# ME451
# Kinematics and Dynamics of Machine Systems

## Introduction

September 2, 2010



Dan Negrut
University of Wisconsin, Madison

# Before we get started…

- Today:
  - Discuss Syllabus
  - Other schedule related issues
  - Start a review of linear algebra (vectors and matrices)

# Instructor: Dan Negrut

- Bucharest Polytechnic Institute, Romania
  - B.S. – Aerospace Engineering (1992)
- The University of Iowa
  - Ph.D. – Mechanical Engineering (1998)
- MSC.Software
  - Product Development Engineer 1998-2004
- The University of Michigan
  - Adjunct Assistant Professor, Dept. of Mathematics (2004)
- Division of Mathematics and Computer Science, Argonne National Laboratory
  - Visiting Scientist (2005, 2006)
- The University of Wisconsin-Madison, Joined in Nov. 2005
  - Research Focus: Computational Dynamics
  - Tech lead, Simulation-Based Engineering Lab - http://sbel.wisc.edu/

# Good to know…

- Time 11:00 – 12:15 PM [ Tu, Th ]
- Room 1152ME
- Office 2035ME
- Phone 608 890-0914
- E-Mail negrut@engr.wisc.edu
- Course Webpage:
  - https://learnuw.wisc.edu – solution to HW problems and grades
  - http://sbel.wisc.edu/Courses/ME451/2010/index.htm - for slides, audio files, examples covered in class, etc.

- Forum Page:
  - http://sbel.wisc.edu/Forum/

- Teaching Assistant: Justin Madsen (jcmadsen@wisc.edu)

- Office Hours:
  - Monday 2 – 3:30 PM
  - Wednesday 2 – 3:30 PM
  - Friday 2 – 3:30 PM

# Text

- **Edward J. Haug: Computer Aided Kinematics and Dynamics of Mechanical Systems: Basic Methods (1989)**
  - Allyn and Bacon series in Engineering
  - Book is out of print
  - Author provided PDF copy of the book, available for download at course website
  - On a couple of occasions, the material in the book will be supplemented with notes
  - We'll cover Chapters 1 through 6 (a bit of 7 too)

# Information Dissemination

- Handouts will be printed out and provided before each lecture
- PPT slides for each lecture will be made available online at lab website
  - I intend to also provide MP3 audio files
- Homework solutions will be posted at Learn@UW
- Grades will be maintained online at Learn@UW
- Syllabus available at lab website
  - Updated as we go, will change to reflect progress made in covering material
  - Topics we cover
  - Homework assignments and due dates
  - Exam dates

# Grading

| | |
|---|---|
| Homework | 40% |
| Exam 1 | 15% |
| Exam 2 | 15% |
| Final Exam | 20% |
| Final Project | 10% |
| Total | 100% |

NOTE:

- Score related questions (homework/exams) must be raised prior to next class after the homework/exam is returned.

# Homework & Final Project

- I'm shooting for weekly homework assignments
  - Assigned at the end of each class
  - Typically due one week later at beginning of class, unless stated otherwise
  - <u>No late homework accepted</u>
  - I anticipate 11 assignments

- There will be a Final Project, you'll choose one of two options:
  - ADAMS option: you'll choose the project topic, I decide if it's good enough
  - MATLAB option: you implement a dynamics engine, simEngine2D

- HW Grading Approach
  - 50% - One random problem graded thoroughly
  - 50% - For completing the other problems

- Solutions will be posted on at Learn@UW

# A Word on simEngine2D

- A code that you put together and by the end of the semester should be capable of running basic 2D Kinematics and Dynamics analysis
  - Each assignment will add a little bit to the core functionality of the sim engine

- You will:
  - Define a way to input (describe) your model
    - Example Model: 2D model of truck, wrecker boom, etc.
  - Implement a numerical solution sequence
    - Example: use Newton-Raphson to determine the position of your system as a function of time
  - Plot results of interest
    - Example: plot of reaction forces, of peak acceleration, etc.)

- simEngine3D link (from last semester's ME751 class):
  - http://sbel.wisc.edu/Courses/ME751/2010/SimulationEngine/index.htm

# Exams

- Two midterm exams, as indicated in syllabus
    - Tuesday, 11/02
    - Thursday, 12/02 (might change to 12/07 due to potential conference travel)
  - Review sessions in 1152ME at 7:15PM the evening before the exam

- Final Exam
  - Tuesday, Dec. 21, at 5:05 PM
  - Comprehensive
  - Room TBA

# Scores and Grades

| Score | Grade |
|---|---|
| 94-100 | A |
| 87-93 | AB |
| 80-86 | B |
| 73-79 | BC |
| 66-72 | C |
| 55-65 | D |

- Grading will not be done on a curve
- Final score will be rounded to the nearest integer prior to having a letter assigned
  - Example:
    - 86.59 becomes AB
    - 86.47 becomes B

# MATLAB and Simulink

- MATLAB will be used extensively for HW
  - It'll be the vehicle used to formulate and solve the equations governing the time evolution of mechanical systems
- You are responsible for brushing up your MATLAB skills
- Simulink used for ADAMS co-simulation
- If you feel comfortable with using C or C++ that is also ok

# Quick Suggestions

- Be active, pay attention, <u>ask questions</u>
- Reading the text is good
- Doing your homework is critical
- Provide feedback
  - Both during and at end of the semester
  - There are small things that are easy to change and could make a difference

# Goals of the class

- Goals of the class
  - Given a general mechanical system, understand how to generate in a **systematic** and **general** fashion the equations that govern the time evolution of the mechanical system
    - These equations are called the equations of motion (EOM)
  - Have a basic understanding of the techniques (called numerical methods) used to solve the EOM
    - We'll rely on MATLAB to implement/illustrate some of the numerical methods used to solve EOM
  - Be able to use commercial software to **simulate** and **interpret** the dynamics associated with complex mechanical systems
    - We'll used the commercial package ADAMS, available at CAE

# Why/How do bodies move?

- Why?
  - The configuration of a mechanism changes in time based on **forces** and **motions** applied to its components
    - Forces
      - Internal (reaction forces)
      - External, or applied forces (gravity, compliant forces, etc.)
    - Motions
      - Somebody prescribes the motion of a component of the mechanical system
    - Recall Finite Element Analysis, boundary conditions are of two types:
      - Neumann, when the force is prescribed
      - Dirichlet, when the displacement is prescribed
- How?
  - They move in a way that obeys Newton's second law
    - Caveat: there are *additional* conditions (constraints) that need to be satisfies by the time evolution of these bodies, and these constraints come from the joints that connect the bodies (to be covered in detail later…)

# Putting it all together…

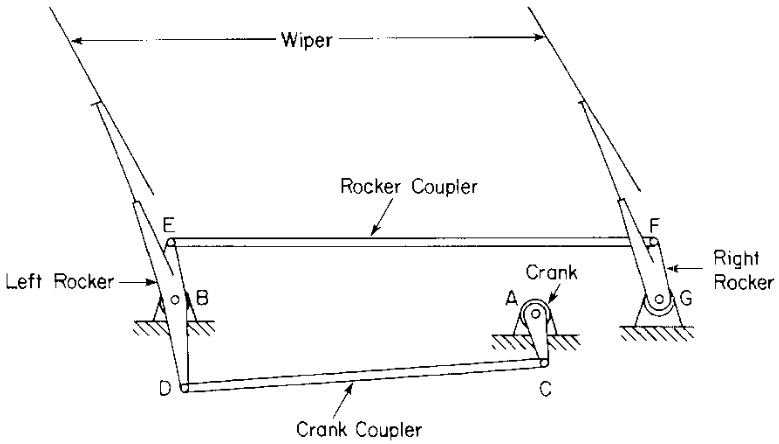
MECHANICAL SYSTEM
=
BODIES + JOINTS + FORCES

THE SYSTEM CHANGES ITS CONFIGURATION IN TIME

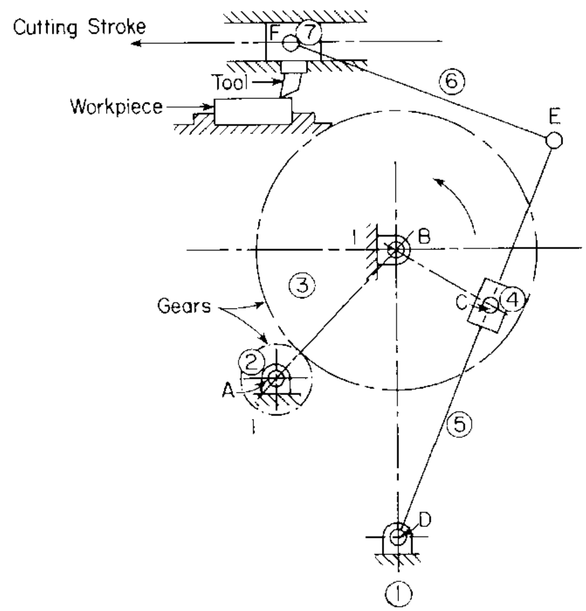
WE WANT TO BE ABLE TO PREDICT & CHANGE/CONTROL HOW SYSTEM EVOLVES

# Examples of Mechanisms

- What do I mean when I say “mechanical system”, or “system”?

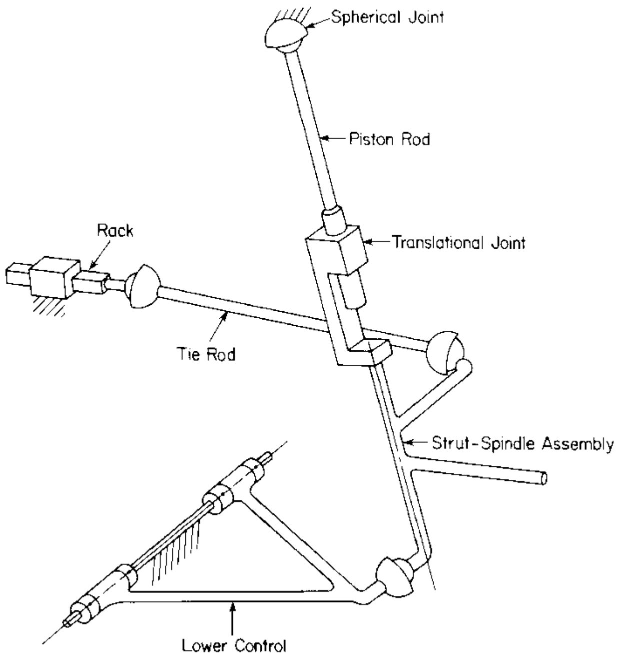



Windshield wiper mechanism

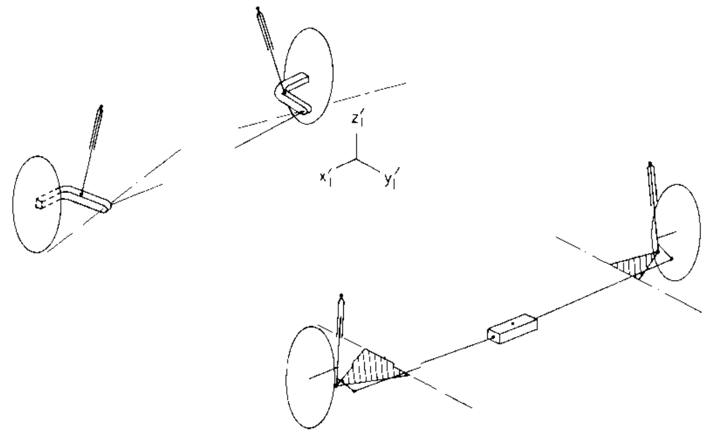



Quick-return shaper mechanism

# More examples …



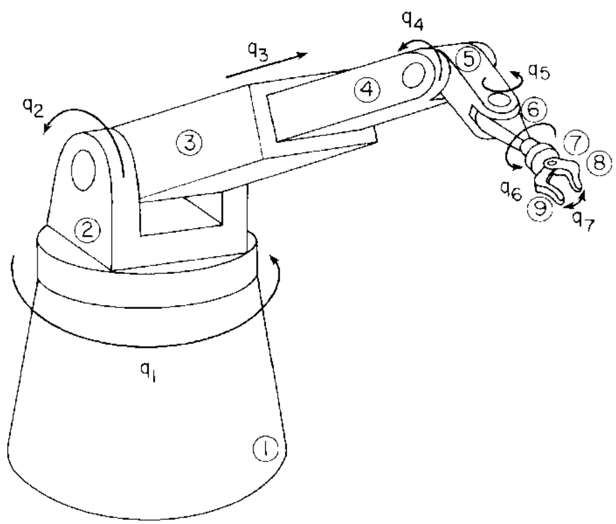

McPherson Strut Front Suspension



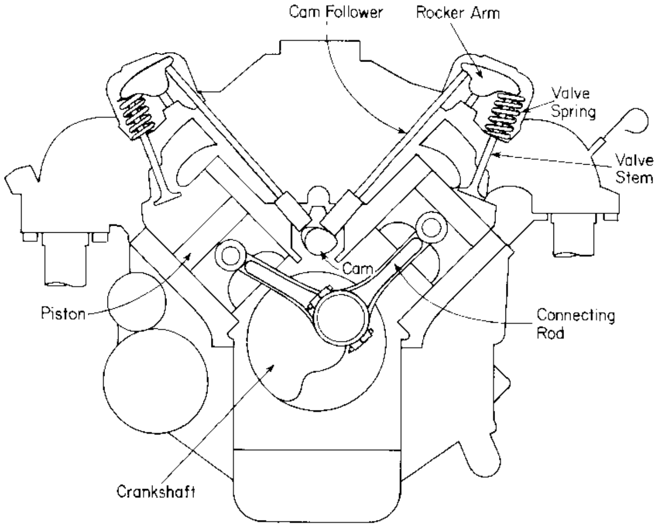
Schematic of car suspension

# More examples …

- Interest here is in controlling the time evolution of these mechanical systems:




Robotic Manipulator




Cross Section of Engine

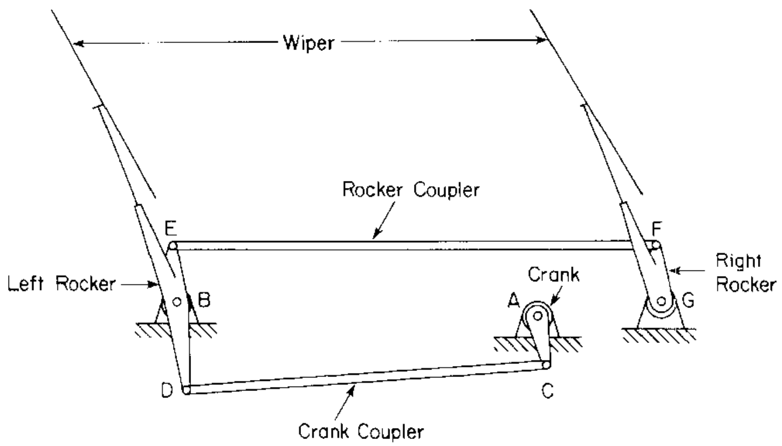
# Nomenclature

- Mechanical System, definition:
  - A collection of interconnected rigid **bodies** that can move relative to one another, consistent with **joints** that limit relative motions of pairs of bodies

- Why type of analysis can one speak of in conjunction with a mechanical system?
  - Kinematics analysis
  - Dynamics analysis
  - Inverse Dynamics analysis
  - Equilibrium analysis

# Kinematics Analysis

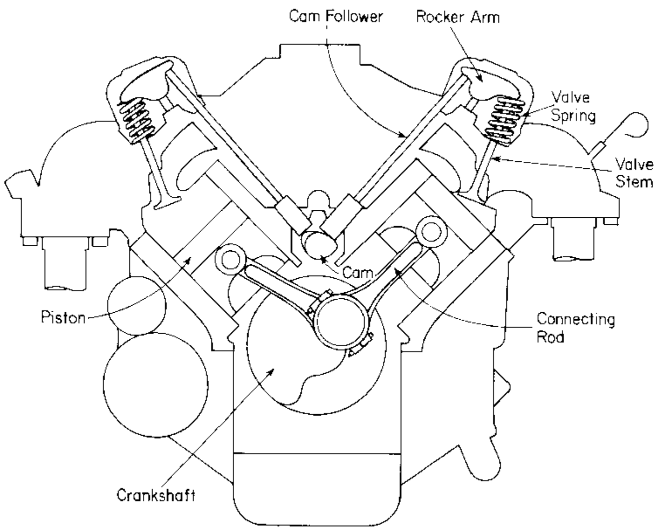
- Concerns the motion of the system **independent** of the forces that produce the motion
- Typically, the time history of one body in the system is prescribed
- We are interested in how the rest of the bodies in the system move
- Requires the solution linear and nonlinear systems of equations




Windshield wiper mechanism

# Dynamics Analysis

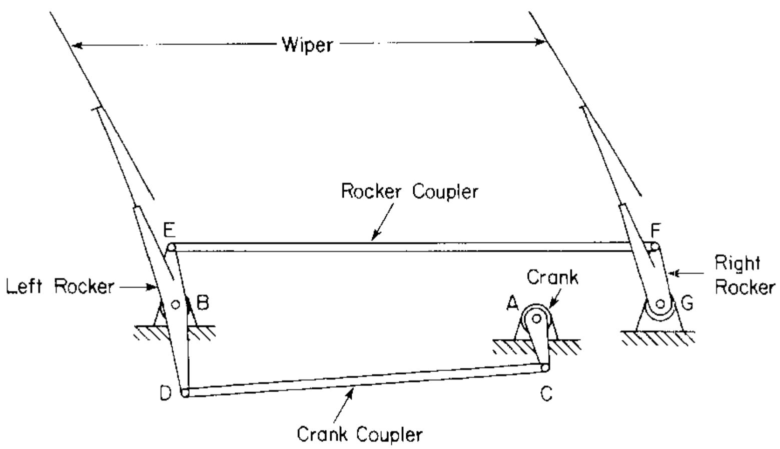
- Concerns the motion of the system that is due to the action of applied forces/torques
- Typically, a set of forces acting on the system is provided. Motions can also be specified on some bodies
- We are interested in how each body in the mechanism moves
- Requires the solution of a combined system of differential and algebraic equations (DAEs)



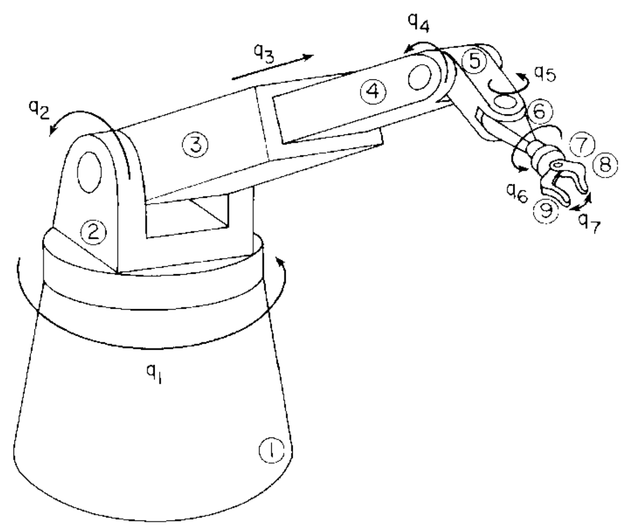

Cross Section of Engine

# Inverse Dynamics Analysis

- It is a hybrid between Kinematics and Dynamics
- Basically, one wants to find the set of forces that lead to a certain desirable motion of the mechanism
- Your bread and butter in Controls…




Windshield wiper mechanism



Robotic Manipulator

# What is the slant of this course?

- When it comes to dynamics, there are several ways to approach the solution of the problem, that is, to find the time evolution of the mechanical system

  - The ME240 way, on a case-by-case fashion
    - In many circumstances, this required following a recipe, not always clear where it came from
    - Typically works for small problems, not clear how to go beyond textbook cases

  - Use a graphical approach
    - This was the methodology emphasized by Prof. Uicker in ME451
    - Intuitive but doesn't scale particularly well

  - Use a computational approach
    - This is methodology emphasized in this class
    - Leverages the power of the computer
    - Relies on a unitary approach to finding the time evolution of any mechanical system
      - Sometimes the approach might seem to be an overkill, but it's general, and remember, it's the computer that does the work and not you
      - In other words, we hit it with a heavy hammer that takes care of all jobs, although at times it seems like killing a mosquito with a cannon…

# The Computational Slant…

- Recall title of the class: “Kinematics and Dynamics of Machine Systems”

- The topic is approached from a computational perspective, that is:
  - We pose the problem so that it is suited for being solved using a computer
    - A) Identify in a simple and general way the data that is needed to formulate the equations of motion

    - B) Automatically solve the set of nonlinear equations of motion using appropriate numerical solution algorithms: Newton Raphson, Euler Method, Runge-Kutta Method, etc.

    - C) Consider providing some means for post-processing required for analysis of results. Usually it boils down to having a GUI that enables one to plot results and animate the mechanism

# Overview of the Class

## [Chapter numbers according to Haug's book]

- Chapter 1 – general considerations regarding the scope and goal of Kinematics and Dynamics (with a computational slant)

- Chapter 2 – review of basic Linear Algebra and Calculus
  - Linear Algebra: Focus on geometric vectors and matrix-vector operations
  - Calculus: Focus on taking partial derivatives (a <u>lot</u> of this), handling time derivatives, chain rule (a <u>lot</u> of this too)

- Chapter 3 – introduces the concept of kinematic constraint as the mathematical building block used to represent joints in mechanical systems
  - This is the hardest part of the material covered
  - Basically poses the Kinematics problem

- Chapter 4 – quick discussion of the numerical algorithms used to solve kinematics problem formulated in Chapter 3

- Chapter 5 – applications, will draw on the simulation facilities provided by the commercial package ADAMS
  - Only tangentially touching it

- Chapter 6 – states the dynamics problem

- Chapter 7 – only tangentially touching it, in order to get an idea of how to solve the set of DAEs obtained in Chapter 6

Haug's book is available online at the class website

# ADAMS

- Automatic Dynamic Analysis of Mechanical Systems

- It says Dynamics in name, but it does a whole lot more
  - Kinematics, Statics, Quasi-Statics, etc.

- Philosophy behind software package
  - Offer a pre-processor (ADAMS/View) for people to be able to generate models
  - Offer a solution engine (ADAMS/Solver) for people to be able to find the time evolution of their models
  - Offer a post-processor (ADAMS/PPT) for people to be able to animate and plot results

- It now has a variety of so-called vertical products, which all draw on the ADAMS/Solver, but address applications from a specific field:
  - ADAMS/Car, ADAMS/Rail, ADAMS/Controls, ADAMS/Linear, ADAMS/Hydraulics, ADAMS/Flex, ADAMS/Engine, etc.

- I used to work for six years in the ADAMS/Solver group

**End: Chapter 1 (Introduction)**
**Begin: Review of Linear Algebra**

# Why Bother with Vectors/Matrices?

- Kinematics (and later Dynamics), is all about being able to say at a given time where a point is in space and how it is moving
  - Vectors and matrices are extensively used to this end
    - Vectors are used to locate points on a body
    - Matrices are used to describe the orientation of a body

# Geometric Vectors

- What is a Geometric Vector?
  - A quantity that has two attributes:
    - A direction
    - A magnitude

- VERY IMPORTANT:
  - Geometric vectors are quantities that exist independently of any reference frame

- ME451 deals entirely with planar kinematics and dynamics
  - We assume that all the vectors are defined in the 2D plane

# Geometric Vectors: Operations

- What can you do with geometric vectors?
  - Scale them
  - Add them (according to the parallelogram rule)
    - Addition is commutative
  - Multiply two of them
    - Inner product (leads to a number)
    - Outer product (leads to a vector, perpendicular on the plane)
  - Measure the angle $\theta$ between two of them