discovery learning as opposed to direct instruction. Results suggest that, since there is no difference in student outcomes between the use of physical and virtual manipulatives, virtual manipulatives may be preferred due to their other advantages (previously mentioned) over physical manipulatives. Zacharia and Olympiou (2011) compared physical labs, virtual labs, and sequences (physical then virtual, or virtual then physical) against traditional instruction without manipulation in learning about heat and temperature at the collegiate level. They found no difference between all of the treatment groups, but found a difference between the treatments and the control (traditional instruction without manipulation) in favor of the treatments. Their results suggest that physicality is not important in learning for this domain, but that the hands-on aspect of manipulatives (physical or virtual) is important. Since prior research presents mixed results in terms of relative advantages of physical or virtual objects on learning, this dissertation investigates both conditions compared to the traditional method of instruction.

Dynamics Education

This section surveys successful technology-based instructional approaches in dynamics education, including computer-based instruction, computer-aided design and virtual environments, as well as non-technology approaches such as hands-on activities and different pedagogical approaches.

Supplementary Computer-Based Instruction

A common approach to addressing student difficulties in engineering mechanics is to use computer-based instruction (CBI), sometimes called computer-aided instruction (CAI), as a supplement to traditional classroom instruction (i.e., lecture). This often takes the form of a series of instructional modules, in which instruction and problems similar to those found in textbooks are either presented to, or worked on, by students. A key aspect of the CBI/CAI versions of these problems is the ability to present animated problem representations, sometimes as passive experiences, but also as interactive simulations. These computer based modules are generally met with positive responses from students (Flori, Koen, & Oglesby, 1996; Kumar & Plummer, 1997; Staab & Harper, 2000; Deliktas, 2009).

Flori, Koen, and Oglesby (1996) describe Basic Engineering Software for Teaching ("BEST") Dynamics, an example of one such CBI package. In their study, students periodically solved problems in BEST Dynamics as part of homework assignments over the duration of a course in Dynamics. Although the software "clearly helped students in the visualization of problems" (p.65), the researchers did not observe improved performance as reflected by exam scores. They felt that the system definitely promoted learning, but that a different form of assessment (one focused on the ability to visualize) was needed to identify this learning. According to Flori, Koen, and Oglesby, much of a Dynamics class consists of the instructor working out problems step-by-step for students, and that the software does a good job of replacing at least part of this activity by providing students with the ability to see many problems worked out (either by the software or assisted by the software) quickly and efficiently. They also observed that students who had used the software were more likely to use solution strategies modeled by the software than those students who did not use the software.

Use of Computer-Aided Design

Computer-aided design (CAD) has been used in engineering education as a means of helping students develop a more intuitive form of mechanical understanding. Bhatt, Tang, Lee, and Krovi (2008) describe how CAD models help students analyze complex mechanisms and understand the motions of the mechanisms. They say, however, that a disadvantage of CAD systems is that they hide the math behind the models, possibly hampering the students’ abilities to learn the theoretical analysis. They recommend using CAD as an intermediary between traditional classroom lecture and a more experiential approach.

Onyancha, Derov, and Kinsey (2009) used CAD to improve students’ spatial reasoning abilities. They used software, in addition to CAD software, which allows students to see multiple views and rotations of CAD models. Exposure to this targeted spatial training resulted in improved performance on a test of spatial reasoning, beyond that which would be expected from regular CAD use alone. This aligns with other research demonstrating that specific, focused practice can help students develop spatial and visualization skills (Sorby & Baartmans, 2000).

Virtual Environments

Efforts have been made to improve engineering education through the use of virtual environments (sometimes called laboratories). Koh, Tan, Tan, Fang, Fong, Kan, Lye, and Wee (2010) found that students learning to use machinery involved in Mechanical Engineering processes, who were first given experience with virtual (simulated) versions of the machines, expressed increased levels of motivation and improved learning. Their simulation-based learning modules were designed to prepare the students for actual workshop experience and to complement regular instruction.

Koretsky, Kelly, and Gummer (2011) found that students were able to suspend disbelief and seriously engage with industrially situated virtual laboratories. They found that while the learning was different between the virtual laboratories and physical laboratories, the virtual laboratories provided "the potential for a rich learning experience" (p.540).

Murphey (2008) describes a course where senior- and graduate-level electrical and computer engineering students learned rigid body mechanics by creating their own virtual environments and mechanical models in *Mathematica*. These students did not have any knowledge of mechanics past their introductory physics courses, and the math they used to build the environments and models did not involve anything more complicated than calculus. According to Murphey, "by the end of the pilot class, the majority of students were able to expertly model and animate high degree-of-freedom systems" (p.45).

Hands-On Activities

Dalrymple, Sears, and Evangelou (2011) investigated the potential of *disassemble/analyze/assemble* (DAA) activities, also known as *reverse-engineering*, to motivate students and promote transfer in engineering education. They found that, compared to the standard approach of analyzing the target functions of a device, breaking it down into subfunctions, then creating designs to meet those requirements, students rated DAA activities higher on measures of motivation (enjoyment, sense of learning, and task helpfulness). Tests of transfer also appeared to favor DAA activities over the traditional method. The authors suggest that specific knowledge of components and mechanisms is needed for “becoming a better design engineer” and that DAA activities are particularly well suited toward developing this knowledge.

Restructuring Pedagogical Approaches

Other attempts to address mechanics education have taken the form of restructuring instruction. Gray and Costanzo (1999) reported on an effort to implement a *studio approach* in dynamics course. The studio approach involved integrating lecture, recitation, and labs into a “single learning experience,” as well as reorganizing the classroom physically and providing access to computers for all students. Howell (1996) introduced cooperative problem solving activities into a Dynamics course. This effort was initially met with skeptical responses from students, but later embraced and received a positive reaction.

There have also been attempts to improve students’ spatial reasoning abilities through the creation of courses designed to address student deficiencies at spatial-visualization (Field, 1999; Sorby & Baartmans, 2000). According to Field (1999), freshman engineering students do not possess any higher spatial reasoning ability than the general university population, and “conventional” engineering courses do not do much to improve it. Field (1999), and Sorby and Baartmans (2000) report improved student performance on measures of spatial ability, as well as other dimensions (such as graphics performance and retention), as a result of participation in these courses.

Summary of Existing Research

Visualizations in education are external graphical representations, and can be static or dynamic, interactive or non-interactive. Animations are a type of dynamic visualization and have been shown to generally be more effective in education than static diagrams. Visualizations tend to support lower performance and lower spatial ability students more so than higher performance and higher spatial ability students. Learners may pay attention to the superficial features of a visualization and not learn what is intended, and they may also overestimate their understanding when viewing visualizations.

Physical manipulatives, such as blocks and science apparatuses, have been used extensively in education. Computer technology has allowed the creation of virtual manipulatives—computer versions of physical manipulatives. Virtual manipulatives afford advantages over physical manipulatives, such as increased control, ease of replication, flexibility, and often less physical space requirements. Virtual manipulatives may also more closely mirror cognitive processes, and research has shown that science learning can be improved when virtual experiments precede physical experiments. Virtual manipulatives may, however, affect students' problem solving strategies by limiting certain actions while enabling others. Virtual manipulatives may also provide more benefit for low-achieving students more so than high-achieving students. Research has shown that students of different achievement groups tended to interact with, and rely on, virtual manipulatives differently. Much research has often shown no difference in student outcomes from learning with physical versus virtual manipulatives.

Efforts to improve engineering education, and Dynamics in particular, have been varied. In Dynamics, educational researchers have introduced computer-based instruction (CBI) and reported positive student outcomes. The CBI usually consists of multiple multimedia instruction modules (sometimes including interactive simulations), covers all of the topics in Dynamics, and is a supplement to traditional instruction. There have also been efforts to use CAD more in attempts to increase students' mechanical analysis and spatial reasoning abilities. Researchers also introduced virtual laboratories; both as a preparation for work in physical laboratories, and also a way to expand students' laboratory experiences. Having students build simulations of dynamic physical systems also appears to help students learn mechanics.

Other related efforts to improve engineering education include the use of hands-on activities and restructuring pedagogical approaches. Reverse-engineering activities in which students disassemble, analyze, and reassemble physical artifacts allow students to see how they work and think about how they can be improved. Efforts to reform pedagogy include restructuring curricula, teaching methods, and physical classroom space. An example is the introduction of courses specifically intended to improve students' spatial reasoning abilities.

Limitations of Existing Research

Much of the research in visualizations just compares static versus dynamic visualizations and does not compare virtual representations to physical representations.

Much of the research in manipulatives compares virtual manipulatives to physical manipulatives and does not compare manipulatives to static visual representations. Studies investigating the introduction of CBI and simulations in Dynamics do not compare the use of these to the use of physical manipulatives, but instead compare their use to their absence (traditional instruction). The same applies to other efforts in engineering education reform: they compare the specific treatment against the traditional method. For Dynamics, a subject about the motion of physical systems that is traditionally taught using static diagrams, the logical question to ask is what happens if we teach it using moving physical systems (i.e., machines) or computer simulations of those moving physical systems, and how do these compare to the traditional method? Existing research does not answer this question.

CHAPTER 3

METHOD

For this study I investigated the research questions in Table 1 using a mixed methods (quantitative and qualitative) approach. These questions were investigated in the context of a Dynamics class offered at a public university in the mid-Atlantic region of the U.S. This chapter details the method I implemented, the instruments I used, and the methods I used to analyze the data.

Table 1

Mapping of Data and Analysis Methods to Research Questions

Research Question	Data	Analysis Method
1. How does student performance compare for students with instruction supplemented with physical manipulatives, instruction supplemented with virtual manipulatives, and traditional methods of instruction?	Pretest performance (spatial skills and prior dynamics understanding) Speed (minutes) and accuracy (% correct) on posttest. Pre- and posttest open response answers	Quantitative: descriptive statistics (mean, standard deviation), ANCOVA (pretest performance as covariate), statistical analysis of contingency tables Qualitative: content analysis
2. How do students use static diagrams, physical manipulatives, and virtual manipulatives when learning rigid body kinematics?	Video observation	Qualitative: grounded theory
a. What kinds of mental models of mechanical systems do students develop using static diagrams, physical manipulatives, and virtual manipulatives?	Pre- and posttest open response question answers	Qualitative: content analysis
3. What do students think about static diagrams, physical manipulatives, and virtual manipulatives as learning aids?	Questionnaire responses	Qualitative: content analysis

Context and Participants

This study was conducted as part of classroom instruction in Dynamics in the Spring 2013 semester. The class met twice a week for a lecture period (each lasting one hour and fifteen minutes) and was scheduled to meet once a week for an evening lab session (lasting two hours). Dynamics is a required three credit-hour course in the fourth semester for students in the Mechanical Engineering and Aerospace Engineering programs at the institution. Dynamics is also an elective for Civil Engineering majors. Dynamics had an enrollment of 138 students. Of these, 107 consented to participate in the study. Participants that did not participate in all of the problem-solving (treatment) sessions, did not take the pretest or posttest, or who explicitly stated that they wished to withdraw from the study, were removed from the study. After attrition, the study considered data from 70 participants. The vast majority of the attrition occurred due to failure to participate completely in the treatment.

Responses to the background questionnaire describe the participants as:

- 73% male, 27% female
- 94% majored in Mechanical/Aerospace Engineering
- 76% white, North African, or Middle Eastern; 10% Asian or Pacific islander; 10% black or African-American; 4% Hispanic or Latino
- 93% were in second year of the undergraduate program
- 94% had taken high school Geometry
- 24% had taken industrial arts prior to college
- 84% admitted to playing computer games
- 100% reported having played with construction toys (e.g., blocks, erector sets) as children
- 89% had prior experience working with Computer Aided Design
- 49% had prior experience in a construction- or assembly-related occupation
- 89% were right-handed

Operational Definitions of Key Constructs and Variables

Student Performance

Student performance is defined as speed and accuracy solving dynamics problems, and the ability to accurately describe the behavior of a machine given a static diagram of it. Speed is measured as the elapsed time from beginning to end (submission) to complete the posttest. Accuracy solving dynamics problems is measured as the percentage score of correct items on the posttest.

Speed and accuracy are operationalized in different ways. Speed is the amount of time in minutes that a student took to complete the multiple-choice portion of the posttest. Accuracy is operationalized in two different ways depending upon the measure. The first way is the percentage of correct items on the multiple-choice section of the pre- and posttests. These items are divided into spatial and conceptual, hence accuracy on the multiple-choice portion may be measured as spatial, conceptual, or total score. Accuracy is also operationalized as being able to correctly describe the behavior of a machine given a set of initial conditions and a static diagram of the machine. Examining student descriptions of machines and noting the presence of salient discriminating characteristics of the behavior of the machine measure this form of accuracy.

Instruction

Instruction was comprised of classroom lecture by the instructor on the topic of rigid body kinetics, and an in-class problem solving session using the treatment models (static diagrams, virtual manipulatives, or physical manipulatives) for the particular treatment group. The lecture periods met twice a week in the morning, and consisted of lecture and problem solving by the instructor. The problem solving sessions were scheduled to meet once a week in the evening, on one of the same days that there was a morning lecture period. The pretest, treatment problems, posttest, and opinion questionnaire were administered during the evening problem solving sessions.

Traditional Method

The traditional method consisted of classroom lecture by the instructor on the topic of rigid body kinetics, and problem solving using static diagrams. All of the students also had access to written homework solutions and video recordings of the instructor solving homework solutions step-by-step. These were available on the university's course web site. The students also had access to the Mastering Engineering web site (http://www.masteringengineering.com) and were assigned problems to solve on that site (with the benefit of automated hints and scoring). Mastering Engineering provides videos of an instructor solving dynamics problems in the same manner as an instructor would do during a class lecture period.

Static Diagrams

Static diagrams are diagrams of dynamic mechanical systems typically found in Dynamics textbooks. The particular diagrams that were used in this study were like those in the dynamics textbook used in the class (Hibbeler, 2012) along with other static diagrams that the instructor used as part of lectures for the whole-class (see Fig. 2).

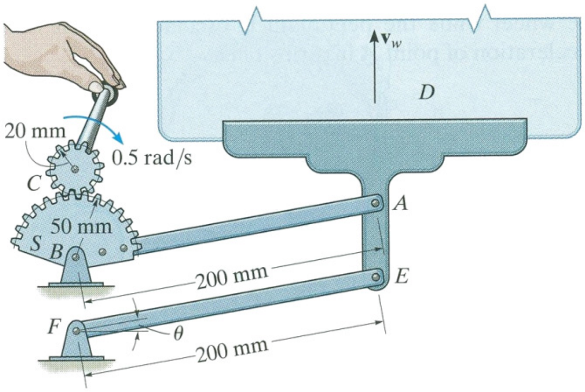

Figure 2. A typical static diagram for a dynamics problem. From R. C. Hibbeler, 2010, *Engineering Mechanics: Dynamics* (12th ed.), p. 324. Copyright 2010 by Pearson Prentice Hall. Used with permission.

Virtual Manipulatives

The virtual manipulatives were 3D interactive animated models of the same mechanical systems described by the static diagrams. These models were realized as *assemblies* in the Autodesk Inventor CAD software package. Participants in the Virtual group loaded the appropriate assembly file in Autodesk Inventor and used a mouse to click and drag parts of the assemblies within the CAD system in order to actuate the moving parts.

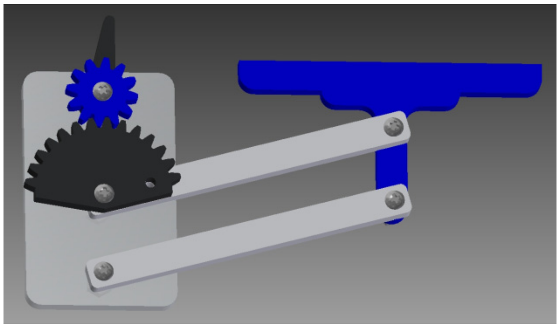

Figure 3. A virtual manipulative.

Physical Manipulatives

The physical manipulatives are models that were assembled from plastic parts cut, using a laser, from quarter-inch-thick sheets of acrylic (plastic), using the same designs for the virtual models that were created in Autodesk Inventor. Each pair of participants in the physical manipulatives treatment group had one model for each problem they worked on during the problem solving sessions. Participants used their hands to actuate the moving parts of the physical manipulatives.

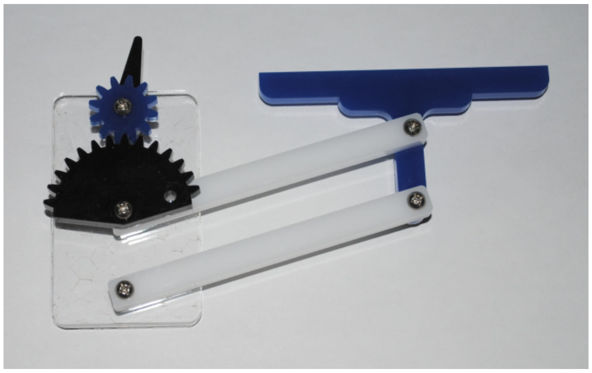

Figure 4. A physical manipulative.

Mental Model

Mental models in this study are inferred constructs of individuals' mental representations of dynamic systems based on explanations of how machines behave. Table 2 presents types of mental models, indicators, and example student excerpts used in this study based on the review of the literature.

Table 2

Indications of Mental Models

Possible types of mental models	Indicators of model types	Example indicators
Intuitive, everyday knowledge (diSessa, 1983)	Statements about everyday interactions with objects	"If I push on a door, that will…" or "when my bike wheel hits the ground…"
Procedural mappings of problems (Young, 1983)	Statements about problem types and references to solution procedures	"The ω at O and A can be related and then v_B can be found using θ." Presence of formulas.
Analogical models (Gentner & Gentner,1983)	Statements referring to analogical systems	"Looks like the reverse piston in an engine. This machine converts rotational energy to translational energy."
Naïve representations (Larkin, 1983)	Statements only referring to structures of systems	"This problem has a gear and two linkages"
Physical representations (Larkin, 1983)	Statements connecting structures to underlying dynamics concepts such as force or moment	"This problem has a gear that is going to produce this force in this direction on this linkage"
Mental simulation (Hegarty, 2004)	Statements of a sequential causal chain of events	"This problem starts with a gear that will rotate in this direction. It will produce a force in this direction on this linkage. The linkage will then…" Description of the operation of intermediate components in a causal chain. Drawings (e.g., arrows) indicating the behavior of intermediate components in a causal chain.

Instruments

Pretest/Posttest

The pretest consisted of four open response questions asking students to describe how given machines work, nine questions from the Purdue Spatial Visualization Test (PSVT; see Appendix D), and the complete Dynamics Concept Inventory (DCI; 29 questions). The posttest was exactly the same as the pretest, with an additional two open response questions.

Purdue Spatial Visualization Test

The *Purdue Spatial Visualization Test* (PSVT) is a commonly used test of spatial reasoning ability that was developed in 1976 by Roland Guay. It has four forms: the PSVT, the *PSVT: Visualization of Developments* (PSVT:D), the *PSVT: Visualization of Rotations* (PSVT:R), and the *PSVT: Visualization of Views* (PSVT:V). The basic PSVT consists of three sections: *Developments*, *Rotations*, and *Views*, each consisting of 12 questions for a total of 36 questions. Each of the other three tests (PSVT:D, PSVT:R, and PSVT:V) consist of 30 questions. These other three forms are specialized tests that concentrate on only one of the three sections covered by the basic PSVT. I selected three problems, one from the beginning, middle, and end, from each of the three sections (developments, rotations, and views) for use in the pre- and posttests.

Dynamics Concept Inventory

The Dynamics Concept Inventory (DCI) is a 29-question multiple-choice exam that covers topics in rigid body dynamics and particle dynamics (Gray, 2010). It was first developed in 2002 and released in 2005. It was used for both the pretest and posttest. Analysis of responses was restricted to 19 questions that the instructor identified as those that students were expected to be able to answer by the time of the posttest.

Student Opinion Questionnaire

Participants were asked to respond to a questionnaire regarding their opinions of using the static diagrams and dynamic manipulatives (virtual or physical, as appropriate) as learning aids (see Appendix G). Participants were asked to respond to the questionnaire after taking the posttest, and received it in paper form.

Video Recordings

Video recordings were used as a supplement to field observations in order to obtain qualitative data about how participants actually used the static diagrams and manipulatives.

Design

Treatment

This study used a quasi-experimental design with a convenience sample and sequential assignment. Participants were sorted by pretest performance, and then sequentially assigned to one of three treatment groups, with the goal of creating groups that had as balanced a composition of participants as possible. The three treatments were:

- Traditional: lecture + static diagrams
- Physical: lecture + static diagrams + physical manipulatives

- Virtual: lecture + static diagrams + virtual manipulatives (CAD models)

During the problem solving sessions, I randomly selected one pair of participants from each treatment group to be video recorded. I analyzed the video recordings qualitatively to look for common themes in how students actually used the diagrams or manipulatives. Posttest data measured speed and accuracy of students' conceptual problem solving abilities, spatial abilities, and mechanical reasoning. I analyzed the posttest data quantitatively to see if there was a relationship between speed/accuracy of problem solving and type of treatment received. Participants answered post-treatment questionnaires, providing their opinions on whether the diagrams and/or manipulatives were useful and, if so, how they were useful. I analyzed questionnaire responses qualitatively using a grounded methodology, looking for common themes in the responses.

Procedure

Problem selection. Prior to the beginning of Dynamics, in the previous semester, an instructor selected problems from the textbook that, in total, covered the four subtopics within rigid body kinematics: absolute, relative velocity, instant centers and relative acceleration, and rotating axes. The criterion for the first round of problem selection was that the problems should be challenging for students to solve, with the expectation that students would work on the problem for 20 minutes and be required to refer to the model repeatedly. I then selected four problems from this set, looking for the problems that had the most components involved in a causal chain of events, and/or required analysis of simultaneous action/interaction. Each problem was originally intended to be the focus for a separate 20-minute problem solving breakout session at the end of the lecture period on the pertinent topic. This was changed due to scheduling concerns such that two problems at a time were worked by students at each of two evening problem solving sessions. Students were allocated the first hour of the problem solving sessions to work on the problems but, with startup and room transition delays, the time spent was approximately 40-45 minutes total for each session.

Creation of manipualtives. After the problems for the problem solving sessions were identified, I created the corresponding virtual manipulatives using Autodesk Inventor. The textbook diagrams did not provide all of the specifications for the machines, so I had to determine what they would be by measuring the diagrams and then scaling the measurements appropriately (based on the measurements that were provided). I used the measurements obtained through this process to create CAD models in Inventor, keeping in mind practical aspects such as the method of construction and assembly, requirements for fasteners, and how the students would use the devices. I used the 3D models to produce drawing files for Corel Draw, which then "printed" the drawings on a laser cutting machine. Instead of printing the drawings on paper as a printer would do, the laser cutter cut the parts out of quarter-inch-thick sheets of plastic. I then assembled the resulting parts using machine screws, nuts, and glue. Due to the fact that I used sheets of plastic as the basis for the physical models, I had to design the CAD models in quarter-inch-thick layers. The designs were also driven by the length and diameter of the screws that I decided to use, and the clearance required for nuts. I created 20 units for each of the four machines, for a total of 80 units. It took 15-20 hours to cut the parts for all of the machines, and about the same amount of time to assemble them. Each unit cost approximately $25 in material, with about 72% of the cost from the plastic and the remainder from fasteners.

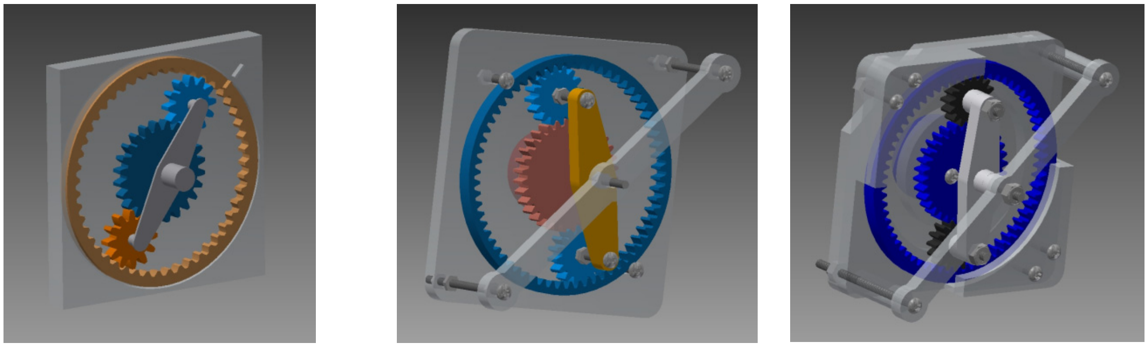

Figure 5. Evolution of the design of the dynamic model of the planetary gear set. From left to right: early CAD-only model, first model made into a physical prototype, final model.

The process of designing the virtual manipulatives went hand-in-hand with creating their physical realizations (the physical manipulatives), progressing through a sequence of iterative design and testing. Although initial CAD designs appeared to work well in simulation, the physical prototypes revealed problems that required modification of the designs. Some parts also needed to be redesigned so that they would not fall into the cracks of the laser cutter during part fabrication.

Data collection: consent forms and background questionnaire. I attended the first class session of Dynamics. At end of this class, I distributed the background questionnaire and consent forms, and briefly described the study. The background questionnaire asked for information such as age, sex, and experience (see Appendix B). The students were told that their participation in the study was voluntary but that it would help determine how to improve instruction in Dynamics. I collected the questionnaire and consent forms at the conclusion of my talk, which was the end of the class period. Some of the signed consent forms could not be identified. I attended the next class lecture period and, at the end of the class, asked students who thought they had consented but for whom I had not yet received consent to come and identify their consent forms. Some did not do so. The end result was that I obtained 106 signed and identified consent forms (this later increased to 107 after a consented student was identified at the first problem solving session).

Data collection: pretest. The pretest was administered at the first evening problem solving session for Dynamics, which was on the same day as the first day of the course. The pretest consisted of four open response questions that asked students to describe the behavior of a machine (describe direction and speed of an output given a set of input conditions, and how the machine produces the output from the input -- see Appendix C for the actual text and diagrams). The multiple-choice portion of the pretest consisted of 38 problems: 9 problems from Purdue Spatial Visualization Test (PSVT), with three from each section of the PSVT (one from beginning, middle, and end of each section, increasing in difficulty within sections); and all 29 problems from the Dynamics Concept Inventory (DCI). The instructor made the test a requirement for all students, regardless of whether they were participating in the study or not. Only scores for students participating in the study are described here. The students first answered the four open response questions. When they turned-in their answers, they were given the multiple-choice portion. The starting time was recorded on the multiple-choice portion when it was given to a student, and then the stop time was recorded when it was submitted. One participant did not attend the evening session when the pretest was administered, and took the pretest later in the week (still prior to the treatment).

Scores for consented individuals were sorted based primarily on spatial score, and secondarily on conceptual score. Consented individuals were then sequentially assigned to the three treatment groups (traditional, physical, and virtual) to achieve a balanced design with samples that were as homogeneous as possible (based on performance). Under this scheme the Physical and Virtual treatment groups had 36 individuals each, and the Traditional treatment group had 34 individuals. I randomly assigned individuals to pairs within treatments. By the end of the study the number of participants per treatment group had dropped to 21 in the Physical, 23 in the Virtual, and 26 in the Traditional treatment groups. This attrition is primarily due to participants failing to attend the treatment sessions. Statistical analysis of the pretest scores for the final composition of the treatment groups showed that there was no statistically significant difference between them before the treatment and they were therefore functionally equivalent.

Data collection: problem solving sessions. All students were encouraged to attend two evening problem solving sessions (spaced one week apart). The first session occurred two weeks after the pretest. The instructor described these sessions as mandatory for those students who consented to be in the study. Any students who attended the sessions but were not consented (and therefore not assigned to a treatment group) were placed with the traditional treatment group participants and given the same materials (their work was not included in the study). All students who attended the problem solving sessions met in the same classroom as the daytime lecture, and were given two worksheets (see Appendix F), one for each problem they were to work on that session. Each worksheet contained the text and static diagram for a problem, just as it appears in the textbook. After receiving instructions on what to do, the students separated to work on the problems. After separating, the Physical group students were given the models for the two problems they worked on that session. After approximately one hour, any students who were still working on the problems were told to stop working. The instructor then discussed the solution to the problems on the board, as he would normally do in class for homework problems previously assigned. Continued attendance for the solution portion of the problem solving session was optional and many students elected to skip it.

Traditional and Physical treatment group participants sat in their assigned pairs, in the same classroom but on opposite sides (Traditional on one side, Physical on the other). The two groups sat far enough away from each other that the Traditional group participants could not make any use of passively viewing the physical models. The Virtual group participants went across the hall to a computer lab and sat in assigned pairs. If a pair member was absent then individuals could elect to work with someone else whose partner was absent. These impromptu pairings were not tracked or recorded.

The Virtual group was required to go to a computer lab and log into the machines, start a web browser, download a zip file from a web site, decompress the zip file to the PC desktop, locate the appropriate Inventor assembly file within the decompressed directory structure, and click on it in order to start Inventor and load the virtual model. This entire procedure was rather time consuming (taking 5-10 minutes), and many students failed to decompress the zip file correctly. After downloading the zip file they double-clicked on it, which revealed the contents of the file but did not decompress the archive. They navigated to the assembly file within the directory structure of the compressed zip file and tried to start it from there. The result is that the model would load without some of its components (the model "broke"). Another problem was that the CAD models only behaved correctly within certain limits of motion, which was not restricted within Inventor. If students moved parts beyond the normal limits, then the behavior of the models became unpredictable and unrealistic (the model "broke"). The easiest way to fix this problem was to close and reload the assembly file—action that students tended not to take despite being told to do so.

Most of my time was spent with the Virtual group. The instructor was present in the classroom with the Traditional and Physical group students. He would circulate around the students and provide assistance as he normally would when students worked on problems during class. I briefly observed the Traditional and Physical group students when I had the time and remembered to do so. I spent a lot of time in the Virtual group addressing problems loading and running the model. Most of the field observations come from the video recordings taken for each of the three treatment groups, and the general sense that I got as I observed the students between addressing problems.

Data collection: posttest. The instructor required all students (consented or otherwise) to take the posttest. The test was administered during the evening session after the second problem solving session. The posttest followed the same format as the pretest, except there were two additional open response questions (for a total of six open response questions). These two open response questions were intended as assessments of transfer performance, and asked students to describe situations that they had not previously seen as part of the study. I recorded the starting and stopping times for the multiple-choice section of the test the same way as I had done for the pretest. Participants were asked to answer the opinion questionnaire (see Appendix G) after submitting the posttest.

Analysis Procedures

Statistical Significance

Statistical significance is a result from a statistical test that indicates that an observed difference is probably not due to chance. It is assessed in statistical tests by comparing the computed probability of a *test statistic* (the output of the statistical test procedures) against a predetermined *alpha* value. The alpha value is the probability of committing a *Type I error*, which is rejecting the *null hypothesis* when it is actually true. The null hypothesis in experimental (and quasi-experimental) designs typically says that there is no difference between the treatments. Therefore, committing a Type I error means that we say that there is a difference between the treatments when, in fact, there is no difference. The de facto standard alpha value for statistical tests in education is $\alpha=0.05$, which means that we are accepting a 5% chance of saying there is a difference when there really is not a difference. Another way of saying this is that we are 95% sure that our result is correct. Setting $\alpha=0.05$ means that the computed significance of the *test statistic* (the numerical outcome of a statistical procedure) of a test, labeled p, needs to be less than or equal to 0.05 in order for an observed difference to be statistically significant. Since it is unlikely that p is ever equal to exactly 0.05, statistical significance is usually written as $p < 0.05$.

Alpha does not have to be 0.05, and there are actually other commonly seen values for alpha including 0.10, and 0.01, corresponding to 10% and 1% chances of committing a Type I error (saying there is a difference when there is not one). It is therefore possible for a result to be significant at one alpha level, but not significant at another alpha level. One might ask why we do not just use the lowest alpha value possible, so as to be sure that we do not commit a Type I error. The reason why we do not do that is because the more rigorous we are (the smaller an alpha we set) about the result, the more rigorous we have to be with the test, and the more rigorous we have to be about our data. Because data in the real world tend to be messy they usually do not conform nicely to the requirements of tests. For example, in order to use a really low alpha value and have tests produce meaningful results, we have to have larger sample sizes (among other things). In fact, smaller sample sizes often result in violation of assumptions of more powerful tests, and force the use of less powerful tests (such as *nonparametric tests*, which do not rely on assumptions about the population being sampled), which are less likely to detect differences that actually do exist (this is committing a *Type II error*, accepting the null hypothesis when it is actually false, or saying there is no difference when there actually is a difference). In general, a higher alpha value increases the likelihood of saying there is a difference when there is not really one, but gives us more leeway in the analysis and data.

Results of statistical tests do not tell the whole story. Just because a statistically significant difference is found does not necessarily mean that it is a practically significant difference, assuming that we did not commit a Type I error. As previously described, it is also possible to conclude that there is no difference because the result of a test was not statistically significant, yet there could actually be a difference. If this is the case, it is likely due to aspects of the design of the experiment, such as small sample sizes or problems with the measurement of the variables of interest.

Analysis of Variance (ANOVA)

Analysis of Variance (ANOVA) is a statistical test for comparing the means of a variable for two or more groups to see if there is a statistically significant difference between them (Boslaugh, 2013). The main test statistic for ANOVA is the *F ratio*. For an ANOVA comparing more than two groups (as in this study, which has three), a significant *F* statistic would indicate that there is a difference between the three groups, but it does not indicate anything about the nature of the difference (which groups are different, or how they are different). If the test indicates the presence of a difference, then one would have to perform *post hoc* tests (other statistical tests) to investigate the difference. A non-significant result indicates that no statistically significant difference was found between the groups on the variable being measured. I used ANOVA to compare treatment groups on the measure of time taken to complete the posttest.

Analysis of Covariance (ANCOVA)

Analysis of Covariance is similar to ANOVA, except that the analysis includes consideration for an independent variable that *co-varies* with the dependent variable (the measurement we are trying to compare). In other words, we are testing the difference between groups of a dependent variable taking into consideration differences in some other variable (the *covariate*) that we expect to have affected the observed values in the dependent variable (Boslaugh, 2013). This is often referred-to as looking for differences in something, while *controlling* for something else. I use ANCOVA in this study to look at differences in posttest scores (the dependent variable), while controlling for differences in the pretest scores (the covariate). In other words, I am asking what the difference between the two groups is, assuming that all of the students performed the same on the pretest. Like ANOVA, the main test statistic for ANCOVA is the *F ratio*, and it is interpreted in the same way. I used ANCOVA to compare treatment groups on the measure of scores on the multiple-choice portion of the posttest, using the pretest scores as a covariate.

Likelihood Ratio Chi Squared Test

The *likelihood ratio chi-squared* test is a nonparametric statistical test for testing the independence of two variables (with an arbitrary number of levels) in cross-tabulated data. Nonparametric tests are statistical tests that are used when little is known about the population from which a sample is drawn, or when data cannot be made to satisfy the assumptions of parametric tests (Boslaugh, 2013). This is often the case for small sample sizes. Nonparametric tests are generally less powerful than parametric tests, which means that they are more likely to result in a Type II error (saying that there is no difference when there actually is a difference).

The likelihood ratio chi squared test is used as an alternative to Pearson's chi-squared test for independence in cross-tabulated data analysis (simply called *chi-squared test*), when assumptions for the chi-squared test are not met. The chi-squared test compares observed versus expected values in cross-tabulated data, and tests the hypothesis that two variables are independent. The chi-squared test has a probability distribution that is approximately χ^2, but this breaks down for small sample sizes. A commonly accepted requirement of the chi-squared test is that expected values should be no less than 5. If expected values are less than 5, then one should not use the chi-squared test. The likelihood ratio chi-squared test, on the other hand, can be used with expected values less than 5 (Upton, 1978).

For data organized in the following table (also called a contingency table):

Table 3

Observed Frequencies in an I x J Table

	B_1	B_2	…	B_J	*Total*
A_1	f_{11}	f_{12}	…	f_{1J}	f_{10}
A_2	f_{21}	f_{22}	…	f_{2J}	f_{20}
.	.	.		.	.
.	.	.		.	.
.	.	.		.	.
A_I	f_{I1}	f_{I2}	…	f_{IJ}	f_{I0}
Total	f_{01}	f_{02}	…	f_{0J}	f_{00}

Note. From G. J. G. Upton, 1978, *The Analysis of Cross-Tabulated Data*, p. 23. Copyright 1978 by John Wiley & Sons Ltd.

The formula for calculating the test statistic, Y^2, for the likelihood ratio chi-squared test is:

$$Y^2 = 2\sum_i \sum_j f_{ij} \log_e \left(\frac{f_{ij}}{e_{ij}}\right)$$ (Upton, 1978, p. 24)

where e_{ij} is the expected value of the cell, calculated by:

$$e_{ij} = \frac{f_{i0}}{f_{00}} \times f_{0j}$$

This is the proportion of the column total for the j-th column, assuming that the cell proportion is the same as the total proportion for that row.

The null hypothesis for the likelihood ratio chi-squared test is that the row and column variables, A and B, are independent (no relationship exists between them). If this is the case, then we expect the proportions of observed frequencies for each case to be roughly equal to the proportions for the total (this is expressed in the formula for the expected cell values), assuming that all of the cases are drawn from the same population. If the observed cell frequencies deviate significantly from the expected values, then we reject the null hypothesis and conclude that A and B are not independent—that there exists a relationship between A and B. This is accomplished by calculating the test statistic Y^2, and comparing it against the χ^2 distribution, with degrees of freedom equal to (I – 1) x (J – 1). In other words, the *p*-value for Y^2 comes from the χ^2 distribution, and we compare that *p*-value against our set alpha level to see if the result is statistically significant. I used likelihood ratio chi-squared tests to compare the treatment groups' explanations of the behavior of machines (open response questions from the pretest and posttest).

McNemar's Test for Matched Pairs

This nonparametric test is commonly used in categorical data analysis to detect a difference in pre-post scenarios. It is used for the analysis for data organized in 2 x 2 tables, where observed frequencies for a two-level categorical variable are measured before and after some treatment for matched or related samples (Boslaugh, 2013).

Table 4

Data Table Format for McNemar's Test

		Post-treatment	
		Level1	Level2
Pre-treatment	Level1	*a*	*b*
	Level2	*c*	*d*

For data arranged as in Table 4, the formula for calculating the test statistic, X^2, is:

$$X^2 = \frac{(b-c)^2}{b+c}$$ (Boslaugh, 2013, p. 135)

The probability of the test statistic has a chi-squared distribution, with one degree of freedom. McNemar's Test tests the null hypothesis that there is no difference between the observed frequencies before and after some condition (the treatment). A significant ($p < \alpha$) test statistic results in a rejection of the null hypothesis and a conclusion that there is a difference (treatment effect). The nature of the difference is dependent upon further examination of the data.

I used McNemar's Test as a way of comparing explanations for the behavior of machines, between pretest and posttest, within treatment groups. This test was used as a finer grain way of analyzing the data after preliminary analysis using the likelihood ratio chi-squared test.

Binary Logistic Regression

Logistic regression is a form of linear regression used to determine the relationship between a categorical dependent variable and several predictor variables (Boslaugh, 2013). Binary logistic regression is a form of logistic regression where the outcome variable is dichotomous (only has two values), such as yes/no. In binary logistic regression we create a linear equation of the variables, which are then used to calculate a probability of a case being in one of the two possible outcome categories. For categorical predictor variables (such as treatment group), the categories are *dummy-coded* into separate binary variables, one for each level of the treatment group. One of the categories is designated as a reference category, and all judgments about the remaining categories are made in relation to the reference category.

Significance values are computed for the coefficients of these dummy-coded variables, which indicate whether a given coefficient (in the prediction equation) significantly differs from zero. A lack of significance would mean that the coefficient is not significantly different from zero, which would indicate that that variable does not play a significant role over the reference variable in determining the value of the outcome variable. Significance would indicate that the variable does play a role, the extent of which is indicated by a computed *odds ratio*, which describes how much the probability of the outcome changes relative to the reference category. I used binary logistic regression to compare the treatment groups' yes/no answers on the student opinion questionnaire.

Qualitative Content Analysis

Content analysis is a “careful, detailed, systematic examination and interpretation of a particular body of material in an effort to identify patterns, themes, biases, and meanings” (Berg, 2007, pp. 303-304). Content analysis as a qualitative research methodology can take many forms, depending on the nature of the research as well as the researcher. A key aspect of content analysis is *counting*, which causes some debate over whether content analysis is a quantitative or qualitative methodology (Berg, 2007). In content analysis, one can analyze *manifest content*, which are those things that are actually present and are countable, or *latent content*, which involves interpretation of meaning from the data (Berg, 2007).

Berg (2007) describes a step-by-step procedure for performing content analysis that is both qualitative and quantitative. The first step is to develop analytic categories related to the research question. The next step is to read through the data and see if the categories actually make sense and are reflected in the data. At this point, the researcher codes the data for the categories, developing *grounded* categories (ones that arise from the data) as necessary. Next, the researcher sorts the data into the categories. The researcher then counts the number of entries in each category and computes descriptive statistics in order to compare the magnitude of categories. The final step is to look for patterns in the magnitudes of the categories, and to attempt to explain the patterns (or lack of patterns) found.

For this study, I used a simplified form of content analysis to identify characteristics of students’ explanations of how machines work (part of the pretest and posttest). The purpose was to characterize and compare differences between treatment groups' explanations. I decided to analyze *manifest content*, only counting what was present in the explanations and not counting what I thought students meant (my interpretations of their explanations). I developed codes based on the possible types of answers for the open response problems, as well as codes for the different mental models. I read through the explanations and made sure these codes were reflected in the explanations. I created additional codes to describe other characteristics that appeared in explanations but were not covered by my original set of codes, and applied these codes to the data. The codes were then grouped into categories that I determined were useful in identifying differences between the treatment groups. I realized through analysis that some codes did not provide sufficient descriptive power to discriminate between treatments, so they were removed from the categories that I analyzed. I used the non-parametric quantitative methods previously described (likelihood ratio chi-squared and McNemar's tests) to compare code frequencies of the three treatment groups. Finally, I looked for patterns in the frequencies and tried to explain these patterns.

I also used a more grounded version of content analysis for examining the student responses on the opinion questionnaire. For those data, I did not create any codes beforehand, but instead created them as I read through the data. I had to read through the data multiple times to detect common themes, and merged codes as appropriate. I then counted the codes in order to determine which codes were the most frequently occurring, and which codes were more common than others.

Analysis Tools

Dedoose

Dedoose (http://www.dedoose.com) is a web-based tool for conducting qualitative and mixed-methods data analysis. A common practice in qualitative analysis is to convert all data into text, and then to code the text and analyze the resulting codes (such as using content analysis, which I previously described). Dedoose provides mechanisms for loading text data, creating codes, and applying codes. It also allows for the creation of *descriptors*, which are other data that describe the participants or data sources. Dedoose also provides analytic summaries (e.g., relative code frequencies grouped by descriptors) and data displays (e.g., pie charts and code co-incidence matrices) that aid in the qualitative and mixed-methods analyses. Perhaps one of the most useful features of Dedoose is the ability to get a *drill-down* by clicking on any data summary number and having the underlying data from which that number was derived displayed on the screen.

I found the majority of the data summaries and displays to be inappropriate for answering my research questions. I found Dedoose to be a nice way to do my qualitative coding, however I had to change my excerpting procedure (the designation of sections of text that are linked to a code) so that entire responses constituted an *excerpt*. This was because I wanted to count the number of *participants* that received a code, not the number of times a code was applied to a given piece of text, or the total number of codes applied. I used the code application matrix feature in Dedoose to see how I applied the codes. I exported the matrices to Microsoft Excel for analysis. I went back to the code application matrices in Dedoose to take advantage of the drill-down capability when looking for example responses while writing this report.

SPSS

SPSS is a statistical analysis software package from IBM. I used SPSS to perform the ANOVA, ANCOVA, likelihood ratio chi-squared, and binary logistic regression tests. I initially calculated the likelihood ratio chi-squared test manually within Microsoft Excel. After determining that SPSS' crosstabs likelihood ratio chi-squared was the same procedure, I used SPSS for all further instances of that test.

Microsoft Excel

Excel is a spreadsheet software application from Microsoft. I used Excel to perform a variety of calculations, including computing McNemar's and likelihood ratio chi squared tests, as well as other cross-tabulated data analyses (e.g., computing proportions, grouping and summarizing data, etc.). I stored all of the data analyzed in the study in Excel workbooks. I exported code application matrices from Dedoose as Excel workbooks and performed code summaries and analyses in Excel.

CHAPTER 4

FINDINGS

This chapter describes the data I collected during this study, the procedures I used to analyze the data, and the conclusions I reached based on the analysis. The data, analysis, and discussion are described separately for each major data source.

Multiple Choice Questions

The pre- and posttests included 38 multiple choice questions which form a large part of the student performance assessment. These 38 problems are composed of 9 spatial questions from the PSVT, and 29 problems from the complete DCI. The DCI questions were filtered down to 19 questions during analysis, based on the instructor's assessment of which questions the students could be expected to know by the time of the posttest.

In order to test the hypothesis that students with lower spatial ability might benefit more from the models than students with higher spatial ability, I classified the students in each treatment group as either high or low spatial ability based on their pretest spatial scores. The median score for all participants was 78%. I classified scores that greater than, or equal to, 78% as high spatial ability, and scores below 78% as low spatial ability.

Total Score: Data and Analysis

I initially looked at total scores (combined spatial and filtered conceptual portions of the multiple-choice questions) across the three treatment groups to see if there was a difference. Table 5 displays the mean scores for pre- and posttest by spatial ability and treatment group.

Table 5

Mean Total Score for Multiple-Choice Questions

			Pretest		Posttest	
Treatment	Spatial Ability	N	Mean (%)	Std. Dev. (%)	Mean (%)	Std. Dev. (%)
Traditional	High	16	57	13	63	16
	Low	10	42	10	51	10
	Total	26	51	14	58	15
Physical	High	13	56	11	55	11
	Low	8	43	9	49	11
	Total	21	51	12	53	11
Virtual	High	12	60	13	62	12
	Low	11	45	10	50	19
	Total	23	53	13	56	17

There appears to be a somewhat linear relationship (R^2=0.567 overall, R^2=0.680 for Traditional, R^2=0.539 for Physical, R^2=0.524 for Virtual) between the pre- and posttest total scores based upon visual inspection of a scatter plot. There was homogeneity of regression slopes since the interaction between the pretest total score and the treatment was not statistically significant, $F(2,64)=0.470$, $p=0.627$. The standardized residuals for Traditional and Physical treatments were normally distributed, as indicated by a Shapiro-Wilk test ($p>0.05$), however the Virtual treatment's residuals were not normally distributed ($p=0.048$) at $\alpha=0.05$. Overall, the standardized residuals were normally distributed, however ($p=0.145$). There was homoscedasticity of the variances, based on visual inspection of a scatter plot of the standardized residuals versus the predicted values for the posttest. Levene's test for equality of error variances revealed that the homogeneity of variance assumption was violated ($p=0.011$).

In order to address the lack of homogeneity of variance, I applied a $\log_{10}$ transformation to the pre- and posttest total scores (Levene's test $p=0.056$ on the transformed data). Subsequent tests using the transformed pre- and posttest scores revealed that the standardized residuals for all treatments were now normal ($p>0.05$) under a Shapiro-Wilk test. Homogeneity of regression slopes for the transformed data was maintained, $F(2,64)=0.837$, $p=0.438$.

I analyzed the transformed posttest scores by treatment using ANCOVA, with the transformed pretest scores as a covariate. The result indicated no significant difference in posttest scores between treatments, controlling for pretest scores, $F(2,66)=1.906$, $p=0.157$. ANCOVA analysis using spatial group (high/low ability) also shows no significant difference between treatments, $F(2,63)=1.938$, $p=0.152$; no difference between spatial groups, $F(1,63)=0.712$, $p=0.402$; and no difference between spatial groups by treatment, $F(2,63)=0.808$, $p=0.450$.

Spatial Score: Data and Analysis

Although there was no significant difference found between treatment groups and spatial ability when examining the total score for the multiple-choice problems, I thought that there might be a difference if I analyzed the spatial and conceptual portions separately. Table 6 displays the mean spatial scores for pre- and posttest by spatial ability and treatment group.

These data also violated the assumption of homogeneity of variances ($p=0.042$). I applied a square transformation to the pre- and posttest spatial scores to address this problem ($p=0.059$ after transformation). I analyzed the transformed spatial scores using ANCOVA with the transformed pretest spatial score as a covariate. The results showed no significant difference between treatments, $F(2,63)=1.987$, $p=0.146$; no significant difference between spatial groups, $F(1,63)=0.137$, $p=0.713$; and no significant difference between spatial groups by treatment, $F(2,63)=1.534$, $p=0.224$.

Table 6

Mean Spatial Score for Multiple-Choice Questions

Treatment	Spatial Ability	N	Pretest		Posttest	
			Mean (%)	Std. Dev. (%)	Mean (%)	Std. Dev. (%)
Traditional	High	16	84	7	88	9
	Low	10	55	10	66	8
	Total	26	72	16	79	14
Physical	High	13	86	7	76	16
	Low	8	56	14	66	15
	Total	21	74	18	72	16
Virtual	High	12	84	7	80	12
	Low	11	57	11	62	21
	Total	23	71	17	71	19

Conceptual Score: Data and Analysis

It could be argued that the conceptual portion of the test is the most important, since acquisition of the concepts of Dynamics is a primary focus of the course. Table 7 displays the mean conceptual scores for pre- and posttest by spatial ability and treatment group.

Table 7

Mean Conceptual Score for Multiple-Choice Questions

			Pretest		Posttest	
Treatment	Spatial Ability	N	Mean (%)	Std. Dev. (%)	Mean (%)	Std. Dev. (%)
Traditional	High	16	45	18	51	23
	Low	10	36	14	44	13
	Total	26	41	17	49	20
Physical	High	13	43	15	45	12
	Low	8	38	11	41	14
	Total	21	41	14	44	13
Virtual	High	12	49	17	54	14
	Low	11	40	14	45	19
	Total	23	45	16	49	17

The conceptual scores exhibited homogeneity of variances without transformation (p=0.099 on Levene's test). I analyzed the posttest conceptual scores using ANCOVA with the pretest conceptual score as a covariate. The results showed no significant difference between treatments, $F(2,63)$=0.617, p=0.543; no significant difference between spatial groups, $F(1,63)$=0.095, p=0.759; and no significant difference between spatial groups by treatment, $F(2,63)$=0.106, p=0.899.

Time

Table 8 displays the mean time to complete the posttest for participants in each treatment group, and also the breakdown by spatial ability.

Table 8

Mean Time to Complete Posttest

Treatment	Spatial Ability	N	Mean Time (minutes)	Std. Dev.
Traditional	High	16	23.56	6.39
	Low	10	26.80	9.24
	Total	26	24.81	7.60
Physical	High	13	23.77	5.57
	Low	8	24.75	7.83
	Total	21	24.14	6.35
Virtual	High	12	23.92	3.80
	Low	11	20.82	5.84
	Total	23	22.43	5.03

I compared the mean times per treatment and per spatial group by treatment using ANOVA in SPSS. The results indicate no significant difference between the mean times for each of the treatment groups, *F*(2,64)=1.154, *p*=0.322; no significant difference between spatial groups, *F*(1,64)=0.056, *p*=0.814; and no significant different between spatial groups by treatment, *F*(2,64)=1.449, *p*=0.242.

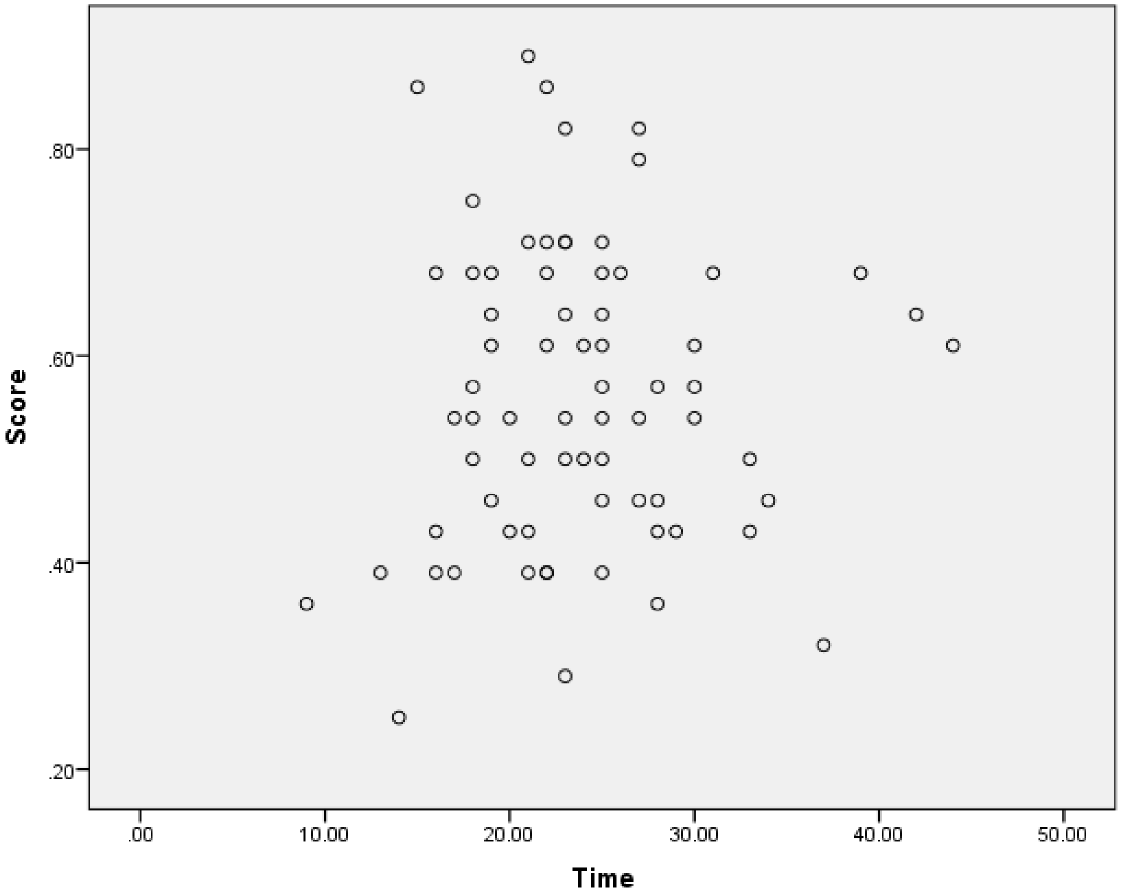

Figure 6. Scatter plot of posttest score versus time.

The scatter plot of Score v. Time reveals no correlation between the two variables (see Fig. 6). Individual scatter plots of Score v. Time for each treatment group show a similar lack of correlation (See Appendix O).

Discussion

All of the quantitative analyses of the multiple-choice posttest scores show no significant difference between the treatments, controlling for the corresponding pretest score, whether this is overall, spatial, or conceptual. The analysis of the time taken to complete the posttest indicates no statistically significant difference between the treatments, and no relationship between time and posttest score. These results suggest that any difference in student performance as a result of the treatments would best be measured using a different method. This takes us to the next set of data, a measurement of students' mechanical reasoning through qualitative content analysis of their explanations of how machines operate.

Open Response Question 1: Four-Bar Linkage

The first open response question asked students to describe how the machine depicted in Figure 7 works, and in particular to describe the direction and speed of D (see Appendix C for the actual problem text). This machine is of a class of machines usually called a *four-bar linkage*. It is called so because it consists of four connected bars that are rigid bodies and whose motion is constrained by their interconnections. In the diagram for this machine, the four bars consist of the linkage AB, linkage EF, the structure D with the connection points A and E, and an imaginary bar BF that is present because points B and F are fixed.

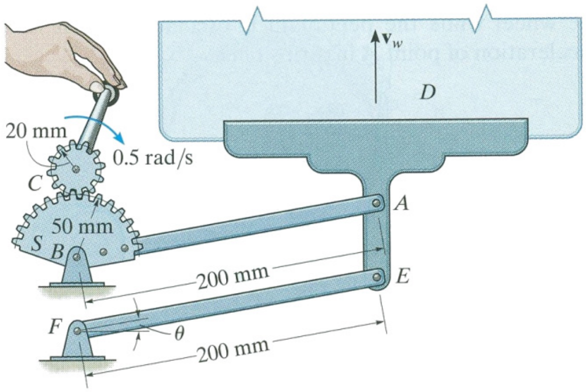

Figure 7. Textbook diagram of a four-bar linkage window control mechanism. From R. C. Hibbeler, 2010, *Engineering Mechanics: Dynamics* (12th ed.), p.324. Copyright 2010 by Pearson Prentice Hall. Used with permission.

In this machine, as the hand cranks the lever clockwise, the cog C rotates clockwise, which turns the gear S counter-clockwise. Since the linkage AB is fixed to S, it also rotates about B counter-clockwise. This causes the point A to translate in a counter-clockwise arc. If the rotational motion imparted by the hand is at a constant speed, then A's speed along its arc will be constant. This will raise D, whose trajectory will match that of A (a counter-clockwise arc), but overall aspect will remain upright.

This diagram is problematic, however, for various reasons. The first is the presence of the $\mathbf{V}_w$ vector. In the actual textbook problem, D refers to the T-shaped structure that contains points A and E. D is a track that holds a window. The window is constrained on its left and right, but is free to slide on D. This means that the window can only move vertically (not in an arc). Because of this, $\mathbf{V}_w$, which is a vector representing the motion of the window (and not the track, D), is pointing up. $\mathbf{V}_w$ is, in fact, analogous to the vertical component of the angular velocity of D. Since D is moving at a constant speed in an arc, the magnitude of $\mathbf{V}_w$ will actually decrease as D approaches the top of its arc. Since it is not clear from the diagram to what D is referring (since the label is located on the window pane and not on the T-shaped track), answers about the direction and speed of D are confounded, as both possibilities for each could be both right and wrong. Since it is not clear whether an answer is right or wrong, we cannot say whether someone has improved or not depending upon what treatment the individual has received for this problem, and measurements for this problem are therefore useless.

As part of the class, the students were required to use the Mastering Engineering web site (http://www.masteringengineering.com). One of the videos that the students had access to on this site showed a detailed problem description and solution for this exact problem. Although it is unknown how many (if any) students viewed the video, its availability constitutes contamination that must be considered. Due to these issues, I decided to remove this problem from analysis.

Open Response Question 2: Planetary Gear Set (Sun Driven)

The second open response question asked students to describe how the planetary gear set in Figure 8 works, and in particular to describe the speed and direction of the output shaft, A, given that the input is constant rotational motion of the sun gear, S (see Appendix C for the actual problem text). If students thought that the speed of A was constant, they were asked to say whether they thought A rotated faster than, slower than, or at the same rotational speed as the sun gear, S. In this problem, the ring gear, R, was specified as held motionless.

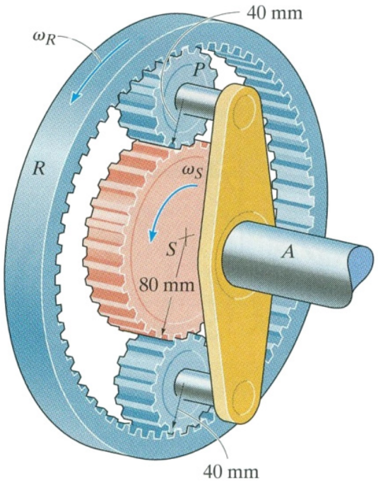

Figure 8. Textbook diagram of a planetary gear set. From R. C. Hibbeler, 2010, *Engineering Mechanics: Dynamics* (12th ed.), p. 347. Copyright 2010 by Pearson Prentice Hall. Used with permission.

This diagram (and the open response problem itself) has problems. A key problem is that there is an arrow, labeled ω_R, indicating a direction of rotation of the ring gear. In the actual textbook problem ω_R is given a magnitude of 0 (meaning it is motionless), despite the presence of the curved arrow. However it became obvious after reading student responses for this problem that they most likely did not read the problem description and just looked at the diagram, saw ω_R, and assumed that the ring gear was rotating. The problem expects that students will make the assumption that the face of the gear set that is visible is the front, and therefore that S is rotating counter-clockwise (as indicated by the curved arrow on S, labeled ω_S). This problem also expects that students will assume that A is fixed to the planet carrier (the diamond-shaped structure that the planet gears, P, are connected to), so that whichever way the planet carrier rotates A will rotate (and at the same rotational speed).

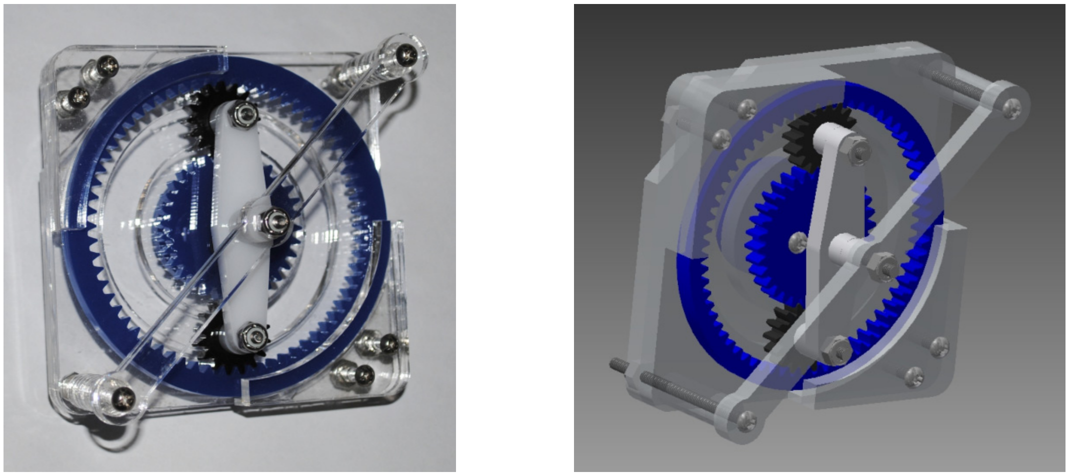

Figure 9. Physical (left) and virtual (right) manipulatives for the planetary gear set problem.

Despite some students making statements in their explanations that violated the initial conditions of the problem, if I was able to deduce a direction and speed of A relative to S when the ring gear could be assumed to be held motionless (the student did not say R was moving), then I still coded their responses as if they had not violated the initial conditions. If, however, they said that the ring gear was moving, or that the input was coming from something other than S, then I did not code their responses.

For this problem, I created codes for direction and speed of A relative to S. The codes for direction were A moving in the same direction as S, and A moving in the opposite direction as S. Initially, the codes for speed were A moving slower than S (A < S), A moving faster than S (A > S), and A moving at the same speed as S (A = S). I had not imagined that a student would say that A did not move given the initial condition that

S was moving. After reading pretest responses, I found that some students actually thought that A did not move in this situation. I then added a code for A not moving (A = 0).

Direction Data and Analysis

The frequencies of direction codes (A rotating in the same direction as S, A rotating in the opposite direction as S) for each treatment group are summarized in Table 9. The expected values for each cell are indicated in parentheses. The correct answer is that A rotates in the same direction as S.

Table 9

Planetary Gear Set (Sun Driven) Direction x Treatment Crosstabulation

		Treatment			
Test	Direction	Traditional	Physical	Virtual	Total
Pretest	Same*	13 (14.3)	9 (9.1)	15 (13.6)	37
	Opposite	9 (7.7)	5 (4.9)	6 (7.4)	20
	Total	22	14	21	57
Posttest	Same*	15 (14.6)	7 (9.5)	16 (13.9)	38
	Opposite	8 (8.4)	8 (5.5)	6 (8.1)	22
	Total	23	15	22	60

* Correct answer

Analysis using the likelihood ratio chi-squared test reveals a non-significant test statistic for the pretest, $Y^2=0.727$, $df=2$, $p=0.695$; and a non-significant test statistic for the posttest, $Y^2=2.629$, $df=2$, $p=0.269$. The lack of significance of these test statistics indicates that treatment and direction are independent for the pretest and posttest. In other words, there is no relationship between treatment and the direction code frequencies, and therefore no significant difference between treatments with respect to direction responses by students.

Another way of analyzing these numbers is to use McNemar's Test to compare pretest and posttest code frequencies within individual treatment groups, looking for significant differences (improvements in particular). The results of McNemar's Test reveal no significant difference between pretest and posttest for the Traditional group (X^2=0.20, p=0.655), the Physical group (X^2=1.00, p=0.317), or the Virtual group (X^2=0.20, p=0.655).

Speed Data and Analysis

The frequency count for speed codes (A rotating slower than S, A rotating faster than S, A rotating at the same speed as S or not rotating) for each treatment group are summarized in Table 10. The expected values for each cell are indicated in parentheses. Note that frequencies for A rotating at the same speed as S, and A not rotating, were combined in order to compensate for low cell expected counts. Both of these answers are wrong and have low counts.

Table 10

Planetary Gear Set (Sun Driven) Speed x Treatment Crosstabulation

		Treatment			
Test	Speed	Traditional	Physical	Virtual	Total
Pretest	A < S *	6 (6.2)	5 (4.4)	5 (5.3)	16
	A > S	10 (8.6)	4 (6.1)	8 (7.3)	22
	A = S | 0	5 (6.2)	6 (4.4)	5 (5.3)	16
	Total	21	15	17	54
Posttest	A < S *	9 (12.1)	12 (10.1)	12 (10.8)	33
	A > S	7 (3.3)	1 (2.8)	1 (2.9)	9
	A = S | 0	2 (2.6)	2 (2.1)	3 (2.3)	7
	Total	18	15	16	49

* Correct answer

Analysis using the likelihood ratio chi-squared test reveals a non-significant test statistic for the pretest, Y^2=1.987, *df*=4, *p*=0.738; and a non-significant statistic for the posttest, Y^2=8.024, *df*=4, *p*=0.091. The lack of significance of these test statistics indicates that treatment and speed are independent for the pretest and the posttest. In other words, there is no relationship between treatment and the speed code frequencies, and therefore no significant difference between treatments with respect to speed responses by students (there is, however, an alternate interpretation—see the following discussion for this open response problem).

I ran McNemar's Test on three 2 x 2 tables, one for each treatment, comparing right/wrong answer codes (frequencies for A > S and A=S|0 were combined) from pretest to posttest. I calculated individually significant test statistics for the Traditional group (X^2=4.00, p=0.046), Physical group (X^2=4.50, p=0.034), and the Virtual group (X^2=7.00, p=0.008). Although all three groups have individually significant results, a closer examination of the data revealed that four individuals in the Traditional group improved from pretest to posttest, which is 15% of that sample. Seven individuals (33%) in the Physical group improved, as well as seven individuals (30%) in the Virtual group. Furthermore, eight individuals in the Traditional group continued to identify an incorrect speed in the posttest, compared to one in the Physical group and four in the Virtual group. From these results, it appears that the Physical and Virtual groups exhibited greater improvement and performance than the Traditional group on the identification of correct speed on the posttest.

Mental Models

Part of my investigation concerns the mental models that students have and develop while they engage in mechanical reasoning using static diagrams and dynamic models. Table 11 summarizes the frequency count of individuals whose explanations of the planetary gear set exhibited characteristics of specific mental models. Corresponding proportions are indicated in parentheses.

The most salient feature of the mental models table is that mental simulation dominates all other models. This could be because I coded any description of the behavior of the planet gears or carrier as mental simulation, because it described an intermediate component in the causal chain from input to output. I also coded explanations as mental simulation if they had accompanying drawings indicating the rotation or translation of the planetary gears, as I considered that as evidence of thinking about the causal chain of events. Another interesting aspect of this table is the fact that the frequency count for mental simulation more than doubles from pretest to posttest for the Traditional group. This increase is rather inexplicable, except that it may reflect an increase in maturity for discourse by students about the operation of machines. Why we do not see a similar pattern for the other two treatments is unknown.

Table 11

Mental Models for Planetary Gear Set Explanations

	Pretest			Posttest		
Mental Model	T	P	V	T	P	V
Intuitive			1 (0.04)		1 (0.05)	
Procedural Mapping	4 (0.15)	2 (0.10)	1 (0.04)			
Analogical						2 (0.09)
Naïve Representations					1 (0.05)	
Physical Representations						3 (0.13)
Mental Simulation	8 (0.31)	13 (0.62)	17 (0.74)	18 (0.69)	12 (0.57)	14 (0.61)

Note. Proportions are indicated in parentheses.

Discussion

The analysis of the direction codes revealed no significant difference between treatment groups for responses regarding the direction of rotation of the output shaft, A, with respect to the input gear, S (the sun gear). Although the Physical group appears to have done worse on the posttest compared to their pretest performance, the overall performance appears to be in favor of correct answers over incorrect ones by a ratio of about 1.8:1. That there appears to be no difference between treatments on this performance measure suggests that the task is independent of treatment differences. It is possible that the task of determining the direction a component rotates at the end of a causal chain of gears is something that can be accomplished without the aid of dynamic representation.

The likelihood ratio chi-squared analysis of speed codes returned no significant results at the default significance level of $\alpha=0.05$. However the test statistic for the posttest speed code, with $p=0.091$, would be significant at $\alpha=0.10$. In comparison to the corresponding p-value for the pretest ($p=0.738$), it suggests some level of difference. Looking at the differences between the actual frequency counts and the expected values, it is evident that the Physical and Virtual groups have higher frequencies than expected for the correct speed code ($A < S$), and lower than expected frequencies for the opposite speed code ($A > S$). This is in contrast to the Traditional group, which scored lower than expected on the correct code, and higher than expected on the opposite code. If we were to compare just the two primary speed codes of $A < S$ and $A > S$, the difference becomes more pronounced, with the posttest likelihood ratio chi-squared $p=0.022$. The results of the individual McNemar's Tests indicate an improvement between pretest and posttest for all three groups, however there is evidence to suggest an advantage of the Physical and Virtual groups over the Traditional group.

These results suggest some degree of improved performance (in this case determining the speed of the output relative to the input) in favor of the Physical and Virtual treatments over the Traditional. If it is true that the treatment had a positive effect for the Physical and Virtual treatments, then it suggests that relative speed is more difficult to determine from a static diagram than a dynamic representation. This is a conclusion that one might expect given that a single-frame static diagram has no representation of changes in time—a critical aspect of speed.

The stability of the numbers for direction from pretest to posttest, and the large numbers of students responding incorrectly regarding the direction of the output shaft, might be explained due to a possible failure of their mental models. The dominant form of mental model is mental simulation, which describes mechanical reasoning as a stepwise analysis of a causal chain of events. This can be seen as a strategy of reducing extraneous cognitive load by focusing on the interaction between two components at a time. In the case of the analysis of the planetary gear set, it is evident from student explanations that they step through the causal chain analyzing the interaction between the sun gear and planet gears, then a planet gear and the planet carrier, and finally the planet carrier and the output shaft. This chain may seem to be reasonable, except that it completely ignores the effect of the stationary ring gear. If one were to follow this chain and ignore the ring gear, then the rotation analysis would seem to be: sun rotates counter-clockwise (CCW), CCW rotation of sun gear causes planet gears to rotate clockwise (CW – opposite the sun gear), CW rotation of planet gears causes them to translate around (relative to) the sun gear in a CW direction, this causes the planet carrier to rotate CW, which then causes the output shaft to rotate CW. This sort of explanation (albeit not quite as complete) is typical of student responses with the wrong direction.

It may be that the effect of the ring gear is overlooked because it is not in the direct path traced by the student from input to output. In fact, the effect of the ring gear is simultaneous with the sun gear (as is everything in the gear set, really) and needs to be considered in concert with the action of the sun gear on the planet gears—but this increases cognitive load. A correct analysis that takes into account the stationary ring gear would reveal that, if the planet gears were translating CW, they would be slipping against the stationary ring gear. The fact that the teeth of the planet gears mesh with the teeth of the ring gear makes this an unlikely scenario, therefore the CW rotation of the planet gears actually force them to translate CCW around the inside of the ring gear (ultimately rotating the output shaft CCW). In this case, an analogical model where the planet gear is like a ball, the sun gear is like your hand, and the ring gear is like a stationary table, might have helped. In this analogical model, when you roll the ball under your hand, it translates in the same direction your hand is moving, much like the planet gear translates in the same direction that the sun gear rotates.

Open Response Question 3: Rack & Pinion

The third open response question asked students to describe how the rack and pinion mechanism in Figure 10 works, and in particular to describe the speed and direction of the slider/sleeve, B, given that the input is constant rotational motion of the pinion gear, O (see Appendix C for the actual problem text). The *rack* is the toothed bar at the bottom of the mechanism, on which the round *pinion* gear rolls. In this particular mechanism, the rack is motionless, and the pinion gear is free to roll horizontally (in this case, the pinion gear is rotating counter-clockwise and translating to the left). The circular translation of point A about the (horizontally moving) center point of the pinion gear (here, labeled O), combined with the horizontal translation of O, imparts a translation on the slider, B, whose motion is restricted such that it can only move horizontally. If the students thought that the speed of B varied, they were asked to describe how it varied in relation to the input.

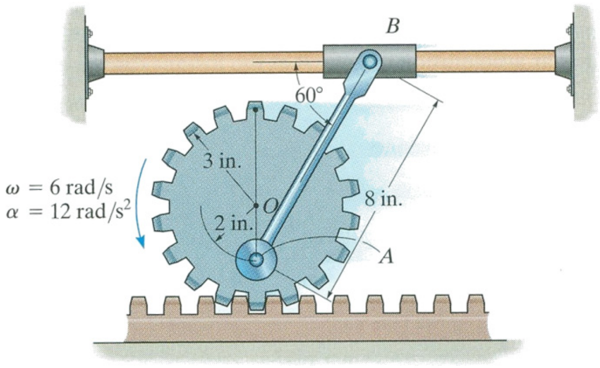

Figure 10. Textbook diagram of a rack and pinion mechanism. From R. C. Hibbeler, 2010, *Engineering Mechanics: Dynamics* (12th ed.), p.375. Copyright 2010 by Pearson Prentice Hall. Used with permission.

This test item presented problems for data analysis. One key problem was the presence in the diagram of a non-zero value for angular acceleration of the pinion gear ($\alpha = 12$ rad/s^2). This directly contradicted the instructions for the open response problem, which specified that the rotational speed of the pinion gear is constant (i.e., $\alpha = 0$). Some students specified that the speed of B was varying because the rotational speed of the pinion gear was changing. This made it difficult to evaluate the correctness of the response that speed varied, since speed could also be varying due to the students thinking that the motion was intermittent, or that the direction of B was changing. In most cases, student explanations were sparse or incomplete, and disentangling these scenarios was impossible. The problem posed by the presence of angular acceleration was fixed in the posttest by crossing-out the value and replacing it with a zero before students took the test, however it makes comparison of this aspect against the pretest difficult, if not impossible.

The idea that the direction of B changes is also a problem. It became apparent from reading student responses that one particular mental model for the operation of this machine considered the effect of the rotation of the pinion on B as if the pinion rotated about a fixed (not translating) point (in which case B would oscillate back and forth, a behavior which many students described). It turns out that I had my own misconception about the behavior of B, which I arrived at based on my own observations of the physical model. It appeared to me that B only moved to the left, and that motion was intermittent, with no motion for about 90 degrees of its rotation (beginning with its starting position indicated in the diagram). It was for this reason that I initially decided that any description of oscillating (back-and-forth) motion of B was wrong. It was not until I saw the instructor's solution for this problem that I realized that I was wrong. According to the instructor's solution, B is actually moving to the left and accelerating to the right (i.e., decelerating) at the instant depicted in the diagram (recall that I thought it was not moving at this point).

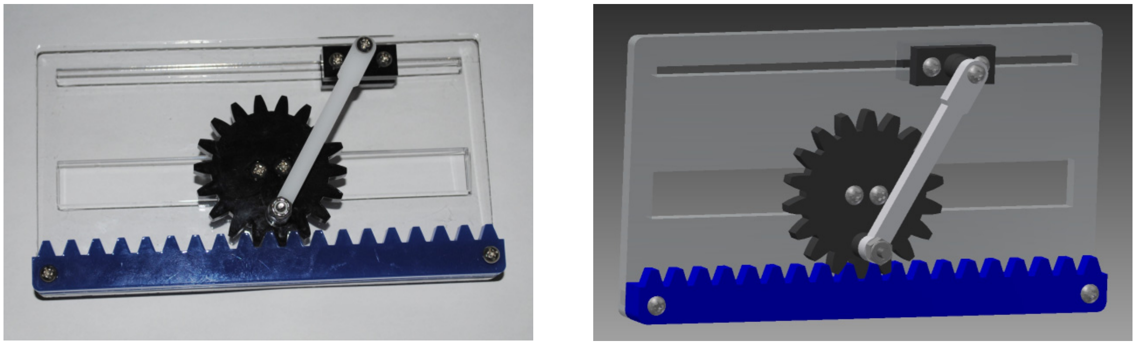

Figure 11. Physical (left) and virtual (right) manipulatives for the rack & pinion problem.

Since it certainly appeared from the physical model that B was not moving, I decided to check the CAD model (its motion should be precise since it contained no real-world error, such as the loose tolerances of the physical model). Sure enough, the CAD model revealed that B was moving a tiny bit to the left. In fact, the CAD model showed that B oscillated back-and-forth a tiny bit where I thought that it appeared to be stationary in the physical model.

Because of these problems surrounding the speed and direction of B, I had to reduce correctness of a response down to very basic characteristics. In the case of speed, I actually cannot determine what a correct response is. I can, however, judge an incorrect response: the speed of B is constant. Rather than dwelling on why speed varies, I just consider responses coded as describing constant speed to be wrong, and therefore responses indicating varying speed as potentially correct. I believe this is sufficient for comparing speed response characteristics across treatments. I took a similar approach examining direction of B in the responses. It is difficult to determine correctness of direction responses, but it is easier to determine incorrect direction responses. In this case, a student that says that B is moving to the right (which covers moving to the right at this moment, and moving to the right overall) is incorrect. A response that says that B moves to the left (either overall or at this moment) is therefore judged to be correct. I disregarded codes for oscillating motion, since it is difficult to tell if students believe the oscillation occurs as the CAD model shows it (tiny oscillations where I thought it appears stationary in the physical model)—which is possible but I believe unlikely—or if the oscillation is due to a mental model that considers the pinion to be rotating about a fixed point.

Direction Data and Analysis

The frequencies of direction codes (B moves left, B moves right) for each treatment group are summarized in Table 12. The expected values for each cell are indicated in parentheses. The correct answer is that B moves left (considering that B moves right is always incorrect).

Table 12

Rack & Pinion Direction x Treatment Crosstabulation

		Treatment			
Test	Direction	Traditional	Physical	Virtual	Total
	Left*	10 (9.3)	7 (8.1)	8 (7.7)	25
Pretest	Right	13 (13.7)	13 (11.9)	11 (11.3)	37
	Total	23	20	19	62
	Left*	13 (15.6)	12 (11.5)	15 (12.9)	40
Posttest	Right	10 (7.4)	5 (5.5)	4 (6.1)	19
	Total	23	17	19	59

* Correct answer

Analysis using the likelihood ratio chi-squared test reveals a non-significant test statistic for the pretest, $Y^2=0.359$, $df=2$, $p=0.836$; and a non-significant test statistic for the posttest, $Y^2=2.504$, $df=2$, $p=0.286$. The lack of significance of these test statistics indicates that treatment and direction are independent for the pretest and the posttest. In other words, there is no relationship between treatment and the direction code frequencies, and therefore no significant difference between treatments with respect to direction responses by students.

The results of McNemar's Tests comparing pretest and posttest code frequencies for the three individual groups reveal no significant difference for the Traditional group ($X^2=3.00$, $p=0.083$), but a significant difference for the Physical group ($X^2=6.00$, $p=0.014$) and the Virtual group ($X^2=5.00$, $p=0.025$). Looking at the frequencies, it is obvious that the difference is an improvement for both Physical and Virtual groups, from pretest to posttest.

Speed Data and Analysis

The frequencies of speed codes (B's speed varies, B's speed is constant) for each treatment group are summarized in Table 13. The expected values for each cell are indicated in parentheses. The correct answer is that B's speed varies.

Analysis using the likelihood ratio chi-squared test revealed a non-significant test statistic for the pretest, $Y^2=0.537$, $df=2$, $p=0.765$; and a non-significant test statistic for the posttest, $Y^2=2.716$, $df=2$, $p=0.257$. The lack of significance of these test statistics indicates that treatment and speed are independent for the pretest and the posttest.

Table 13

Rack & Pinion Speed x Treatment Crosstabulation

		Treatment			
Test	Speed	Traditional	Physical	Virtual	Total
Pretest	Varying*	15 (14.3)	14 (14.3)	13 (13.4)	42
	Constant	1 (1.7)	2 (1.7)	2 (1.6)	5
	Total	16	16	15	47
Posttest	Varying*	14 (16.8)	13 (11.7)	16 (14.6)	43
	Constant	9 (6.2)	3 (4.3)	4 (5.4)	16
	Total	23	16	20	59

* Correct answer

In other words, there is no relationship between treatment and the speed code frequencies, and therefore no significant difference between treatments with respect to speed responses by students. Furthermore, the results of McNemar's Test indicate no significant difference between pretest and posttest for the Traditional group ($X^2=3.00$, $p=0.083$), the Physical group ($X^2=0.33$, $p=0.564$), and the Virtual group ($X^2=2.00$, $p=0.157$).

Mental Models

Table 14 summarizes the frequency count of individuals whose explanations of the rack and pinion mechanism exhibited characteristics of specific mental models. Corresponding proportions are indicated in parentheses.

As with the planetary gear set mental models table previously described, the most salient feature of this table is that mental simulation dominates all other models (probably for the same reasons). For this machine, any description of the role of the point A, or the linkage, constituted a description of intermediate components in the causal chain from input (the pinion) to output (the slider, B). The almost complete lack of any other model codes in the posttest could be an indication of convergence in the manner of description, resulting from students' maturation of discourse about the subject matter.

Table 14

Mental Models for Rack & Pinion Explanations

	Pretest			Posttest		
Mental Model	T	P	V	T	P	V
Intuitive	1 (0.04)					
Procedural Mapping						2 (0.09)
Analogical	1 (0.04)	2 (0.10)				
Naïve Representations						
Physical Representations	1 (0.04)	1 (0.05)	2 (0.09)			
Mental Simulation	9 (0.35)	8 (0.38)	12 (0.52)	12 (0.46)	10 (0.48)	13 (0.57)

Note. Proportions are indicated in parentheses.

Discussion

The inability of the likelihood ratio chi-squared test to detect a difference between treatments might be due to the small sample sizes. The results of McNemar's Test comparing pretest and posttest frequencies for the individual treatment groups revealed a significant difference (improvement) for the Physical and Virtual groups with regards to identifying the correct direction. The results of McNemar's Tests run on the speed code frequencies, however, revealed no significant difference between pretest and posttest for all three treatment groups. This suggests an advantage of the Physical and Virtual groups over Traditional in the identification of correct direction but not correct speed for this mechanism.

Looking at the posttest frequencies for both direction and speed, we also see that the Traditional group has a lower than expected observed frequency for the correct answers, and a higher than expected frequency for the wrong answers. This is in contrast to the Physical and Virtual groups, which exhibit the opposite results: higher than expected on correct answers, and lower than expected on wrong answers. This pattern also appeared for the speed code frequencies of the planetary gear set problem discussed previously.

I described a possible mental model failure at the beginning of this section on the rack and pinion problem, where I believe that students were analyzing the problem as if the pinion gear was rotating about a fixed axis. The evidence for this comes from the high frequency of student responses indicating a rightward direction for the slider, B. This response is so frequent that it outnumbers the correct response across all treatments in the pretest. Rightward motion of B is consistent with analysis that does not take into account the leftward translation of the pinion. It is also possible that students feel that the leftward translation is not sufficient to negate or overcome the action of the linkage “pushing” B to the right. Some students tried to accommodate the leftward translation of the pinion gear by describing the pinion as dragging the oscillating slider gradually to the left. These analyses are similar to the failed analyses of the planetary gear set, in that students appear to ignore the effect of the motionless rack as it is not in their path of causal chain reasoning that goes from the pinion gear to the point A, A to the linkage, and the linkage to B. The influence of the rack (and resulting leftward translation of the pinion gear) is something that must be considered simultaneously with the motion of other parts of the system, and this increases cognitive load.

One might think that exposure to a dynamic model of this machine would clear up any sort of misconception that B moves to the right. There were, however, problems with the virtual manipulatives where they behaved in unrealistic and unpredictable ways when components were moved beyond their intended limits. Many students, rather than reloading the assembly files to re-initialize the model, just used it in a broken state. This could lead to an inaccurate experience of the behavior of the dynamic model. However, in the physical model the slider (B in the diagram) *never* appears to move to the right (unless you rotate the pinion clockwise). How did five people in the Physical group still reach the conclusion that B moves to the right? Field observations and comments from students confirm the suspicion that not everyone in the treatment groups engaged with the model, despite having been deliberately instructed to do so. Being around the model is not the same thing as using the model, and even if the students used the model they may have reverted back to their original analysis method when faced with the posttest. The fact that the balance shifts away from the incorrect response on the posttest is encouraging.

Open Response Question 4: Geneva Mechanism

The fourth open response problem asked students to describe how the Geneva mechanism depicted in Figure 12 works, and in particular to describe the direction and speed of the star wheel, A, as a result of constant rotation of the drive wheel, B (see Appendix C for the actual problem text). The Geneva mechanism converts constant rotational motion of the drive wheel, B, into intermittent rotational motion of the star wheel, A. This is accomplished when the pin, P, connected to the drive wheel engages with a slot on A and turns the star wheel in the opposite direction as B. When the pin exits the slot after rotating the star wheel the appropriate amount (in this case, 60 degrees) the star wheel stops rotating. The process repeats when the pin comes around to engage the next slot in the star wheel.

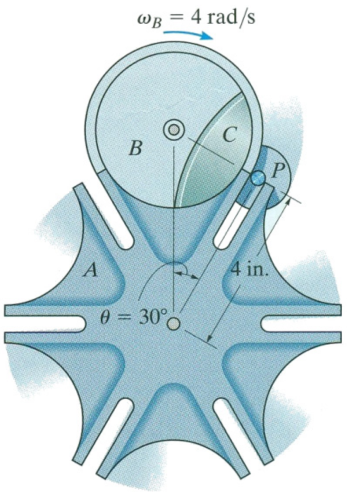

Figure 12. Textbook diagram of a Geneva mechanism. From R. C. Hibbeler, 2010, *Engineering Mechanics: Dynamics* (12th ed.), p. 390. Copyright 2010 by Pearson Prentice Hall. Used with permission.

On the pretest, the students were not told what this mechanism was or how it worked. The students solved the textbook version of this problem during the treatment problem solving session. The textbook version of the problem describes the mechanism and its operation (see Appendix F).

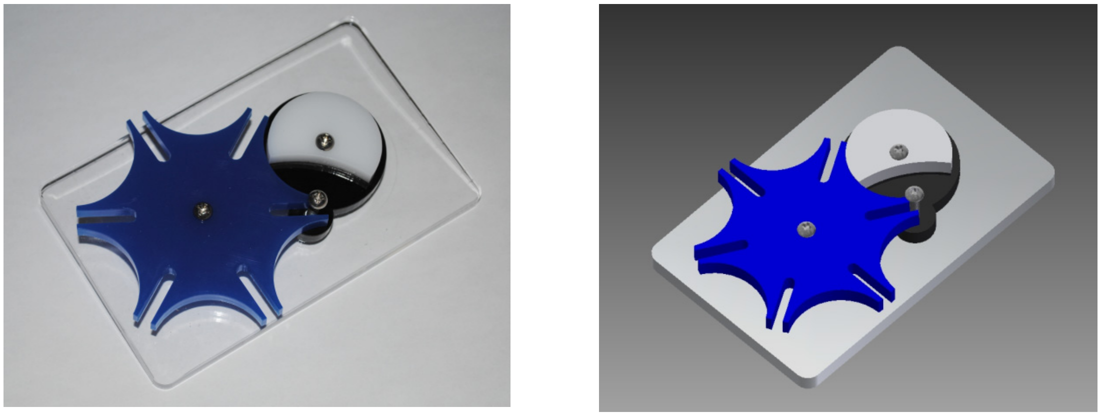

Figure 13. Physical (left) and virtual (right) manipulatives for the Geneva mechanism problem.

As with the previous open response problems, this one posed its own set of challenges for analysis. The problem asked students to describe the speed of A as either constant or varying. Unfortunately, describing speed as *varying* does not capture the salient aspect of the motion of A, namely that its motion is *intermittent*. It is possible that students who described the motion of A as varying conceived it as speeding up or slowing down, but not necessarily periodically stopping. To say that the speed of A varies would not be incorrect, but to say that the speed is constant *would* be incorrect. Because of this, for the analysis of speed, I only considered responses that indicated that the motion (speed) of A is intermittent (a correct response), and responses that indicated that the speed of A is constant (an incorrect response). The analysis of direction is straightforward, as there are only two possibilities (clockwise and counter-clockwise).

Direction Data and Analysis

The frequencies of direction codes (A rotates in opposite direction as B, or CCW; A rotates in the same direction as B, or CW) for each treatment group are summarized in Table 15. The expected values for each cell are indicated in parentheses. The correct answer is that the star wheel, A, rotates in the opposite direction as the drive wheel, B (CCW based on the initial condition that B rotates CW, as indicated by the curved arrow above B).

Table 15

Geneva Mechanism Direction x Treatment Crosstabulation

		Treatment			
Test	Direction	Traditional	Physical	Virtual	Total
Pretest	Opposite/CCW*	16 (17.3)	17 (14.8)	14 (14.8)	47
	Same/CW	5 (3.7)	1 (3.2)	4 (3.2)	10
	Total	21	18	18	57
Posttest	Opposite/CCW*	21 (20.4)	14 (13.9)	16 (16.7)	51
	Same/CW	1 (1.6)	1 (1.1)	2 (1.3)	4
	Total	22	15	18	55

* Correct answer

Analysis using the likelihood ratio chi-squared test revealed a non-significant test statistic for the pretest, $Y^2=3.096$, $df=2$, $p=0.213$; and a non-significant test statistic for the posttest, Y^2=0.628, df=2, p=0.730. The lack of significance of these test statistics indicates that treatment and direction are independent for the pretest and the posttest, and independent with respect to the test (pre- or post-). In other words, there is no relationship between treatment and the direction code frequencies, and therefore no significant difference between treatments with respect to direction responses by students.

The results of McNemar's Tests comparing pretest and posttest code frequencies for the individual treatment groups revealed no significant difference for the Traditional groups (X^2=0.00, p=1.000), Physical group (X^2=0.00, p=1.000), and Virtual group (X^2=0.00, p=1.000). The reason all three groups had identical test statistics (X^2=0.00) was because, for each individual group, the number of individuals who improved on the posttest was the same as the number of individuals who did worse on the posttest (three each for the Traditional group, one each for the Physical group, and four each for the Virtual group).

Speed Data and Analysis

The frequencies of speed codes (intermittent, constant) for each treatment group are summarized in Table 16. The expected values for each cell are indicated in parentheses. The correct answer is that the star wheel, A, rotates intermittently.

Analysis using the likelihood ratio chi-squared test revealed a non-significant test statistic for the pretest, Y^2=3.265, df=2, p=0.195; but a significant test statistic for the posttest, Y^2=6.220, df=2, p=0.045. The lack of significance of the test statistic for the pretest means that we cannot reject the null hypothesis that treatment and speed codes are independent (before the treatment). This supports the assertion that the groups were functionally equivalent prior to exposure to the treatment.

Table 16

Geneva Mechanism Speed x Treatment Crosstabulation

		Treatment			
Test	Speed	Traditional	Physical	Virtual	Total
Pretest	Intermittent*	4 (5.0)	2 (3.3)	6 (3.7)	12
	Constant	11 (10.0)	8 (6.7)	5 (7.3)	24
	Total	15	10	11	36
Posttest	Intermittent*	11 (14.2)	17 (15.1)	18 (16.7)	46
	Constant	6 (2.8)	1 (2.9)	2 (3.3)	9
	Total	17	18	20	55

* Correct answer

A significant test statistic for the posttest means that we can reject the null hypothesis that the two variables (treatment and speed) are not independent, and conclude that there is a relationship between them (after the treatment). The data reveal that, on the posttest, the Physical and Virtual groups had higher observed frequencies than expected for the correct response (intermittent speed) and lower than expected frequencies for the incorrect response (constant speed), whereas the Traditional group had lower than expected frequency for the correct response and higher than expected frequency for the incorrect response. This pattern appears in the cross-tabulated data for the planetary gear set (sun driven) and rack and pinion problems as well. The frequencies for the Physical and Virtual groups are almost identical, and therefore suggest that there was not any difference between the Physical and Virtual groups' posttest performance on this measure, but they both appear to have outperformed the Traditional group.

The results of McNemar's Tests comparing the prestest and posttest code frequencies for individual treatment groups revealed no significant difference for the Traditional group (X^2=3.00, p=0.083), but significant differences for the Physical group (X^2=6.00, p=0.014) and Virtual group (X^2=4.00, p=0.046). Looking at the data, it is obvious that these differences for the Physical and Virtual groups are improvements. These results suggest an advantage of Physical and Virtual over Traditional in the identification of the correct speed.

Mental Models

Table 17 summarizes the frequency count of individuals whose explanations of the Geneva mechanism exhibited characteristics of specific mental models. Corresponding proportions are indicated in parentheses.

As with the exploration into mental models for the preceding problems, the most salient feature of this table is that mental simulation dominates all other models (probably for the same reasons). For this machine, any reasonably accurate description of the role of the pin, P, constituted a description of an intermediate component in the causal chain from input (the drive wheel, B) to output (the star wheel, A). The complete lack of any other model codes in the posttest probably reflects the fact that students who gave explanations of how the machine works (many students did not) realized that the action of the pin plays a crucial role in its operation.

Table 17

Mental Models for Geneva Mechanism Explanations

	Pretest			Posttest		
Mental Model	T	P	V	T	P	V
Intuitive						
Procedural Mapping						
Analogical	2 (0.08)					
Naïve Representations	1 (0.04)					
Physical Representations	1 (0.04)		3 (0.13)			
Mental Simulation	6 (0.23)	3 (0.14)	9 (0.39)	17 (0.65)	16 (0.76)	20 (0.87)

Note. Proportions are indicated in parentheses.

Discussion

This was the only problem on the pretest where students admitted that they did not understand the diagram. The following are some student responses from the pretest:

> "It would be a lie if I said I had any idea how this machine works. I don't understand it yet."

> "I have no idea what this is or how it is turning, perhaps the pin is force into the collum [sic] by the driving wheel and then the wheel hops over the pin to the next gap which allows for the pin to move after it."

> "I can't tell what this machine does, the picture is kind of confusing."

There were six such responses on the pretest in the Traditional group, two in the Physical group, and five and the Virtual group. It was apparent that the diagram by itself was not necessarily intuitive, and thus imparted extraneous cognitive load. However, by the posttest, no students reported any such confusion. Students either felt that they understood the machine at that point, or did not admit to being confused.

The confusion during the pretest and subsequent understanding of the machine is probably what is responsible for the large shift from pre- to post- on the speed measure. Many students were confused on the pretest, and only some of them admitted to being so. Others may not have expressed their confusion or uncertainty, but rather tried to explain the operation of the machine they thought they were looking at. One student described the machine on the pretest as being the same as two gears:

> "It works like a system of gears. The small disk rotates and the star wheel rotates. Since the disk rotates clockwise, the star wheel rotates counter clockwise at constant speed. The star wheel is turning slower because it has a larger radius than the driving wheel B."

When faced with a situation that the student did not understand, this student used analogical reasoning to make inferences about this new machine, based on the behavior of a superficially similar system. In this case, an inference made about the direction of rotation of the star wheel is correct, but the inference about the constant speed is incorrect. It is likely that many other students used a similar analogical model, however they did not provide concrete evidence for that model in their descriptions (credit for the analogical model was only given when the student explicitly stated that the current system is similar to another).

The significant improvement from pretest to posttest for the Physical and Virtual groups (and not the Traditional group) in the identification of correct speed, as well as the higher frequency (relative to the expected frequency) of explanations describing the intermittent motion of the star wheel for the Physical and Virtual groups over the Traditional group, suggests that the dynamic model may have conveyed a better sense of this motion than a text description and the static diagram. This is as we might expect, because the intermittent motion of the star wheel is obvious after observing the operation of a dynamic model for even less than one revolution of the drive wheel. The virtual and physical manipulatives of the Geneva mechanism performed quite well, although slow computer performance caused lag when students in the Virtual group actuated the drive wheel. Students in the Traditional group had to determine that the motion of the star wheel was intermittent based on mechanical reasoning, a task that is probably made more difficult by the extraneous load imparted by the static diagram (as evidenced by confusion on the pretest), whereas the students in the Physical and Virtual group could *experience* the intermittent motion directly as a result of their interaction with the manipulatives. However students in all treatments improved from pretest to posttest, a result that suggests that an explanation of how the Geneva mechanism works may be sufficient for getting around the problem of identifying its intermittent motion.

Mechanical reasoning for the Geneva mechanism is different than for the planetary gear set and rack and pinion problems. In those two previous problems the influence of a critical motionless component needed to be considered simultaneously with the action of other components in the system. The non-moving component was not directly part of the causal chain followed by many students. In the Geneva mechanism there is no such sideline component—all of the components are part of the causal chain. The chain described by students goes from the drive wheel, to the pin, a slot in the star wheel, to the rotation of the star wheel. This simpler (compared to the other two mechanisms') causal chain analysis may be responsible for the exclusive coding of the *mental simulation* mental model in the posttest responses, and also partially responsible for the dramatic shift from pretest to posttest observed in the speed code analysis for all treatments.

Open Response Question 5: Planetary Gear Set (Ring Driven)

The posttest included two additional open response problems that were not on the pretest. These two problems were intended to test transfer of learning, and the students did not know that they would be tested on this. I theorized that if students exposed to dynamic manipulatives exhibited improved performance over students in the Traditional group, and that this improved performance might be due to improved mental models or spatial visualization, then I should see improved performance for the Physical and Virtual groups over Traditional on tests of transfer.

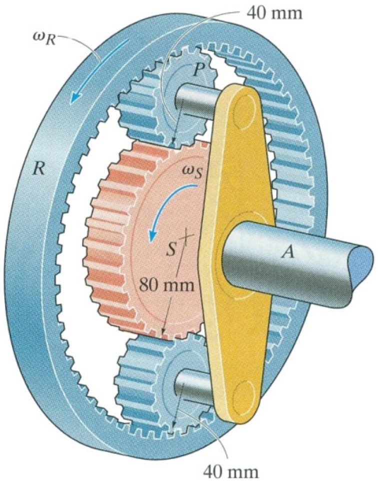

Figure 14. Textbook diagram of a planetary gear set. From R. C. Hibbeler, 2010, *Engineering Mechanics: Dynamics* (12th ed.), p. 347. Copyright 2010 by Pearson Prentice Hall. Used with permission.

The first of these two additional problems was intended to test *near transfer* (transfer in a very similar situation as previously experienced), and asked students to reason about the behavior of output shaft A in the same planetary gear set from open response problem 2, given a different set of initial conditions. In problem 2 the sun gear, S, was the input and the ring gear, R, was held motionless. For the transfer situation, I asked students to consider the case where R is now the input and S is held motionless. The results from the analysis of problem 2 suggest that there might be a benefit of using the dynamic manipulatives in the determination of the speed of A relative to the input. If this result is due to an improved mental model or spatial visualization then we would expect to see similar findings for the transfer case.

Direction Data and Analysis

The frequencies of direction codes (A rotating in the same direction as R, A rotating in the opposite direction as R) for each treatment group are summarized in Table 18. The expected values for each cell are indicated in parentheses. The correct answer is that A rotates in the same direction as R.

Table 18

Planetary Gear Set (Ring Driven) Direction x Treatment Crosstabulation

		Treatment			
Test	Direction	Traditional	Physical	Virtual	Total
Posttest	Same*	13 (13.9)	12 (11.4)	13 (12.7)	38
	Opposite	9 (8.1)	6 (6.6)	7 (7.3)	22
	Total	22	18	20	60

* Correct answer

Analysis using the likelihood ratio chi-squared test reveals a non-significant test statistic, Y^2=0.279, *df*=2, *p*=0.870. The lack of significance of the test statistic indicates that there is insufficient to reject the null hypothesis that treatment and direction are independent. In other words, there is no relationship between treatment and the direction code frequencies, and therefore no significant difference between treatments with respect to direction responses by students.

Speed Data and Analysis

The frequency count for speed codes (A rotating slower than R, A rotating faster than R, A rotating at the same speed as R or not rotating) for each treatment group are summarized in Table 19. The expected values for each cell are indicated in parentheses. Note that frequencies for A rotating at the same speed as R, and A not rotating, were combined in order to compensate for low cell expected counts, and also to keep analysis consistent with the sun-driven planetary gear set problem (open response problem 2).

Table 19

Planetary Gear Set (Ring Driven) Speed x Treatment Crosstabulation

		Treatment			
Test	Speed	Traditional	Physical	Virtual	Total
Posttest	A < R *	3 (6.8)	7 (5.1)	8 (6.1)	18
	A > R	12 (9.0)	4 (6.9)	8 (8.1)	24
	A = R | 0	6 (5.3)	5 (4.0)	3 (4.8)	14
	Total	21	16	19	56

* Correct answer

Analysis using the likelihood ratio chi-squared test reveals a non-significant test statistic, Y^2=7.156, *df*=4, *p*=0.128. The lack of significance of the test statistic indicates that there is insufficient to reject the null hypothesis that treatment and speed are independent. In other words, there is no relationship between treatment and the speed code frequencies, and therefore no significant difference between treatments with respect to speed responses by students.

Discussion

The analysis revealed that there was insufficient evidence to statistically substantiate a claim that treatment had an effect on students' responses for direction and speed of the output shaft in this transfer case of the planetary gear set. However, two key aspects of this study influence my interpretation of this result: (1) small sample sizes, (2) non-parametric tests. Both of these aspects result in lower power analysis, which means that the analysis is less likely to detect differences that might actually exist.

Examining at the data more closely, a pattern emerges which suggests that there might be a difference. If we look at the residuals (the difference between the observed frequency and expected frequency for each cell) for direction, we see that they are all less than 1. This suggests that there truly is no difference for direction. Looking at the residuals for speed, however, we see that they are greater than 1. If we look at just the frequencies for the two primary speed codes, A < R and A > R, a familiar pattern emerges: Physical and Virtual group students' responses score higher than expected for the correct response, and lower than expected for the incorrect response, while the Traditional group students' responses score lower than expected on the correct response and higher than expected on the incorrect response. This possible difference between the treatments looks more so when examining the frequencies in Table 19 converted into proportions (by dividing the observed frequency for each cell by the size of each treatment group), as displayed in Table 20.

Table 20

Planetary Gear Set (Ring Driven) Speed x Treatment Proportions

		Treatment			
Test	Speed	Traditional (n=26)	Physical (n=21)	Virtual (n=23)	Total (n=70)
Posttest	A < R *	0.12	0.33	0.35	0.26
	A > R	0.46	0.19	0.35	0.34
	A = R | 0	0.23	0.24	0.13	0.20
	Total	0.81	0.76	0.83	

* Correct answer

The fact that there were higher proportions of students in all treatments that give an incorrect answer than the proportions giving the correct answer is distressing, and shows that mental models across all treatments usually failed. It might also be quite perplexing that one student from each treatment thought that A would not move at all in this situation, except that, as previously noted, not all of the students in the Physical and Virtual groups actually interacted with the manipulatives.

Overall, despite the lack of statistical significance found through the analysis, I believe the results are encouraging. The pattern of responses is similar to those of open response question 2, where Physical and Virtual group students appear to outperform the Traditional group students in correctly identifying the speed of the output relative to the input. It is possible that with larger samples, a more precise instrument, better manipulatives (although designed to have a movable ring gear, the physical and virtual manipulatives' ring gears were fixed in place), and more in-depth (longer and more involved) exposure to the manipulatives, the results of the statistical analyses would reveal significant differences.

Open Response Question 6: Quick-Return Mechanism

The second transfer problem on the posttest was intended to test farther transfer (analysis of a machine for which students did not have prior exposure). This problem asked students to describe the behavior of the pivoting linkage, CD, in the *quick-return* mechanism displayed in Figure 15 (see Appendix C for the actual problem text).

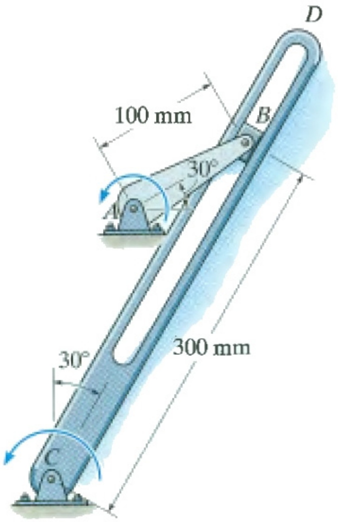

Figure 15. Textbook diagram of a planetary gear set. From R. C. Hibbeler, 2010, *Engineering Mechanics: Dynamics* (12th ed.), p. 390. Copyright 2010 by Pearson Prentice Hall. Used with permission.

In the quick-return mechanism, the input comes from constant rotational motion of the crank, A. This moves the slider, B, in the slot of the linkage, CD. As A rotates counter-clockwise, B is driven upwards in the slot simultaneously causing CD to pivot about C in a counter-clockwise direction. When the crank arm, AB, is vertical, B will begin to move downwards in the slot. Eventually, CD will change directions and pivot clockwise. The speed of the pivoting of CD is faster on the return (clockwise) than when it pivots counter-clockwise, due to the difference in the radii from C to B for the two cases, hence the name *quick-return* mechanism.

I discovered after the posttest that virtually the same mechanism was discussed in detail and solved, both in class and on a video on the Mastering Engineering web site. Since this item was intended to test a case for which students were supposed to have no prior exposure, the appearance of the problem as part of the course instruction rendered it pointless to analyze.

Field Observations

I had originally intended to conduct observations during the treatment problem solving sessions. Unfortunately, due to logistics, I spent most of the time with the Virtual group in a computer lab separated from the Traditional and Physical group students. My time spent with the Virtual group was primarily consumed with helping students load and operate the virtual manipulatives. Most of the field observation results come from my memory of what I saw, as well as observations made of video recordings taken during the treatment problem solving sessions.

One pair of students from each treatment group was randomly selected each night of the treatment (there were two nights) to be video recorded. The complexities and demands of getting the classroom and recording equipment set up, distributing worksheets and delivering instructions, handing out physical manipulatives, and getting virtual manipulatives loaded resulted in my failure to begin recording on time. By the time I first began video recording, one of the pairs was almost done with the problems. I had to switch the recording to another pair after the original pair completed their work. I also captured video of an individual working with the model, taken at a make-up session (that student had missed the first night of the treatment, but worked on the problems alone the next night, but before the next treatment session). Since the individual student was working alone, I could not hear any recorded conversation to elaborate on thinking processes using the model. I was not able to hear the conversations on the other video recordings either, due to high levels of ambient noise or students talking too softly. All field observations are therefore visually based. I describe here the major findings from the field observations.

Limited Use

Students' actual use of the physical and virtual manipulatives was very limited relative to the amount of time they spent working on the problems. The majority of the time was spent reading the problem, doing the math, or thinking about the problem (I assumed that they were thinking about the problem when I observed them staring at the problem or the work they had done). For example, a student observed working on the planetary gear set problem took about 15 minutes to solve the problem. During that time span, the student interacted with the physical model a total of seven times, with an average interaction time of about 20 seconds (the actual range was 9 – 29 seconds for this case, but observed interactions could take as little as five seconds). This level and pattern of interaction was observed in students working with the virtual manipulatives as well.

Tool for Testing/Verification

Students were observed using the manipulatives to test theories or verify assumptions they had about the operation of the machine. Students were observed making statements about how something worked, sometimes using hand gestures while describing the motion of a component, and then actuating the manipulative to see how it actually worked. A student using the physical manipulative for the planetary gear set actually marked the gears with a pencil, apparently as a way to measure displacement or relative speed.

Aid for Communicating

Often occurring hand-in-hand with use of the manipulatives for testing and verification, students working in pairs would use the manipulatives in order to convey information about how something moves. Students in the Virtual group were observed discussing the motion of a gear in the 4-bar linkage problem. One of the students was gesturing with his hands to describe the motion of the gear to his partner, then he actuated the virtual manipulative to show the motion to his partner. His partner looked at the manipulative and made comments about it, pointing at the screen to draw attention to key areas. This sort of behavior was observed in the Traditional group as well, but the students had to use the static diagrams as the foci of the discussions, gesturing around the diagrams to show the direction of motion of parts while discussing it with their partners. Traditional group students also gestured in the air in an attempt to give their partners a dynamic visual of the motion they were describing.

Playing with Models

I frequently observed students picking up the physical model and moving the parts repeatedly. This tended to occur more with the physical manipulatives than with the virtual manipulatives. The reduced observed frequency of this behavior in the Virtual group is probably due to the fact that the Virtual group experienced a lot of problems with the virtual manipulatives, both in loading the manipulative (incorrect loading procedures led to missing parts, plus the load time was laborious and slow) and in using them (moving parts beyond their intended limits caused the model to behave unpredictably, and slow computer performance caused the animation to skip and introduced lag between user input and seeing the result on the screen). I also frequently observed students using the physical manipulatives attempting to tighten the nuts on the models (the models were assembled using nylon-insert locking nuts, so their attempts to turn the nuts by hand were ineffectual).

Opinion Questionnaire Responses: Did the Model Help?

I asked participants to fill out a questionnaire after they turned-in the multiple-choice portion of the posttest. This questionnaire asked them for their opinions about the helpfulness of the models (static diagram, for the Traditional group) and their comments about the study (see Appendix G). The responses on the questionnaire answer the research question regarding what students thought about the manipulatives. The first question asked students to respond *yes* or *no* if the model/diagram helped them solve the problems. The summary of the responses to this question is displayed in Table 21. All participants who submitted a questionnaire answered this question; therefore, responses not listed in the table were negative. Only one participant from the Traditional group did not submit a questionnaire, all other participants submitted a questionnaire.

Table 21

Opinion Questionnaire Responses Indicating the Model/Diagram Helped

Treatment	N	Frequency of Yes	Proportion of Yes
Traditional	25*	21	0.84
Physical	21	17	0.81
Virtual	23	15	0.65

* Missing a questionnaire from one participant in the Traditional group

The first thing to note about the responses to the question of whether or not the model helped is that all of the proportions are above 0.50, which means that most participants thought that their model (diagram, for the Traditional group participants) helped them solve the problems. Comparing the proportions between the treatments, it appears that there is no difference between the Traditional and Physical group participants, but there looks like there might be a difference between Traditional/Physical and the Virtual group. I performed a binary logistic regression to test the hypothesis that there is a difference between the Virtual group responses and the other two groups.

Since the proportion of the Traditional group is further away from the Virtual group proportion, and since the Traditional group is the control group in this quasi-experimental study, I designated the Traditional group as the reference group in the binary logistic regression. I used SPSS to perform the regression, which dummy-coded the treatment variable as three dichotomous variables. The result indicated a lack of significance for the coefficients of the Physical (*p*=0.786) and Virtual (*p*=0.141) treatment terms in the equation, which means that those coefficients are not significantly different than zero. In other words, those treatments do not have a significant effect (beyond membership or lack of membership in the Traditional group) in predicting whether a student responds with a *yes* to the question of whether the model helped or not. In plainer terms, the analysis showed no significant difference between the responses of the three treatment groups.

Discussion

Although it appears that there is a difference from the number of "yes" responses from the Virtual group versus the other two groups, statistically it appears that there is no difference. Since the majority of responses are favorable towards the models, I conclude that students across all three treatments think that their respective models helped them solve the problems. This, however, does not really tell us much by itself. The real question is "how did the models help?" This is the subject of the following section.

Opinion Questionnaire Responses: How the Model Helped or Not

Although most participants in all three treatments responded that the model helped them solve the problems, the actual meaning behind this response varies between the treatments. The same holds true for responses that the model did not help them solve problems. The questionnaire asked the students to explain how the model helped or did not help them solve the problems. I analyzed the responses to this question using a qualitative *grounded* approach, which involved reading through the responses, developing codes based the ideas expressed in the responses, then going back and coding the responses using the codes. I counted the codes to see what kinds of responses occurred the most frequently, in order to identify common themes in the responses. Some student responses are virtually identical, however the students may have responded differently to the question of whether the model helped or not. For this reason, I report the most frequent *themes* describing how the model helped, and *themes* describing how the model did not help.

Traditional

For the Traditional group, the most common type of explanation indicated that having the static diagram was better than not having the static diagram. One would assume that a situation where the diagram was absent would mean that the student would just have a text description of the problem. Some responses simply stated that a visual aid helps:

> "I could look at it, better than a description."

> “A visual aid is always helpful to understand the problem.”

Other responses cited learning modes (e.g., visual) or mental simulation/visualization as reasons that a visual aid helps:

> "Visual person, I need to see or hold it in my hand to understand how it works."

> "Being able to see the mechanism helps me to visualize its motion in my head."

Other responses described how the static diagram was helpful because it gives you a basic idea of how the parts of the machine connect; however the students are quick to say that it did not help them get a sense of the motion:

> "The diagram helped me get a visual for what the machine would look like stopped, but in some cases it was difficult to tell how it would move."

> "It helped as it gave at least a slight representation of the physical objects. However, it didn't help with the understanding of motion."

> "While the diagram gave me the physical form of the object, it didn't help to convey how the pieces moved and worked together."

Another perspective is that the static diagrams are helpful because they provide information necessary to solve the problem:

> "Well, without the diagram, I would have been missing the ideas of how the parts relate to each other which is necessary for the calculations."

> "The diagram provides all numerical information necessary to solve the problem. For the most part I could visualize the motion of the diagram."

In summary, students in the Traditional treatment group reported that the static diagram was helpful because:

- A static diagram is better than a description alone
- It gives you a basic idea of how the parts go together
- It provides information necessary to solve the problem

Students reported that the static diagram was not helpful in that it:

- It does not help you see the motion of parts
- It does not help you see complex motion (interaction of multiple moving parts)

Physical

By far the most common explanation for how the physical manipulatives helped students solve problems was that they allowed them to see how the machines worked, particularly by allowing one to see the motion and interaction of parts:

> "The model helped explain the motion of paticular [sic] pieces."

> "It helped me visualize how the machine worked and the directions that it moved."

> “The model helped by allowing me to visualize exactly how the device worked and see how moving/rotating the different components affected each part.”

> “1st it showed the motion. 2nd you could check relative velocities”

An additional benefit reported by students was that the model could be used to make predictions or check theories about the behavior of the machine:

> “I was able to see the relationships between the parts of the model and use it to make reasonable guesses about what was going on (e.g. should be slower)”

> “I was able to confirm how I thought the model should act before trying to solve a problem.”

> “It gave a basic understanding of the mechanisms and gave a rough indication for what the answers should be.”

Explanations for how the model did not help Physical group students solve problems mostly have to do with either the student reporting that they did not have any problems visualizing without the model, or that the main issue in solving the problems is the math:

> “I could usually picture what was happening without the model. Knowing the equations helped me solve.”

> “I already knew what most of the machines would look like before using the model.”

> “It's nice to see a model of it, but it doesn't help me see relative velocities, etc.”

That last quote is most likely referring to quantitative measurements of relative velocity, as opposed to qualitative assessments of relative velocity, since you can see qualitatively whether a component is moving faster than, slower than, or approximately at the same speed as another component in the physical model.

In summary, the physical model helped students solve problems by:

- Allowing one to see how the machine moves/works
- Helping make predictions prior to calculation, or check theories about the motion of the machine

The physical model did not help students when they felt they did not have any problems visualizing the machine from a static diagram, or when computation dwarfs other factors in difficulty solving the problem.

Virtual

The common themes expressed in explanations from the Virtual group students are similar to those of the Physical group students. The Virtual group students report that the virtual manipulative was helpful because it allows one see how the machine works; in particular, how the parts move and interact:

> “The virtual model really helped me be able to visualize what was happening in the problem. It especially helped me understand the way different components interacted - particularly in the star wheel problem.”

> “Being able to visualize the relationships of the moving parts.”

> “It allowed a clear representation of the sometimes complex motions of the problems.”

One student described the ability to see motion as a result of manipulation as helpful:

> “It was very hands on and allowed me to visualize the movement that was produced.”

Like the students in the Physical group, those in the Virtual group also described how the virtual manipulative allows one to confirm expectations about motion, or see the motion before doing calculations:

> "It confirmed my initial expectations for motion, but nothing more really."

> "I knew which way the motion was without doing the problem."

The most frequent theme in explanations of how the model was not helpful reflects the problems the students experienced while using the model:

> "While the model made it more clear for me to understand the question for the questions that we did it made me more confused because things look like they were moving faster when they were slower or vise versa."

> "Many times the CAD software has glitches which prevented the model from operating as it would in real life. Gears would skip or slide, and it was a pain. Most of the time could already tell what it was doing."

> "It could help sometimes but mostly it just messed up a lot!"

Other explanations indicate that the model was not helpful when students could already visualize from the static diagram, and when math is the issue:

> "I can visualize the problem based on a diagram. The model does not help with applying equations."

In summary, the Virtual group students' explanations for how the manipulatives helped them solve problems are basically the same as those for the Physical group. The manipulatives helped by:

- Allowing one to see how the machine moves/works
- Helping make predictions prior to calculation, or check theories about the motion of the machine

The virtual models were not helpful when:

- The virtual model "broke"
- Students could already visualize from a static diagram
- Math is the issue

Discussion

For the Traditional group, the most frequent descriptions of how the model helped say that having a diagram is better than not having a diagram, and that the diagram gives you the information you need to solve the problem. The most frequent descriptions of both the Physical and Virtual group responses are that the model helped the students by helping them see how the machine works. These descriptions highlight the inherent advantage of the dynamic models over the static diagrams: being able to observe the motion of the machine.

From the negative responses, we see that the main way that the static diagrams were not helpful was that they did not adequately convey motion. Both the physical and virtual groups included individuals who reported that they did not need the dynamic models to help them visualize the operation of the machines, and these make up some of the most frequent responses (although the actual total frequency is low). Some students also felt that the computational aspect of solving the problem was a more important issue than visualizing the problem. The software-related problems experienced by students in the Virtual group appear to be a major issue impacting the assessed helpfulness of the virtual models.

Opinion Questionnaire Responses: How the Model Could Be Improved

The questionnaire asked students to provide their suggestions for how the models could be improved. This section describes their responses, grouped by treatment (since the suggestions are specific to the type of model used by each treatment).

Traditional

The most frequently suggested improvement for the static diagrams are the inclusion of multiple views showing the machines at different points in time. This would allow students to perceive motion through displacement. Some examples:

> "More movement indicators regarding direction and motion of particular parts or a second diagram later in time."

> "Creating an image of where the object should be in a 1/4 revolution or translation would help."

> "Draw the diagram in different stages of its cycle."

> "Show two pictures in a diagram, before movement, after movement"

Other suggestions included improving the description of the motion or operation of the machine, adding indicators for direction of travel of components, improving the labels on diagrams, and meaningfully color-coding components (although the diagrams used in the study were originally printed in color in the textbook, they were reproduced on tests and worksheets in grayscale).

Physical

The most common theme in the responses from Physical treatment participants is about problem with the model. In many cases, this appeared in responses as a suggestion to “tighten tolerances.” I assembled physical models somewhat loosely; hand-adjusting each one to make sure that the parts did not bind. Despite my efforts, some of the models (the rack and pinion models in particular) would not operate smoothly and even jam. Field observations suggested that students thought that the loose assembly was the cause of the jamming problems, so I classified suggestions to “tighten tolerances” as a reference to the jamming problems. The following quotes are typical of responses from Physical group participants:

> “The models could have been made in a way where they didn't stick or they have a possibly crank on the back to move them.”

"More precise."

"Make models more ideal. One model was too loose."

"Decrease tolerances so it functioned better."

Other suggestions included improving user controls, adding component labels, adding reference or measurement markings, meaningfully color-coding the components, and simplifying designs.

Virtual

Like the Physical group, the most common theme in responses for the Virtual group has to do with problems they experienced while using the virtual manipulatives. As I described earlier, the process to load the manipulatives was time consuming and had lots of room for user error. The main problem experienced by students during loading was that the CAD software would not load all of the parts correctly if the student clicked on the assembly file from within a zip archive that had not been correctly decompressed. This happened quite frequently (and repeatedly), despite having been told and shown the correct way to start it. Another problem was that a model's behavior would become unpredictable if components were moved beyond their intended limits. When this happened, the easiest way to fix it was to reload the model and students usually opted to just use the "broken" model instead. Keeping this in mind, the following quotes, which are typical for this group, are quite understandable:

“Make it not break”

"The virtual model in CAD would ‘break’ frequently when pushed too far. This could be confusing at times."

“Use other software that doesn't have these shortcomings.”

“Fix constraints so the model doesn't break”

The second most common theme in the suggestions from the Virtual group is to add measurements for quantities such as velocity and acceleration to the virtual manipulatives, and/or to provide math help/hints. Some examples:

“Show numbers on the CAD ie. the w input and look at actual #'s outputted.”

"List real-time physical information (v,w,?, etc.) next to the model."

"Label each component with v, a, w, x or any other variables and give the equation."

"Perhaps outputting the numbers as well to give an idea not just how system moves, but how another different parts relate to each other."

Another suggestion was to provide looped animation, where the student can press a play button and the software animates the motion of the machine automatically. It is likely that this suggestion is a response to the problem of slow computer performance that caused parts to appear to skip when students clicked and dragged them. Students complained that they had difficulty making parts move smoothly, and this had an adverse effect on their ability to judge any kind of resulting motion of another part.

Discussion

The main way suggested for the static diagram to be improved is to add better descriptions of motion, perhaps in text but primarily in terms of adding multiple views. Showing the position of components at multiple points in time would give students a better sense of the movement of the components and thereby aid in their understanding of the behavior of the machine. Many students suggested tightening tolerances on the physical model, which I interpreted as complaints about the models jamming. Students may have realized that the loose fit of parts may have been affecting the accuracy of the position of parts and thereby affected the accuracy of the behavior of the model, but, based on observation, I think it is more likely that they were putting forth their idea of what would fix the jamming problems exhibited by many of the physical models. Fixing problems with the virtual models is also top on the list of suggestions from the Virtual group. However the students in the Virtual group also appear to have an expectation of the capabilities of software, suggesting that the virtual model also include features such as real-time measurements (e.g., velocity and acceleration), as well as user-controllable animations. These features are particular to the nature of the model (computer-based), and students would not expect such things from a static diagram or physical model (although a physical model could also include real-time measurement by way of gauges, and one student from the Physical group also suggested adding reference markings; the model could also be made automotive).

Opinion Questionnaire Responses: Other Things that Might Help

The questionnaire also asked students to suggest other things that might help them solve the problems. This section describes these suggestions, organized by treatment. It is necessary to group them by treatment since students in different treatment groups wanted some different things.

Traditional

The most requested additional aid for solving problems requested by students in the Traditional group is to have a physical model. The second most requested thing is a virtual model. There were twice as many (n=12) total requests for a physical model than for a virtual model (n=6), although some of these are requests for either physical or virtual, sometimes for both. The fact that there were more total requests for a physical model than for a virtual model is probably due to the fact that the Traditional and Physical treatment groups shared the same classroom (they were on opposite sides of a wide room). I heard students in the Traditional group making comments about how the people on the other side of the room (the Physical group) had an easier time because they had a physical model.

Other suggestions for things that would help included better math and theory preparation, better explanations of how the machines worked, and videos or animations of the machines.

Physical

The aids most frequently (n=3) requested by the Physical group were providing equations, having an explanation of how the machines work, and having some way of taking measurements (such as velocity). Two individuals requested a virtual model. Other suggestions were for solutions to a similar problem, better math/theory preparation, and adding component labels to the models.

Virtual

Not surprisingly, the most requested (n=8) additional aid for the Virtual group is physical models. This is probably because of all of the problems the Virtual group experienced with the virtual models. They also requested better explanations of how the machines work, videos or animations of the models, better math/theory preparation, equations, and solutions to similar problems.

Discussion

It comes as no surprise that the most requested additional aid for students in the Traditional group is a physical or virtual model. It is somewhat surprising that the students in all three groups appear to recognize the importance, and their own deficiency, in math skills. A couple students in the physical group wanted a virtual model, and several students in the virtual group wanted a physical model. This could be because they imagined what the other groups' model might be like and were fixated on the problems they experienced with their own model. It could also be that they wanted additional representations to help them get a better sense of how the machines work.

Opinion Questionnaire Responses: Comments/Suggestions

The last question asked students for any additional comments or suggestions. The most frequent response was that students felt they needed better math or theory preparation:

> "Need to learn the material better first then add the visual aids."

> "Simply allow the students more time to familiarize themselves with the problems before giving them a model. Or giving them a model during class to follow along would be helpful as well."

> "The physical model was helpful but as for us solving the problem it still required knowledge of the material learned in class."

> "It's better if we are familiar with all the equations before we participate in the study."

The rest of the comments are less thematically related. They run the gamut from providing varied suggestions for how to redesign the experiment, to comments about the course (e.g., Dynamics is challenging), to general words of encouragement, to recurring complaints about the models (see Appendix N for a full listing of the comments). One of the comments agrees with field observations, where the student reports that he/she had two partners, neither of which used the virtual model. Another comment suggests using the models during lecture, and another comment suggests using web-based models.

CHAPTER 5

SUMMARY

In this chapter I summarize the work that I did and the findings from the study. I return to the original research questions and provide answers to them based on the findings. I describe limitations of this study, how this work contributes to the body of literature, and suggestions for further research.

Overview of Work

In this study I investigated the use of physical and virtual manipulatives in the context of a Mechanical Engineering course in Dynamics. Dynamics is the study of motion. A topic within Dynamics, rigid body kinematics, was the focus of this study. Rigid body kinematics is the study of accelerating motion that cannot be reduced to analysis of the motion of a single point, and includes motion such as that of rotating objects. This subject matter is traditionally taught using lecture and static diagrams, which typically do not convey motion, or do not convey motion well (motion might be implied by the use of direction vectors or motion blurs). Physical and virtual manipulatives, as dynamic realizations of the machines depicted in static diagrams, would seem to be a logical way of providing the experience of motion that static diagrams lack.

Summary of Findings

In this section I summarize the findings from this study. The research questions and key findings for each question are described in Table 22.

Student Performance

The first research question is concerned with student performance under the three treatments. I define performance as speed and accuracy solving dynamics problems, and the ability to accurately describe the behavior of a machine given its static diagram. I collected speed and accuracy data from posttest results. Speed was measured in minutes, and is the elapsed time between the start of the posttest until submission of the posttest. Accuracy was measured as the percentage of correct items on the posttest. I measured the ability to accurately describe the behavior of a machine using qualitative content analysis of the written responses to the posttest open response questions.

Under the three treatments, the traditional (T) method is considered to be a control group. The physical (P) and virtual (V) manipulatives treatments are experimental groups. I compared scores on the multiple-choice portion using ANCOVA (pretest scores as a covariate) at $\alpha=0.05$. I compared mean speeds for the three treatment groups using ANOVA at $\alpha=0.05$. I compared characteristics of the open response question explanations using likelihood ratio chi-squared analysis at $\alpha=0.05$, and McNemar's Test at $\alpha=0.05$.

Table 22

Research Questions and Key Findings

Research Question	Key Findings
1. How does student performance compare for students with instruction supplemented with physical manipulatives, instruction supplemented with virtual manipulatives, and traditional methods of instruction?	• No difference between treatment groups on spatial and conceptual measures. • Physical and Virtual appear to outperform Traditional group students on measures of mechanical reasoning (the correct analysis of salient characteristics of the behavior of certain machines)
2. How do students use static diagrams, physical manipulatives, and virtual manipulatives when learning rigid body kinematics?	• Students tend to use the models for short amounts of time. • Models are used to test theories/assumptions, and as communication aids
a. What kinds of mental models of mechanical systems do students develop using static diagrams, physical manipulatives, and virtual manipulatives?	• Mental simulation is the dominant form of mental model observed in students' explanations of the behavior of the machines. • Students often engage in shortcut analyses that result in incorrect inferences.
3. What do students think about static diagrams, physical manipulatives, and virtual manipulatives as learning aids?	• Students feel that all of the models (dynamic and static) are helpful; however the dynamic (physical and virtual) models are beneficial in that they show how the machines work. • The physical and virtual models used in this study had problems and could be improved. • Math tends to be an issue commonly identified by students.

The quantitative analysis revealed no significant difference between treatments for scores on the posttest, and no significant difference between treatments for time taken to complete the posttest. Furthermore, there was no correlation between time and score on the posttest.

I divided the analysis of the explanations for the open response problems into comparisons of qualitative code frequencies for direction and speed of the output for each mechanism. The results of the analysis suggested that there were significant differences in favor of the Physical and Virtual over the Traditional treatment in the identification of the correct relative speed of the output shaft in the sun-driven planetary gear set, the identification of the correct direction of the output in the rack and pinion mechanism, and the correct identification of intermittent motion in the Geneva mechanism. I found no significant difference between treatments in the correct identification of the direction of the output shaft in the sun-driven and ring-driven planetary gear sets, and no significant difference in the correct identification of the relative speed of the output shaft in the ring-driven planetary gear set. There was also no significant difference between the treatment groups in the case of identifying the correct speed (varying versus constant) of the output in the rack and pinion mechanism.

In addition to statistical tests, looking at the speed code frequencies for all of the open response problems reveals a pattern. The Physical and Virtual groups tend to have higher than expected observed frequencies for the correct answer, and lower than expected observed frequencies for the primary incorrect answer, whereas the Traditional group tends to have lower than expected observed frequencies for the correct answer and higher than expected frequencies for the primary incorrect answer. This pattern suggests that there might be a difference between the treatments despite any inability to show a *statistically significant* difference. Small sample sizes and lower statistical power of non-parametric tests (i.e., the likelihood ratio chi-squared test) versus parametric statistical tests likely affect the outcomes.

It appears that the ability to correctly identify speed and direction of the output varied based on the machine as well as the treatment. It is possible that the advantage of the Physical and Virtual groups over Traditional in the correct identification of relative speed, but lack of advantage in identifying direction, is due to the fact that relative speed is much more salient in a dynamic model than it is in a static diagram. The fact that the output in the rack and pinion mechanism does not go to the right is plainly obvious from looking at a dynamic model, but not obvious from looking at a static diagram. This is reflected in the increased frequency of the correct answer from pretest to posttest of the Physical and Virtual groups, and the lack of difference pre- to post- for the Traditional group. The intermittent motion of the Geneva mechanism is also the salient aspect of its operation and is obvious from observing a dynamic model, but must be deduced from a static diagram using mechanical reasoning. However a description of its operation may be sufficient for many students to understand that the star wheel rotates intermittently and that may be why students across all treatments performed better on the posttest than on the pretest (plus, the Geneva mechanism proved to be unfamiliar and thus confusing to many students during the pretest). It appears that the results of the analysis agree with an expectation that Physical and Virtual group students should outperform Traditional group students on measures of an aspect of motion that is better represented by a dynamic model than a static diagram.

Usage Characteristics

The second research question asks how students use the static diagrams, physical manipulatives, and virtual manipulatives, while solving dynamics problems. I conducted field observations and analyzed video recordings to determine the answer to this. I recorded my observations as text, and analyzed the text for common themes. I found the following:

- Students' actual time using the physical and virtual manipulatives is very limited, compared to the total time they spend working on a problem
- Students use the physical and virtual manipulatives as a tool for testing their theories about how a machine behaves
- Students use the static diagrams, physical manipulatives, and virtual manipulatives as a visual aid in communicating about the problem with their partners

Mental Models

To investigate the kinds of mechanistic mental models students may develop within the different treatments, I examined students' answers to the open response questions on the pretest and posttest. I looked for characteristics that reflected the indicators of types of mental models (Table 2). I found that the dominant form of mental model, both on the pretest and on the posttest, for all treatment groups, is mental simulation. There tended to be more variety in the types of explanations on the pretest, but posttest explanations were virtually always classified as mental simulation. Recall that mechanical reasoning by mental simulation involves the analysis of a causal chain of events. I coded students' explanations as mental simulation if they described (either through writing or drawing) the involvement of an intermediate component in the causal chain from the input to the output. This categorization only applied when students actually gave explanations, as some of the students gave partial answers that did not explain how the machine worked (they might just describe the direction and/or speed of the output).

I also found that this mental simulation might actually cause problems during mechanical reasoning. It was clear from student explanations that they were walking along a causal chain, but they often took the direct route from input to output, disregarding other factors that might be considered peripheral (but integral) to that chain. Here is an example typical of the analysis of the output shaft in the sun-driven planetary gear set:

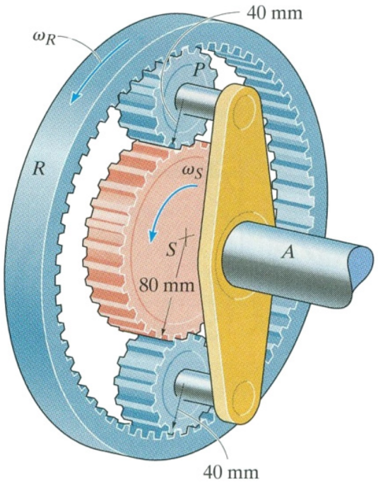

Figure 16. Textbook diagram of a planetary gear set. From R. C. Hibbeler, 2010, *Engineering Mechanics: Dynamics* (12th ed.), p. 347. Copyright 2010 by Pearson Prentice Hall. Used with permission.

> "S turning anticlockwise causes P to turn clockwise while P' also turns clockwise. This causes the plate A is connected to to turn clockwise, thus moving A in a clockwise circular path at a constant speed equal to that of P and P' and greater than S."

This is clearly mental simulation, as it describes a stepwise progression along a causal chain, going from the sun gear (S), to the planet gears (P and P'), the planet carrier (described here as "the plate A is connected to"), and then to the output shaft (A). However this analysis fails to take into account the simultaneous action of the motionless ring gear, which needs to be considered when determining which direction the planet gears will translate as they rotate clockwise. As a result, this student has incorrectly deduced that the planet gears will translate clockwise (which might be the case if the ring gear was not in the picture) around the sun gear.

I observed what appears to be the same sort of analysis failure in explanations of how the output in the rack and pinion mechanism is propelled. Here is an example:

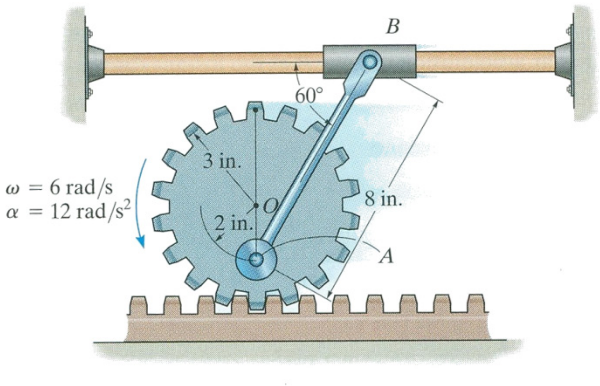

Figure 17. Textbook diagram of a rack and pinion mechanism. From R. C. Hibbeler, 2010, *Engineering Mechanics: Dynamics* (12th ed.), p.375. Copyright 2010 by Pearson Prentice Hall. Used with permission

> “at this time, the gear rotates which causes the connection beam AB to have a radial velocity ω_{AB}, this pushes B to the right horizontally and when A is directly above O, the movement will stop for an instant then B will change direction. Movement is not constant, depends on A position in relation to O.”

This is also clearly a mental simulation stepwise description of the causal chain from input to output. Just like in the previous example where the student failed to take into account the influence of the motionless ring gear, this student fails to take into account the influence of the motionless rack (the toothed bar at the bottom of the diagram). Here, it appears that the student is visualizing the action of this machine as if the pinion gear was rotating in space on a fixed axle, the AB linkage pushing B toward the right and then pulling it back to the left as A travels around the center point, O, of the pinion gear.

These causal chain analyses that disregard the influence of this other motionless component seem to be attempts to reduce the problem space, and thereby reduce negative (intrinsic or extraneous) cognitive load. It appears that if the student is actually able to navigate along a path in the causal chain and reach a conclusion at the end, then this is considered sufficient. The simultaneous influence of this peripheral component increases cognitive load because it adds a component to the mix and complicates the analysis path (see Figure 18).

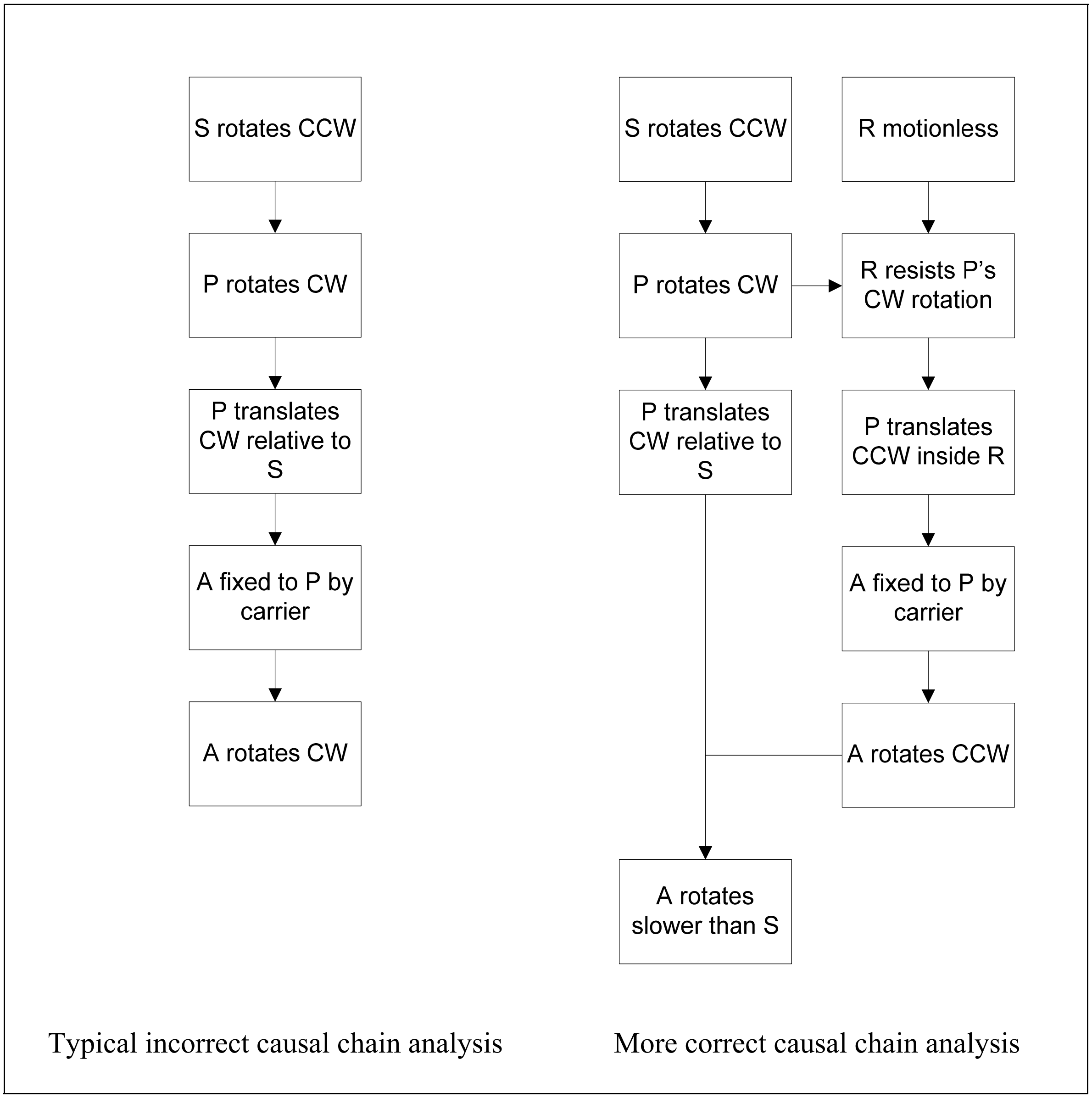

Figure 18. Different causal chain analyses for the sun-driven planetary gear set.

Student Opinions

The last research question asks what students think about the static diagrams, physical manipulatives, and virtual manipulatives as learning aids. Data to answer this question came from the student opinion questionnaire administered at the end of the study. The first question on the questionnaire asked students to indicate what treatment group they were in. This served as a check to make sure the participants were in the treatment groups that I assigned them to. The second question asked students whether they felt that the model they used (static diagram or dynamic model) was helpful in solving the problems. The majority of students in all treatment groups responded that they felt that their model helped them solve the problems. I performed a binary logistic regression to see if there was a difference between treatments in the numbers of these responses; the result showed no significant difference between treatments.

The rest of the questionnaire was composed of open response questions that asked the students how the model was or was not helpful, what could be done to improve the model, what else would have helped them, and asked for any additional comments or suggestions. I analyzed these responses using qualitative content analysis, looking for common themes, assigning codes to these themes, and then counting the frequency of common themes. Although the majority of participants felt that the models were useful, how they were useful (or not useful) depended on the specific type of model.

The Traditional group felt that the static diagram was useful because it was better than not having a diagram at all (better than just a description), it gives you a basic idea of how the parts go together, and it provides information necessary for solving the problem. However, they felt that the static diagrams did not help you see the motion of parts, especially the complex motion of multiple parts moving together.

The Physical and Virtual groups felt that their models were helpful because they allowed you to see how the machine moves/works, and could serve as a check of ideas about how the machine moves, or let you see what the motion would be like before doing any calculations. The Virtual group experience a lot of problems with their models, and this issue appeared in the questionnaire responses. Some students in both groups indicated that the model was not helpful for them because they did not have any problems visualizing from a static diagram. Some students in both groups also indicated that math and dynamics theory proficiency is the problem (not visualization).

The Traditional group suggested adding multiple views of the machine over time as a way to improve the static diagram. The Physical group experienced problems with some models jamming, and many students felt that the physical manipulatives were too loosely assembled. The problems that the Virtual group suggested fixing the problems with the model that they experienced, as well as adding real-time measurements and automated motion (animation). The problems that the Virtual group experienced were mostly due to user error: the students were not loading the models correctly and were moving parts beyond their intended limits. Other issues had to do with inadequate computer or software performance which introduced lag between user input and output displayed on the screen. A way to address these issues (as well as the other suggestions from the Virtual group) would be to use software that is intended for this purpose (Autodesk Inventor is intended to be a design tool, not a simulation tool for teaching).

When asked what other things might help, the Traditional group responded that they wanted a physical or virtual model. The Physical group wanted to be provided with equations, and also some way of taking measurements from the model. A few people in the Physical group wanted a virtual model. Students in the Virtual group wanted physical models. Students in all groups wanted better math and theory preparation. In fact, better math and theory preparation is the most common theme in the additional comments and suggestions from students as well.

Discussion

The ability to interpret and analyze static two-dimensional diagrams of machines is a necessary and critical skill in Mechanical Engineering. This study does not aim to replace analysis of two-dimensional diagrams, but instead seeks to find other instructional technologies that can help students develop these skills. Thus, the posttests ask students to analyze two-dimensional diagrams.

One of the key differences between experts and novices within a discipline is that experts typically have access to a fund of experience that novices lack. A key assumption in this study has been that difficulty reasoning about mechanical systems based on their diagrams is likely due to limited experience with such machines. Indeed, this notion has been given support by student comments such as those that describe confusion over the Geneva mechanism, and the fact that prior exposure to it gave rise to understanding of the machine. The aim of this study was to provide students, assumed to have limited exposure to the machines in question, with hands-on experience with those machines, and to see if that experience could then lead to improved mechanical reasoning using static two-dimensional diagrams. The results of this study suggest that even limited amounts of exposure to the actual moving machines can have positive effects on students' abilities to reason about such machines. It remains for future research to see if the ability to reason about some stereotypical examples of classes of machines transfers to all similar instances and variations of those classes.

One question that naturally rises from this study is whether it would be more efficient to invest in physical or virtual manipulatives, or perhaps both, given the potential benefits identified. I believe that the best solution would be to use both, as each type of dynamic model has its own set of benefits, as well as taking advantage of the different affordances of the manipulatives. Of course it would probably not be practical or an efficient use of resources to have physical and virtual models of every machine. Allowing students to have an experience with a physical model of stereotypical examples of classes of machines (e.g., a planetary gear set) could be done without necessarily having one for each student, especially considering the rather limited amount of time students actually use the models. The space requirements, as well as the cost, of the physical models make them prohibitive to use in large quantities.

Virtual models, on the other hand, provide many advantages over physical models in terms of flexibility, replication, storage, transmission, and user feedback. Virtual models can be made to change on the fly, responding to user inputs. Once created, they can be easily and cheaply reproduced. As computer data, they can be stored in great numbers on physically small media, as well as transmitted great distances in milliseconds over computer networks. Virtual models can also provide user feedback, such as those requested by students, including real-time measurements of displacement, velocity, and acceleration. I therefore recommend the use of virtual models or manipulatives at large scale, but also the use of some physical models on a smaller scale. There is a precedent for the use of both virtual and physical models from industry as well, where actual engineers use virtual models in CAD simulations, but then ultimately create and test physical models prior to final production of their designs.

In addition to the actual findings, I also learned about running this kind of study. It was clear from this experience that I could have done things differently. Perhaps the most important is to have enough people. I could not have executed this study alone, despite my initial estimation that I could. The instructor for the course and his assistant provided necessary assistance proctoring the treatment sessions and assessments. I should have separated the Traditional and Physical groups to reduce the chances of contamination. Such a separation of the three groups necessitates at least three people to proctor each of the three treatments. Having more research assistants would also allow greater exploration of certain aspects of the study, such as mechanical reasoning. Future iterations of the study could pull aside individuals and ask them to use a think-aloud protocol while reasoning about the machines from static diagrams and while using the dynamic models. Such activity is manpower and time intensive.

In addition to ramping up manpower resources, other resources could be increased to improve the study. More time needs to be allocated to handle training and overhead for the virtual group, so as to minimize problems such as those that resulted from students' inability to correctly download and run the virtual models. It would have helped to video record more individuals, as well as the treatment groups in their entirety. This, of course, comes with an increased cost for video recording resources, as well as a manpower/time cost for analysis of the video.

The assessments for mechanical reasoning should be refined for any future iteration or follow-up study. This study provided some typical answers from students for the open response questions that asked them to describe how the machines worked. These questions should be converted into multiple-choice questions, using typical incorrect student responses as distractors, in order to standardize student responses for systematic analysis. Qualitative analysis of students' mechanical reasoning would benefit from the individual think-aloud sessions previously described.

Ethical Considerations

There may be some concern that the students in the Traditional group did not receive comparable benefits that the students in the Physical and Virtual groups appeared to have received from using the dynamic models. Benefits that the Physical and Virtual groups received did not, however, translate into performance gains on the visualization and conceptual measures, and are therefore probably limited. The highly specific nature of the observed advantages in mechanical reasoning, and the fact that these advantages appear to be tied to the specific machines in question, suggest that the extent of any disadvantage is likely to cover only aspects particular to this study (mechanical reasoning for the planetary gear set, the specific rack and pinion mechanism used, and the Geneva mechanism). Even so, now that the study is concluded, the physical models will be made available to all students (including those from the Traditional group and those that were enrolled in the class but did not participate in the study) in order to mitigate any possible negative side effects resulting from lack of exposure to the dynamic models.

Limitations

This study investigated the effect of physical and virtual manipulatives on student learning in Dynamics. It is unknown to what extent findings from this study apply to other topics. It seems reasonable that near-transfer contexts, such as Statics (the preceding course in the two-course series in engineering mechanics, of which Dynamics is the second course) and topics in physics (mechanics in particular) are similar enough that findings will probably apply to a large extent. The more dissimilar a topic is from dynamics and mechanics, the less likely findings are to apply (although they still may apply).

The findings from this study are also dependent on the nature of the manipulatives themselves. User interface issues can moderate learning from virtual manipulatives, with user interface constraints possibly affecting what is learned and how it is learned. The problems experienced by the students in the Physical and Virtual groups also mediated the experience for them. It is conceivable that a smoother experience might have had more positive results (at least with less to complain about, the students might pay more attention to other aspects). The size of the models (both physical and virtual) may also be a factor that affects the usability of the models for learning.

A change in instructional technology also requires a change in accompanying pedagogy. The theory of Technological Pedagogical Content Knowledge (TPCK; Mishra & Koehler, 2006) suggests that specific knowledge is required for how to best use technology in order to teach a particular subject matter. Changing the technology without changing the instruction to best take advantage of the technology may not reveal the true benefits of the technology.

The findings showed, within this context, that the instructional technology had effects that were particular to the nature of the problem, as well as specific characteristics of the machines themselves (i.e., the salient aspect, such as the direction of the output shaft in the planetary gear set, the direction of the slider in the rack and pinion mechanism, and intermittent motion in the Geneva mechanism). This is not an uncommon phenomenon dealing with instructional technology. Just as TPCK describes a mediation of the outcomes by the pedagogical context, so too does the technology itself mediate the effects. These effects cannot be generalized for all students, and therefore we must be cautious not to see any particular technology as one-size-fits-all solution.

This study was conducted in a particular situated context (a Dynamics class in a school of engineering at a public university in the mid-Atlantic region of the United States). It is possible that characteristics of the sample of participants in this study are significant factors that influence the results. The apparent lack of attention to detail, and lack of earnest participation by students, as evidenced by failure to answer test questions completely, violation of initial conditions of the open response problems, and lack of use of models despite being instructed to do so, have likely affected the results. The timing/scheduling of the assessments and treatments also most likely affected the results. Many students elected to participate in extra-curricular activities rather than attend the study, despite having agreed to participate, and there was a basketball game on the same night as the posttest (many students were obviously in a rush to finish the test and get to the game). The fact that participation in the study, and performance on the assessments, had no direct influence on their grades in the course did not encourage a high level of motivation and earnest participation either.

There were some incidents of contamination that may have affected the results. I tried to limit the effect of contamination on the analysis by excluding two of the open response problems due to their appearance as part of the classroom instruction. It is possible that there was contamination between the Traditional and Physical groups. At the end of the first treatment problem solving session, I returned to the classroom in which the Traditional and Physical groups worked, and found that some of the Traditional group students were handling the physical manipulatives (after having completed their worksheets). I made sure that they did not do this on the second night of the treatment, but I do not know to what extent that episode affected the results (the four-bar linkage was one of the problems from the first night, so its elimination from the analysis probably reduced any effect from that first night's contamination).

It is also possible that confounds not identified in this study significantly influence the results. For example, entering behaviors and knowledge may dwarf experimental treatments, portions of the classroom instruction besides the experimental treatments may dwarf the experimental treatments, and there may be contamination effects from influences students receive outside of class (or even between students during the treatment periods). Indeed, some of the students suggested that math ability and dynamics theory knowledge were the major factors influencing their ability to complete problems, and therefore influenced their perception of how helpful the models were.

Finally, I, the researcher, am a limiting factor in the results of this study. My own biases, misconceptions, level of subject matter knowledge, design decisions, and analysis decisions affected the outcomes. I realized, during analysis, that I had a misconception of the operation of the rack and pinion mechanism. This came too late to change the wording of the assessment item, which would have affected the answers that students gave. My decision to use open response items also gave students too much flexibility in their answers, which reduced the accuracy and resolution of the measure. Had I made these multiple-choice questions I probably would have been able to measure their responses better, as it would mitigate such things as responses that do not answer the question at all, partial answers, and answers that violate initial conditions set by the problem. My choice of how to conduct the qualitative analysis definitely affected the conclusions I drew from the data (as it always does for qualitative research).

Significance of the Study

This study contributes to knowledge of how students learn with physical and virtual manipulatives, and also learning with manipulatives compared to learning with static diagrams. It contributes to the body of literature on mental models, particularly mental models involved with mechanical reasoning. This study also contributes to knowledge about how students learn dynamics, and informs future efforts to improve dynamics education and engineering education. One key suggestion from this study is that students’ mechanical reasoning abilities should be assessed, as well as their spatial reasoning and conceptual knowledge. As a study of how students learn with manipulatives, this study expands the body of literature for instructional technology, higher education, and education as a whole.

Further Research

This study was exploratory in nature. Findings from this study come not only from the answers to the research questions, but also in other areas of interest that arose during the study, and also in follow-up studies that are more refined or examine specific areas in detail. One obvious future study would be conducting this study again, but with improved models, better scheduling (to avoid conflicts), more incentives for participation (to increase numbers, retention, and earnest participation), more control of contamination and confounds, better measures (such as converting the open response questions into multiple-choice questions), increasing the extent of the treatments, and taking steps to mitigate the effect of poor math performance and limited subject matter knowledge.

The data collected in this study could also be analyzed differently. More in-depth qualitative analysis could be performed on student explanations, student background information could be compared to performance, and student performance during the treatment could be compared to performance measures on the pre- and posttests.

Future iterations of the same study could include course grades as a performance measure, and compare grades to other measures and descriptive data obtained in the study. Entering math achievement could also be measured (or included from prior assessment), and examined in relation to student performance under the treatments.

Specific areas that were involved in this study could be examined separately. Examples include examining whether spatial ability as measured on the pretest predicts final course grades, examining the correlation between performance on the DCI and final course grades, examining the influence of motivation on Dynamics performance, and the influence of Dynamics performance on motivation.

Mechanical reasoning is an area that could be investigated more. In this study I suggested that students often take an easier (i.e., simpler) route in their causal chain analyses, resulting in incorrect conclusions, because a more correct route induces more negative (intrinsic or extraneous) cognitive load. This idea could be examined in more detail. The development of a standard measure for mechanical reasoning would also help in the assessment of mechanical reasoning ability.

Finally, I found the process of designing, fabricating, testing, and mass producing the manipulatives to be highly educational and motivating. As a former undergraduate in Mechanical Engineering who became disillusioned with the program, I found my interest in Mechanical Engineering reinvigorated. I believe that further research into the effect of including design and fabrication on student motivation and performance should be investigated in engineering, especially for traditionally difficult classes such as Dynamics.

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Appendix A: Biographical Sketch of Researcher

My education and experience are varied, but related to my research focus. I initially attended The George Washington University (GW) in 1991 as an undergraduate in Mechanical Engineering. I dropped-out in 1993, in the middle of my fourth semester, after experiencing disillusionment in the program. I worked in information technology for over ten years, beginning in 1991 as a computer technician while a student at GW, and ending in 2002 as a senior computer network engineer at the Blue Cross Blue Shield insurance company in Washington, D.C. From 2000 to 2002 I attended night school at Lincoln Technical Institute and earned a certificate in automotive mechanics. I was (and remain) interested in the use of computer simulations and visualizations to help people learn about cars, as well as other applications of simulations and visualizations in education. I quit work in information technology and went back to school full-time. I received an A.S. in computer science and an A.S. in mathematics from Northern Virginia Community College in 2003 and 2004 (respectively). I continued my studies in computer science at the University of Virginia (UVA) and received a B.S. in computer science in 2007. I attended graduate school, pursuing a Ph.D. student in Instructional Technology, at the University of Virginia from 2007 until 2013.

I have participated in a variety of educational research. For my undergraduate thesis at the School of Engineering and Applied Science at UVA I developed a simplified method for instructors to test instructional methods in their classes. For three years in graduate school I worked as a research assistant on the MyTeachingPartner Mathematics-

Science project at the Curry School of Education at UVA, and developed curriculum and instructional technology for pre-kindergarten science. I conducted a clinical study comparing science learning with computer visualizations versus learning the same material with text. I helped develop, and was the lead programmer for, the WISEngineering web-based learning environment, a joint project of UVA, Hofstra University, and The City University of New York (CUNY). I was also a research assistant in the Mixed Reality Labs project at UVA, in collaboration with the Concord Consortium in Massachusetts, which is investigating the combination of simulations and sensors in science education.

Appendix B: Background Questionnaire

Name:____________________________________ Student ID:___________________________

For the following questions, please circle the answer that best describes you. You can skip any questions that you are uncomfortable with.

1. Did you take geometry in high school? Yes No
2. Did you take industrial arts (or "shop") in high school? Yes No
3. Did you, or do you currently, play video games? Yes No
4. When you were a child, did you play with construction toys (such as blocks, Lego™, Lincoln Logs™, Erector Sets™, etc.)? Yes No
5. Do you have previous experience in design-related activities (such as drafting, mechanical drawing, CAD, and art)? Yes No
6. Do you have previous experience in construction-related activities (such as carpentry, building construction, and product assembly)? Yes No
7. Major: Mech/Aero Other Engineering Other Non-Engineering
8. Year in School: 1st 2nd 3rd 4th 5th other
9. Sex: Female Male
10. Age: under 18 18-22 over 22
11. Race/ethnicity:

    American Indian

    Asian / Pacific Islander

    Black / African-American

    Hispanic / Latino

    White / North African / Middle Eastern

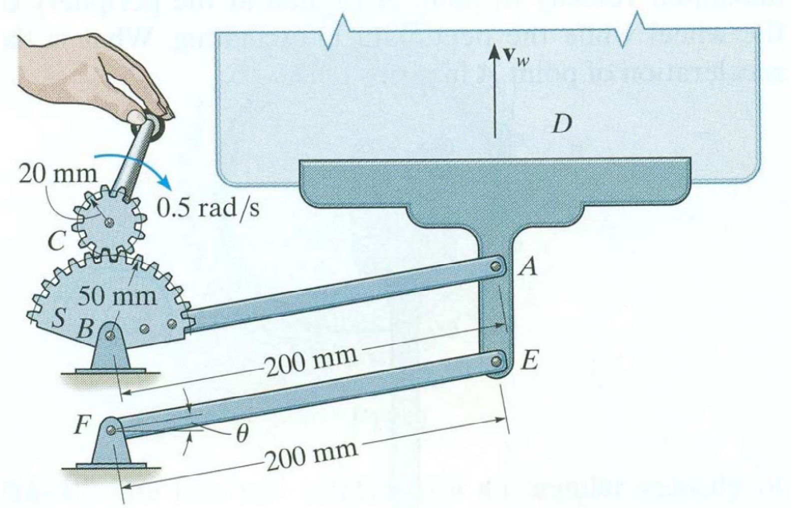
12. Handedness: Left Right Ambidextrous

Appendix C: Open Response Questions

These questions come from the pre- and posttests and were administered before the multiple choice questions. Questions 1-4 were used on both the pretest and posttest. Questions 5 and 6 were only on the posttest. The diagrams for these questions come from *Engineering mechanics: Dynamics* (12th ed.), by R. C. Hibbeler (2010), and used with permission from the publisher (Pearson). These problems were presented one per page, with space below each diagram for students to write their responses.

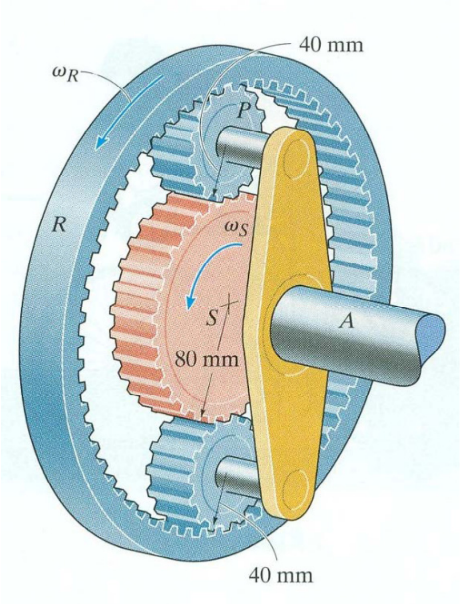
Question 1: Four-Bar Linkage

O1. Describe how this machine works. Please include a description of the direction and speed (constant, varying) of the structure at D in relation to the input (constant rotational motion provided by the hand). If the speed varies, please describe how it varies in relation to the input. DO NOT PERFORM CALCULATIONS.



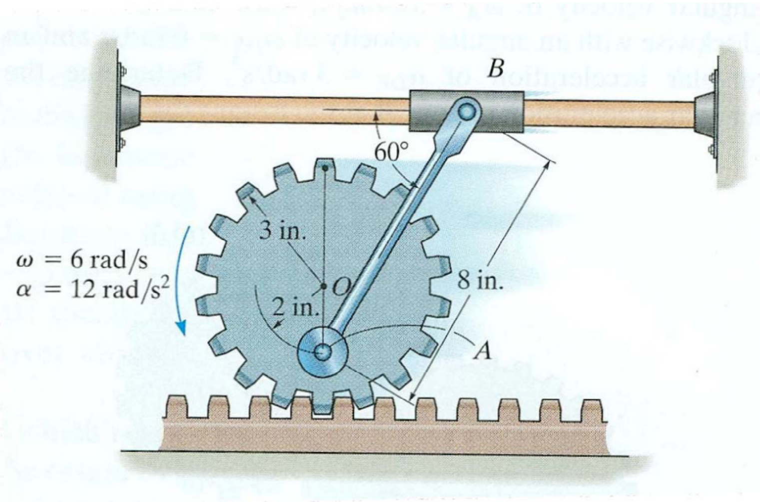
Question 2: Planetary Gear Set (Sun Driven)

OR2. Describe how this machine works. Please include a description of the direction (clockwise, counterclockwise) and speed (constant, varying) of the structure at A in relation to the input (constant rotational motion of the inner gear S) when the outer gear R is held motionless. If the speed varies, please describe how it varies in relation to the input. If the speed is constant, please describe whether it is faster than, slower than, or the same as, the rotational speed of the gear S. DO NOT PERFORM CALCULATIONS.



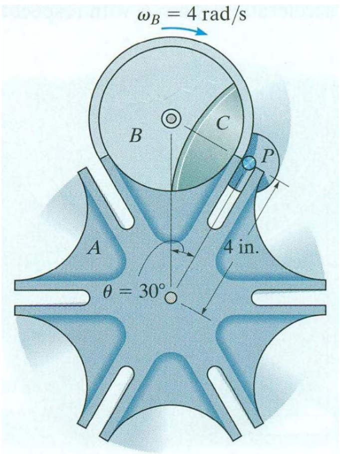
Question 3: Rack & Pinion

OR3. Describe how this machine works. Please include a description of the direction (left, right) and speed (constant, varying) of the structure at B in relation to the input (constant rotational motion of the circular gear O). Note that the gear O is free to move horizontally and the structure at B is also free to move horizontally. If the speed varies, please describe how it varies in relation to the input. DO NOT PERFORM CALCULATIONS.



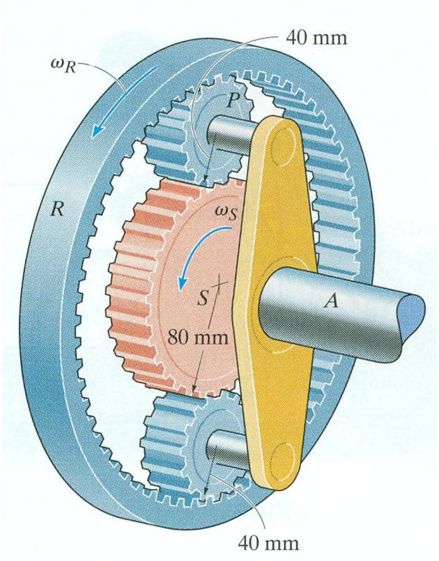
Question 4: Geneva Mechanism

OR4. Describe how this machine works. Please include a description of the direction (clockwise, counterclockwise) and speed (constant, varying) of the star wheel A in relation to the input (constant rotational motion of the driving wheel B). Note that the guide C and pin P are fixed to the driving wheel B. If the speed varies, please describe how it varies in relation to the input. If the speed is constant, please describe whether it is faster than, slower than, or the same as, the rotational speed of the driving wheel B. DO NOT PERFORM CALCULATIONS.



Question 5: Planetary Gear Set (Ring Driven)

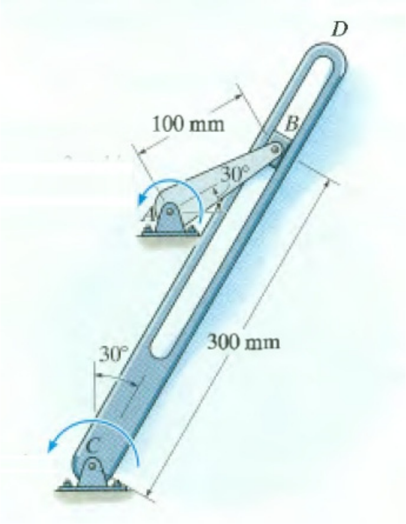
OR5. Describe how this machine works. Please include a description of the direction (clockwise, counterclockwise) and speed (constant, varying) of the structure at A in relation to the input (constant counterclockwise rotational motion of the outer gear R) when the inner gear S is held motionless. If the speed varies, please describe how it varies in relation to the input. If the speed is constant, please describe whether it is faster than, slower than, or the same as, the rotational speed of the gear R. DO NOT PERFORM CALCULATIONS.



Question 6: Quick-Return Mechanism

OR6. In this machine, B is a slider block that fits inside the slot in link CD. Slider block B is attached by a pin to crank AB. Slotted link CD is free to pass behind the crank AB, and crank AB is free to rotate 360˚.

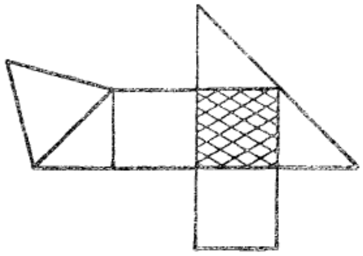
Describe how this machine works. Please include a description of the behavior and speed (constant, varying) of the slotted link CD in relation to the input (constant counterclockwise rotational motion of the crank AB). If the speed varies, please describe how it varies in relation to the input. If the speed is constant, please describe whether it is faster than, slower than, or the same as, the rotational speed of crank AB. DO NOT PERFORM CALCULATIONS.



Appendix D: Spatial Test

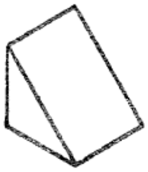
The spatial portion of the pre- and posttest was comprised of 9 questions from the Purdue Spatial Visualization Test (PSVT). The instructions were simplified from the original version. These are the questions used in the assessments.

1. If you were to fold this pattern:

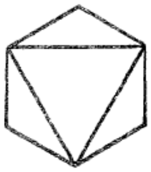


Which one of these 3D shapes would it form? (circle the best choice)

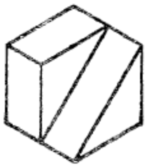
A



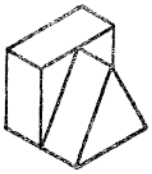
B



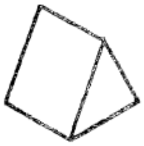
C



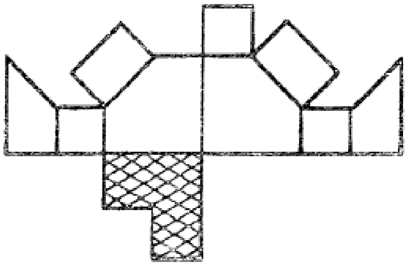
D



E

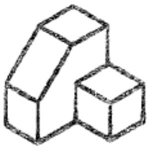


2. If you were to fold this pattern:

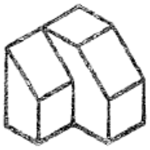


Which one of these 3D shapes would it form? (circle the best choice)

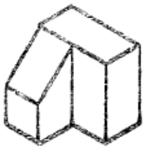
A



B

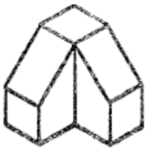


C



D

E



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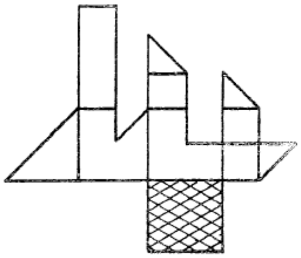
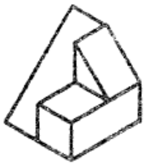
3. If you were to fold this pattern:

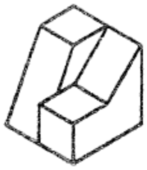


Which one of these 3D shapes would it form? (circle the best choice)

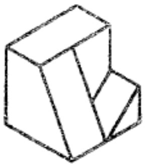
A



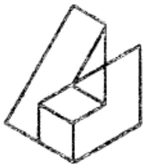
B



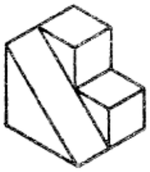
C



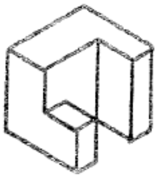
D



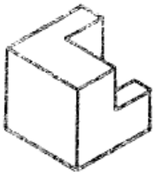
E



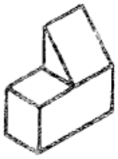
4.



IS ROTATED TO



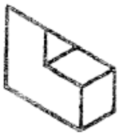
AS



IS ROTATED TO: (circle best choice)

A

B

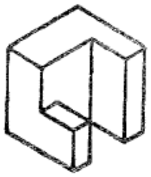


C

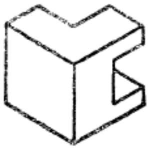
D

E

5.



IS ROTATED TO



AS

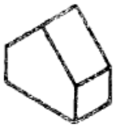
IS ROTATED TO: (circle best choice)

A

B

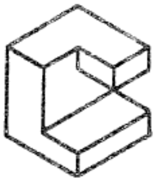
C

D

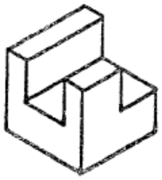


E

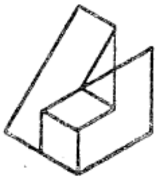
6.



IS ROTATED TO



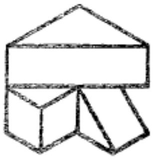
AS



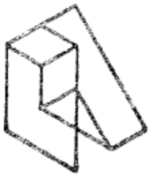
IS ROTATED TO: (circle best choice)

A

B



C



D

E

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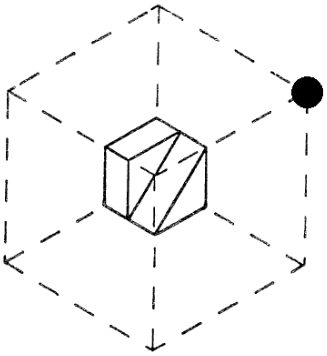
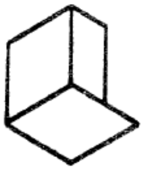
7. Imagine you are viewing the object from the BLACK DOT located at one of the corners of an imaginary box with the object floating in the center of it.

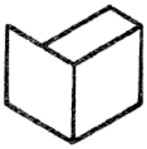


Which of the following views is what you would see? (circle the best choice)

A

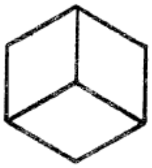


B

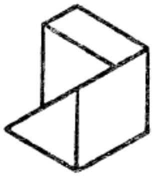


C

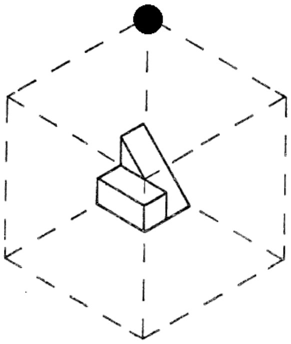
D



E

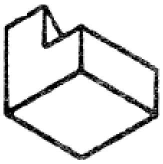


8. Imagine that you are viewing the object from the BLACK DOT located at one of the corners of an imaginary box with the object floating in the center of it.

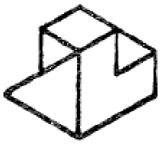


Which of the following views is what you would see? (circle the best choice)

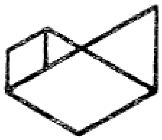
A



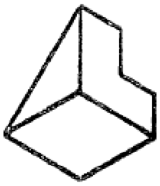
B



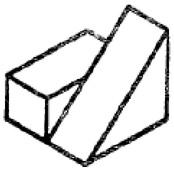
C



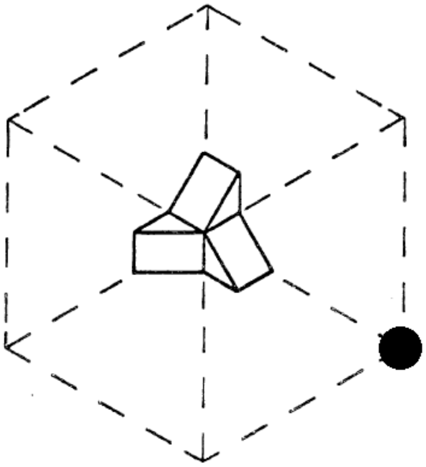
D



E

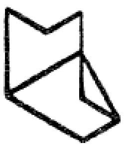


9. Imagine that you are viewing the object from the BLACK DOT located at one of the corners of an imaginary box with the object floating in the center of it.

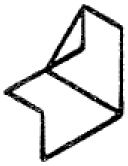


Which of the following views is what you would see? (circle the best choice)

A

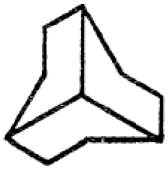


B

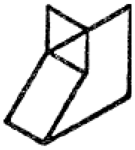


C

D



E



Appendix E: Dynamics Concept Inventory (DCI)

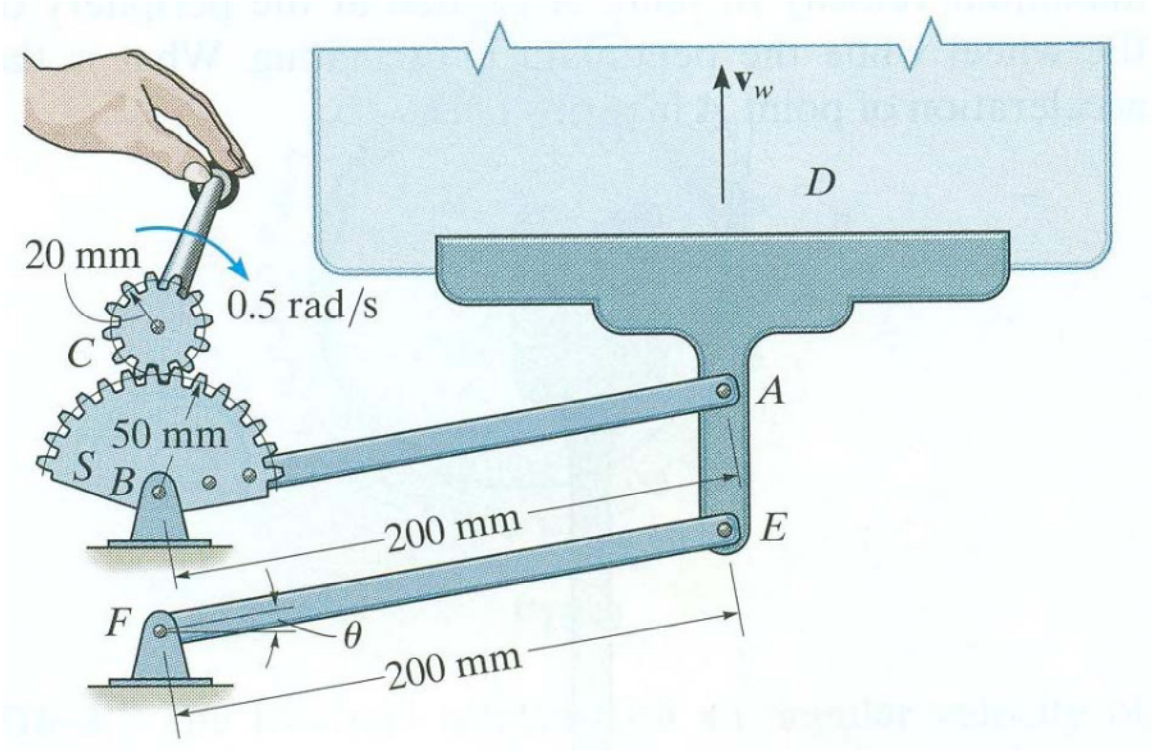
The conceptual portion of the pre- and posttest were the 29 questions from the Dynamics Concept Inventory (DCI). The DCI is a multiple choice test that covers important concepts in Dynamics. It was created by Gary L. Gray, Don Evans, Phillip J. Cornwell, Brian Self, and Francesco Costanzo. The distractors on the test are based on the common misconceptions that students have about the concepts. The test does not require any calculation, but rather asks students to give responses in qualitative or relative terms, such as whether the velocity of one component in a given situation is greater than, less than, or equal to the velocity of another component. The DCI is proprietary and cannot be included here as the authors request that it not be made public. See http://www.esm.psu.edu/dci for more information.

Appendix F: Problem Solving Session Problems

The participants worked on these problems during an evening problem solving sessions that met once a week. The first two problems were worked at the first evening session, and the second two problems were worked one week later at the second evening session. Students in the Physical and Virtual treatment groups used their respective models during these sessions to solve these problems. The problems are taken directly from *Engineering mechanics: Dynamics* (12th ed.), by R. C. Hibbeler (2010), and used with permission from the publisher (Pearson). Each problem was presented on a separate sheet of paper, with blank space beneath the diagram for students to write their work and answers.

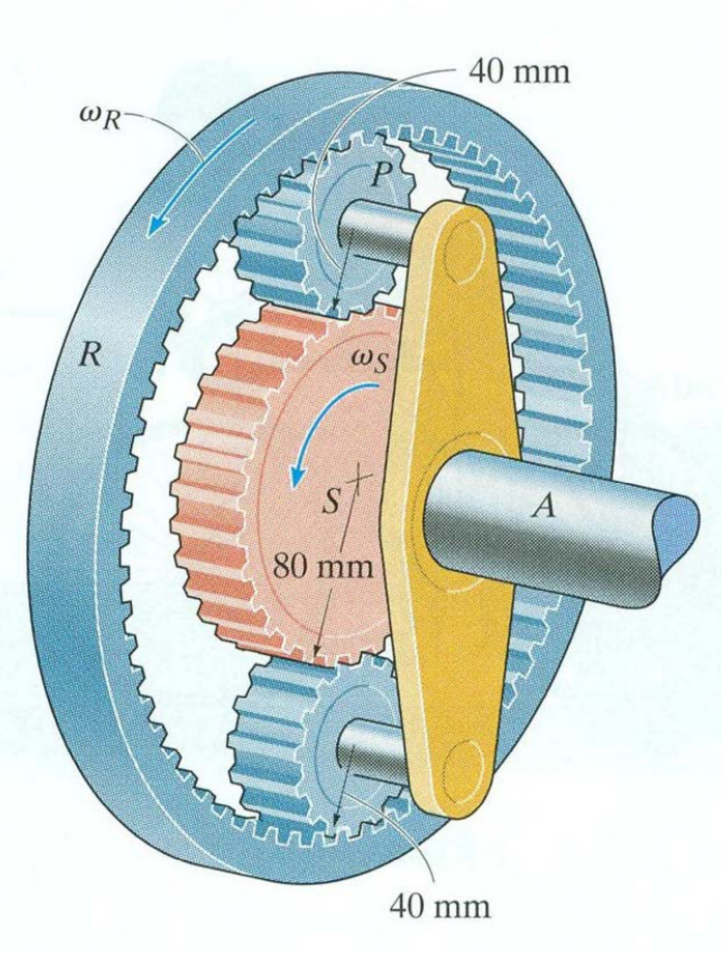
Problem 1(Hibbeler problem 16-6, p. 324)

The mechanism for a car window winder is shown in the figure. Here the handle turns the small cog *C*, which rotates the spur gear *S*, thereby rotating the fixed-connected lever *AB* which raises track *D* in which the window rests. The window is free to slide on the track. If the handle is wound at 0.5 rad/s, determine the speed of points *A* and *E* and the speed v_w of the window at the instant $\theta = 30°$.



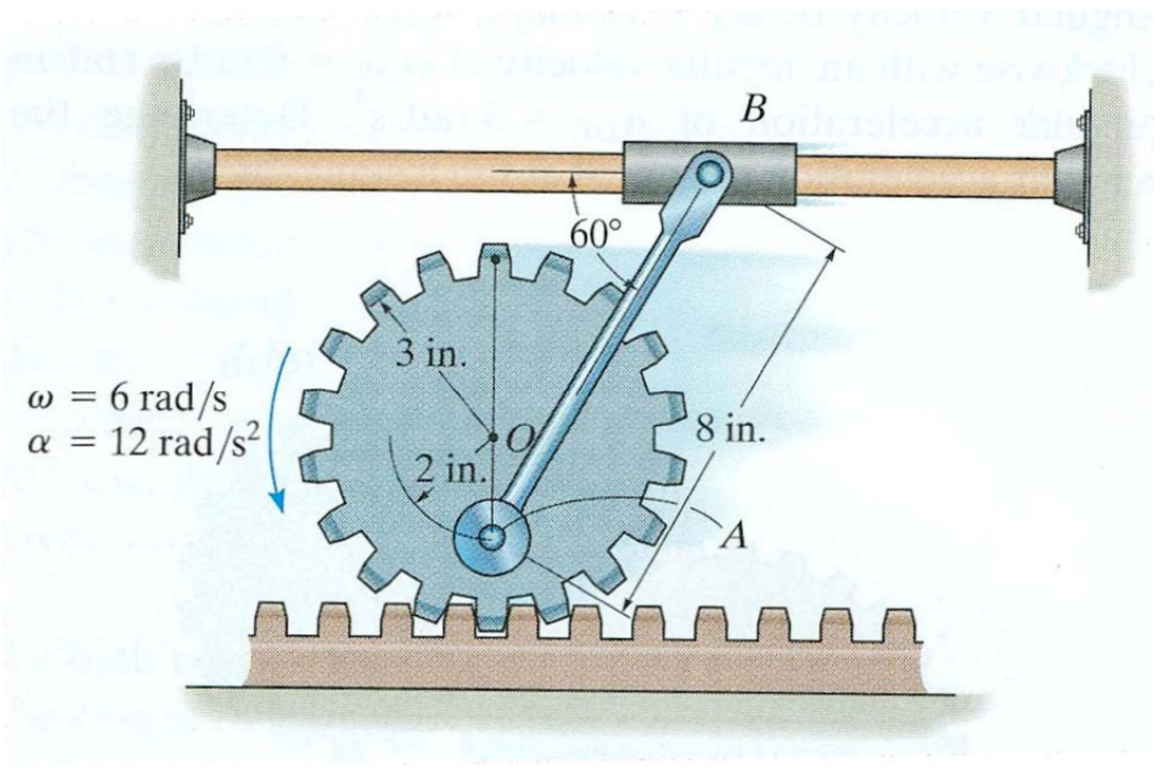
Problem 2 (Hibbeler problem 16-64, p. 347)

The planetary gear system is used in an automatic transmission for an automobile. By locking or releasing certain gears, it has the advantage of operating the car at different speeds. Consider the case where the ring gear R is held fixed, $\omega_R = 0$, and the sun gear S is rotating at $\omega_S = 5$ rad/s. Determine the angular velocity of each of the planet gears P and shaft A.



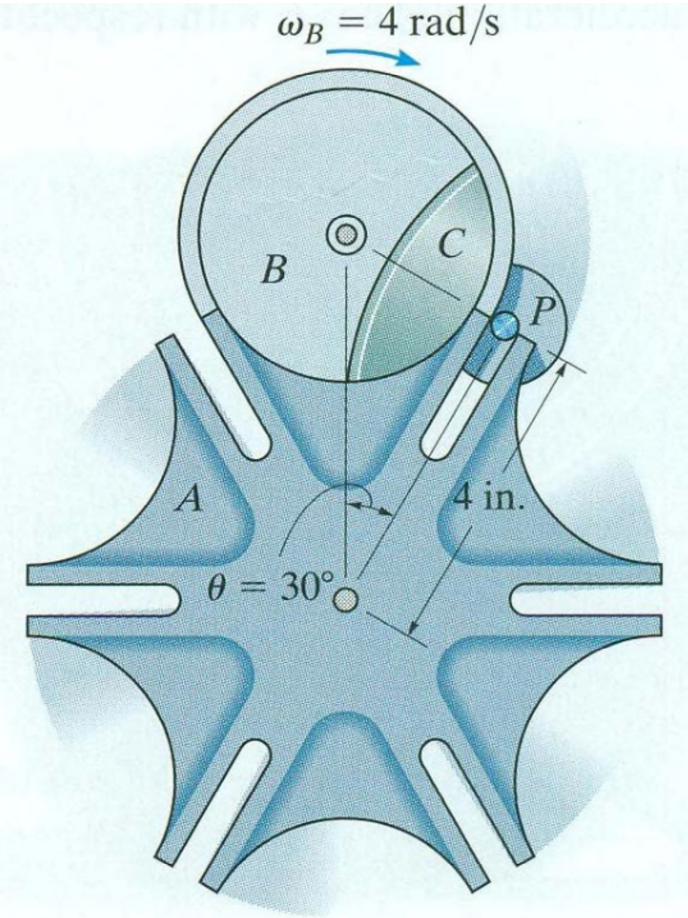
Problem 3 (Hibbeler problem 16-128, p. 375)

At a given instant, the gear has angular motion shown. Determine the accelerations of points *A* and *B* on the link and the link's angular acceleration at this instant.



Problem 4 (Hibbeler problem 16-160, p. 390)

The Geneva mechanism is used in a packaging system to convert constant angular motion into intermittent angular motion. The star wheel A makes one sixth of a revolution for each full revolution of the driving wheel *B* and attached guide *C*. To do this, pin *P*, which is attached to *B*, slides into one of the radial slots of *A*, thereby turning wheel *A*, and then exits the slot. If *B* has a constant angular velocity of $\omega_B = 4$ rad/s, determine ω_A and α_A of wheel *A* at the instant shown.



Appendix G: Student Opinion Questionnaire

The participants were asked to answer the following questionnaire after submitting their posttests.

Please answer the following questions. You can skip any questions that you are uncomfortable with.

1. Which treatment group were you in? (circle one)

   Traditional Virtual (CAD) Physical

2. Did the model (diagram for the Traditional group) help you understand and solve the problems?

   Yes No

3. Please explain how the model (diagram for the Traditional group) helped or did not help you understand and solve the problems:

4. What could be done to the model (diagram for the Traditional group) to improve its usefulness in helping you understand and solve the problems?

5. What else would have been helpful to have to aid you in understanding and solving the problems?

6. Please write any other comments/suggestion that you have regarding your experience:

Appendix H: Background Questionnaire Responses

Q7-MAJ:
1=Mech/Aero
2=Other Engineering
3=Other Non-Engineering

Q8-YR
1=1st
2=2nd
3=3rd
4=4th
5=5th
6=other

Q10-AGE
1=under 18
2=18-22
3=over 22

Q11-RACE
1=American Indian
2=Asian/Pacific Islander
3=Black/African-American
4=Hispanic/Latino
5=White/North African/Middle Eastern

	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12
ID	GEO	SHP	GAM	LEG	CAD	EXP	MAJ	YR	SEX	AGE	RACE	HND
1	y	n	y	y	y	y	1	2	m	2	5	r
2	y	n	n	y	y	y	1	2	f	2	5	r
3	y	n	y	y	n	n	1	2	m	2	2	r
4	y	n	y	y	y	n	2	3	m	2	5	r
5	y	n	y	y	y	n	1	2	f	2	3	r
6	n	n	y	y	y	n	1	2	m	2	3	r
7	y	n	y	y	y	n	1	2	f	2	5	r
8	y	n	y	y	n	n	1	2	m	2	5	l
9	y	y	y	y	y	n	1	2	m	2	5	l
10	y	n	y	y	y	n	1	2	f	2	5	r
11	y	n	y	y	y	y	1	2	m	2	5	r
12	y	y	n	y	n	y	1	2	m	2	5	r
13	y	n	y	y	n	n	1	2	m	2	5	l
14	y	n	y	y	y	n	1	2	m	2	5	r
15	y	n	y	y	y	n	1	3	f	2	3	r
16	y	n	y	y	y	y	1	2	m	2	5	r
17	y	n	y	y	y	n	1	2	m	2	4	r
18	y	n	y	y	y	y	1	2	m	2	5	r
19	y	y	y	y	y	y	1	2	m	2	5	r
20	y	n	y	y	y	n	1	2	m	2	3	r
21	y	n	y	y	y	y	1	2	m	2	5	l
22	y	n	n	y	y	n	1	2	m	2	5	r
23	y	n	y	y	y	y	1	2	m	2	5	r
24	y	n	y	y	y	n	1	2	m	2	5	r
25	y	n	n	y	y	n	1	2	f	2	5	r

ID	Q1 GEO	Q2 SHP	Q3 GAM	Q4 LEG	Q5 CAD	Q6 EXP	Q7 MAJ	Q8 YR	Q9 SEX	Q10 AGE	Q11 RACE	Q12 HND
26	y	n	y	y	y	y	1	2	m	2	5	r
27	n	n	y	y	y	y	1	2	m	2	5	r
28	y	y	n	y	y	y	1	2	m	2	5	r
29	y	y	y	y	y	y	1	2	m	2	5	r
30	y	n	y	y	y	y	1	2	m	2	5	r
31	y	y	n	y	y	y	1	2	m	2	5	r
32	y	y	y	y	y	y	1	2	m	2	5	r
33	y	n	y	y	y	n	1	2	f	2	5	r
34	y	n	y	y	y	n	2	3	m	2	5	r
35	y	n	y	y	y	n	1	2	m	2	5	r
36	y	n	y	y	y	y	1	2	m	2	2	r
37	n	y	y	y	y	n	1	2	m	2	5	r
38	y	y	y	y	y	n	1	2	m	2	5	r
39	y	n	n	y	y	n	1	2	f	2	5	r
40	n	n	y	y	y	n	1	2	f	2	2	r
41	y	n	y	y	y	n	1	2	m	2	5	r
42	y	n	y	y	y	y	1	2	m	2	5	r
43	y	n	y	y	y	y	1	2	f	2	2	r
44	y	n	y	y	y	y	1	2	m	2	5	r
45	y	n	y	y	y	n	1	2	f	2	5	r
46	y	n	y	y	y	y	1	2	f	2	3	l
47	y	n	y	y	y	n	1	2	m	2	5	r
48	y	y	y	y	n	n	1	2	m	2	5	r
49	y	n	y	y	y	y	1	2	m	2	2	r
50	y	n	y	y	y	y	1	2	m	2	2	r

ID	Q1 GEO	Q2 SHP	Q3 GAM	Q4 LEG	Q5 CAD	Q6 EXP	Q7 MAJ	Q8 YR	Q9 SEX	Q10 AGE	Q11 RACE	Q12 HND
51	y	y	n	y	y	n	1	2	m	2	2	r
52	y	n	y	y	n	n	2	4	m	2	5	r
53	y	y	y	y	y	y	1	2	m	2	5	r
54	y	y	y	y	y	y	1	2	m	2	4	r
55	y	n	y	y	y	y	1	2	m	2	5	l
56	y	n	y	y	y	n	1	2	m	2	5	r
57	y	n	y	y	y	y	2	3	f	2	5	r
58	y	n	y	y	y	n	1	2	f	2	5	r
59	y	n	y	y	y	y	1	2	m	2	5	l
60	y	y	y	y	y	y	1	2	m	2	5	r
61	y	n	y	y	y	y	1	2	m	2	5	l
62	y	y	y	y	y	n	1	2	f	2	4	r
63	y	y	y	y	y	n	1	2	f	2	3	r
64	y	n	n	y	n	y	1	2	f	2	5	r
65	y	n	y	y	y	n	1	2	m	2	5	r
66	y	n	y	y	y	y	1	2	m	2	5	r
67	y	n	n	y	n	n	1	2	f	2	5	r
68	y	n	y	y	y	n	1	2	m	2	3	r
69	y	n	n	y	y	y	1	2	f	2	5	r
70	y	y	y	y	y	y	1	2	m	2	5	r

Appendix I: Treatment Group Assignments

The following table lists the ID's of participants assigned to each treatment group.

Traditional (n=26)	Physical (n=21)	Virtual (n=23)
1	4	2
6	5	3
8	7	9
10	11	14
18	12	15
19	13	16
21	17	20
25	23	22
27	24	28
29	26	30
33	31	34
37	32	35
41	36	38
43	40	39
44	46	42
48	50	45
51	55	47
53	56	49
54	59	52
57	60	58
61	63	62
66		64
67		65
68		
69		
70		

Appendix J: Pretest Open Response Answers

Question 1: Four-bar Linkage

ID	Student Answer
1	The hand turns the crank that causes the platform to move up slower than the speed of the handle. At some point it will reach a maximum at which the direction of the crank will have to be reversed to lower it.
2	The direction of the structure at D in relation to the input will cause D to move down if the hand rotates clockwise. The speed will vary because at a certain point it will be in the same direction as gravity so gravity will help assist it & therefore make it faster. Once the bar gets past 45˚ diagonal it will start to speed up until the end. As the person turns the gear C it causes D to either be raised or lowered due to A&E. clockwise = lowered, counterclockwise=raised.
3	The structure at D moves upwards with constant speed. The speed does not vary.
4	The faster the hand pushes the handle in the clockwise direction, then the faster the velocity (Vw) of object D in the positive direction directly vertical. If the handle is pulled counterclockwise then the faster D descends in the negative direction directly downward.
5	The lever thing that the hand is turning turns the little gear clockwise which then turns the big partial gear counterclockwise moving the bar BA up and towards the gears so that this thing [picture of the track, D] ends up moving up and then moves back down when the crank is turned the other way. Speed varies. [curved arrow drawn on B, arrow drawn between and parallel to linkages BA and FE pointing left]
6	As you turn the lever with your hand, it turns the small gear which turns the large gear to produce translational motion in the y-axis. The direction of the speed is vertical and it is constant. This is because angular velocity and translational velocity are directly proportional in the form v=wr
7	As the hand pushes the lever (to the right) D moves up so Vw varies, since the lever is on a smaller gear, Vw will move slower than in relation to input.
8	If hand moves clockwise, gear S inclines BA, and FE inclines, remaining parallel, causing D to move up. If hand moves quicker, D raises more quickly.
9	When the handle is moved the structure at D increases in height with a constant speed to the motion of the handle.

10	Gear around C moves clockwise. Gear around B moves counter-clockwise. Bar AB rotates around point B w/ gear. Bar EF rotates around F as result of bar AB moving structure. A+E points remain vertical. Structure D is raised when gear C is turned clockwise. Not sure how speed effects [sic] the structure, but I would guess speed of moving structure is greater than speed of input.
11	As the hand turns the crank clockwise, the structure S will rotate counterclockwise, causing θ to increase + members AB + EF to raise up, pushing on D. The speed should be constant while the input is, + vary proportionally to it.
12	As the handle is rotated forward, the 50mm gear attached to bar A rotates slower than the input and moves the structure D up. The bar between F and E serves to keep the machine stable.
13	With a constant rotational motion provided, the structure at D will lift upwards at a constant speed. With a larger input, then the structure will lift faster and vice versa.
14	I think the structure at D will move up with CW rotation of hand. D's speed will not be constant. It will decrease as θ increases, and θ will increase with time to a max and the system won't be able to move any more.
15	The hand provides a constant rotational motino that allows the gears to move at C D to move up if the lever is pulled backward and down if it is pushed forward.
16	As the handle is turned clockwise the gear around B is rotated counterclockwise which lifts object D. D moves with a velocity that is relative to how fast the handle is turned.
17	Pushing the lever forward causes member AB to move up and then D to move up the speed is constant.
18	When the lever is pushed in direction of rotational arrow D moves in direction Vw. Constant rotational motion provided by hand will result in constant Vw.
19	As the hand pushes forward the first gear C rotates down while turning the other gear (B) counter clockwise. As gear B turns counter clockwise the arm connected to pin A is lifted upward. Because of the arm between F & E the structure lifts up uniformly and with constant speed if the hand provides constant speed.
20	The crank turns the cogs which gradually turn the cog at B, lifting the lever. The two levers support and lift the load at D w/ constant velocity (upwards) slower than .5 rad/s velocity.
21	As the hand rotates the lever, the two interlocking gears will rotate in opposite orientations, causing a pully motion on bar AB. This will in turn cause an upward velocity, Vw, as shown on the diagram. Speed would be varying, not constant, since the 50 mm gear is not circular and will not rotate a full 360˚.

22	As the hand provides constant clockwise rotational motion, the smaller gear at the end of the shaft turns clockwise at 0.5 rad/s, turning the 50 mm-radius gear under it counter clockwise. As this 2nd gear rotates counter clockwise, the bar attached to this gear will also rotate counterclockwise (this bar will be called shaft A. As shaft A rotates counter clockwise about point B, θ will increase, causing the structure at D to rise with constant velocity Vw. Vw will increase for higher input values. [curved arrow drawn indicating rotation of B]
23	As the crank rotates clockwises [sic], the gear at B will rotate counterclockwise. As a result, D will move upward. The speed remains constant as long as the rotational input motion remains constant.
24	The machine converts rotational motion of the first gear into rotational motion of the second gear, which in turn generate leverage to lift the load at D up at a constant speed.
25	Turning the handle in a clockwise motion lifts the area at D. The speed at D is less than that at C but the torque is higher at B than at C. The speed is constant so long as the gears are in contact with each other and the hand turning speed is constant.
26	As the crank is turned The part D is moved along a circular path at constant velocity.
27	The 20 mm gear turns the 50 mm gear at an angular velocity < .5 rad/s thus increasing the torque produced at B relative to C. The torque at B is transmitted by the lever arm BA and FE to lift the weight. For a constant speed of C[,] D will rise at a decreasing speed. As θ increases some vertical speed at d is lost to horizontal motion.
28	D will move in an arc up and to the left at constant rotational speed and will remain level.
29	D will remain in the same orientation and move counterclockwise around points B and F. It will move with an angular velocity less than the input angular velocity. [the word 'constant' is circled in the problem description regarding speed of D]
30	S will rotate counterclockwise this will make the bar connected follow the wheel, first moving up and right, then up and left. This will in turn make the A-E-D piece move right then left.
31	D will move up, the surface will remain horizontal but the whole platform will move in an arc about B. It will move up faster than the input force at a constant speed.
32	The structure at D moves vertically upward and to the left. The point at A moves along an arc centered at B counterclockwise, but the line from A to E remains vertical at all times. The speed around the arc is constant in relation to the rotational motion provided by the hand.

33	The hand pushes the gear at C which moves the joint A (& E) up. The speed is constant since the speed of the hand is constant.
34	By rotating the 20mm gear clockwise, the 50mm gear rotates counterclockwise, which pushes point A (and thus the structure A is attached to, D) vertically upward. The faster the 20mm gear rotates clockwise (input), the faster structure D will rise. The same is true if the input turns counterclockwise, except then structure D will lower. So if the hand rotates at a constant speed, D will rise at a constant speed (or fall). [arrow drawn indicating rotation of S]
35	As the hand crank rotates, the structure at D will be pushed upward with constant speed. This speed will be slower than that of the hand crank because the gear B is larger than gear C. As the gear is rotated, the larger gear turns counter clockwise, and the Bar AB pushes the structure at D up. [arrow drawn indicating rotation of S]
36	As C is rotated clockwise D moves up vertically but does not move as fast as the rotational motion of the hand.
37	As you crank the handle it turns the gear located at point C which will then turn the gear at Point B counter clockwise which will cause beams BA and FE to lift up causing the plate to exert a force at D. The speed of the structure at D will be constant if the crank is constant and moving in the upward direction. As you crank faster the structure at D will move faster just not as fast as you are cranking.
38	As C is pushed forward, B moves CCW and forces A upwards. F and E push back up as C is rotated further along.
39	The structure at D moves up as the hand moves forward. Speed of the vertical motion is constant because the gears are spinning at a constant angular velocity.
40	When the crank is pushed forward, the piece D rises at a constant velocity because the supporting bar is rigid.
41	As the hand turns the crank clockwise, the machine moves up, and as the crank turns counterclockwise, the machine moves down. The speed of the machine is related closely to the rotational speed of the crank - an increase in turning speed corresponds to an increase in linear speed.
42	The structure at D will move upward with a diminishing speed.
43	D will move upward. The speed varies in relation to the angle between point AB and the horizontal line.
44	As the hand rotates the crank forward, the part D moves up and as the hand moves back, D goes down. The crank moving forward pushes the semi gear at B back, lifting the end connected to the rod attached to A. Rod FE prevents horizontal motion.

45	"+ Hand pushes lever at .5 rad/s (CW). + Gear C turns at .5 rad/s (CW). + Gear B rutns at << .5 rad/s (CCW). + Connecter AE moves to left at << .5 rad/s. +"Whole" D part moves up at constant speed, Vw, slower than input.
46	This machine works by having the input (hand) turn the gear which causes the 2 bars to move counter clockwise. This causes the object at D to move upwards and to the left at a constant speed if the input is turned at a constant rate. The speed varies based on the rate at which the input turns the gear. [angled arrow drawn above D pointing up and left]
47	As the hand generates motion around "C" in a clockwise motion the wheel/gear around "B" will rotate in a counterclockwise direction at about 2/5 the rotational speed. This will cause the plate attached at points "A" and "E" to move in the positive y direction and negative x direction. However, its orientation will remain constant because of member "EF" [arrow drawn indicating rotation of S]
48	Gear C is rotating clockwise, which rotates gear B counterclockwise. Gear B moving counterclockwise moves bar AB up and down, increasing θ (theta), and also causes bar FE to move up and down, increasing θ (theta) by the same amount. Bar AB and bar FE moving up and down causes part D to move up (forward) + down (backward). Speed is constant at S, but slower at B, A, F, E, and D.
49	When the crank is turned, the small gear transmits the rotation to the large gear, which in turn moves the linkages and lifts structure D. This mechanism allows users to lift heavy objects with relatively little effort. The speed at which the structure D moves is proportional to the rate the crank is turned. - Note: this is similar to a bicycle drivetrain.
50	This machine is a compressive steam [?] generator in which the experimenter cranks a handle at a constant speed of 0.5 rad/s clockwise. This moves the small 20mm gear that moves another gear of 55 mm [sic] radius. The second gear raises a bar, connected to the gear and the compressor. The higher the speed of the crank, the faster the lift/compressor moves. Plate D will lift up and remain horizontal.
51	As the input of rotation motion provided by the hand is constant, the structure at D will move up with an increasing speed as it gets higher up and as the input motion go [sic] more down in rotation.
52	Turning the crank at C relays the force to B then up at A. clockwise input -> positive force at D. Counterclockwise input -> negative force at D. Speed Vw at D is directly proportional to input speed.

53	When a force is applied to the handle, gear C acts on gear B to apply a rotational force on member BA. Structure D then raises vertically. If gear C is moved with constant speed in the direction indicated, structure D will raise at constant speed. Member FE is in place to keep structure D from rotating around point A.
54	This machine appears to lift or put down a load of some sort based on the actions of the lever being pulled or pushed. Structure D appears to be a platform that holds a force + the speed appears to have to be constant based on C. Because for C, this appears to control height (up/down) not speeds
55	It acts as a complex lever rotating the arm as shown raises the block at a constant velocity the rate will differ base [sic] on the relationship of the gears.
56	At D, the velocity is constant going counterclockwise around point C.
57	Pushing the lever will cause gear S to move CCW and therefore pull arm AB to the left. This will then tilt the platform at D. The speed will remain the same as long as the lever is being pushed in the same direction.
58	The hand pushes causing the little gear to spin clockwise the bigger gear will then spin counterclockwise pushing the aparatus [sic] up. The speed is constant.
59	This machine works by converting rotational energy applied on the lever attached to point C to translational energy at point D. The input direction is tangent to the gear at C and the output direction is straight vertically upward. The input speed will be constant + faster than the output speed at point D. A good ball park estimate would be around 1/4.
60	As the hand moves to the right it creates an interaction between the two dials that lead, to D moving down. If the hand moves with constant velocity, D will as well.
61	Vertical upwards motion until the end of the gear centered at B, then stops. Speed varies directly with input.
62	Lever 1 rotates gear 2 [C] clockwise which exerts a torque determined by radius & rad/s onto gear 3 [S] which turns counter clockwise. As gear 3 turns, beam 4 [AB] exerts a force on object 5 [D]. Object 5 maintains a vertical position with a rotational motion only because of the beam and pin 6 [EF] rotating as well. The force exerted on object 7 is vertical and the object is moved is [sic] an arc proportional to the radians rotated in gear 3. at a speed faster than the input speed. [curved arrow drawn indicating trajectory of point A]
63	The user pushed on the lever in a direction towards the machine causing the large gear to move towards the user. As the larg [sic] gear moves the lever from B to A moves upward [sic]. As a result the lever at F to E moves up at a constent [sic] speed. These to [sic] levers push up the Figure at D.

64	The gear attached to the hand crank moves the second gear which raises rod BA and raises the structure at D. The speed the object is raised at should be directly proportional to the speed at which the crank is turned.
65	By pushing forward to create constant rotational motion at C, B will rotate constantly in the opposite direction, causing the structure D to move upwards, but at a different speed than the C/B system, because of how it's oriented and b/c its not in rotational motion.
66	The rotation of the gear and crank C rotates the gear S at a lower rad/s rate than that of C in the counter clockwise direction at a constant speed until it reaches the end of the gear S. This motion moves the A end of the arm AB upward, which in turn propels object D upward at a higher velocity than the input rotation speed.
67	The machine lifts the structure at O as the handle is cranked at a constant speed.
68	Gear C is rotated clockwise causing gear B to rotate counter-clockwise. Constant motion in gear C would cause gear B to move constantly. Motion would presume [sic] until C comes into contact with the beam. Since A is pin jointed at Beam AD motion in the Beam would not effect [sic] the Object A ["Object A" is circled on the diagram -- this is actually track D]
69	The hand moves the gear (C) @ constant speed, which in turn moves the gear (B) at constant speed. C goes clockwise, B anticlockwise. D moves upward (as if on a jack) at a speed (constant) proportional to the speed of the initial hand crank.
70	With constant rotation, the structure at D should move up with a constant speed.

Question 2: Planetary Gear Set (Sun Driven)

ID	Student Answer
1	As S rotates counterclockwise, it rotates P and its counterpart clockwise. If R is motionless, this causes A to rotate counterclockwise at a constant speed that is faster than S.
2	The direction of the structure at A is counterclockwise and the speed is varying. As the system moves counterclockwise in R it will be easier & faster near the 90˚ mark (starting is at 0 then move 90˚ to horizontal) until it hits vertical where it will then be harder to move P slower. Turning A causes S to turn which makes P & the other joint turn & if R is held constant they move around the circle. [circular arrows drawn on P gears]
3	The structure at A moves in a counterclockwise manner w/ a constant speed which is slower than the speed of gear S.

4	As S rotates at a constant speed in the counterclockwise direction, A rotates in the counterclockwise direction at a constant speed slower than the rotational speed of the gear S. [curved arrow drawn on P]
5	If R is held motionless, then the little gears will move at a constant rate, they will move a little faster than the bigger S gear and they will turn in opposite directions of each other. The structure A will not move. [curved arrows drawn on P and S]
6	The direction of the speed at A is clockwise. The speed is constant. Because the larger gear is turning the smaller gear the [sic] is a mechanical advantage so the speed is faster. The machine works in the following way. The inner gear S turns counterclockwise while the two small gears turn clockwise along a track and in turn spin A.
7	A will move opposite of S, so if S is moving CCW, A will move CW. A will move with constant speed, same as input A same as S, since A uses 2 gears that are 1/2 the size of S.
8	A moves counter clockwise if S moves counter clockwise. Speed of A increases as speed of S increases. A moves faster than S.
9	The structure at A will start to turn counter-clockwise. Since the gear P is smaller than S it will rotate quicker than S. [circular arrows drawn on P gears]
10	S rotates counterclockwise. Structure A rotates counter clockwise. Again guessing that speed is constant, same as rotational speed of gear S.
11	The motion of gear S will cause gear P and its opposite to rotate clockwise around gear R, taking the structure at A with it. The speed of the rotation should be proportional to Ws + constant while Ws is.
12	A rotates counterclockwise when gear R is motionless and S is rotated counterclockwise. The speed of A is constant and faster than the rotational speed of gear S. [there are circular arrows drawn on P and R]
13	With constant rotation of S, the structure at A will move in a counterclockwise direction like S itself at a constant speed slower than the gear S.
14	As the central wheel rotates it causes the outer two wheels to rotate in the opposite direction (as the center wheel) and the rotation of both outer wheels moves the structure at A moves clock wise [sic] at a constant rate. I think speed of A will be faster than the speed of S. [circular arrows drawn on P gears]
15	At A, the structure will move in a clockwise direction and the speed will be constant in relation to the input when R is held motionless. The constant speed is faster than the rotational speed of gear S.
16	Gear S turns both gears O and P clockwise making them move along stationary gear R in a counterclockwise direction. This makes A rotate counterclockwise with a constant speed greater than that of S.
17	As the large gear is turned at S the two smaller gears will move in a clockwise motion. the speed at A will be constant and the same as S.

18	When S is turned counterclockwise A will turn clockwise. Constant rotational motion at S = constant rotational motion at A. A will turn slower than S b/c radius is larger.
19	If the outer gear is held motionless none of the other gears move.
20	constant counterclockwise rotation at A, faster than Ws. [arrows drawn on P and indicating rotation of A]
21	This machine would rotate counterclockwise at a constant speed with constant rotational motion of inner gear S. Since speed is constant, it would be at a faster rate than the rotational speed of S.
22	As inner gear S rotates counter clockwise w/ constant rotational motion, the structure at A will remain motionless. [arrows drawn on P gears, and also on carrier indicating rotation of P gears]
23	When the inner gear S moves, it will cause the two outer gears to move in the opposite direction. Because of this, the structure A remains completely stationary and does not rotate or move in any way.
24	The shaft A will rotate counterclockwise at a constant speed. The shaft will have a lower angular speed than the driving gear S. [curved arrow drawn on P]
25	The direction of the structure at A is clockwise with a constant speed that is faster than the rotational speed of gear S.
26	The part A moves counter clockwise at an angular velocity twice that of input. [curved arrows drawn on P gears]
27	For a constant counter-clockwise angular speed of the gear S the structure at A will rotate counter clockwise at a lower angular velocity than S. For a given torque at S a larger torque will be generated on A.
28	A will rotate CCW at a slower rate compared to S, but will be constant.
29	A turns counter clockwise with constant speed. S turns counter clockwise, turning both of the outer, smaller gears clockwise. Because the [sic] are on opposite sides of the gear R, the [sic] receive opposite normal force reactions, causing A to rotate counter clockwise.
30	When S is counterclockwise, A will also be counterclockwise. Speed will be constant, and faster than the rotational speed of S.
31	When R is held motionless A will rotate clockwise at constant speed faster than the input.
32	This is a planetary gear set. The rotational movement of A has a constant speed which is counter-clockwise and is slower than the input.
33	A does not move and the speed does not vary.

34	When S rotates clockwise, the structure at A rotates clockwise. Vice versa is also true if S rotates counterclockwise. The faster S rotates, the faster A rotates. A will always have a higher rotation speed than S, including constant speeds. As S rotates, it turns the gears P. R is fixed, so the gears P must move and when they do they will carry A with them.
35	As Gear S rotates counter clockwise, Gears P and the lower Gear will clockwise around the inner gear, rotating axel [sic] A. The speed is constant and will be faster than Gear S's speed.
36	The structure A is rotated in the same direction as the gear S. The speed of A is substantially lower while its torque provided by S is increased. The speed is constant. [curved arrows drawn on P gears, R, and indicating direction of travel of P]
37	When the inner gear S is spun counter clockwise It will cause the structure at A to spin in a clockwise rotation at a constant speed. If the speed of S changes the speed a [sic] A will also change. The two have a direct relationship. A will rotate faster then [sic] S if the speeds are constant.
38	As S is turned counter clockwise, it causes the gears at P to move in the opposite direction. P then in turn causes R to go counter clockwise and since A is connected to P it too spins clockwise. It seems as though this machine would be used to create torque and power for A.
39	The large gear S is being rotated counter-clockwise at a constant velocity, this causes the two smaller gears to rotate clockwise around the large circle R. The structure at A moves clockwise at a constant rotational velocity than that of gear S.
40	If I turn S counterclockwise as shown at speed "W", A will turn at the same speed same direction. It magnifies the force at S because of torque (radius S > radius of A) [curved arrows drawn indicating direction of travel of individual P gears]
41	The direction is counterclockwise and the angular speed is constant. The angular speed of the structure at A is equal to the angular speed of S.
42	The structure at A will rotate counterclockwise at a constant speed the same as the drive gear. [arrows drawn on P gears]
43	A will rotates [sic] clockwisely. It's speed will be constant if we ignore the effect of each machine part's [sic] own weight. The angular speed will be smaller.
44	As the inner gear turns counter clockwise the part A moves counter clockwise as a resultant constant speed. The inner gear spins the two smaller gears which move along the grooved inside of the outer ring.
45	"+ Gear R turns at WR CCW. + Gears P at edges turn at > WR CW. Gear S turns at WS, where WS > WR but less than gears P CCW. + The cylinder A rotates at WR CW.

46	This machine works by causing the 2 gears attached to A to move in a clockwise direction. When the outer gear R is motionless, this causes piece A to turn at a clockwise direction with a speed based on that of the gear S. [curved arrows drawn on P gears]
47	"A" will spin in same direction as "S" but at a lesser rotational velocity. This will be constant at constant Ws. [curved arrows drawn on P gears]
48	Part R is rotating counterclockwise (looking from side of A). Gear S is rotating in the same direction as R, causing gear P + gear Q to rotate clockwise. Part A is rotating clockwise. Speed constant at A, but speed at P + Q is faster than at A.
49	As the internal gear S is rotated counter-clockwise as shown, the structure at A will also rotate counter-clockwise, but at a faster rate than S. [curved arrows drawn on P gears and on A, arrows are numbered 1 on S, 2 on P, 3 on A]
50	When the two gears (the large outside gear and the center gear) turn, the two small gears connected to the Structure A will turn. Depending on the lift, rod A might remain still while the "arms" turn or turn with them. The speed of the two gears will be slowed if the large and center gears are slowed.
51	As gear S is rotated in counterclockwise motion, structure at A also moves in counterclockwise direction at a constant speed but faster than S rotating.
52	A will have rotational motion in the same direction as S equal to the speed of S
53	When outer gear R is motionless and S is at constant speed in the counterclockwise direction as indicated, shaft A will be rotating counterclockwise slower than gear S. If the speed of S increases, the speed of shaft A will increase and vice-versa.
54	This machine appears to move in a counter-clockwise motion of constant speed. The speed is constant because of the bar at A. The speed is greater than the rotational speed of the gear S.
55	The speed will be the same as the inner gear going counter clockwise and constant.
56	The structure at A moves clockwise when the outer gear R is held motionless. The speed will be faster because the radii are smaller.
57	A will spin in the same direction as S (CCW from this view). The speed will be constant as long as the speed of S is constant, and A will spin just as fast as S.
58	The structure A will be moving the same direction as the inner gear S. In this instance counterclockwise with constant speed. If R is held motionless A would behave in the same manner counterclockwise at a constant speed. The speed is slower than the inner gear S. [curved arrows drawn on P gears]
59	This machine decreases rotational velocity from rod A to gear S. The direction is clockwise _ the speed is constant. The angular speed at S is faster than at R.

60	If R is held motionless, then the movement at A will cause P and the other gears to move. P and the bottom gear should have the same speed and S should be half of those translationally, but not rotationally.
61	A rotates counterclockwise at constant speed. Speed varies directly with input, and rotational speed of A is slower than rotational speed of S.
62	Object A will rotate counter clockwise at a constant speed in comparison to the input. If the input is faster the rotational speed will be faster as well but by a smaller amount. [delta] vS > [delta] vA. [curved arrows drawn on P, curved arc lightly scratched apparently tracing rotation of planet carrier]
63	If R is motionless then A is motionless. Once the gear moves in a canterclockwise [sic] motion the Gear P will move clockwise as well as the gear on the bottom. This cause A to move along with its components in a clockwise fashion. Due to the moving of P the Gear S moves in a canterclock [sic] motion. The speed will only vary based on the speed of R.
64	Given the counter-clockwise direction of rotation of gear S, the structure at A would rotate counter-clockwise. Gear S works on the other two gears, pushing them in a counter clockwise direction and rotating the structure at A. The speed of rotation of A will be this [sic] same or similar to the speed of S. [curved arrows drawn on P gears]
65	Structure A spins clockwise with a constant speed that is the same as S b/c the radii of P's are half S but there are 2?
66	As gear S rotates counterclockwise at W, gears P and the lower gear rotate at a higher angular velocity clockwise. When the outer ring is held constant, the shaft A will rotate at a constant lower angular velocity than gear S. Therefore, gear S causes shaft A to rotate, as gear P and the lower gear rotate, they move the shaft clockwise around the mechanism.
67	The structure at A rotates clockwise as the inner gear S rotates counter clockwise. The speed of A is constant, faster than the gear S.
68	WR assumed to be moving counter clockwise. This causes Gear P and B [B is the second P] to rotate clockwise at a rate faster than that of gear R. Forces acting on S should make it have a faster period of rotation that [sic] gear R. R < S < B = P by order of rotation speed. Also S should be rotating counter clockwise.
69	S turning anticlockwise causes P to turn clockwise while P' also turns clockwise. This causes the plate A is connected to to turn clockwise, thus moving A in a clockwise circular path at a constant speed equal to that of P and P' and greater than S.
70	If R is motionless then as the gear S rotates CCW, the two other gears will rotate CW around S so that A spins at the same speed (faster than S) as the two smaller gears in a CW direction.

Question 3: Rack & Pinion

ID	Student Answer
1	As O moves counter clockwise, it moves to the left. Since it is rotating, this causes the link to move B right and then left in a cyclic nature. However, B slowly moves left over all because the gear O is moving left. B continues its left right cycle with a net movement left.
2	The direction of the structure B will be to the left. As O is rotated it brings B (pull) or if rotated the opposite direction (pushes B). The speed would vary again based on specific direction where force of gravity would either help or hurt it.
3	The structure at B moves to the left with varying speed. The speed of the structure varies sinusoidally w/ O.
4	As gear O is turned counterclockwise, B initially moves horizontally to the right at a faster speed but then slows down and reverses directions towards the left as the connecting arm between B and O reaches the top of gear O and begins to rotate back towards its starting point at the bottom of the gear.
5	As big gear O rotates left or right the structure B moves in the opposite direction. The speed varies because big gear O has to stop and change direction in order to continue turning easily.
6	As you rotate this, B slides translationally (back & forth in the x axis). When you turn the machine counter clockwise B moves to the right. There is an acceleration included so the speed is not constant.
7	The direction & speed of B will vary if O moves right, B moves left. If O moves left, B moves right. The speed will be like a sine function increasing & decreasing.
8	B will move in the [sic] to the right, but speed will vary with the location of A given constant rotational motion.
9	The structure at B will move right first then hit a maximum point and change directions to go left. The speed is varying. The speed varies because the rigid arm will make the structure at B change direction which would show that the velocity would equal 0 at some point.
10	Gear O rotates counterclockwise. Structure at B moves left. Speed varies in relation to input. B does not begin to move until gear O has been rotating for t>0 (depending on speed of rotation).
11	As the gear rotates, the structure at B will slide along the horizontal bar first right then left, and the speed at which this happens increases due to the acceleration α, so the total speed varies.

12	The structure at B varies in speed as the gear O accelerates. Its speed increase as W increases. As O rotates B moves farther away from O in the rightward direction until the point of attachment A is at its Rightmost position, as rotation continues, B moves closer to the gear once again, overall, B moves leftwards. Its speed varies based on Point A's position around the gear.
13	With constant rotation of O, the structure will move left with an increasing speed. With a larger or smaller w, the structure will start off moving at a faster or slower speed respectively. With a larger α, the system will increase in speed at a faster rate.
14	B will move at a constant speed to the left.
15	B moves to the left as the gear moves in a counterclockwise motion. The speed varies in relation to the input. The speed of the gear is faster than that of B.
16	As gear O rotates it moves along the track dragging structure B with it. The maching [sic] moves to the left at an increasing speed. It is rotating 12 radians faster each second.
17	As the gear rotates the shaft moves upward and the collar at B slides along the Beam, left at first then right. The speed increases as the gear rotates.
18	B will accelerate towards the right, stop, change direction and accelerate towards the left.
19	As the gear rotates the arm A will push the structure B and pull it depending on the direction the gear is traveling and the part of the rotation pin A is at.
20	Varying velocity, oscillating motion along the shaft. The B structure moves at the same speed as the gear, but linearly back and forth. [curved arrow indicating rotation of O, horizontal arrows - left and right - indicating motion of B]
21	This machine would move to the left with varying velocity. The velocity is directly related to input velocity.
22	As gear O turns C.Clockwise at constant angular velocity, the structure at B will move to the right at constant speed. [arrows drawn indicating translation of O to the left, and rotation of point A CCW]
23	If the gear O rotates in either direction, the structure at B will initially move to the right. As point "A" reaches its maximum vertical height, the speed slows to zero and reverses direction as point "A" begins to lose height.
24	B will move initially to the right with a positive acceleration. The acceleration will be greater as the angle θ increases and less as θ decreases.
25	The structure at B moves to the left. The speed of B varies. It moves more slowly as the pinned point on O reaches the top of the gear rotation but more quickly as it falls to the bottom.
26	The gear O will move to the left with constant velocity. B will also move to the left but at varying speeds that follow a sinusoidal function.

27	Given constant angular velocity of gear O the structure B will move to the right with decreasing speed before moving to the left with increasing speed to the left as gear O translates to the left.
28	B will move back and forth and its velocity will follow a sinusoidal path, but its average velocity will be to the left.
29	The slider at B slides left, slowly at first and increasing in speed as the gear rolls. The velocity reaches a maximum when point A is at its highest point.
30	B will move left and right as O rotates. It will move right more slowly, and left more quickly as gear O is moving counter-clockwise. The speed will not be constant, due to the acceleration and horizontal movement of gear O.
31	B will slide at varying speeds at first right then left.
32	B's motion is periodic to the left, with it stopping completely at an instant and then accelerating to the left before decelerating again. If B does not hit the end of its track the frequency of its motion will increase with the acceleration of the gear.
33	B moves to the right because the gear moves to the right. The speed is increasing because α =12 rad/s2 $\neq 0$
34	When O rotates clockwise (moves to the right), B moves to the right. When O rotates counterclockwise, B moves to the left. The speed of B will increase if w increases, for both directions. As O rotates, the lever arm moves vertically and horizontally such that point A is a shorter distance from B, or would be if the arm connecting A & B did not push B away.
35	B will first move right, then left as the shaft joint at A approaches the top of the gear. Its speed will accellerate [sic] then come to a stop, then accellerate [sic], moving in the opposite direction. [arrows drawn - left and right - indicating motion of B]
36	The structure at B moves right initially then moves left as the cog rotates counterclockwise. Speed is varying.
37	As the gear at O moves it will first cause the structure at B to move to the right and then stop and then the structure at the B will begin to slide to the left as the gear continues to rotate. As the speed of the gear increases the absolute value of the acceleration of the structure at B would be larger in magnitude.
38	As O is turned CCW, B will remain at a constant speed going right until a point at which it will accelerate rapidly back to the left then come to the end of the pipe. Acts as a basic piston.
39	The large gear moves to the right along the structure labeled "D" [the rack]. The gear does not move at a constant velocity (linear or angular). The linear velocity is greatest when the piece "A" is on the bottom half of the circle. Angular velocity is increasing with a constant angular acceleration.
40	B moves left with the speed varying sinusoidally, peaking when A is highest.

41	The machine at point B moves to the left with varying speed that is quadratically related to the wheel's acceleration.
42	The structure will move left in small bursts of speed that get closer together as the angular acceleration increases.
43	B will move right then left then right recursively. The speed varies according to the angle between part AB and the horizontal bar which part B attaches on.
44	As the gear rotates counter clockwise the part B is pushed right, when the rod connected to A reaches the apex of the gear and starts going down the left side, the part B moves left. As rotation accelerates part B does this motion faster.
45	"+ Gear rotates at W, accelerating at α speed (CCW). + The 8 in connector moves around the inner circumference of the gear at the same speed but in the opposite direction (CW). + B slides back and forth along its shaft at a velocity which increases as it moves right, then decreases until it switches direction whereupon it begins to increase again. + Whether this speed is greater or less than the input speed, I am not sure.
46	This machine works by having the input at A turn in a counterclockwise direction which in turn causes the point at B to move to the left at a constant speed.
47	The sleeve at B will translate somewhere sinusoidally along the rod starting to the right with constantly increasing translational velocity. "O" will also translate somewhere sinusoidally but starting to the left the difference in translational speed being proportional to their respective momentums. B will always stay to the right of O.
48	Gear O is at a constant speed until it hits the wall. After it hits the wall, it can either stop or change direction. B will do the same action as the gear. Gear O is rotating counter clockwise and is pulling B along the slide to the left. Both Gear O and Part B have limited mobility due to the walls.
49	The structure at B will move the opposite direction that [sic] gear O moves in and will move faster when the pin connecting the rod to the gear is closest to the vertical axis of the gear. The entire structure has a rocking pattern that moves back and forth.
50	When the gear turns, the rod connected will move in a locomotive manner and moves B towards the right, then left. The speed of B depends on the gear. Point O will move to the right and up. The gear will move counterclockwise.
51	the structure at B will go right, speeding up as the joint of A go [sic] up through rotation.
52	B will move to the right, then back to the left, repeating as O turns with varying speed. Fastest when the joint on O connecting B is towards the top or bottom of the gear.

53	If gear O rotates as indicated, the structure B will move left at varying speed. If the rotation speed increases, the overall speed of structure B will increase along with the frequency of its "fast and slow" cycles.
54	Machine appears to be moving to the right with varying speed due to the rotational acceleration. This machine appears to work very similar to an engine valve.
55	If the gear moves counterclockwise the sleeve will move right but at varying speeds.
56	The structure at B will move right at a constant speed.
57	As O spins, it will move B left and right. B will slide left for half of one turn of O, then stop & slide right for the other half of turn O, then stop & slide right for the other half of the turn of O. Therefore, its velocity will vary at each direction change.
58	Structure B moves horizontally to the left. The speed varies because the arm is not centered and gear O has acceleration α=12 rad/s[^]2.
59	Looks like the reverse piston in an engine. This machine converts rotational energy to translational energy. The cylinder at B will move to the left at a proportional speed to the angular velocity. The speed varies in that the two have different forms of energy, so you would need to convert the numbers, and it is also increasing.
60	I think this is a piston of sorts, as the circular gear moves clockwise, B should move left, and vice versa. The speed of B will be directly related to the rotational speed of O. O is clearly accelerating, so will B.
61	B travels right along the bar with oscillating speed. The magnitude of the oscillation varies with input speed but the bar does not has [sic] velocity < 0 m/s. [this student appears to have analyzed this thinking that O rotates clockwise -- see original paper]
62	As the input continues B will ocsilate [sic] between a forward and backward horizontal motion. When the connection between the gear and the beem [sic] are below O, B will move in the positive x direction. When above O it will move in a negative x direction. Its speed will be faster in the middle and slower on the edges. As speed varies, vB will vary proportionally.
63	As the gear O moves to the right the lever connecting the gear to the structure at B moves its base in the same direction as the gear at at [sic] varying speed [sic] since there is an angular acceleration. This pushes the structure at B horizontally to the left at varying speeds.
64	As the gear continues moving to the left, O will move up horizontally and lessen the now 60° angle, pushing point B to the right. As O comes round the gear, it will pull B back to the left. The speed at which B moves is proportional to the input speed.

65	Structure B moves right as O's arm is on the right side of the gear but moves left once it once it [sic] is on the left side. The speed varies and is faster when the arm is rounding the bottom and top parts of the gear
66	As gear O rotates counterclockwise, the shaft is driven, which causes structure B to move at varying speeds (higher near when B is located in the middle of the shaft it rides on and lower when it reaches the end. The structure B will continue to move right until the point at A is at 90˚ in relation to the gear. It will reverse and travel left after that until it reaches 270˚. Speed in the middle is faster than input speed.
67	The structure at B moves to the left at varying speed. It varies depending on the location of A on the wheel.
68	Gear O rotates counterclockwise and its rotational speed is increasing at 12 rad/s[^]2. Rotation gear O causes B to move toward wall A [right] by brushing across the pipe. At the top of the gear when A is at its highest point, B will be closest to wall A. As the gear continues to rotate the pin joint at A will exert a pulling force on B until it reaches the bottom once again restoring B to its original position. Since the speed of rotation is increasing the amount of times B repeats this cycle will also increase.
69	O moves to the left due to its anticlockwise motion, bringing the shaft B to the left at a constant speed, then varying as it is hated [sic] by the end of the bar (Q) [left end of the slider]. This force will cause O to change directions (going clockwise & to the right). Now B travels to the right until it is halted by the end of the bar (V) and the process is repeated until the loss of momentum due to collision brings the system to a permanent stop.
70	As the gear rotates and accelerates, the structure B is pushed right* with varying speed that varies as the acceleration of the gear. *initially right, and then left

Question 4: Geneva Mechanism

ID	Student Answer
1	As B moves constantly clockwise, it causes P to move into the slot in the star wheel. Eventually this will cause the star wheel, A, to rotate counterclockwise till P comes out. The cycle is then repeated to cause A to 'tick' with intermittent clounterclockwise motion.
2	This machine causes the star to move clockwise with a varying speed. As B gets past 45˚ gravity helps increase it until after 90˚ where it has to overcome gravity. The star turns due to the C, B, & P connection.
3	The star wheel spins in a counterclockwise direction with a varying speed. The speed varies sinusoidally w/ the driving wheel.

4	As B rotates clockwise at a constant speed, star wheel A rotates counterclockwise at a speed slower than the rotational speed of the driving wheel B.
5	As driving wheel B turns clockwise the star wheel A is turned counterclockwise. Both move at constant speed, star wheel A moves slower.
6	It works like a system of gears. The small disk rotates and the star wheel rotates. Since the disk rotates clockwise, the star wheel rotates counter clockwise at constant speed. The star wheel is turning slower because it has a larger radius than the driving wheel B.
7	if B moves CW A moves CCW. if B moves CCW A moves CW. Speed varies, I would assume it would be like [picture of curved sawtooth wave, where speed increases exponentially, then immediately drops to 0, then repeats] and so on.
8	Star wheel moves counter clockwise, slower than driving wheel B. If speed of B increases, speed of star wheel increases proportionally.
9	A will move in a counter clockwise motion. It will move at a varying speed. The moving disc will be in contact with the object at some points and not at others so there will be times of no motion and times of increasing motion.
10	Wheel B moves clockwise. Wheel A moves clockwise due to applied force from pin P. Speed varies. B must be turning for t>0 before A moves to give the pin P time to move into place & exert force on wheel A.
11	The star wheel A will rotate counterclockwise around the driving wheel with a varying speed that is parabolic in relation to the input.
12	The star wheel will move counterclockwise and the speed will be constant. The speed will be slower than the speed of B.
13	With constant rotation of B, the star wheel A will move in a counterclockwise direction at a constant speed slower than the speed of B.
14	As B rotates in one direction P causes the star wheel A to rotate in the oposite [sic] direction by being pushed down the slot and eventually leaves one slot rotating and entering the succeeding slop [sic]. In this pic I think A will rotate counter clockwise at varying speed.
15	The star wheel is moving counter clockwise at a constant speed. As the driving wheel moves clockwise, the star wheel moves counterclockwise. The speed of the star wheel is slower than the driving wheel because it makes less rotations.
16	As the wheel around B rotates clockwise the star wheel rotates counterclockwise at a constant speed. It is slower than that of the driving wheel.
17	As the wheel spins it causes the star wheel to spin counterclockwise with a speed that is the same as the wheel.
18	I have no idea what this is.

19	As the driving wheel B turns clockwise it also rotates the pin P in the same direction. As pin P moves it slides down the rectangular slot in the star wheel A. At the same time guide C moves the crescent shaped part of star wheel A. The effect of pin P and guide C acting on the star wheel turn it counter clockwise. During the pins [sic] rotation it will travel the length of the slot and then back up as the star wheel rotates. As both drive wheel B and star wheel A rotate eventually pin P and guide C will repeate [sic] the before mentioned sequence.
20	The star wheel rotates counterclockwise with varying speed b/c the pin follows the guide to the bottom, pushing the star along until the motion is complete and the pin leaves the guide. The star continues its motion due to inertia until the pin makes a full cycle and returns to the next guide rail. The speed is either equal to (pin at bottom of the guide) or less than (pin out of guide -- star is coasting) the speed of the driving wheel. [circular arrow drawn on A]
21	This machine moves counter clockwise at a constant speed, which will be slower than the rotational speed of the driving wheel.
22	As B rotates at constant speed - clockwise, star wheel A ... I do not know - maybe I don't fully understand the diagram.
23	The star wheel will rotate in a direction opposite to that of the driving wheel. The rotational speed of the star wheel will be constant but slower than that of the driving wheel.
24	The star wheel A will move counter clockwise constant speed, but slower than the driving wheel B.
25	Star wheel A will move clockwise at a constant speed. The star rotation is slower than the rotational speed of the driving wheel B.
26	The Part A will rotate counter clockwise at an average speed 1/6 of the input. It will only rotate when pin P is in contact and will stop until P comes back around.
27	Given a constant clockwise angular velocity of wheel B the star wheel will rotate at constant counter clockwise angular velocity which is lower than the angular velocity of B so long as the pin p is in a slot in the star wheel. The star wheel is at rest as the pin cycles around to catch the next slot in the star wheel.
28	A will rotate CCW and its velocity will increase as P approaches its closest point to the center of A and it will decrease to 0 as it leaves the slot on A.
29	The star wheel rotates counter clockwise at varying speed. It reaches a maximum velocity when the pin, P, is furthest into the slot.
30	* cannot understand this diagram... Random guess: star wheel will spin around driving wheel B
31	Wheel A will rotate counter clockwise at varying speeds.
32	This is a smart device to get stop and go motion from a constant input. The wheel periodically rotates 60° counter clockwise.

33	I don't understand what the guide C does, but it seems that the machine rotates counterclockwise as the driving wheel rotates. The speed should be constant for the star wheel (A) but slower than that of the driving wheel.
34	As B rotates, the pin P slides down the guide path in the star wheel to push the structure A in the same direction as B (if B is clockwise => A is clockwise and vice versa). The faster B turns, the faster A will accelerate because if B is moving with a constant rotational speed, then the pin P is moving at a constant speed down the path, but as P gets closer to the center of A it is reducing the effective radius about which A turns. A constant tangential force with a decreasing radius will result in an increasing torque and thus an increasing angular acceleration. So a constant speed for B will not produce a constant speed for A, it will produce a constant acceleration.
35	As wheel B turns clockwise, the star wheel will rotate counter clockwise in a periodic burst. It will rotate slower than wheel B will.
36	No idea how this works.
37	I am not really sure but I think A will spin counterclockwise also the speed will be constant. The rotation of wheel A will be faster than B if B is going at a constant speed.
38	As B is rotated clockwise, A will rotate counter clockwise and rotate at a constant velocity. It will move at a slower rate than the steering wheel.
39	The star wheel does not move. Maybe?
40	The driving wheel turns the star wheel as pin P is pushed into the slots. It will turn at a constant speed, rotating counter clockwise. The speed of A equals the speed of B.
41	This picture is unclear to me. I think the machine moves counterclockwise with constant speed. The angular speed should be the same as that of the driving wheel B.
42	The star wheel will rotate counterclockwise by 60° every time the pin comes around with the same speed as the drive wheel. It remains motionless between turns.
43	Star wheel A will rotate counterclockwisely at a constant speed slower than the driving wheel B.
44	As driving wheel B rotates, star wheel A rotates in the same direction at the same speed.
45	"+ Part B rotates CW at WB. + A rotates in the opposite direction at W < WB (CCW)
46	This machine works by causing the wheel at A to move in a counterclockwise direction at a constant speed which is slower than the rotation of B.

47	As the driving wheel turns, the star wheel will also turn the opposite direction with the same rotational speed while the peg is in a slot. However, the star wheel will not move while the peg is not in the slot causing regular intervals of motion for the star wheel. [curved arrow indicating rotation of A CCW]
48	the speed of B will remain constant. B is rotating clockwise. Pin P is rotating counter clockwise and is at a constant speed higher than wB. Star wheel A is rotating counterclockwise and is at a constant speed slower than wB.
49	When B rotates clockwise, A will rotate counterclockwise at a slower rate. Pin P will move along the length of the slot of A to transmit B's rotational motion before exiting. Completing a revolution and entering the subsequent slot. A's rotation is periodic, not constant, as it will not move when P is not in a slot.
50	When the wheel B turns clockwise, Pin P pushes towards the left and turns wheel A counter clockwise. The guide C keeps the wheel A turning and makes sure pin P makes contact with the slot in wheel A. The wheels are dependent on one another. The slower B spins, the slower A spins.
51	I can't see/understand how or what is being moved.
52	A will move clockwise, constant slower than B
53	If the input wheel is rotated at constant speed as indicated, the star wheel will rotate counter clockwise at varying speed. A will rotate slower than B. If the speed of B is increased, the overall speed of A will increase as well. There are times during the cycle when A will be motionless.
54	Machine appears to be a disk changer. The direction is clockwise at constant speed. The speed of B is faster than that of A or C. Machine appears to rotate + select different disks with A while P reads the disk.
55	Counterclockwise motion with varying speeds due to the pin.
56	The star wheel A is moving clockwise at a varying speed.
57	The wheel does not look like it will move.
58	The star will move clockwise at a constant speed which is slower than driving wheel B.
59	I can't tell what this machine does, the picture is kind of confusing.
60	I believe when B is put in rotational motion the contact between it and the surface will lead to the whole structure moving opposite. The wheel should rotate with the same speed as B.
61	A moves counter clockwise with on and off periods as the pin leaves its slots. The speed varies with each on period, maxing where θ = 0 and decreasing until it stops at θ = 30, -30.
62	I have no idea what this is or how it is turning, perhaps the pin is force into the collum [sic] by the driving wheel and then the wheel hops over the pin to the next gap which allows for the pin to move after it.

63	As the driving wheel moves constantly clockwise the star wheel will move canter [sic] clockwise constently [sic]. The speed of the star wheel should move at the same speed as the driving wheel.
64	It would be a lie if I said I had any idea how this machine works. I dont't understand it yet.
65	The structure A moves counter clockwise at a varying speed that is slower once the pin P hits the bottom of the shaft in A and B has to roll over to the next notch.
66	As B move [sic] clockwise at 4 rad/s, this propels star wheel A clockwise once pin P slides into the slot on the star wheel. The speed of A increases as the pin travels closer to the center of the wheel, and reduces as it moves away. It is a non-constant speed that has a slower rad/s rotational W than the driving wheel.
67	The star wheel will rotate counterclockwise with varying speed because of the guide C and pin P. Dont really understand this one.
68	The speed of rotation is constant and wheel B rotates counterclockwise. Wheel A should rotate slower and in a counterclockwise motion.
69	If B is constant, A will also be constant, but slower. If B varies, A will vary but on a lesser degree due to its larger diameter.
70	The star wheel rotates around the structure B CCW with constant speed, as it moves the pin P is moved in and out of each slot in the star wheel.

Appendix K: Pretest Multiple Choice Scores

Traditional Group

Treat	ID	Time	Spatial	Concept	Total	Spatial%	Concept%	Total%
T	1	0:49	5	12	17	56%	63%	61%
T	6	0:53	5	8	13	56%	42%	46%
T	8	0:30	8	6	14	89%	32%	50%
T	10	0:43	3	5	8	33%	26%	29%
T	18	0:37	8	10	18	89%	53%	64%
T	19	0:28	8	7	15	89%	37%	54%
T	21	0:32	7	3	10	78%	16%	36%
T	25	0:36	7	9	16	78%	47%	57%
T	27	0:18	8	16	24	89%	84%	86%
T	29	0:38	8	11	19	89%	58%	68%
T	33	0:32	4	9	13	44%	47%	46%
T	37	0:31	6	7	13	67%	37%	46%
T	41	0:33	7	14	21	78%	74%	75%
T	43	0:59	7	7	14	78%	37%	50%
T	44	0:31	8	8	16	89%	42%	57%
T	48	0:37	5	2	7	56%	11%	25%
T	51	0:45	5	6	11	56%	32%	39%
T	53	0:47	7	10	17	78%	53%	61%
T	54	0:46	7	7	14	78%	37%	50%
T	57	0:27	7	5	12	78%	26%	43%
T	61	0:25	8	12	20	89%	63%	71%
T	66	0:38	8	7	15	89%	37%	54%
T	67	0:36	7	5	12	78%	26%	43%
T	68	0:37	5	8	13	56%	42%	46%
T	69	0:27	5	6	11	56%	32%	39%
T	70	0:36	6	5	11	67%	26%	39%

Physical Group

Treat	ID	Time	Spatial	Concept	Total	Spatial%	Concept%	Total%
P	4	0:44	7	5	12	78%	26%	43%
P	5	0:47	4	6	10	44%	32%	36%
P	7	0:30	6	6	12	67%	32%	43%
P	11	0:32	8	6	14	89%	32%	50%
P	12	0:47	6	6	12	67%	32%	43%
P	13	0:38	6	8	14	67%	42%	50%
P	17	0:38	7	8	15	78%	42%	54%
P	23	0:36	8	8	16	89%	42%	57%
P	24	0:26	3	7	10	33%	37%	36%
P	26	0:32	8	14	22	89%	74%	79%
P	31	0:25	8	13	21	89%	68%	75%
P	32	0:27	6	11	17	67%	58%	61%
P	36	0:36	8	11	19	89%	58%	68%
P	40	0:34	9	6	15	100%	32%	54%
P	46	0:45	8	6	14	89%	32%	50%
P	50	0:42	5	4	9	56%	21%	32%
P	55	0:29	7	8	15	78%	42%	54%
P	56	0:30	8	6	14	89%	32%	50%
P	59	0:30	7	7	14	78%	37%	50%
P	60	0:23	4	9	13	44%	47%	46%
P	63	0:48	7	7	14	78%	37%	50%

Virtual Group

Treat	ID	Time	Spatial	Concept	Total	Spatial%	Concept%	Total%
V	2	0:32	6	6	12	67%	32%	43%
V	3	0:34	5	14	19	56%	74%	68%
V	9	0:32	5	8	13	56%	42%	46%
V	14	0:50	5	10	15	56%	53%	54%
V	15	0:48	5	7	12	56%	37%	43%
V	16	0:31	7	8	15	78%	42%	54%
V	20	0:46	8	11	19	89%	58%	68%
V	22	0:24	5	7	12	56%	37%	43%
V	28	0:37	9	11	20	100%	58%	71%
V	30	0:33	6	8	14	67%	42%	50%
V	34	0:49	7	12	19	78%	63%	68%
V	35	0:41	8	9	17	89%	47%	61%
V	38	0:24	6	3	9	67%	16%	32%
V	39	0:30	7	4	11	78%	21%	39%
V	42	0:35	8	14	22	89%	74%	79%
V	45	0:37	3	6	9	33%	32%	32%
V	47	0:25	8	13	21	89%	68%	75%
V	49	0:34	8	7	15	89%	37%	54%
V	52	0:36	6	7	13	67%	37%	46%
V	58	0:39	4	8	12	44%	42%	43%
V	62	0:36	7	10	17	78%	53%	61%
V	64	0:34	7	7	14	78%	37%	50%
V	65	0:39	7	5	12	78%	26%	43%

Appendix L: Posttest Open Response Answers

Question 1: Four-bar Linkage

ID	Student Answer
1	As the handle rotates, it causes the window to crank upwards. At some point it will reach a max height and need to have the handle reverse direction to come down. The window will move with a constant velocity upwards. The speed of the window is probably slower than the speed of the hand.
2	The direction of the speed at D is down when the crank is rotated clockwise and upwards if it is rotated counterclockwise. The machine works because of the wheels together at C & B. The speed does vary as B is turned around here it will slow down & speed back up if returned to position shown. [arrow drawn indicating ccw rotation of S, arrow drawn indicating downward motion of D]
3	D moves up & to the left @ constant speed.
4	As the hand rotates the crank in the clockwise direction, the structure at D moves upward at a constant speed. If the hand rotates the crank counterclockwise, then the structure at D moves downward at a constant speed.
5	As the hand turns the crank, the crank turns the gears, the gears move bar AB, which moves bar FE with it, up and moves the structure D up. It moves with constant speed.
6	The direction of D is vertically upwards. The speed of D is constant. When you turn the lever, it rotates the gear counterclockwise and raises the two arms upward.
7	like a car window. As C rotates CW, Vw/D moves up at a slower speed than C.
8	Gear C turns B, pushing BA and FE up, causing D to go up with a decreasing V
9	When the crank is turned the gear turns which turns the halve [sic] gear this then gives BA an W that raises platform D.
10	Gear C is turned in a -k direction. Gear B rotates in a k direction. The rotation of B causes bar BA to move, so point A is raised up. Since A + E are attached rigidly, both move vertically up at the same speed. Point D also is raised at the same speed. Angular velocity is constant at C + B + F (WF = WB). Linear velocity is constant at A, E, D.
11	The motion of the crank causes the wheel S (or partial wheel) to rotate at a constant rate proportional to the input. D's speed will be constant and at an angle to the upper left [diagonal arrow drawn pointing up and left] because of the beams AB & EF

12	The speed of D is constant; As C is rotated clockwise, S moves counterclockwise, this causes structure D to move upwards.
13	Structure D rises with a constant speed
14	Hand rotates CW leads to gear SB rotating CCW and window D thing moving up w/ speed ↑ Vw in Y Vw will be constant
15	Gear C rotates in a clockwise direction due to the force applied by the hand which pushes the lever forward. This motion causes the gear c to move and in turn Gear S to move. As the gears move forward D is lowered. Because C and S are in contact, they have the same velocity, meaning D is moving at a constant speed.
16	As the hand turns gear C clockwise B rotates counterclockwise raising A at a constant velocity.
17	The handle is pushed forward which causes AB & FE to move upward with the same velocity and Vw to move upward with the vertical component of the velocity of AB
18	handle pushed forward, S rotates counterclockwise, lifts D up at constant velocity and slides sideways.
19	As gear "C" is turned in the negative k direction the partial gear "S" rotates in the positive k at constant angular velocity. Because the structure AE is stabilized by arms BA & FE it does not have angular velocity but the angular velocity of BA is turned into velocity in the positive j direction. All velocities are constant.
20	Crank rotates gear C, which rotates gear B. D is lifted b/c it rotates w/ gear B (upward speed as shown). Constant upward speed at D less than angular speed of C.
21	The structure, as the handle is rotated clockwise, turns gear B, providing a downward force at points A and E. The speed stays the same if there is constant rotational motion.
22	Structure at D moves with Constant velocity ↑ only in the j direction. CW W imparted on C by hand translates into CCW W at gear B. WAB-> WB and FE constrains point A to only translate in the j direction due to WBA
23	As the crank rotates counterclockwise, Gear B rotates counter clockwise, causing the member BA to have a certain angular velocity. A constant turning of the crank will cause an acceleration in the window as the motion is circular.
24	The constant rotational motion of the hand crank is turned into rotational motion of gear B which then causes structure D to translate upward. The upward velocity of B decreases with time.
25	The crank C is turned clockwise which rotates the gear B counterclockwise which causes the window D to move upwards as A and E also rise. Speed is directly proportional to the speed of the hand turning the gear.

26	The arm moves C clockwise rotating B counter clockwise both at constant speed. the velocity A is constant and tangential to the arc. only the verticle [sic] velocity of A is causing Vw so it is moving up but slowing down.
27	The 20 mm gear rotates clockwise at .5 rad/s turning the 50 mm gear at < .5 rad/s. The 50 mm gear turns link BA which lifts the structure D. The magnitude of the velocity of D is constant but changes direction as AB & FE rotate. A line through A & E remains vertical. The magnitude of the velocity of D is likely lower then [sic] the velocity of the hand.
28	D moves with decreasing vertical speed and increasing speed to the left, but it remains level.
29	When the handle is rotated, bars BA and FE rotate, in the opposite direction. They push the window straight up at velocity equal to the vertical component of the velocity of points A and E. The speed that the window is rising varies based on the direction of the velocity of A and E, because only the vertical component is being transferred to the window. This means that the window slows down as θ decreases. The output rotation of gear S is less than that of gear C.
30	A and E will move up and to the left. The speed will remain constant, but the direction will change as it rotates.
31	D is moving up at constant speed.
32	D moves vertically and decelerates (up) as it moves horizontally and accelerates (left). It moves as the arc of A but AE remains vertical.
33	The speed at D is constantly upward. The hand pushes the bar forward, which spins the top gear clockwise & the bottom gear counterclockwise. This gear is attached to the lever which moves the window up.
34	The small gear C is rotated by the hand clockwise which rotates the larger gear B counterclockwise at a speed proportional to C where the ratio of their radii (rc/rB) is the proportionality constant. Point A has the same w as B, so as it rotates with gear B, its tangential velocity has a vertical component at the instant shown: that vertical component is Vw. Thus the faster C rotates clockwise, the faster B rotates counterclockwise and the faster D rises. If B rotated clockwise, D would lower.
35	When the crank is rotated forward, gear S turns along with bar BA sliding D upward. D will swing upward like so [drawing showing ccw curved trajectory of D, but displacing up and to the right]
36	D will have a velocity towards the upper left direction and speed faster than the velocity of the hand that is rotating the crank. [diagonal arrows drawn on A and E indicating trajectory towards upper left]

37	By moving the crank gear C rotates in a clockwise rotation at a constant velocity which causes gear B to move counter clockwise at a constant velocity And the Structure D moves up and to the left at a constant velocity. If the speed input increases it will increase everywhere.
38	As the hand pushes c forward it causes B to turn and points E and A to go up with a velocity W in Wcrc=WBrB. D moves at the same speed as A.
39	The hand pushes the lever forward which turns gear C clockwise. Gear B rotates counter clockwise and causes block D to be raised at a constant velocity.
40	Structure d moves in the upward j direction, with a constant velocity.
41	The structure at D has a constant speed when the input is constant. If the input is increased the speed increases.
42	D moves upward w/ constant speed
43	D will move upwards. Its speed will decrease as the angle θ increases.
44	As the hand rotates the crank clockwise, member BA rotates clockwise, leading to structure D translating downwards as a result. The faster the crank turns, the faster D translates.
45	"+ slower than input. + Gear at C turned by lever (CW). Gear B turns (counter CW). Structure AE moves up with platform D.
46	This machine works by turning the lever which causes the structure D to move up and to the left. The speed varies based on the speed of the rotation at C.
47	As the lever is pushed forward gear C turns clockwise. Gear B turns counter clockwise at a lesser W and D moves toward the top left corner of the page with the same orientation.
48	Gear C turns clockwise at a constant speed + gear B turns at a constant speed equal to the velocity of C. The part D can only move in the vertical direction.
49	When the crank is rotated (point c) clockwise, the gear B will rotate counterclockwise at a slower rate. The rotational motion is translated along arm AB into pseudo-linear motion for body D, which will move up. 4-bar linkage [arrow drawn showing circular motion of D]
50	The handle is connected to the gear "C" which turns the gear B and raise the handle AB by "θ". The arm FE is connected to the lift that is also connect to the arm AB and arm FE will rotate "θ" along with AB. The lift will remain straight throughout.
51	D & AE will move upward at an increasing speed as C is turned CW.
52	As C is cranked in direction shown, D moves up, at a constant rate with the shown .5 rad/s applied. The faster C is cranked, the faster Nw is.
53	If the hand propels the gear C at a constant speed, gear B will move at a constant speed, which will raise D at a constant speed.

54	As the lever is rotated, point L [the lever], the angular velocity increases causing D to go up as well as Vw. Vw ↑ as Wc ↑ + D goes up or down based on the rotation of L. However Vw + D do not vary since Wc is constant.
55	D moves vertically up/down faster than hand crank
56	the structure at D moves up at a constant speed when constant rotational motion is provided by the hand.
57	D will rock slightly & move up & down. With constant input by the hand, its speed should be constant.
58	Wheel C spins clockwise B goes counter the lever arms go up pushing up block Do. Blcok D has constant speed up.
59	It translates the rotational energy at gear C into translational energy at point D. Its [sic] the mechanism used in car windows. The structure at D is moving upward at a constant velocity in relation to the input.
60	As the input is increased the rotational speed of the wheel causes D to move up. If the input is a constant velocity the [sic] D will rise with a constant velocity.
61	Varying upward motion at d, upwards but decreasing as BA moves off the horizontal. As the crank is turned clockwise, the window rises.
62	C rotates and moves gear B which rotates and A move upwards and to the left (counter clockwise). The velocity w is upwards and counter clockwise [curved arrow drawn indicating ccw] at a constant speed relative to the hand.
63	As a person rotates the lever in the clockwise motion the gear rotates in the opposite direction. This movement then moves the Lever from B to A upward moving the window upward and the lever from F to e in the same fashion. As long as the hand remains moving in a constent [sic] velocity so will the gears and window.
64	The structure at D moves up in a positive "y" direction as the floating hand turns the crank clockwise direction. As the small gear rotates clockwise, it rotates the larger portion of a gear counterclockwise, lifting bar BA which lifts structure D. Bar FE keeps the structure straight. Speed Vw varies proportionally with the speed of the floating hand that rotates the small gear.
65	D: moves upwards at varying speed that is decreasing as C and B spin the rod A back more.
66	The rotation of C counterclockwise causes S to rotate clockwise. This in turn moves the bar BA and the bar EF upward with a constant velocity in the y direction. Structure D moves upward at a varying velocity that decreases in the y direction over time as the structure is raised.
67	The crank at C is rotated clockwise at a constant angular velocity. this raises the window at D at a constant velocity

68	Gear C is rotated clockwise with constant angular rotation. Gear B is rotated counterclockwise with constant angular rotation. Structure D moves upward in positive y-direction. Points A and E rotate counterclockwise with respect to B.
69	The hand crank at C turns B clockwise which raises the bar BA and pushes the structure D upward with constant velocity
70	The gear C rotates at w=0.5 rad/s and because the velocity of the contact point between C and S is the same on both gears, gear S rotates counterclockwise at a slightly slower angular velocity. The bar AB rotates with the same angular velocity as gear S. This rotational motion gives D a linear velocity in the vertical direction which is constant.

Question 2: Planetary Gear Set (Sun Driven)

ID	Student Answer
1	The sun gear turns causing the outer planet gears to turn faster in the opposite (clockwise) direction. This then causes the shaft A to turn clockwise because it is pinned to the planet gears. It turns slower than the sun gear and has a constant speed.
2	This machine works because all the gears are aligned & they will move around a "orbit" like a sun gear does. The speed will vary depending on where it is in relation to the center at A (angle could change). The direction is clockwise. [arrows drawn on P gear showing cw rotation, and on planet carrier showing ccw rotation]
3	A has a constant CCW angular velocity. WA < WS.
4	As S rotates in a counterclockwise direction, P moves in a clockwise direction at a constant speed faster than the rotational speed of S. Since P rotates clockwise, this means that A also rotates clockwise.
5	If after gear R is held constant, the inner gear S moves the two smaller gears at a constan [sic] speed faster than the inner gear S so that the part of A connected to the gears rotates clockwise at a constant speed slower than the little gears.
6	Since the outer ring is not rotating, As S turns, clockwise it rotates each planetary gear clockwise. The planetary gears move around [something] constant speed. it is faster than the speed of S.
7	it rotates/turns, S is CCW, P is CW, R is steady. P & S move at same V. A moves slower than P & S.
8	The sun gear turns the planetary gears clockwise causing shaft A to move counter-clockwise with constant W. The speed of A will vary directly with the speed of S

9	Gear S spins gears P and the same rate. With the velocity on P the axil [sic] at A turns counter clockwise.
10	Gear S rotates in k direction. Gears P rotates in -k direction. WA is constant + slower than Ws. A rotates in k [ccw] direction.
11	While ring R is motionless, the rotation of wheel S will cause the position of the two P gears to rotate clockwise around the origin (opposite of Ws). The speed of the structure at A is constant and slower than Ws.
12	As gear S is rotated counterclockwise, the two smaller gears move clockwise, which causes structure A to also move clockwise. The speed of A is slower than the speed of S. It is constant speed.
13	speed is constant, clockwise, and slower than the rotational speed of S.
14	A will rotate CW at constant speed, as Ws ↑ WA ↑, WA wil be slower than Ws i believe
15	As R remains motionless, gears P and S rotate in a clockwise direction. As gear S turns, gear p also turns, thus causing the structure A to rotate at a constant speed. Gear P ahs a radius of 40 mm, while gear S has a radius of 80 mm. For every 1 rotation of gear S, Gear P will have to make two revolution [sic]. Because P and S are in contact with each other, the speed will be the same.
16	As S turns CCW both P turn CW in a circle around the track. This makes A turn CCW with a constant speed. The speed is slower then [sic] that of S.
17	The sun gear rotates Counterclockwise Causing the planetary gears to rotate clockwise which causes Shaft A to rotate all speeds are constant A is slower than the Sun gear.
18	Speed constant. A rotates counter clockwise.
19	As S turns counterclockwise it turns the planet gears clockwise. Because gear R is stationary the planet gears travel around the center at a constant angular velocity counterclockwise. The structure at A turns as the planet gears do. All angular velocities are constant.
20	Gear S rotates which causes rotation of planet gears due to fixed R. Planet gears are attached to A, which rotates with them. A: ccw, constant speed; faster than Ws. [curved arrows drawn on P gears, curved arrows drawn indicating ccw rotation of planet carrier and shaft A]
21	The structure at A is moving counterclockwise @ a constant speed, faster than the rotational speed of gear S. [curved arrow drawn to indicate cw rotation of second P gear, curved arrow ccw next to R]
22	CCW Constant at S -> Constant W at A CW. Varying CCW at S -> Varying WA at A CW slower than Ws.

23	By rotating the inner gear S counterclockwise, the two outer gears P will begin to rotate about S as a unit and cause A to also rotate. Their velocity will be constant as long as S has a constant velocity. The angular velocity of A will be equal to the angular velocity of S.
24	The structure A rotates counter clockwise at a constant angular velocity, which is lower than gear S. [curved arrows drawn indicating cw rotation of P, ccw translation of P about S, and ccw rotation of A]
25	Frame R is held constant as S spins counterclockwise which causes gear P to move clockwise which rotates A clockwise. Speed does not vary. It is faster than gear S.
26	S moves counter clockwise at a constant velocity. P rotates clockwise but moves counterclockwise inside R. they are constant speed and the angular velocity of A is less than S.
27	Given dW/dt at S is zero structure A rotates at a constant WA which is less than Ws. Both structures rotate counter clockwise.
28	A rotates CCW at a constant rate, slower than Ws [curved arrow indicating ccw rotation of A]
29	The structure at A is rotating counterclockwise at a constant speed. A is rotating slower than the structure at A. [arrows drawn indicating rotation of P gears, ccw rotation of planet carrier, ccw rotation of shaft A]
30	When S rotates, the p gears will rotate opposite from S, and A will rotate in the same direction as S, but at a different (constant) speed.
31	A is rotating counter clockwise at a constant speed slower than Ws
32	Output shaft A of the gear-set rotates counter-clockwise slower than input S.
33	The speed of A is constant if the speed of S is constant. A rotates clockwise with the inputs from P & B [the second P gear]. The gear at S propels P & B which propel A | the bar connecting P & B to A [curved arrows drawn indicating cw rotation of P gears]
34	As S rotates counterclockwise, P rotates clockwise and is translated about S in a counterclockwise direction. Thus A rotates in counterclockwise. The rotational speed of A is proportional to the speed of rotation of S and the proportionality constant depends on the gear ratios between S & P and between P & R. In summary: If S -> faster : A -> faster; S-> constant : A -> constant; S-> counterclockwise : A -> counterclockwise.
35	as S turns counter clockwise, the planetary gears rotate faster around S clockwise, which turns A slower, clockwise.
36	The structure at A rotates at constant angular velocity in the counterclockwise direction that is faster than the rotational speed of the gear S. [arrows drawn indicating cw rotation of P]

37	The P gears are going to rotate clockwise causing structure a to rotate clockwise. If the speed is constant A will move faster than S.
38	As a rotates constantly clockwise, gear P moves in that direction but rotates at a [formula], this causes gear S to spin same direction as A and R remains fixed.
39	The sun gear S rotates counter clockwise with a constant angular velocity. This causes the smaller planetary gears to rotate clockwise around ring R. The structure at A rotates counter clockwise at a slower rotational velocity than gear S.
40	the structure a rotates counter clockwise same direction as S. It moves slower than s. at a constant velocity.
41	The angular speed of A is constant and equals the angular speed of S. A sthe speed of S is increased, so is the speed of A. A turns counterclockwise.
42	A rotates counterclockwise at a constant speed slower than S
43	Speed of A will be constant. It's slower than S.
44	The sun gear rotates The planet gears clockwise, which rotates A counter clockwise. The rotation of A a constant speed. The speed is slower than gear S..
45	[table indicating A turns CW slower than S] turn A. turns carrier gears P. turns sun gear S.
46	The structure at A moves in a clockwise direction and at a speed of about 1/3 that of S.
47	The smaller planetary gears "orbit" the center gear S in a counter clockwise direction, but rotate in a clockwise direction. A rotates counter clockwise at about 1/3 of the angular velocity.
48	The sun gear is rotating counter clockwise if looking from shaft A at a constant speed. The planetary gears are rotating clockwise at a constant speed equal to the sun gear. The outer gear is stationary.
49	When sun gear S is rotated counterclockwise, the planetary gears P will rotate clockwise at a faster angular velocity, which in turn will rotate the planetary carrier C counterclockwise. The carrier will rotate at a slower rate than S. A will rotate with the same angular velocity of C [the carrier] it it [sic] is attached, but will not rotate if it is connected w/o a bearing system. Planetary Gears
50	The planetary gear system above is dependent upon the sun gear's rotation. As the sun gear rotates, the two planet gears will rotate along with the arm in the opposite direction. The speed will remain the same as the rotating sun gear.
51	As S moves CCW, P will move CW. This makes A structure move cW at a lower but constant speed than S.
52	with constant Ws counterclockwise, A rotates counterclockwise at a constant speed slower than S.

53	If S spins at a constant speed counter clockwise as shown, A will spin counterclockwise at a slower, but constant speed.
54	The gears move counter clockwise with constant speed due to WA. S + A both have the same speed + it is constant.
55	Constant speed of outer. Clockwise motion
56	The structure at A moves clockwise at a constant rotational motion slower than that of inner gear r. [arrows drawn indicating cw rotation of P gears]
57	A will rotate in the same direction as S (CCW). Its speed is constant, but not the same as S (faster than S)
58	A will have constant clockwise speed.
59	This machine works by increasing the speed coming from the inner gear to the shaft at A. Its used in transmissions of cars. The planetary gears at P rotate about gear S while inside the outer gear R. The structure at A rotates counter clockwise at a speed relative to the input at gear S.
60	The user will have a hold of A and will move their hand either clockwise or CCW. As a result of the two wheels, labeled P, will begin to rotate. The two smaller wheels will rotate with half of the speed as S.
61	As S turns, it pushes the planetary gears along the ring gear slower than it is turning, causing a to rotate CCW slower than S. [arrows drawn indicating ccw rotation of planet carrier and ccw rotation of A]
62	This is a sun & planetary gear problem. The input radial velocity to the sun gear rotates the sun gear and causes the 2 planetary gears to rotate and move in a counter clockwise [curved arrow indicating ccw] path around the sun gear when WR=0. This movement rotates A at the same radial velocity at their path. It is constant velocity.
63	If a rotational force is place on the structure at A in a constent motion then the two planetery [sic] gears will rotate at a constent speed in the clockwise direction. Then the sun gear will rotate in the counter clockwise direction. If a is accelerated then the planetery gears will accelerate.
64	Gear S rotates at constant angular velocity Ws counterclockwise. It in turn rotates gears P1 and P2 clockwise. As gears P1 + P2 rotate against a stationary outer rim, they move counter clockwise, spinning bar A counter clockwise as well. The speed at A is constant dependent on (proportional to) the speed Ws. The speed would be the same as Ws.
65	A: rotates counter clock at constant speed that is the same as S.
66	The inner gear rotating at Ws causes the P gears to rotate clockwise at a constant speed. Shaft A therefore rotates counterclockwise at a constant velocity. [arrows drawn indicating cw rotation of P, ccw rotation of S]
67	Gear S rotates counterclockwise, which rotates P clockwise which moves A clockwise as well at a constant velocity. The velocity of A is faster than S.

68	S moves with constant angular velocity in a clockwise direction. Gear P has a larger angular felocity than gear S but moves with counterclockwise motion. The angular velocity in P is constant. R does not move. Shaft A rotates counterclockwise at a rate faster than S. The angular velocity at A is constant.
69	A moves clockwise at constant velocity (faster than S)
70	The sun gear S rotates with a counterclockwise angular velocity, making the planetary gears rotate clockwise with a great angular velocity (radius is smaller). This rotation causes the system to revolve around fixed R in a counterclockwise direction with constant velocity that is smaller than Ws. Because of this, A will also spin counterclockwise with a smaller W than Ws.

Question 3: Rack & Pinion

ID	Student Answer
1	As O rotates counterclockwise, it translates left with a constant velocity. This rotation also causes B to translate right then left and back to right in a cyclic fashion. This purely horizontal motion of B is not at a constant velocity but varies with time. This is due to which part of gear O is where as it rotates with a constant velocity. As the gear O moves further down, it will drag B with it slowly moving B to the left. Assumedly there is a stop or reset point to prevent breaking.
2	The bar (A) rotates around the gear & either pushes B or pulls depending on the direction. So since it starts out with a counterclockwise angular velocity it will move left & pull B left. The speed will vary depending on the location & value you put the position vector at. v = w x r
3	B moves left with a varying speed. The speed varies sinusoidally with O.
4	As A rotates counterclockwise about gear O, B moves horizontally to the right at varying speed. While A is at the bottom of O, B's speed is slower, but when A is at the top of O, B's speed is faster.
5	As gear O moves to the left at a constant speed, it pushes the slider B to the right at a constant speed.
6	When the gear rotates counter clockwise, B slides back and forth on its track. since $\alpha = 0$ the velocity of B doesnt [sic] vary.
7	As O rotates CCW, and moves in -i direction B will follow it, move left, at a slower speed.
8	Gear O moves to the left pulling B along with a varying V. V will increase if the input W is increased
9	Gear O translates to the left while the slider at B has different speeds at each point due to the acceleration between the gears.

10	Gear O moves in k [ccw] direction. Point A rotates with Gear O. As gear moves to the left, B is pulled along from rod. Velocity of B depends on location of A. When A is at (i,O) position, VB is slowest (to the left). When A is at (-i,O), VB is vastest (to the left). B only moves in the horizontal direction to the left.
11	The gear rotates in a counterclockwise direction, which causes A's position to vary with time. This variation of A's position causes the speed of B to change drastically over the course of time, as it will have a period of motion similar to a sine wave.
12	The speed of B is varying based on the position of the gear. As gear O rotates counter clockwise, gear B is pushed farther away. it is farther away from the gear when A is at the top of the gear. As rotation continues, B moves closer to O once more. Overall, B moves left.
13	Speed at B is constant to the left
14	VB will be constant to the left
15	As the gear moves from left to right, in a constant motion, B moves in the opposite direction from Right to left. In relation to O, B is moving at a constant speed.
16	As O moves to the left B also moves leftward but at a varying speed. Point A rotates around point O, its circular motion causes a sinusoidal like velocity for B. B slows almost to a stop when A is below O and is moveing [sic] quickly when A is above O.
17	As the gear spins Counterclockwise Point A begins to move Counterclockwise which causes B to move to the left with a constant speed.
18	Speed constant. B moves to the left.
19	As gear "O" rotates in the positive k direction the velocity of its center moves left in negative i at constant velocity. At the instant shown structure AB is being pushed to the right giving it a negative angular velocity in +k. The structure at B is in turn pushed right in positive i. All w & v constant.
20	Gear rotates as it follows gear rack. Link A moves with gear, which moves B, which moves B, which is constrained to only horizontal motion. B: constant speed to the left.
21	The speed is going leftward at a varying pace. It varies because point A is not located at the center of the gear, or point O. Because of this, rotational motion cannot be the same as the gear rotates 360˚, and therefore varies.
22	<- Vo so VB <- less than Vo as O rotates, point a rotates and so does AB, slower than D. as AB rotates, B moves to the left.
23	If gear O is rotating counter clockwise, the structure B will move to the right. It will be decellerating [sic] at [sic] O continues to rotate at a constant speed until it changes direction where it will then begin to move to the left.

24	Structure B moves to the right with a positive acceleration. Structure B will move with higher velocity when the angle between the bar and the link is smaller.
25	B moves to the left. The speed varies. The speed is slowest as the pin A is on the bottom half of the circle. [there is a drawing illustrating how speed is slowest when A is on the bottom half of O, and fastest when it is on the top half]
26	the point moves to the left at constant velocity and B alternates between moving faster and slower than O.
27	Gear O rotates at a constent [sic] angular velocity of 6 rad/s and translates to the left. At the position shown B is travelling [sic] to the left with an accelleration [sic] to the right. The speed of B will vary depending on where gear O is in its rotation and translation.
28	B will vary between 0 speed and moving to the left. At the moment shown, the speed of b would be close to 0.
29	The structure at B is moving at varying speed to the left. The motion begins slow but speeds up as the gear rolls.
30	The gear and B will both move left. Speed of O will be constant, but speed of B will vary. When A is moving from bottom to top counterclockwise, B will move slowly. When A moves from top to bottom, B will move very quickly left.
31	B moves left at a varying speed. When A is near the bottom of the gear it will move more slowly the [sic] speed up as A approaches the top of the gear.
32	B moves to the left constantly, but accelerates and decelerates to a stop. When A is at the bottom, VB=0, when it is at the top, VB is max.
33	As the gear turns, the arm AB moves to the right at a constant speed. (If the arm was connected at O, it would move to the left.)
34	As O rotates, the lever arm comes up and pushes B. The relationship is not linear though, if O moves to the right, B will accelerate rightward, then deccelerate thus decreasing its rightward velocity. Similaryly [sic] if O moves to the left, B will accelerate, then deccelerate depend on : the radius of O, the radius of A, the speed of O, and the length AB.
35	As gear O is rotating counter clockwise, the bar AB swings and slides back and forth to the right then left. B's motion will be entirely translational in the x direction, accelerating, then decelerating.
36	The structure at B has varying velocity in the left direction. As the gear rotates counterclockwise, the structure at B receives varying pushes and pulls as the piston AB rotates.
37	As the gear rotates to the left at this instant B will slide to the right however as the gear continues to rotate B will start moving again to the left. The input speed and the other speed vary proportionally.

38	Since O has a constant W and isn't accelerating, B is going to move left since the joint AB will move left as a whole as well. The W at 0 and A can be related and then VB can be found using θ.
39	The structure at B will move to the left at a speed that varies with the location of point A in the circle. This machine will break after only a few rotations.
40	B is moving left with a varying velocity. as point A gets higher, B moves faster.
41	The machine moves to the left with varying speed. The average speed of B increases with an increase in the angular speed of gear O.
42	B moves left at a non-constant speed that varies with the angular position of the gear
43	B will move to the right. It's speed will be constant because $\alpha o = 0$.
44	B moves to the right, then left based on the position of A on the gear, and how far O has moved left.
45	Gear A turns along platform (Vo to the left). Rider B move along shaft, following same direction as O. B moves faster than gear.
46	The structure B moves to the left as A rotates at a constant rate.
47	As the gear turns constantly, the slider B moves left with accelerating pace.
48	The gear is rotating to the left at a constant speed. Collar B is sliding to the left at a constant speed.
49	When gear O rotates counterclockwise and the angle is 60˚, the slider B will be at minimal velocity to the left. The velocity of B will be greatest when point C is located at point D [the leftmost point on the circumference of gear O]. Rack & pinion
50	The gear "O" will cause the arm to rotate in the same direction as the gear and the pinion B will be moved to the left as the gear is rotated counter clockwise. The change in speed will result in faster rotation and translation of gear O, arm AB, and B. B can only move horizontally.
51	At the instant B will move to the right horizontally as A moves CW. B speed will increase when A moves upward & CW.
52	At the instant shown, B is moving to the right. Speed of B varies, with maximums where B is in the middle and minimums when B is at the far left or right.
53	If O spins at a constant angular velocity counterclockwise as shown, B will move to the left with varying speed. The speed will vary depending upon where point A is with respect to point O.
54	The gear moves counter clockwise + B moves to the right both at angular constant or constant speed, respectively.
55	left speed varies as a function of sin

56	The structure B moves to the left at a varying speed which depends on the angle.
57	When gear O rotates CCW, the link at A revolves around O. this revolution pushes the slider B back and forth horizontally. Even if O is spun at a constant velocity, slider B will be accelerating & decelerating each time it changes direction.
58	B has constant speed to the left.
59	This machine works by turning constant rotational energy of the gear into varied translational motion at B, going to the left. The speed at point B would vary over time, most likely sinusoidally with respect to the gear.
60	B will have a relationship with O in this picture as B is moved to the left. O will rotate counter clockwise and move left as well. The faster B is moved, the faster O will rotate and move.
61	B moves left with varying speed based on the relative location of A with respect to O.
62	at this time, the gear rotates which causes the connection beam AB to have a radial velocity WAB, this pushes B to the right horizontally and when A is directly above O, the movement will stop for an instant then B will change direction. Movement is not constant, depends on A position in relation to O.
63	As the gear moves from left to right in a constent [sic] motion the arm connecting A to B begins to move in the opposite direction causing the collar at B to slide along the Bar. Therefore no acceleration will occur due to the constent [sic] motion of the gear.
64	The speed at B is varying based on the rotation of the gear. As the gear rotates counter clockwise, B will initially move right, then to the left after A passes the top of the gear. Speed varies based on position of gear. e.g. VB = 0 when point A is directly above point O.
65	B: moving right at varying speed that is decreasing so that B will move left after A is on top of the gear.
66	As O rotates, shaft AB moves at a varying speed. Structure B moves left and right depending on the point A is located at due to the rotation of O. The structure will move right now for a time until it reaches the 90˚ point, at which it will begin to move left once more. The speed of B varies with the point at which A is in terms of the rotation, as it is higher when A is closer to the shaft, but also slows down at 90˚.
67	The Gear rotates counterclockwise and moves to the left. The structure at B also moves to the left but the speed varies with where A is.

68	B slides along the shaft in a horizontal motion. As A rotates counterclockwise B slides right and as A rotates to the top of the gear, B approaches the far right most point of its path. When A rotates down from its top most point B slides left until A reaches its initial point again. Velocity in B is constant translational motion.
69	B moves to the left at constant speed.
70	As gear O rotates at constant Wo, the gear moves left on the flat teeth, moving A up and to the right. This causes B to first move right at constant velocity before being pulled left as gear O moves along the teeth.

Question 4: Geneva Mechanism

ID	Student Answer
1	As B rotates clockwise, this causes A to rotate counterclockwise. The velocity of A is intermittent and only rotates, on average, 1/6 of a rotation for every rotation of B. This is due to the pin sliding in the slot rotating the wheel then sliding out again. This creates a slower "ticking" of the star wheel clockwise [sic].
2	This machine lets the wheel do a 1/6th revolution. It moves to star by allowing P to go in to the groove in order to push it around. The structure will move counterclockwise with a clockwise angular velocity. The speed varies depending on the location being used.
3	The star wheel A turns CCW w/ varying angular velocity. The star wheel turns 60˚ for each complete rotation of B.
4	As B rotates clockwise at a constant speed, star wheel A rotates in a counter clockwise direction at varying speeds. Star wheel A moves when P slides into the slot, but it is motionless as P then revolves around the rest of B.
5	As the driving wheel B rotates at constant velocity, the star wheel A rotates every 1/6, or when driving wheel B makes one full rotation, star wheel A makes 1/6 a rotation counterclockwise.
6	As B rotates clockwise, A rotates counterclockwise. The machine works in the following way. The pin P slides into the slot, then slides into one of the 6 slots on A and slides out and locks it. [something] that position and the process repeats itself again. There is no acceleration in the system. A rotates with constant speed.
7	rotor' with 6:1 ratio, P goes in towards O, allowing B to rotate around to the next 'chink'. The speed is 6:1 where O is moving faster as b can only move when P goes in one of the gaps. O:ccw, B:cw, P:cw

8	B rotates clockwise, as pin P enters the slot causing A to rotate counterclockwise. When the pin leaves the slot, B continues to rotate until P enters the next slot. WA will vary directly with WB.
9	B is turned with some W and the pin at P comes in contact with the wheel at A turning it at a changing speed determined at the angle.
10	B, C, + P all rotate in -k [cw] direction. Angular speed is constant at A. WA < WB.
11	As the driving wheel B rotates, the pin P will slide into a slot and rotate the star wheel until the pin is on the other side of B and comes out of the slot, whereupon further rotation of B starts the process over. The speed of A changes greatly, and is periodic in the shape of a plateau, with speeds a 0 + WB
12	Star wheel moves counterclockwise with varying speed. The speed is intermittent, speed is zero until the pin goes in the slot and then slower than the rotation of B while it is in the slot.
13	Star wheel A moves counterclockwise at varying speed. A moves 1/6 a revolution for each of B's revolutions. The wheel A only moves while the pin P is in a slot.
14	A will rotate CCW at various speed in relation to position of pin P and wheel BC to pin wheel A. When BC-P is not [something] A then WA will be 0
15	The driving wheel rotates in a clockwise direction at a constant speed as the star wheel rotates in a clockwise direction at a constant speed, causing Pin P to drop. Because B and A are in contact they have the same speed.
16	Point P rotates around B, it enters the groves [sic] of A and spins it 1/6th of a rotation CCW each time P makes one full rotation.
17	The "gear" at B spins clockwise with a constant velocity. Eventually the pin will enter the slot and cause the star wheel to move 90˚ and then exit to repeat the process Wheel A has varying speed moves clockwise. the speed will be the same when its moving.
18	P pushes star wheel in counterclockwise direction. Velocity increases as P enters notch, constant when P is fully in notch and decreasing when P is exiting notch.
19	As wheel "B" turns the guide C and pin P drive the star gear in the positive k direction [based on previous answers, "positive k" = CCW]. WA is slower than WB and WB = WP because they are attached. All w & v constant.
20	As pin P enters and leaves star wheel, wheel is turned. When P leaves wheel, no rotation. A: varying rotation in ccw direction. Speed is a maximum when the pin (P) is in the grooves of the star wheel. There is no speed when the pin leaves the grooves (-π/6 -> 5π/6)
21	The star wheel will be moving counterclockwise at a constant speed. Speed will be slower than the rotational speed of the driving wheel.

22	A rotates CW at Constant rate less than WB. Pin P moves down each slot until it pushes on the bottom of the slot, spinning A.
23	A constant angular velocity in the driving wheel B will cause the star wheel A to rotate. A will begin to rotate when the pin enters a groove and will move with constant angular velocity until the pin exits the groove on the opposite side. It will then be stationary until the pin completes another rotation about B.
24	Point P slides into and out of the slots of the geneva gear A, causing it to periodically rotate. the periodic rotations occur at a lower angular velocity than the constant driving rotation of wheel B.
25	Star wheel A moves counter clockwise. The speed varies. There is time when it does not rotate followed by a brief rotation to the next star divet in the wheel.
26	B moves clockwise at a constant speed. A makes 1/6 of a revolution for every turn of B. When the pin begins to touch A accelerates to its max angular velocity then decelerates as P moves past the midpoint of A.
27	Wheel B turns with constant angular velocity 4 rad/s. When pin C catches a slot on A A is turned with a rising then falling angular velocity < 4 rad/s. When Pin C leaves the slot A will be motionless while pin C rotates around to catch the next slot.
28	right after the moment shown, A would increase angular velocity ccw until P is in its lowest position. At that point WA would decrease to 0 and remain at 0 until P engages the next slot.
29	The star wheel is moving counterclockwise. It moves at varying speed when the pin, P, is engaged in the slot. After it leaves the slot / the star wheel has made a sixth of a full rotation, the star wheel remains motionless until [sic] the pin rotates back to the slot on the other side
30	A will rotate in a step-like manner as B turns, from the time P enters the groove until it leaves. A will rotate slowly when P is near the edge of the groove, and quickly when it's towards the center.
31	The star gear move at varying speeds in the counter clockwise direction.
32	A moves counter clockwise intermittently. It moves 60˚ counter clockwise, and W first increases until it has rotated 30˚, then decreases to zero until P is back to where it is above.
33	The star wheel rotates counterclockwise at varying speeds. As the guide C rotates clockwise, the pin P moves the star wheel counterclockwise until the pin exits the slot & the guide completes a revolution before repeating the process.

34	As B rotates clockwise, A rotates counterclockwise. The pin P, rotating with B, enters the groove of A and pushes A to rotate as P rotates. A has rotational acceleration because as P moves along the groove, it is reducing the effective radius about which A rotates. Thus, at the moment shown, A is rotating slower than B but it will soon rotate faster.
35	As B rotates clockwise, A rotates counter clockwise with periodic motion. rotating 1/6th every time B makes 1 revolution.
36	As B is rotated clockwise the star wheel is rotated counterclockwise at varying speed with intermittent stops every [sic] between the time that P is not in the slots of the star wheel.
37	As B rotates constantly it causes the pin at P to move and when it moves far enough the gear A will rotate a sixth of a turn. A rotates counterclockwise with a varying speed. Rotation of A is slower than driving wheel B.
38	WB forces B to rotate which in turn forces P into the slot which turns A opposite as B. B moves without an acceleration, but P forces A to accelerate rapidly and then be stationary for the rest of the cycle.
39	The star wheel A makes 1/6 of a rotation counterclockwise with each full rotation of B. A makes 1/6 of a rotation in the time it takes B to move the pin down the slow and is motionless the rest of the time.
40	for each full revolution of B, A rotates 60˚. It has a varying speed, where V=0 when P is not in contact with A, and V is max when P is closest to the center of A.
41	A moves counterclockwise with varying velocity. When the ball is slotted, the angular speeds are equal but opposite in direction.
42	The star wheel moves with intermittent motion when the peg comes around. It is non-constant: slow, fast, and then slow.
43	A will move counterclockwisely. Its speed is constant. It's slower than the rotational speed of B.
44	As pin P rotates about B, A does not turn until P reaches the slot. When in the slot P pushes A 1/6 of a revolution before exiting. A rotates counterclockwise. When rotating the speed will be less than driving wheel B.
45	No motion until P reaches bottom of slot, then machine turns to the next gap; periodic motion.
46	The star wheel A moves in a counterclockwise direction as the driving wheel B rotates. A moves at a constant speed that is slower than the driving wheel B.
47	As the driving gear turns and P is in the slot, the other star wheel turns at a slower angular velocity in the counterclockwise direction. the star gear is stationary when P is not in a slot.
48	The wheel B is rotating clockwise at a constant speed. The pin P is sliding into the slot at a speed equal to velocity of wheel B. When pin P reaches the bottom of the slot, the star wheel rotates at a constant speed.

49	This assembly transforms constant angular velocity from B to intermittent angular velocity at A. A will make 1/6 of a rotation for every full rotation of B. When B rotates clockwise and Pin P makes contact with a slot in A, the pin will accelerate A counterclockwise until it exits at point D, whence motion of A will cease until the pin enters the next slot. Geneva wheel
50	The Geneva gear operates by having the wheel B spins [sic] in a direction and have pin "P" slide into one of the slots in wheel A in order to move wheel A forward a fraction fo a full rotation. The number of slots will indicate how much wheel A will rotate for one full revolution of B. This particular scenario says that wheel B will be spinning clockwise @ 4 r/s and wheel A will rotate 1/6 of a rotation (CounterClockwise).
51	A rotates CCW w/ varying speed. It will accel & turn when B shoves P down into the groove. But then A will stop rotating until P completes one revolution. Overall, the speed of B will be slower than B [sic].
52	A moves counter clockwise, varying speed (only moves when P is in a groove). A makes one full revolution for every 6 revolutions of B.
53	If wheel B rotates at a constant angular velocity clockwise as shown, star wheel A will rotate counterclockwise with varying speed. When P is engaged in one of the slots on A, the star wheel will speed up in its rotation until $\theta=0$, then slow down until $\theta=-30^\circ$, at which time P will disengage and star wheel A will stop rotating until P re-engages with another slot in A.
54	Clockwise with constant speed at B + constant speed at C/P that is faster than the speed of B.
55	counterclockwise varying speed, star only moves when peg is in groove
56	Star wheel A moves counterclockwise at a speed that goes to zero when pin P is not engaged with the star wheel.
57	If B is spinning with a constant velocity CW, P will rotate around B & slide in & out of the slots of A, pushing it CCW. Since there are times when P is sliding and not actually putting force on the wheel A, the speed of A will vary.
58	A will have varying speed counterclockwise. It speeds up when pin P is touching it + stops when its taken away.
59	This machine works by turning constant rotational motion into staggered rotational motion. The star wheel would rotate counterclockwise in an average speed of 1/6 that of WB. At the completion of 1 turn at B, A would rotate 1/6 of 360 or 60˚.
60	As B is rotated clockwise, the entire structure should rotate w/ it. If the speed is constant the rotational speed should be lower.
61	A moves intermittently CCW, completing one rotation for every 6 rotations of B. The speed within each sixth rotation starts at O, peaks when $\theta=0$, and returns to zero.

62	P rotates A in intervals by entering slot and moving to the opposite side. [curved arrow indicating cw rotation] then when P leaves the slot, A is non moving until P enters the next slot after travelling around B [curved arrow indicating cw rotation]. A rotates counter clockwise.
63	During this process the driving wheel rotates clockwise to the star. As the star wheel moves it rotates in a constent [sic] speed until it reaches a hole for the pin P to slide in. At this point no acceleration occurs until the pin P begins to move up the column again and the star wheel rotates in the counter clockwise direction.
64	The pin at P rotates the star wheel at 1/6 the angular velocity of rotating driving wheel B. As the driving wheel rotates, the pin is inserted into the slot, turning the star wheel along with the driver. Speed is constant in star wheel if it is constant in driving wheel. WA = WB / 6.
65	A: rotating counter clock at varying speed that is zero when P is outside of the slots or at the very bottom of the slot closest to A's center
66	As the wheel B rotates, star wheel A rotates counterclockwise as pin P slides into the slot in A. This causes a varied velocity, where the velocity is greater as the pin slides toward the center of A.
67	B rotates clockwise and as it does, P goes down into the slot. When it reaches the bottom it comes back up because B is still rotating. The speed of the star varies, faster when the pin is all the way in the slot.
68	WB allows the wheel to rotate around pin P, forcing the pin down toward the center of A with constant velocity. The pin then rises around B to come to a similar position. As this process takes place, A rotates counter clockwise with constant angular velocity but if the angular speed of the wheel B changes so will A. If the direction of B changes, the angular velocity of A will change and be opposite to that of B.
69	A moves anticlockwise at varying speed - the driving wheel B moves at a varying speed [therefore] A also varies. WA slower than WB
70	The gear A will rotate counterclockwise 1/6 of a rotation every time B makes one full rotation. As the Pin P moves in and out of the slots, the gear A is motionless until forced to make the 1/6 rotation.

Question 5: Planetary Gear Set (Ring Driven)

ID	Student Answer
1	As R rotates, it causes the planet gears to rotate counterclockwise which, in turn, cause the shaft A to rotate counterclockwise. This is because the gear S is fixed. A will rotate with a constant velocity that is counter clockwise and faster than R.

2	If the inner gear S is held motionless then the outer gear is given a counter clockwise rotation, A will move in a clockwise motion with a constant speed that is faster than R because the radius is smaller.
3	A has a constant CCW angular velocity. WA < WR
4	As R rotates in the counterclockwise direction at a constant speed, A moves at a constant but slower speed in the clockwise direction.
5	As outer gear R rotates with constant angular velocity, the two smaller gears will rotate at a constant faster rate than R and the structure A will rotate at a constant rate slower than the little gears and counterclockwise
6	When S is held motionless, because the outer ring gear is rotating counter clockwise, the planetary gears rotate clockwise and thus A rotates clockwise. The speed is faster than gear R.
7	R is CCW, P is CW, A would also be CW, and slower than P
8	Planetary gears rotate counterclockwise, causing A to rotate counterclockwise. The WA varies directly with WR.
9	Outer ring gear R moves with some W which rotates P at a continuous rate but quicker than WR. Crank A then rotates clockwise.
10	R moves in k [ccw] direction. Gears P move in k direction. Structure at A turns in -k [cw] direction. WA is constant. WA > WR. [arrows drawn indicating ccw rotation of P gears, cw rotation of A]
11	The rotation of R will cause the P gears to rotate counter-clockwise (opposite of R). Since A is attached to the P wheels, it too will rotate counterclockwise but at a much slower rate than the wheel R.
12	If gear S is held motionless, the rotation of gear R will cause counterclockwise rotation of A that is at the same speed as R.
13	Structure A has constant counterclockwise speed faster than the speed of the outer ring R
14	A will rotate CCW at constant speed. It will be faster than Wr
15	R is rotating in a counter clockwise direction. P is also rotating at a constant speed in the counter clockwise direction. A is then turning as P turns, thus having the same speed.
16	The CCW rotation of R makes P move around S in a CCW manner as well. This makes A move CCW at a constant speed faster then [sic] that of R.
17	As ring R rotates that causes the planetary gears to move clockwise and the shaft to move clockwise. Speed is constant and less than the speed of R.
18	Structure A turns clockwise at a constant speed higher than that of Structure R.
19	As R turns counter clockwise the planet gears are turned clockwise. Because S is not turning the planet gears turn about the axis of the structure clockwise which in turn rotates structure A about the axis clockwise. All w & v constant.

20	R rotates, turns P gears, P gears turn gear S. A: constant cw speed, slower than WR. [curved arrows drawn on P gears, curved arrow indicating cw rotation of planet carrier and shaft A]
21	Structure A will rotate clockwise at a constant speed. The speed is constantly faster than the speed of gear R.
22	A Rotates CW with Constant W. WA will increase with increase in WR. P Rotates CW which pulls A to rotate CW.
23	With S help [sic] motionless, structure A will rotate counter clockwise. The velocity of A will be equal to the velocity of the outer gear R.
24	Structure A will rotate clockwise at a constant angular velocity, which is lower than that of gear R. The angular motion of the outer gear R is translated into angular motion of the planet gears, which then causes structure A to rotate. [circular arrows shown indicating cw rotation of P gears, cw translation of P gears about S, ccw rotation of R]
25	Gear P would move clockwise which would turn A clockwise. Speed is constant and the rotational speeds of the outer gear R and the structure at A are the same.
26	R moves counter clockwise at a constant angular velocity causing P to move counter clockwise about S. the angular velocity of A is more than R.
27	When R rotates at constant WR and Ws = 0 A will rotate counter clock wise with a constant angular velocity > WR.
28	A would move at constant rotational velocity CCW, at a rate slower than WR.
29	The structure at A will rotate counter clockwise at a constant speed that is less than the angular velocity of R. [arrow drawn indicating ccw rotation of A]
30	P will rotate counterclockwise at well at [sic] a constant speed, and A will also rotate at a constant speed, but at a smaller speed than R.
31	A is going to move counter clockwise at a constant speed slower than WR [arrows drawn on P indicating ccw translation about S]
32	Output A rotates counter clockwise with a speed lower than gear R. This speed is constant.
33	The outer gear rotates counterclockwise, which turns P & B [the second P gear] counterclockwise (if S is allowed to rotate) and turns S clockwise (if S can move, otherwise gears P & B would jam). A moves counterclockwise too. The speed of P & B is the same as that of R. [curved arrows drawn on P gears indicating ccw rotation, curved arrow indicating ccw rotation of A, curved arrow indicating cw rotation of S]

34	"-If R rotates counterclockwise, then P rotates counterclockwise and thus A rotates counterclockwise. - If R rotates with constant speed, the [sic] A rotates with constant speed. The vice versa is true if R rotates with varying speed. -The rotational speed of A will be less than the rotational speed of R. -As R rotates, it pushes (and thus rotate) the P gears, which are rigidly attached to A so A rotates as well.
35	As R rotates counter clockwise, the planetary gears move around S counter clockwise, rotating the same speed as r. This turns A at a slower speed counterclockwise.
36	A rotates counterclockwise at constant angular velocity that is the same as WR. [arrows drawn indicating ccw rotation of P]
37	The gear P will rotate counter clockwise causing A to rotate counterclockwise at a speed faster than the rotational speed of R, but it will be constant.
38	Relatively the same as the other problem like this except the outer gear R moves at a slower W than A, but in the same direction.
39	The ring R rotates counter clockwise which leads to a constant clockwise rotation of the planetary gears and the structure at A.
40	"a" rotates counterclockwise (same direction as R) at a slower speed (constant velocity).
41	The angular speed of A equals the angular speed of R. It turns CCW.
42	A will rotate anticlockwise with a constant speed faster than R
43	A will rotate with the same speed as R counterclockwisely.
44	As R rotates counter clockwise, the planet gears rotate counter clockwise, causing them to force A to rotate counter clockwise. The WA will be larger than WR, at a constant rate.
45	S doent [sic] move therefore nothg [sic] moves. Motionless.
46	Structure A moves in a clockwise direction as R rotates and moves at a constant speed that is the same as R's speed.
47	As the outer gear turns counter clockwise, the planetary gears orbit counter clockwise and rotate clockwise. The [something] center axle turns counterclockwise at a slower angular velocity.
48	The gear R is rotating counterclockwise at a constant speed. The planetary gears are rotating clockwise at a constant speed. The sun gear S is not moving.
49	When sun gear S is held motionless and ring gear R is rotated counterclockwise, planetary carrier C will rotate counterclockwise at a faster rate than R. If A is attached to C, it will rotate with the same angular velocity. If it is attached via a bearing it will not rotate. Planetary Gear, hybrid vehicle [drawn arrows indicate ccw rotation of P, ccw rotation of planet carrier, ccw rotation of A]

50	In this scenario, both the sun and ring gears are rotating counterclockwise @ Ws and Wr respectively and the speed is constant. If two speeds are equal, the the [sic] planet gears will stay in one place, if they are different, then the planet gears will turn in either direction (depending on which gear is faster).
51	R will turn CCW at a slower speed than A but the speed will be constant.
52	A moves counterclockwise, constant speed, faster than WR.
53	If R rotates as shown and S is motionless, A will rotate in a counterclockwise direction with a constant angular velocity slower than that of R.
54	Counter clockwise motion with constant speed + S having a slower speed than WR.
55	faster constant speed clockwise
56	The structure A moves counter clockwise at a constant speed faster than gear R.
57	If R is spun at constant velocity CCW, gears P will spin CCW. This will cause them to move around S slower than R is spinning, but in the same direction as R. A will then spin CCW too, but faster than R.
58	Structure A will have a constant speed of the same magnitude of R also counterclockwise.
59	This is the same type of machine as in R2 except the drive is on the outer ring. A still rotates counterclockwise. The speed will vary proportionally to WR + will remain constant.
60	As A rotates clockwise, and inner gear S is held motionless, only the outer gear R will rotate.
61	A moves in a counter clockwise direction at constant speed slower than WR. [arrows drawn indicating ccw rotation of P, ccw translation of P axes, ccw rotation of A]
62	When S is motionless, velocity of the outer gear r rotates in a counter clockwise direction which causes the planetary gears to rotate counterclockwise as well around the sun gear. WA is still constant, but is slower than the input radial velocity.
63	If the gear S is held motionless, then the two planatery [sic] gears would not move nor would the structure at A. The gear at R would rotate around the inner structure at a constent [sic] velocity. The speed will be slower than R due to the resistence [sic] of the gears.
64	When Ws = 0 and WR = c, the outer gear R rotates counter clockwise, causing gears P1 + P2 to rotates clockwise at the same angular velocity. This causes the gears P1 + P2 to rotate clockwise around stationary gear S. Speed is constant at A and the same as the speed of R.
65	A: rotate clockwise at constant speed that is faster than r [curved arrows drawn indicating ccw rotation of P gears, curved arrows drawn cw on face of S gear]

66	With the inner gear held motionless, gear P rotates counterclockwise as well. This causes shaft A to rotate at a constant speed in the counterclockwise direction. [arrows drawn indicating ccw rotation of P, ccw rotation of planet carrier]
67	If S is held still and only R moves. P will rotate with R in the counterclockwise direction. The speed is constant. A also moves counterclockwise with the same velocity as R.
68	When R rotates counterclockwise, gear P will rotate clockwise about its axis at a constant angular velocity, so long as R is not accelerating. Gear P will be rotating with a faster angular velocity than R. A will rotate clockwise along its axis and the speed will be constant. Shaft A will have a larger angular velocity than R.
69	Clockwise, same speed as R, constant
70	As WR rotates CCW, the system will move CW, so A will rotate clockwise with a constant speed greater than that of WR.

Question 6: Quick-return Mechanism

ID	Student Answer
1	As A rotates, it causes B to slide up and down the slot in CD. This causes CD to rotate to the left (counter clockwise) and stop then move back to the right (clockwise) this is then repeated in a cyclic fashion. The speed is varying depending on the angle of A and the rotation of CD is slower than that of A.
2	C is rotated & while it rotates counterclockwise A also goes counterclockwise but faster since the radius is smaller. BD distance will slide with the various movements.
3	Link CD has an angular velocity which varies sinusoidally with the input. It goes left & right like a metronome.
4	As AB rotates counterclockwise, CD also rotates counterclockwise but at a varying speed. As B moves closer to D, the rotational speed of CD starts to decrease.
5	As crank AB rotates at a constant angular velocity, slide block B will move slotted link CD counterclockwise at a slower rate than itself.
6	As AB rotates, B slides up and down in CD. And at the same time. The rotation of AB causes CD to rotate. CD rotates counterclockwise. The rotational speed is less that [sic] AB.
7	As AB turns CCW, B moves towards D until CD passes the 90° mark then D will start to move towards C than [sic] switch again @ 270°. Speed is varying depending on placement of B.

8	AB rotates counterclockwise causing CD to rotate with a smaller W then that of AB. WCB varies with the position of AB
9	When link CD rotates the slider at B moves up or down depending on the direction and θ. Arm AB moves in relation to B in the track.
10	As rod AB rotates in k [ccw] direction, rod CD rotates left + right, back + forth. rod CD is at its rightmost position when r(B/A) = i,O. [rod CD is at its] leftmost position when r(B/A) = -i,O. Speed of CD varies - max when r(B/A) = 0,j. min when r(B/A) = +/- i,0. At its max, WCD is still lower then WAB.
11	The rotation of AB will cause the slotted link CD to rotate as well, but at a much slower rate. The speed of rotation of CD will vary as the link CD + AB aren't always tangential in their paths.
12	The speed of CD varies and is counterclockwise. The speed is slowest when crank ab is straight up and when AB is horizontal. As crank AB goes around, link CD moves back and forth.
13	Link CD moves counterclockwise at a constant speed slower than the crank AB
14	CD will rotate up w/ constant speed.
15	C rotates in a counter clockwise direction, at a constant speed. As AB is cranked B will slide down the slot. CD is moving slower than CD [sic].
16	CD oscilates [sic] back and forth at a constant speed slower then [sic] that of AB as the slider link pulls and then pushes it back and forth.
17	As C moves left the slider B will move upward until crank AB is perfectly vertical at which case as CD continues to swing left the block at B will move down. Link CD constant velocity to CD's constant velocity Speed is faster than.
18	Slotted link CD rotates counter clockwise at a decreasing speed on the way up and increasing speed on the way down ie the close [sic] B is to D the slower the rotational motion
19	As crank AB turns counterclockwise slider block B travels through slot CD. This also drives link CD counter clockwise. WCD > WAB. Block B must have acceleration because its velocity is not constant.
20	AB rotates, which moves B. B is fit into slot, which moves and moves arm CD. CD: The slotted link has a varying speed in the CCW direction. The speed varies due to an acceleration caused by the relative rotational motion of crank AB.
21	The speed of link CD will be counterclockwise and vary, because sliding block B is only allowed to move in the j direction on the written coordinate system [there is a 2D Cartesian coordinate system drawn at B, where y is parallel with CD and points up towards D, x goes to the right of y axis]
22	CD Rotates CW at Constant W. CD Rotates at the same W as AB

23	The velocity of CD will be less than the velocity of the crank AB and will be in the counterclockwise direction. The speed will change as the crank AB rotates further and will decrease.
24	The counterclockwise rotation of link A forces point B up the slider block, causing it to rotate counter clockwise as well. The link CD undergoes angular deceleration as it travels.
25	Slotted link CD moves counterclockwise. Speed does not vary. Speed of link CD in relation to the input has a slower rotational speed. [there are lines drawn which appear to be the position of link CD at 60 degrees and the corresponding position of AB, with an arrow indicating the trajectory of CD ccw]
26	AB rotates counterclockwise at a constant velocity causing CD to oscillate between left and right from its farthest point to either side it accelerates until A is lined up with CD then it decelerates back to 0. the arm AB always has a faster angular velocity then [sic] CD.
27	Given constant clockwise angular velocity of link AB slider block B will cause link CD to rotate counter clockwise while translating along the slot on CD towards D. At the moment shown CD is rotating CCW with increasing magnitude. The angular velocity of CD will increase till CD||AB. WCD always less than WAB.
28	WCD will be CCW slower than WAB at the instant shown. As AB turns, CD will rotate to the left, reaching a local max speed at θ=0˚. It will return to the right at a higher W than when it went left.
29	D rotates counterclockwise with a varying angular velocity. The angular velocity of CD increases as θ of AB increases.
30	CD will rotate counterclockwise, then clockwise, as AB rotates. The rotational speed will vary, and be sometimes slower and sometimes faster than AB.
31	CD will move at varying speeds in the counterclockwise direction while BA is rotating from 0˚ - 180˚ and clockwise from 180˚ - 360˚
32	CD moves back and forth about C. Its speed is varying. It is slower than AB.
33	The slotted link CD rotates counterclockwise at a constant speed if αc = αA = 0. If αc ≠ αA = 0, then the speed will vary. At a constant speed, CD would have a different speed as AB. At a varying speed, CD would have a different speed as AB. (they always have different speeds)
34	As AB rotates constantly, CD experiences first angular deceleration then angular acceleration such that their instantaneous angular velocities are not equal, but their angular velocities over time are. The same is true if AB experiences angular acceleration. The slider block B is moving up and down within CD as AB rotates and as it does so, it increases or decreases the effective radius about which CD rotates. Thus CD has angular acceleration and deceleration respectively. AB and CD rotate in the same direction.

35	As AB rotates to become vertical, CD will rotate counter clockwise to become less than vertical as well, with B sliding up CD. CD will then pivot back and forth with sinusoidal velocity as AB rotates, first moving left, then back right as AB finishes rotation. [there are drawings of the system at different points in time]
36	Slotted link CD rotates counterclockwise with varied angular velocity. The closer AB and CD are to being parellel [sic], the slower the W.
37	As AB rotates it causes CD to rotate at a varying speed and the speed depends on where AB is at in its rotation and how fast it is spinning
38	As A rotates, the piece at B forces CD to rotae the same direction as well. CD decreases α as θ gets closer to 90˚. After 90˚ CD Begins to accelerate left as θ gets farther from 90˚.
39	The angular velocity of CD is constant and counter clockwise.
40	Slot CD has a varying angular velocity, peaking when link AB is orthogonal to CD. CD rotates counter clockwise.
41	CD rotates CCW with varying angular velocity. The speed is less than AB when B is above A, and it is greater during the next quarter rotation.
42	CD will follow the rotation of AB with a non-constant speed varying with the position of B in the slot.
43	CD rotates counterclockwisely. Its speed varies depending on the angle between AB and CD.
44	As crank AB rotates counter clockwise at a small speed than AB, the speed varies as the direction of relative motion changes with the angle of the crank.
45	Speed is constant. rod AB moves CCW; B slides in Pin up' as B slides Up CD moves CCW much slower then AB.
46	Link CD rotates partially (not a full circle) in a counterclockwise direction. CD moves at a slower speed than AB that is constant.
47	The speed and acceleration of the slotted link will vary sinusoidally with the motion of the driving crank AB. Though CD will always have a slower rotational speed.
48	The arm AB is rotating counterclockwise at a constant speed. The arm CD is moving back and forth at a slower speed than AB.
49	Slider B transforms constant rotational motion into intermittent back and forth motion on CD. The velocity of CD is maximum when AB is vertical, and at a minimum when AB is horizontal. An application of this machine is filling a container with two different items from different hoppers and the linkage is used to alternate the feed system between the two. Metronome
50	As the arm CD is turned clockwise, the arm A will rotate clockwise and Block B will slide down the arm CD. If the arm CD is turned CClwise, the arm AB will rotate CClwise and Block B will rise up the arm CD. The arm AB will move at a relative velocity to arm CD.

51	Speed of CD will vary. The more vertical CD gets, the slower it rotates. CD will rotate CCW along w/ AB.
52	CD has varying speed as AB is turned. It is fastest when [perpendicular] to the ground (in the middle) and slowest when at the far left or right
53	Link CD will wave back and forth with varying speed. The angular velocity of CD will vary depending upon where AB is in its rotation. CD will be faster than AB when the angle is below the horizontal, and slower when AB is above the horizontal.
54	CD has constant speed moving to the Left + right + has a slower speed than that of AB
55	slower constant speed
56	The slotted link CD moves at a constant speed slower than that of crank AB
57	CD will move right & left about pin C as A rotates CCW. Its velocity & direction would therefore change throughout its motion.
58	CD will have varying speeds. As the angle at A gets closer to 90 it will slow down.
59	This machine works by turning rotational energy at AB into energy at CD. It basically just moves in a waving motion. The speed varies proportionally with the input velocity.
60	As crank AB goes counter clockwise CD will move upward to compensate.
61	CD alternates between counter clockwise and clockwise [rotation]. The speed of CD on the clockwise stroke is faster than the CCW stroke.
62	as CD rotates with some angular velocity, B slides along the slot which causes crank AB to rotate. The reverse can also be [something] with the input as AB rotational movement sliding the part B along the shaft. rotational velocity of CD is much lower than that of AB in this case. also the speed varies with the angle of AB.
63	As the link rotates at C in the counterclockwise direction the block at B slides up the slot in the link causing the crank at AB to rotate in the counter clockwise direction. No angular acceleration occurs at A and B due to the fact that CD link moves at a constant acceleration.
64	Speed of rotation at C will vary depending on the degree S of horizontal or vertical movement at B (Wc = sin(θ)WA or something). As A rotates, B rotates, sliding in CD up/down and left/right, moving bar CD with it as it rotates at point C.
65	CD: speed is varying and is slowest when AB is most horizontal.
66	As AB rotates, slotted link CD rotates as well with a fixed point C. It moves at a varying speed in the x and -x directions with the max occurring when AB is at 0˚ or 180˚

67	As AB rotates CD will shift from right to left then back, like windshield wipers. B will shift in the link, up and down. The speed of CD will vary depending on where B is.
68	B will slide freely between the open space in CD. As A rotates counterclockwise B will also rotate about A and force CD to rotate about C. As B approaches 180˚, the direction of motion of CD will change and CD will move in the opposite direction. At 180˚ CD will have completed half of a full cycle. CD should have a slower angular velocity than A. [curved arrows drawn indicating alternating motion of CD]
69	CD slides up and down while turning anticlockwise [something] point C. moves slower than AB, constant
70	As AB rotates, B moves up the slot, causing CD to rotate counterclockwise at a constant speed that is slower than AB

Appendix M: Posttest Multiple Choice Scores

Traditional Group

Treat	ID	Time	Spatial	Concept	Total	Spatial%	Concept%	Total%
T	1	0:39	6	13	19	67%	68%	68%
T	6	0:44	7	10	17	78%	53%	61%
T	8	0:19	8	10	18	89%	53%	64%
T	10	0:33	7	5	12	78%	26%	43%
T	18	0:22	8	12	20	89%	63%	71%
T	19	0:24	8	6	14	89%	32%	50%
T	21	0:20	7	5	12	78%	26%	43%
T	25	0:25	9	5	14	100%	26%	50%
T	27	0:15	7	17	24	78%	89%	86%
T	29	0:27	8	15	23	89%	79%	82%
T	33	0:20	6	9	15	67%	47%	54%
T	37	0:17	6	9	15	67%	47%	54%
T	41	0:18	9	12	21	100%	63%	75%
T	43	0:42	7	11	18	78%	58%	64%
T	44	0:23	9	11	20	100%	58%	71%
T	48	0:22	5	6	11	56%	32%	39%
T	51	0:21	5	6	11	56%	32%	39%
T	53	0:31	8	11	19	89%	58%	68%
T	54	0:28	7	3	10	78%	16%	36%
T	57	0:18	7	9	16	78%	47%	57%
T	61	0:21	8	17	25	89%	89%	89%
T	66	0:22	9	8	17	100%	42%	61%
T	67	0:22	7	4	11	78%	21%	39%
T	68	0:29	6	6	12	67%	32%	43%
T	69	0:18	5	9	14	56%	47%	50%
T	70	0:25	6	11	17	67%	58%	61%

Physical Group

Treat	ID	Time	Spatial	Concept	Total	Spatial%	Concept%	Total%
P	4	0:27	6	7	13	67%	37%	46%
P	5	0:37	6	3	9	67%	16%	32%
P	7	0:28	6	7	13	67%	37%	46%
P	11	0:17	4	7	11	44%	37%	39%
P	12	0:23	7	8	15	78%	42%	54%
P	13	0:25	7	8	15	78%	42%	54%
P	17	0:21	4	8	12	44%	42%	43%
P	23	0:23	8	10	18	89%	53%	64%
P	24	0:21	5	9	14	56%	47%	50%
P	26	0:25	8	12	20	89%	63%	71%
P	31	0:19	7	12	19	78%	63%	68%
P	32	0:18	6	13	19	67%	68%	68%
P	36	0:21	8	12	20	89%	63%	71%
P	40	0:19	7	10	17	78%	53%	61%
P	46	0:27	8	7	15	89%	37%	54%
P	50	0:33	7	7	14	78%	37%	50%
P	55	0:16	7	5	12	78%	26%	43%
P	56	0:30	8	7	15	89%	37%	54%
P	59	0:30	8	8	16	89%	42%	57%
P	60	0:13	3	8	11	33%	42%	39%
P	63	0:34	6	7	13	67%	37%	46%

Virtual Group

Treat	ID	Time	Spatial	Concept	Total	Spatial%	Concept%	Total%
V	2	0:25	5	6	11	56%	32%	39%
V	3	0:23	8	15	23	89%	79%	82%
V	9	0:18	5	10	15	56%	53%	54%
V	14	0:25	7	12	19	78%	63%	68%
V	15	0:28	5	7	12	56%	37%	43%
V	16	0:19	5	8	13	56%	42%	46%
V	20	0:24	7	10	17	78%	53%	61%
V	22	0:09	4	6	10	44%	32%	36%
V	28	0:27	9	13	22	100%	68%	79%
V	30	0:22	9	10	19	100%	53%	68%
V	34	0:25	6	12	18	67%	63%	64%
V	35	0:23	7	7	14	78%	37%	50%
V	38	0:14	4	3	7	44%	16%	25%
V	39	0:30	7	10	17	78%	53%	61%
V	42	0:16	8	11	19	89%	58%	68%
V	45	0:16	4	7	11	44%	37%	39%
V	47	0:22	8	16	24	89%	84%	86%
V	49	0:23	8	12	20	89%	63%	71%
V	52	0:26	7	12	19	78%	63%	68%
V	58	0:23	3	5	8	33%	26%	29%
V	62	0:25	7	9	16	78%	47%	57%
V	64	0:25	6	7	13	67%	37%	46%
V	65	0:28	8	8	16	89%	42%	57%

Appendix N: Opinion Questionnaire Responses

Q1 (Treatment Group), Q2 (Did the model help?), Q3 (How did model help/not?)

ID	Q1	Q2	Q3
1	T	Y	It would be very difficult to even know what they wanted if they described a mechanism I had never seen. By seeing this, it improves my understanding of how they connect and move together.
2	V	Y	I was able to see how the gears worked instead of the misconceptions I had before.
3	V	Y	It allowed us to determine the sense of velocities. It also helped me realize that sometimes velocities would be zero.
4	P	Y	It helped me by allowing me to see the motion of the model first hand instead of trying to visualize it in my head.
5	P	Y	The models at the very least helped me to see how the object moved and work toward a starting point.
6	T	Y	I figured it out quite easily. For the problem that had to do with the six sided big gear and a pin sliding in and out, I only figured it out because I had seen it on tv before. Otherwise I had no clue.
7	P	Y	We were able to see exactly how it worked, instead of assuming how.
8	T	Y	For most of the problems I was able to figure out the motion of the machine from the diagram. Some, the Geneva wheel specifically, were hard to visualize from the diagrams.
9	V	N	While the model made it more clear for me to understand the question for the questions that we did it made me more confused because things look like they were moving faster when they were slower or vise versa.
10	T	Y	I had a lot of trouble understanding the movement of some of the structures, even with someone explaining the movement. I would have better understood the problem had I been able to see how it moved through a virtual or physical model.
11	P	Y	It helped to see how the machine worked and the reactions b/w the components
12	P	Y	You could actually see and manipulate how the machine moved. This was especially helpful when I was unsure how the machine moved.
13	P	Y	It served as verification for my assumptions on how parts moved.

14	V	N	I think it gave me a notion of how the system would move, but not of the [something] relationship between velocity of different components of system.
15	V	Y	The model helped me understand how the object moved.
16	V	Y	A few of the models we didn't understand by the diagram and seeing it in motion helped.
17	P	Y	I was able to see the relationships between the parts of the model and use it to make reasonable guesses about what was going on (e.g. should be slower)
18	T	Y	A written description by itself would have been inadequate.
19	T	Y	Having a picture is useful but lacking information on all of the motion can be a hinderance [sic].
20	V	Y	The model helped me to understand the motion and interactions in more complex systems.
21	T	Y	It gave me a basic understanding of the machine but I was not 100%.
22	V	Y	Showed which parts do not move
23	P	N	I could usually picture what was happening without the model. Knowing the equations helped me solve.
24	P	Y	I had a hard time visualizing the geneva gear problem until I saw the model.
25	T	Y	Well, without the diagram, I would have been missing the ideas of how the parts relate to each other which is necessary for the calculations.
26	P	Y	1st it showed the motion. 2nd you could check relative velocities
27	T	Y	The diagram provides all numerical information necessary to solve the problem. For the most part I could visualize the motion of the diagram.
28	V	N	I can visualize the problem based on a diagram. The model does not help with applying equations.
29	T	Y	I [sic] helped in a limited way. It was challenging sometimes to picture in my head, for instance, how the speed of an object may vary at different points in its motion
30	V	Y	CAD model helped see how things moved, and at what relative speeds
31	P	Y	It gave a basic understanding of the mechanisms and gave a rough indication for what the answers should be.
32	P	Y	I could see and interact with the problem rather than just thinking about the problem.
33	T	Y	A visual aid is always helpful to understand the problem.

34	V	N	Can't explain, staring at a 3D image on a 2D screen doesn't activate the same neurons as a physical model.
35	V	N	Many times the CAD software has glitches which prevented the model from operating as it would in real life. Gears would skip or slide, and it was a pain. Most of the time could already tell what it was doing.
36	P	Y	Actually seeing how the model moves under certain inputs heightened my understanding.
37	T	Y	It helped me to see what was going on in the problem.
38	V	Y	It was very hands on and allowed me to visualize the movement that was produced.
39	V	N	The models did not work very well, my ability to visualize was not much improved.
40	P	N	It's nice to see a model of it, but it doesn't help me see relative velocities, etc.
41	T	Y	The diagram helped me see the dimensions and geometry of the problem but did not help me see how the machine worked.
42	V	Y	It allowed a clear representation of the sometimes complex motions of the problems.
43	T	Y	The diagram gives me some ideas how different parts are connected to each other.
44	T	N	While the diagram gave me the physical form of the object, it didn't help to convey how the pieces moved and worked together.
45	V	Y	Helped: Visualize the problem; understand the restrictions on the directions at certain velocities. Did not help: sometimes we assumed things that maybe weren't true ("A looks like o, let's go with that" "They look like they're going the same speed")
46	P	Y	The model helped by allowing me to visualize exactly how the device worked and see how moving/rotating the different components affected each part.
47	V	N	It confirmed my initial expectations for motion, but nothing more really.
48	T	N	It was difficult to visualize how the parts were moving.
49	V	Y	It gave a description of the system at a given instant.
50	P	Y	
51	T	Y	Gives me a visual to work w/ rather than imagining it myself
52	V	Y	Being able to visualize the relationships of the moving parts.
53	T	Y	Being able to see the mechanism helps me to visualize its motion in my head.

54	T	N	Visual person, I need to see or hold it in my hand to understand how it works.
55	P	N	I had trouble solving the problems.
56	P	Y	It helped me visualize how the machine worked and the directions that it moved.
57	T	Y	It helped to visualize & mark on the 2D picture, but it was very hard to determine exactly what the motion was in some cases (especially the star wheel & pin picture.
58	V	Y	I knew which way the motion was without doing the problem.
59	P	N	I already knew what most of the machines would look like before using the model.
60	P	Y	I was able to confirm how I thought the model should act before trying to solve a problem.
61	T	Y	I could look at it, better than a description.
62	V	Y	It helped me visualize the mechanism and observe the less [something]
63	P	Y	The model helped explain the motion of paticular [sic] pieces.
64	V	Y	The virtual model really helped me be able to visualize what was happening in the problem. It especially helped me understand the way different components interacted - particularly in the star wheel problem.
65	V	N	It could help sometimes but mostly it just messed up a lot!
66	T	Y	It helped as it gave at least a slight representation of the physical objects. However, it didn't help with the understanding of motion.
67	T	Y	It was an okay representation but for some of was harder. Couldn't tell constant vs. varying speed
68	T	N	Many times I had to imagine the figure moving to understand how to solve the problem.
69	T	Y	The diagram helped me get a visual for what the machine would look like stopped, but in some cases it was difficult to tell how it would move.
70	T		

Q4 (How could the model be improved?)

ID	Q1	Q4
1	T	Give either better shading/color coding and provide multiple views. Either a different angle or later in time.
2	V	I really liked the CAD model and couldn't find anything particularly wrong with it.
3	V	Real time measurements for angular velocity, acceleration, etc.
4	P	Make sure that it is better put together so that it doesn't get jammed while using it.
5	P	Clean them up a bit, some of the models were bulky which was sometimes a little confusing.
6	T	If we had a 3D model beside the 2D model.
7	P	I thought it was good, as long as it's to scale.
8	T	A more descriptive explanation of the motion might help the diagram.
9	V	The only problem was I relied too heavily on the model if only used for guidance to understand then they were great.
10	T	More detailed description of the motion.
11	P	Make the drawings more clear about the function of the machine.
12	P	More precise tolerances so the machine always moved as designed.
13	P	Smoother motion, less resistance.
14	V	Perhaps outputting the [other] numbers as well to give an idea not just how system moves, but how another different parts relate to each other.
15	V	Maybe explore other options for making the models. Inventor was sort of frustrating and some of the pieces didn't work correctly.
16	V	Nothing.
17	P	The model wasn't all that accurate and would get stuck or the gears weren't meshed together.
18	T	It could have [something] a written description of the components
19	T	Show all angular directions or enough within reason to determine all of the motion.
20	V	It was about as useful as it could have been aside from some constraint issues that made things ambiguous in a few cases.
21	T	I don't feel the diagram could be improved. Other resources should be introduced.
22	V	A start button with motion on a loop
23	P	The physical models were sometimes difficult to manipulate.
24	P	Increase the use of the model with other problems

25	T	Two different diagrams that somehow indicate the motion of the machine.
26	P	Tighten the tolerances
27	T	The diagrams could not be made better in an obvious way.
28	V	Label each component with v, a, w, x or any other variables and give the equation.
29	T	Not much. They are clearly labeled and easy to understand for the most part, but like I said ...[arrow drawn referring answer number 3]
30	V	Fix constraints so the model doesn't break
31	P	Higher tolerances because the model would get stuck.
32	P	Decrease tolerances so it functioned better.
33	T	Multiple diagrams (over time)
34	V	List real-time physical information (v,w,α, etc.) next to the model.
35	V	Use other software that doesn't have these shortcomings.
36	P	Make models more ideal. One model was too loose.
37	T	If there was more of an explanation of how the model moved.
38	V	I don't think there us much else to improve the virtual diagram.
39	V	Make something that is tangible and doesn't immediatelly [sic] break.
40	P	Have coloured markers on individual pieces to see the relative movement. [a drawn diagram]
41	T	I would have liked to see two pictures of different instances of the motion so I could understand how the machine worked.
42	V	Perhaps add a premade animation option that would run on loop so you could watch it more easily.
43	T	Diagrams of a series of instances showing how each parts move.
44	T	Show two pictures in a diagram, before movement, after movement
45	V	Not sure
46	P	Making them move more easily with less force would help.
47	V	Some of the models were very glitchy as if [something] could be fixed it would be better.
48	T	Describe the motions better.
49	V	Add additional images/diagrams showing various positions of components at different times.
50	P	
51	T	
52	V	Nothing comes to mind.

53	T	Some of the problems where the model was drawn in 2-d could have been made easier to understand if the model was drawn in 3-d or if there was another view.
54	T	3D version beforehand or multiple views.
55	P	More precise.
56	P	The gears could be colored differently to represent the direction they were moving in.
57	T	Draw the diagram in different stages of its cycle.
58	V	If it worked a little better.
59	P	Honestly it's the math (dynamics equations) that was tripping me up.
60	P	Possibly have labels on the model like the problem.
61	T	MORE LABELS!
62	V	Show numbers on the CAD ie. the w input and look at actual #'s outputted.
63	P	The models could have been made in a which where they didn't stick or they have a possibly crank on the back to move them.
64	V	The virtual model in CAD would "break" frequently when pushed too far. This could be confusing at times.
65	V	Make it not break
66	T	More movement indicators regarding direction and motion of particular parts or a second diagram later in time.
67	T	Say if it was constant or varying, have step by step drawings.
68	T	Creating an image of where the object should be in a 1/4 revolution or translation would help.
69	T	Provide one diagram for one point in time and another t time later.
70	T	

Q5 (What else would have helped?)

ID	Q1	Q5
1	T	Personally I prefer hands on so I believe a physical model. I know these are expensive so maybe origami version or showing multiple views in time as mentioned above.
2	V	I would've liked to see the physical model too and hear an explanation how each one worked some someone.
3	V	Perhaps a description in words of how the model works.
4	P	Equation sheet.
5	P	Better understanding of how the objects moved relative to one another.
6	T	

7	P	I've never been good @ these kinds of problems so they models already helped a lot, being able to move the gears and whatnot helped.
8	T	A short video of the 3D models might have been helpful. I'm sure the physical and virtual models would have helped had I been in those groups.
9	V	Once you know how the movement happens it is all up to the student to use the correct formulas.
10	T	A virtual or physical model or just someone explaining how the structures moved.
11	P	
12	P	A CAD model that moved would have eliminated some of the guesswork regarding what was a constant speed, etc.
13	P	Two pictures with reference points to serve as a before and after to understand the motion.
14	V	Must be a preset animation as well, were unrealistic bugs and movement due to inventor.
15	V	More problem solving --> spend lecture time on problem solving (i.e, have lecture on Tues. and Thurs. be devoted to problem solving).
16	V	Seeing the physical models.
17	P	An equation sheet.
18	T	Obviously I can't say for sure but I don't think using the model would have helped much. Comprehensive knowledge of the proper application of the formula is required.
19	T	A physical model.
20	V	A model (physical)
21	T	Any of the other resources so I could actually see the part move.
22	V	Step by step solution description in sync with a video of motion of the objects.
23	P	Labeling the different parts of the model would have helped.
24	P	
25	T	Actual physical models.
26	P	Nothing
27	T	
28	V	A hint as to which variables in which equations was related to which component.
29	T	I can't think of anything to improve the traditional way
30	V	More than one type of model (ie CAD and physical)
31	P	Nothing.
32	P	Nothing other than explanations beforehand.

33	T	An actual model (physical or video of use)
34	V	Seeing it used in a machine (i.e. a real like application).
35	V	Physical model to hold.
36	P	Speedometer to track velocities of inputs and outputs.
37	T	If I had a 3-D model to play with.
38	V	A simulator that allows us to use autodesk to track points speeds + accelerations on a figure.
39	V	A physical model
40	P	Not much else.
41	T	A physical or computer model.
42	V	Nothing really virtually. I would have liked to try the physical models because I feel those would help me the most.
43	T	More practice.
44	T	Besides personally practicing more, I do not believe more could have aided me.
45	V	If someone had been talking about the motion of the machine ... I realize th [sic]
46	P	Using the CAD models along with the physical models may have helped more.
47	V	I feel like a physical model might have been better.
48	T	A better way to visualize motions.
49	V	Improved locational awareness of parts (how one piece is located (in 3-D) with respect to another, especially if overlap is involved.
50	P	The physical model was a good way to learn.
51	T	Know laws or how machine works together.
52	V	
53	T	I found myself wishing I had either a physical or CAD model multiple times.
54	T	More visual learning than 2D and paper.
55	P	Equation sheet.
56	P	A better explanation of the exact movement of the physical model to emulate the problem.
57	T	Having a physical model to use
58	V	I don't know.
59	P	A walkthrough of a similar problem.
60	P	If you were able to see quantitatively how fast things were moving
61	T	A physical model

62	V	Knowing and remembering equations. More important than conceptualizing the problems.
63	P	Having more experience with the type of problems being solved. If we had a class period on a subject then the models were useless if we did not know the material.
64	V	While it helped my understanding to be able to manipulate the model myself, I think it would have been additionally helpful if I had set the rotation to a set speed and watched that. Sometimes my inability to rotate or move parts at a precisely constant speed made it more difficult to grasp the relations between parts completely.
65	V	Equations for velocities and accelerations b/c I forgot them from lectures earlier those days.
66	T	The models would have been useful or a video of the motion in the problem.
67	T	Knowing how it moved and how to do the problem in general.
68	T	A good visual on some of the problems would have saved me a lot of time. Multiple views may also be helpful.
69	T	not sure
70	T	

Q6 (Comments/suggestions)

ID	Q1	Q6
1	T	I might not be the best to ask because this subject has not "clicked" for me yet.
2	V	
3	V	Interaction with the model helps a great deal. It takes a lot less time to do problems since you don't have to spend any time thinking of how everything moves. You can jump right into calculations.
4	P	N/A
5	P	None.
6	T	It was a good experience. I am excited to see if the people who used the models were better off than the traditional people.
7	P	It was fun getting to use the models.
8	T	It seems like the CAD models are the best idea, because you could just make one and everyone could use it. And computer files last longer than toys as well.
9	V	N/A

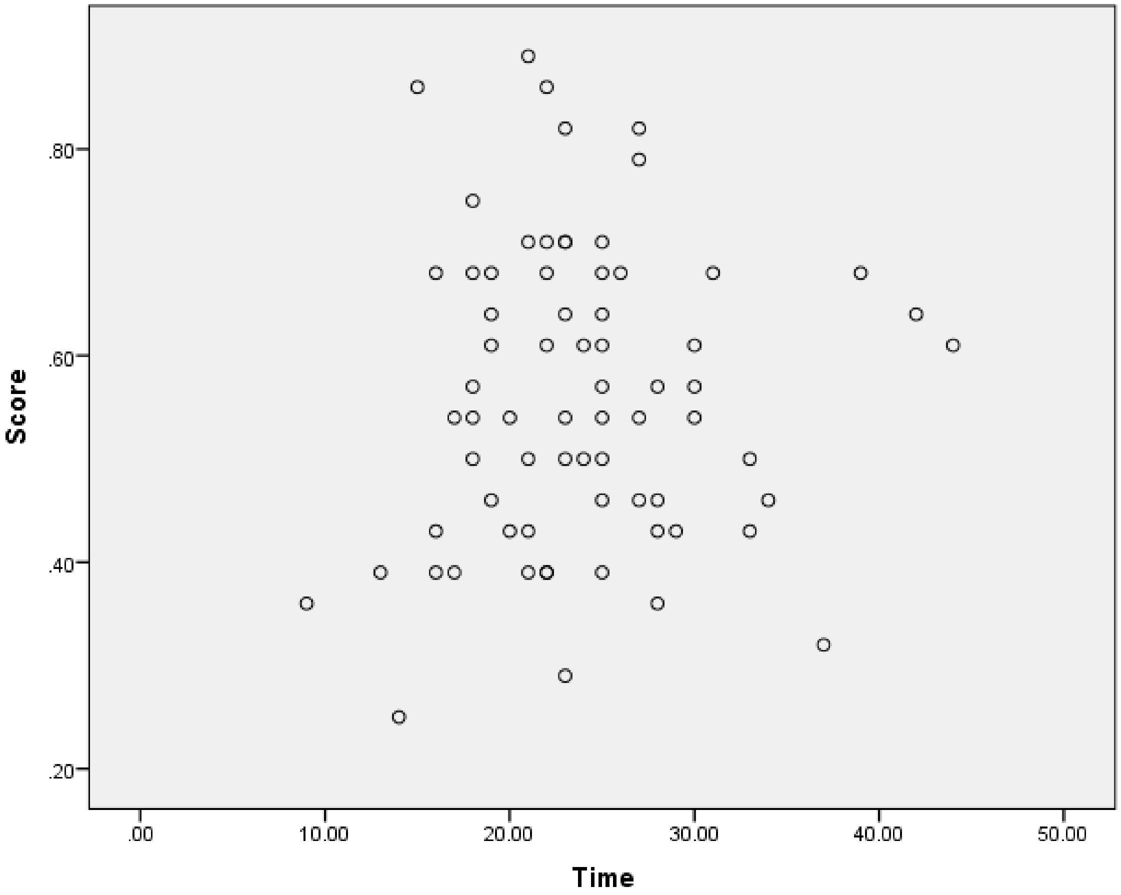
10	T	It's pretty difficult to understand motion without seeing it for myself (i.e. not traditional diagrams)
11	P	The model really helped when stuck + with conceptual understanding of the problem.
12	P	
13	P	The models didn't seem to help significantly. A picture diagram was largely used over anything else.
14	V	Found playing with physical model helpful, though only did so briefly
15	V	I felt really ill-prepared for the problems presented during this study. It had only been presented earlier in day during lecture. Generally, I am a "creature of habit" in that I learn by doing problem after problem and talking with my peers. I don't think I performed as well as I could have had I been given the opportunity to practice and review beforehand. I am glad that this study was conducted. Thus far, Dynamics has proven to be quite challenging. It is comforting to know that more alternatives for mastering this material in the future.
16	V	N/A
17	P	
18	T	This must be taught thoroughly by the professor and studied by the student.
19	T	No complaints.
20	V	The issue with the CAD, in my opinion, was that I relied too heavily on it to determine the answers. If I saw something in the model (whether due to constraint error or not), I generally took it to be true, which caused me to do a few things incorrectly.
21	T	N/A
22	V	
23	P	The tuesday time was not great. Most people had not done the homework yet and were not proficient at the problems.
24	P	
25	T	For the second round, I didn't have a partner so that was no good. And I didn't have my books/notes for either of the rounds.
26	P	none
27	T	A virtual or physical model would help, but more experience would be most productive.
28	V	

29	T	You had everyone do the same method in both sessions, and I thought that it might have been beneficial to switch up everyone's method so you could observe in a majority of people in one method improved after switching to another method. They may be a reason you didn't do that so I could be wrong.
30	V	
31	P	It really didn't make that big of a difference.
32	P	
33	T	
34	V	I was in virtual group, would have preferred physical model. Had 2 partners, neither used the virtual model.
35	V	At least in my experience, I was held back more from not knowing the formulas rather than "understanding what the system was doing."
36	P	Thanks. It was fun playing with the models.
37	T	I would have liked to play with the physical models.
38	V	Good study, very applicable and interesting.
39	V	Put students in groups of 3 or 4 to work.
40	P	Nothing. Hope your study goes well!
41	T	I hope the results of the study provide good data. I think web-based models would really help students understand these problems better.
42	V	
43	T	It's better if we are familiar with all the equations before we participate in the study.
44	T	
45	V	N/A
46	P	Some of the drawings in the book are vague and difficult to understand when you have seen them in real life.
47	V	Overall, I think the virtual model helped a little, but not enough to justify spending the time making one or dealing with glitches.
48	T	It was a worthwhile experiment. I would gladly participate again.
49	V	Space the experiment sessions further apart so that a more noticeable difference may be noted.
50	P	It was a fun study and the physical model did help with the visualization and mechanisms of the device.
51	T	
52	V	
53	T	I think CAD or physical models do help students fain a better understanding of the models. I can say this as one of the people that didn't have them and wished I did.

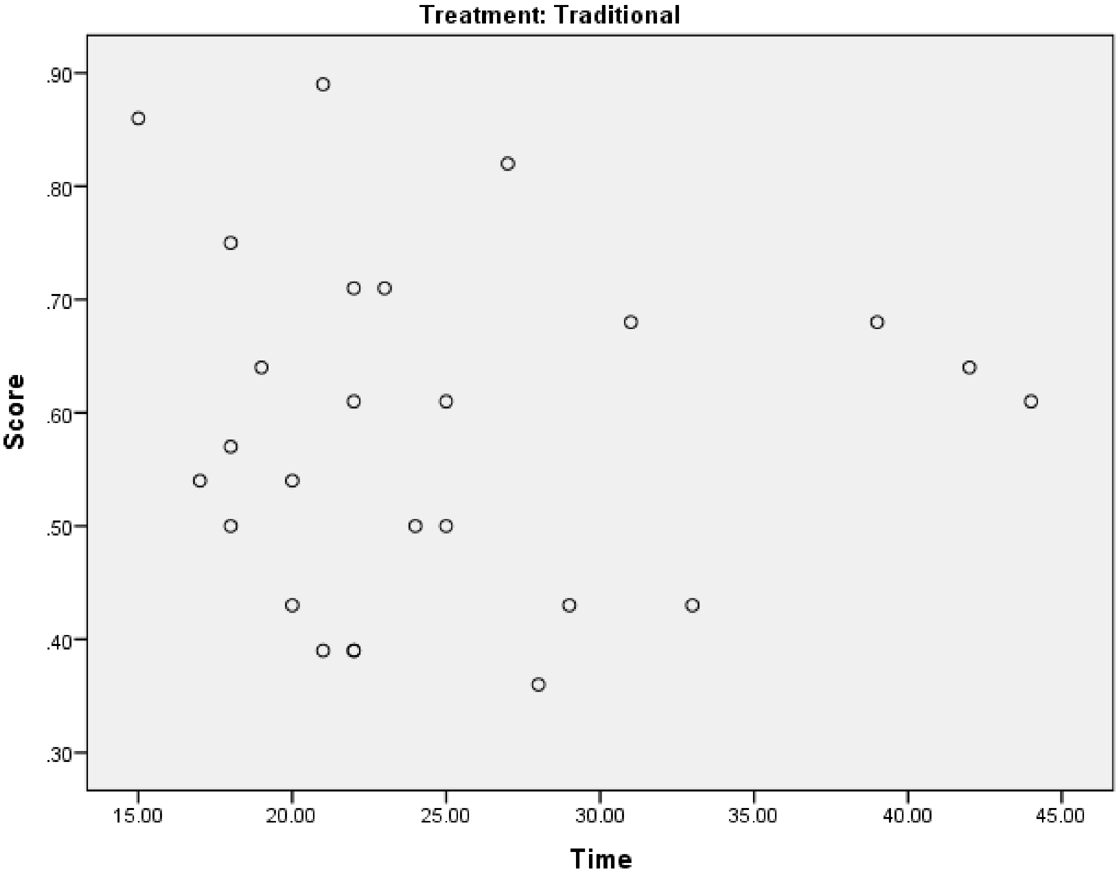
54	T	N/A
55	P	
56	P	The physical model was helpful but as for us solving the problem it still required knowledge of the material learned in class.
57	T	
58	V	None.
59	P	Provide some help with math if you want to isolate the effects of the model alone.
60	P	Had a good time
61	T	Traditional was as helpful as more class time.
62	V	
63	P	Simply allow the students more time to familiarize themselves with the problems before giving them a model. Or giving them a model during class to follow along would be helpful as well.
64	V	Sometimes, working in partners made it more difficult to focus and present my knowledge of the problem accurately. Good luck with your study!
65	V	
66	T	Improving the diagrams to make them more understandable (particularly the star wheel ones) would have been useful.
67	T	Need to learn the material better first then add the visual aids.
68	T	
69	T	
70	T	

Appendix O: Score v. Time Scatter Plots

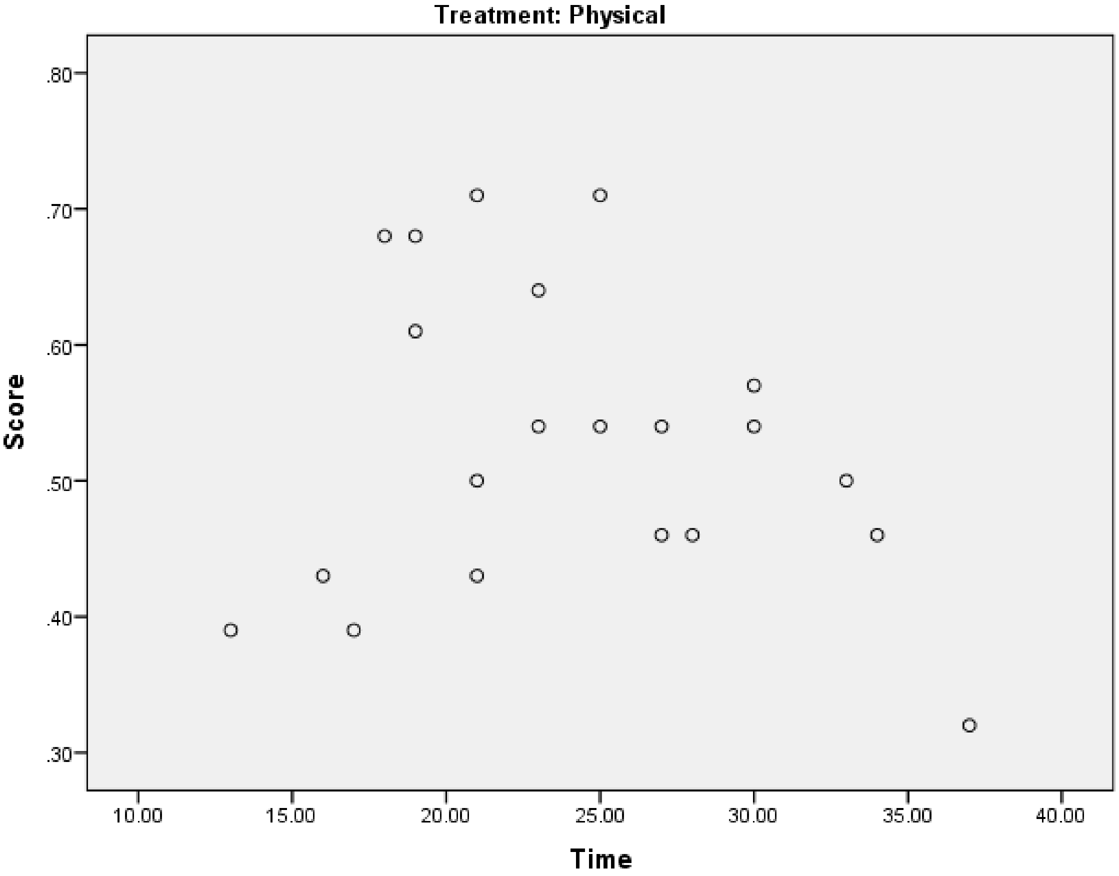
Score vs. Time Scatter Plot for All Treatments Combined



Score vs. Time Scatter Plot for Traditional Treatment Group Only



Score vs. Time Scatter Plot for Physical Treatment Group Only



Score vs. Time Scatter Plot for Virtual Treatment Group Only