ME 599/AA 589/EE 546: **Biology-inspired robot control**

Lecture 2

Sawyer B. Fuller

Goals:

- Review feedback, control, and simulation
- Introduce next week's paper, Mcleod96: "Do baseball players know where the ball will land or only how to get there?"

UNIVERSITY of WASHINGTON

administration

1. course survey and paper preferences: if you intend to take the course for credit, please make sure I have that sheet by today

2. paper presentation assignments available next week

3. post your review paper review on canvas under "discussions"

recap

- defined “biology-inspired robot control”:
  learning from biology to design better robot motion control systems

- course material loosely divided into two areas:

  - reflexive or model-free control

  - mechanical intelligence

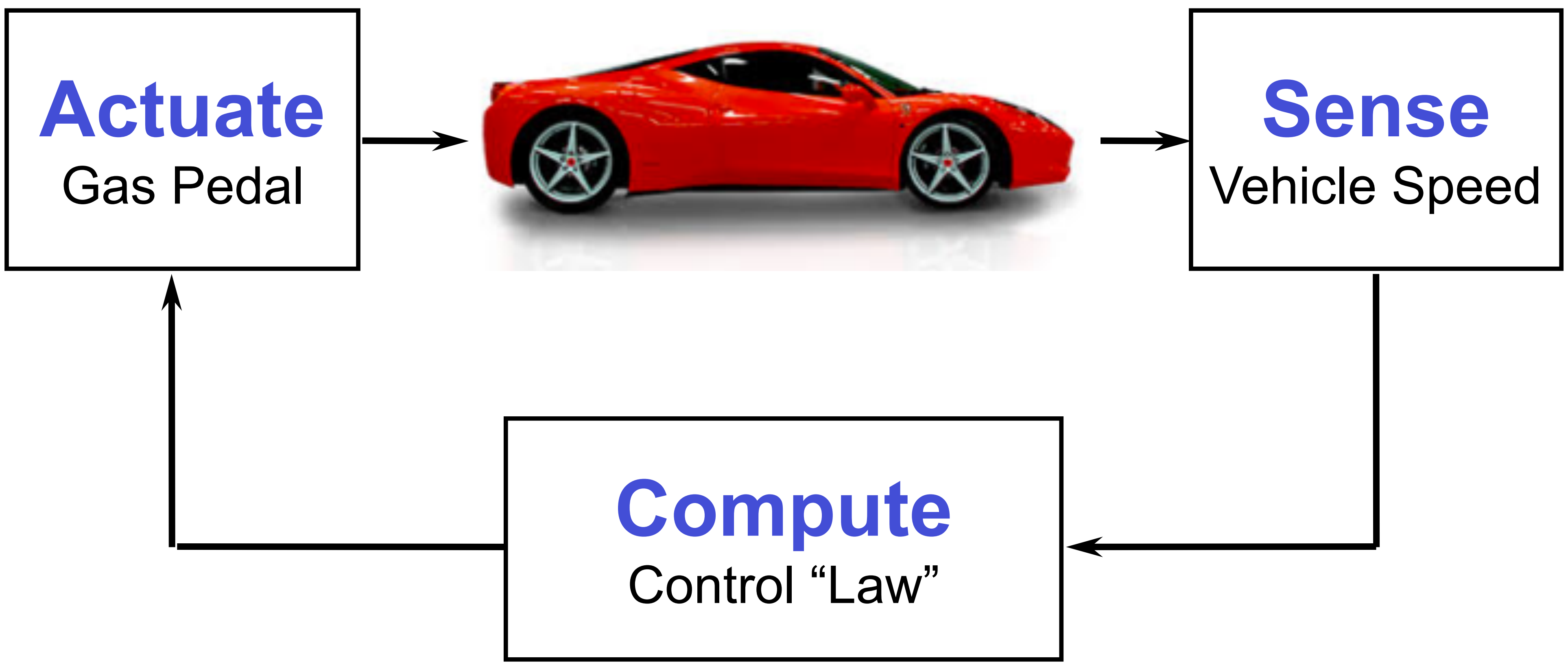
- course content consists of paper readings + final project

Review of control, feedback, and modeling

What is control?

Control = Sensing + Computation + Actuation

In Feedback “Loop”



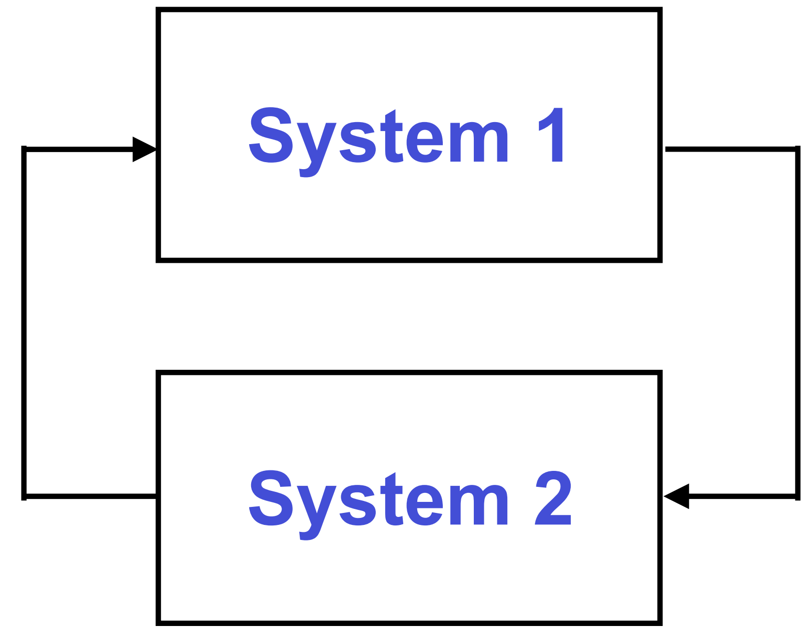
Goals - example

- Stability: system maintains desired operating point (hold steady speed)
- Performance: system responds rapidly to changes (accelerate to 6 m/sec)
- Robustness: system tolerates perturbations in dynamics (mass, drag, etc)

The central theme in control is *feedback*

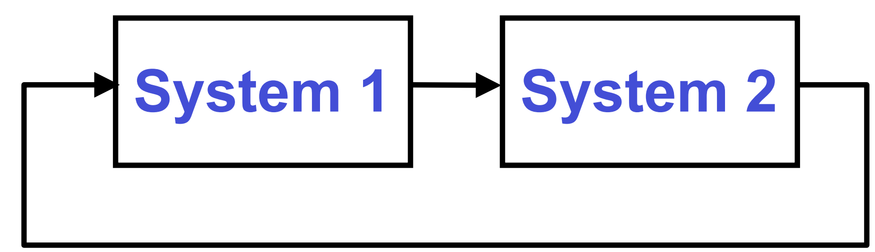
***Feedback* is the mutual interconnection of two (or more) systems**

- System 1 affects system 2
- System 2 affects system 1
- Cause and effect is tricky; systems are mutually dependent

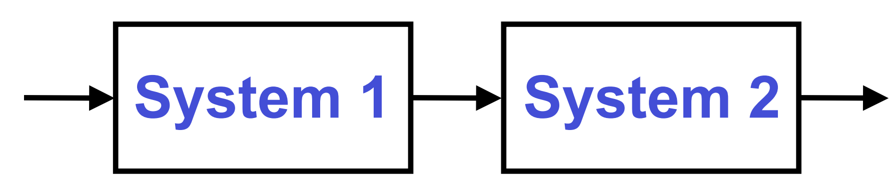


Feedback is ubiquitous in natural and engineered systems

Terminology



Closed Loop

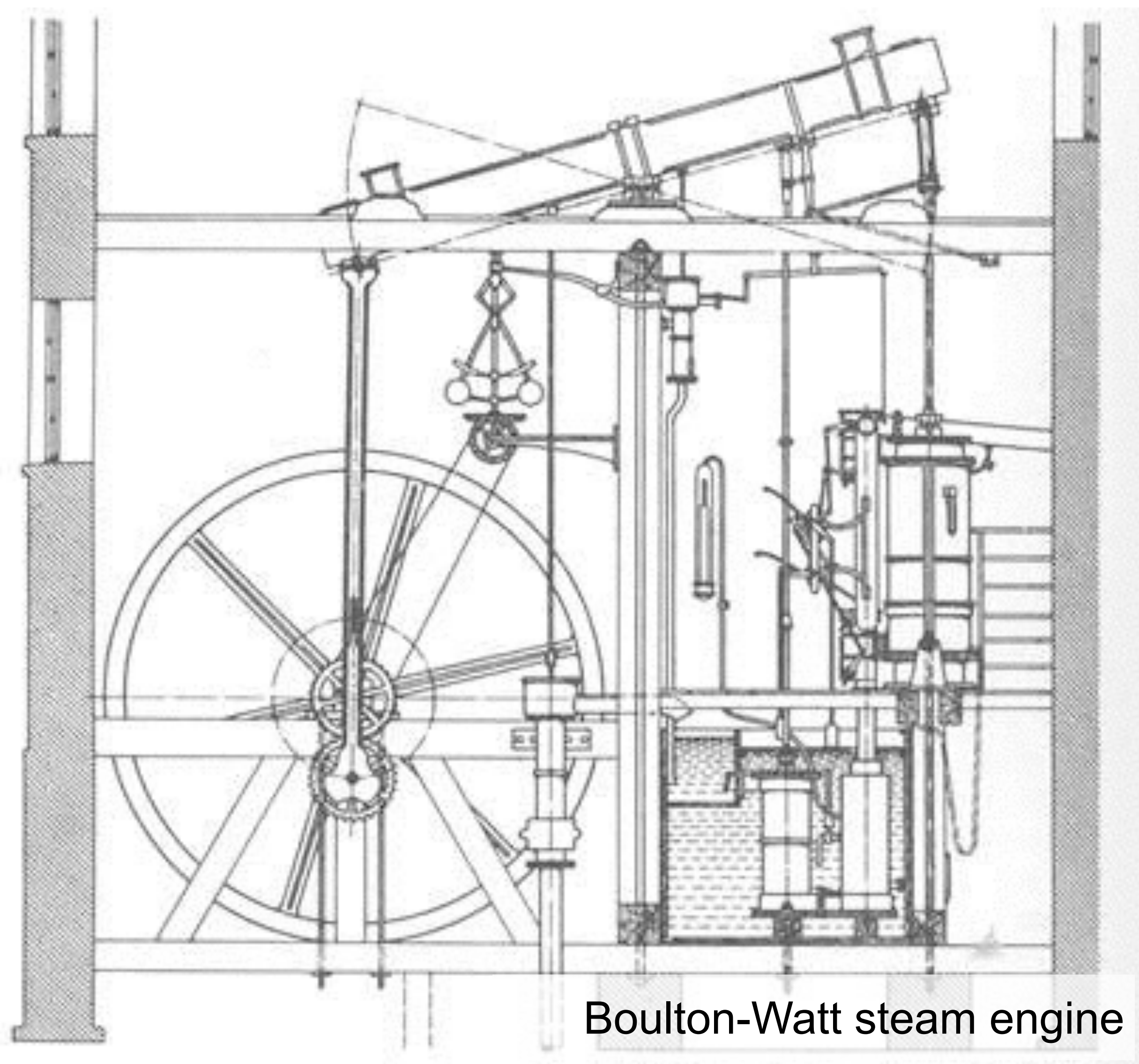


Open Loop

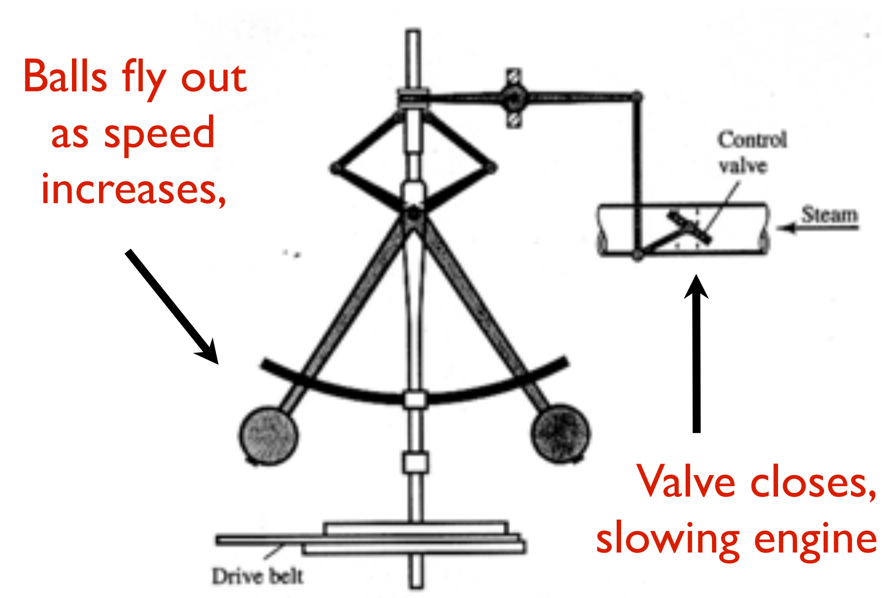
Example #1: Flyball Governor

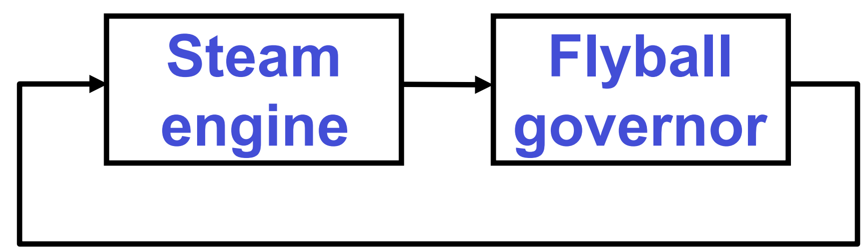
“Flyball” Governor (1788)

- Regulate speed of steam engine
- Reduce effects of variations in load (disturbance rejection)
- Major advance of industrial revolution
- engineered “mechanical intelligence”



Boulton-Watt steam engine

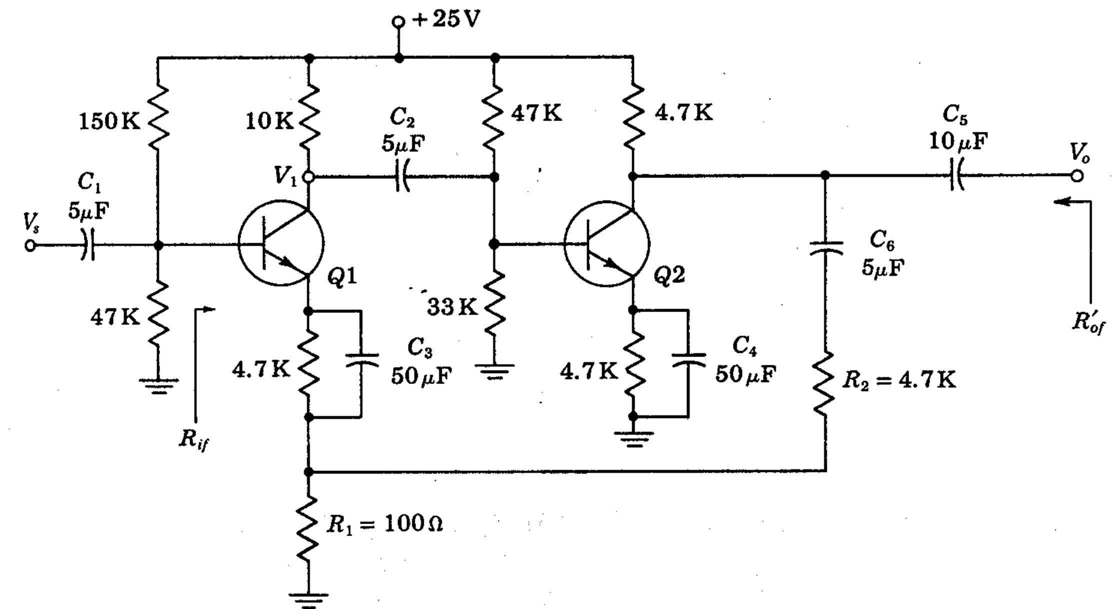




Two Main Principles of Feedback

Robustness to Uncertainty through Feedback

- Feedback allows high performance in the presence of uncertainty
- Example: repeatable performance of amplifiers with 5X component variation
- Key idea: accurate *sensing* to compare actual to desired, correction through *computation* and *actuation*

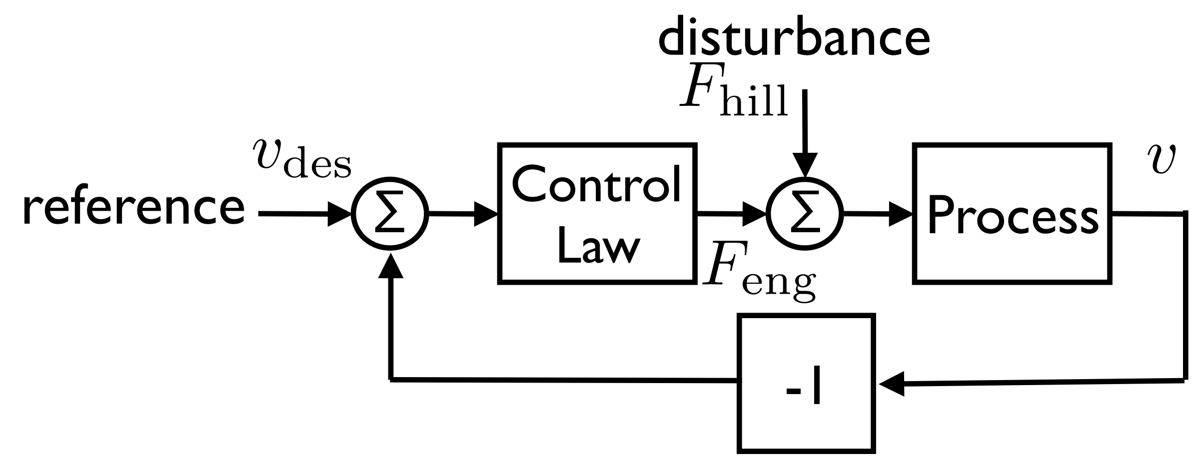


Design of Dynamics through Feedback

- Feedback allows the dynamics (behavior) of a system to be modified
- Example: stability augmentation for highly agile, unstable aircraft
- Key idea: interconnection gives *closed loop* that modifies natural behavior

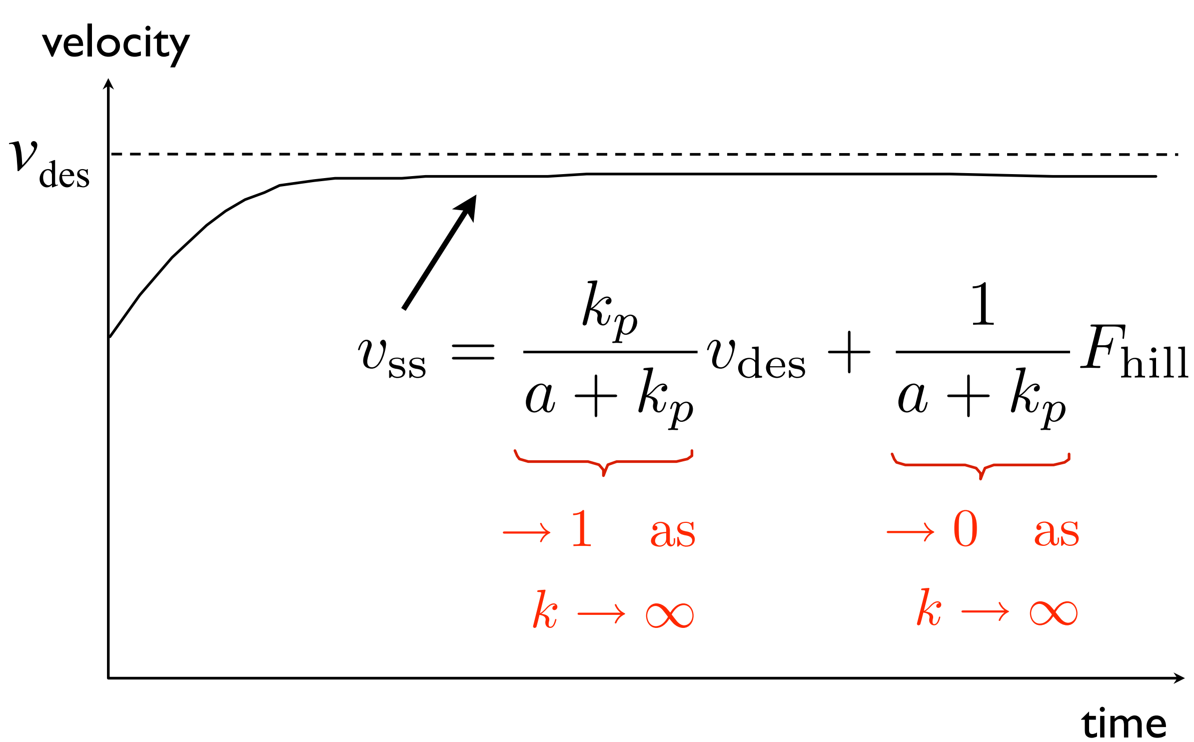
X-29 experimental aircraft (NASA)

Example #2: Speed Control



$$m\dot{v} = -av + F_{\text{eng}} + F_{\text{hill}}$$

$$F_{\text{eng}} = k_p(v_{\text{des}} - v)$$



Stability/performance

- Steady state velocity approaches desired velocity as $k \to \infty$
- Smooth response; no overshoot or oscillations

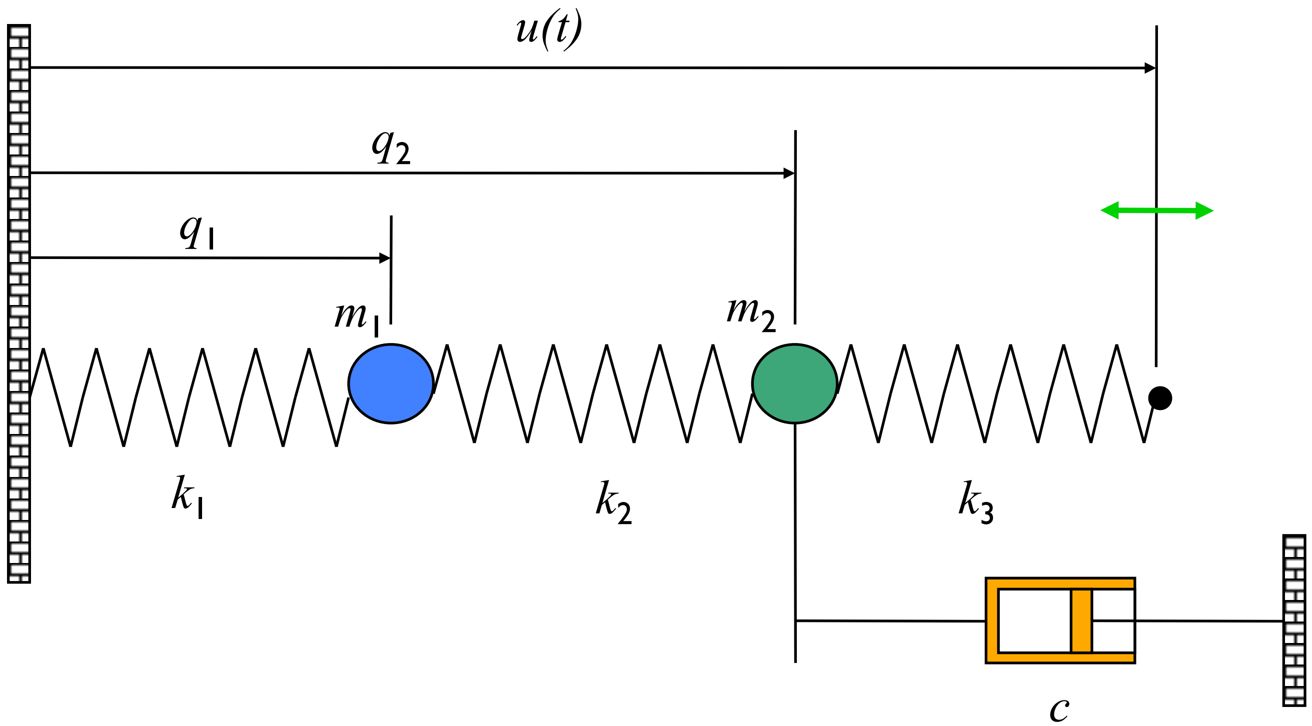
Disturbance rejection

- Effect of disturbances (eg, hills) approaches zero as $k \to \infty$

Robustness

- Results don't depend on the specific values of a, m or k_p, for k_p sufficiently large

Modeling



Analysis based on models

- *prediction* of system behavior
- feedback can give counterintuitive behavior; models can explain
- type of model needed depends on questions you want to answer

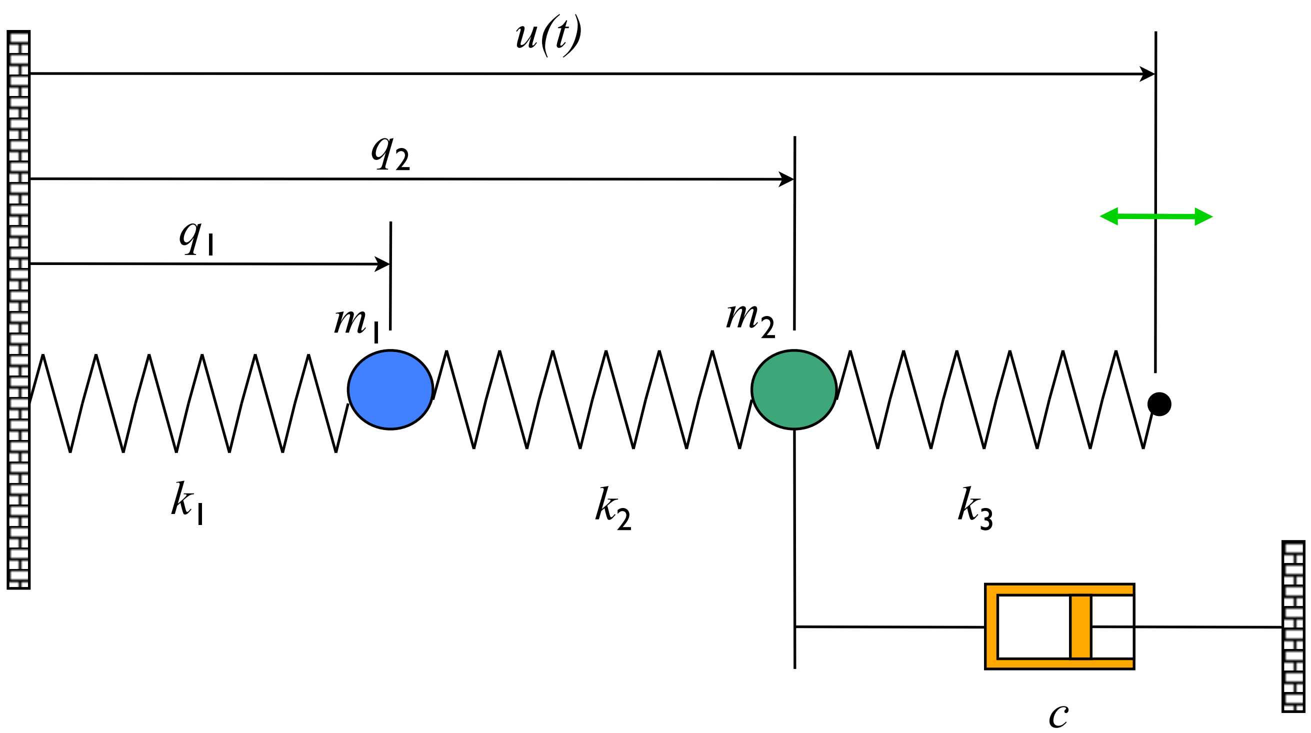
Questions to answer

- How much do masses move as a function of the forcing frequency?
- What happens if I change the mass?
- Will the car fly into the air if I take that speed bump at 25 mph?

Modeling assumptions

- Mass, spring, and damper constants are fixed and known
- Springs satisfy Hooke's law
- Damper is (linear) viscous force, proportional to velocity

Modeling a Spring Mass System



Model: rigid body physics

- Sum of forces = mass * acceleration
- Hooke's law: $F = k(x - x_{\text{rest}})$
- Viscous friction: $F = c\,v$

$$m_1\ddot{q}_1 = k_2(q_2 - q_1) - k_1 q_1$$
$$m_2\ddot{q}_2 = k_3(u - q_2) - k_2(q_2 - q_1) - c\dot{q}_2$$

Converting models to state space form

- Construct a *vector* of the variables that are required to specify the evolution of the system
- Write dynamics as a *system* of first order differential equations:

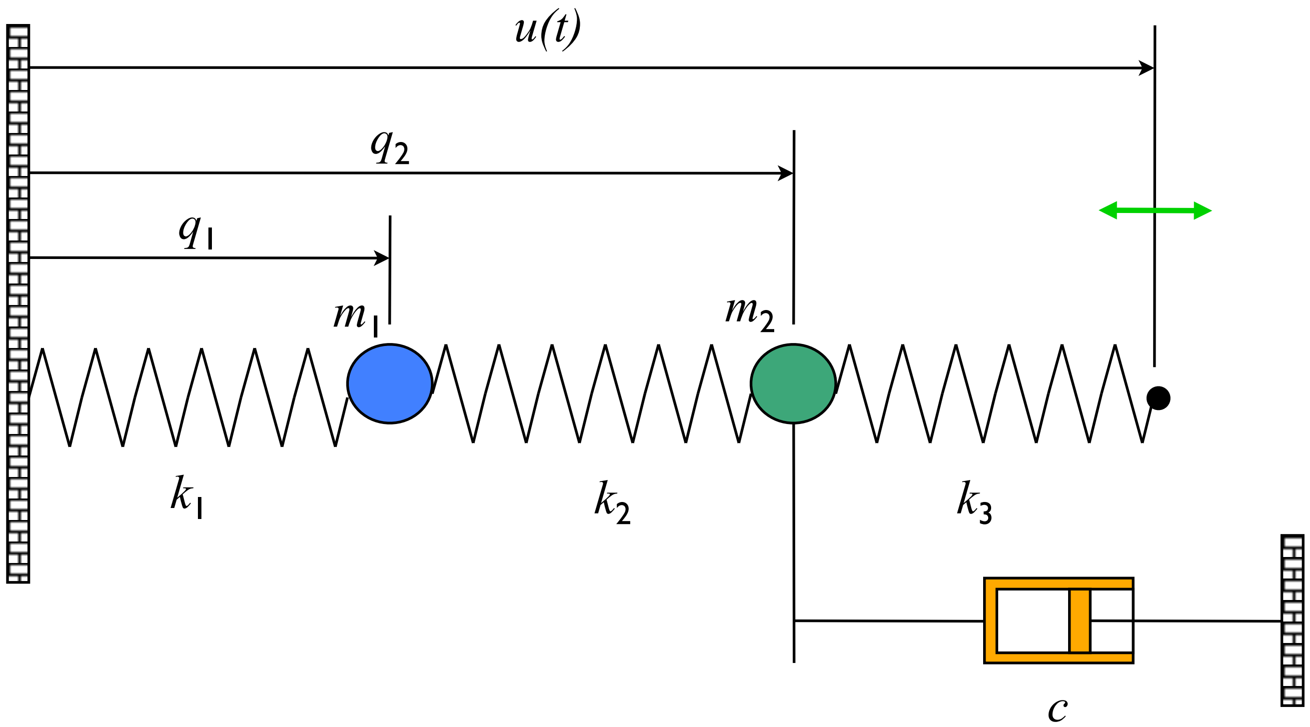
$$\frac{dx}{dt} = f(x, u) \qquad x \in \mathbb{R}^n,\ u \in \mathbb{R}^p$$
$$y = h(x) \qquad y \in \mathbb{R}^q$$

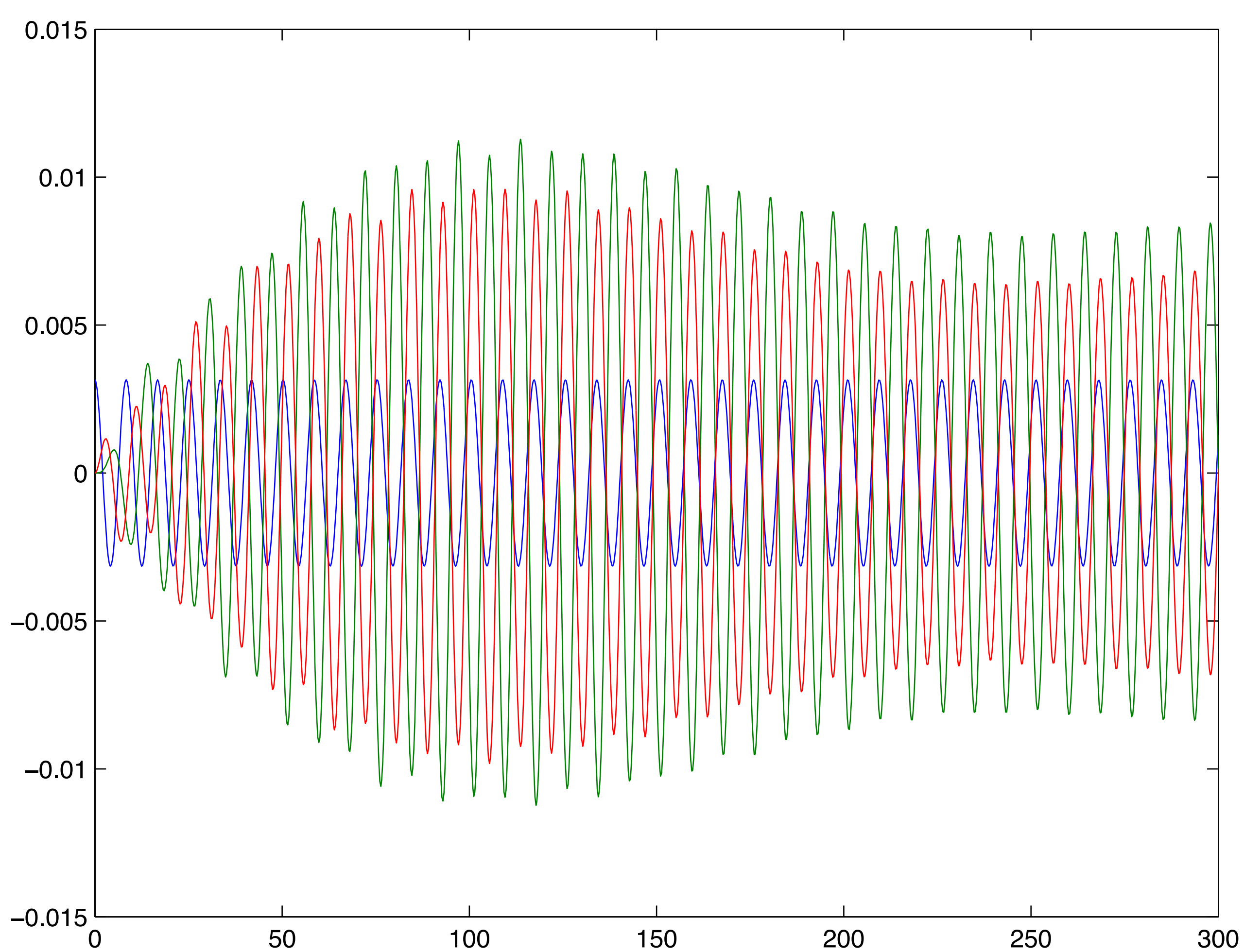
$$\frac{d}{dt}\begin{bmatrix} q_1 \\ q_2 \\ \dot{q}_1 \\ \dot{q}_2 \end{bmatrix} = \begin{bmatrix} \dot{q}_1 \\ \dot{q}_2 \\ \frac{k_2}{m}(q_2 - q_1) - \frac{k_1}{m} q_1 \\ \frac{k_3}{m}(u - q_2) - \frac{k_2}{m}(q_2 - q_1) - \frac{c}{m}\dot{q} \end{bmatrix}$$

$$y = \begin{bmatrix} q_1 \\ q_2 \end{bmatrix}$$

"State space form"

Simulation of a Mass Spring System





Steady state frequency response

- Force the system with a sinusoid
- Plot the "steady state" response, after transients have died out
- Plot relative magnitude and phase of output versus input (more later)

Matlab simulation

```
function dydt = f(t, y, ...)
u = 0.00315*cos(omega*t);
dydt = [
   y(3);
   y(4);
   -(k1+k2)/m1*y(1) + k2/m1*y(2);
   k2/m2*y(1) - (k2+k3)/m2*y(2)
        - c/m2*y(4) + k3/m2*u ];

[t,y] = ode45(dydt,tspan,y0,[],
k1, k2, k3, m1, m2, c, omega);
```

Modeling Terminology

***State* captures effects of the past**

- independent physical quantities that determines future evolution (absent external excitation)

***Inputs* describe external excitation**

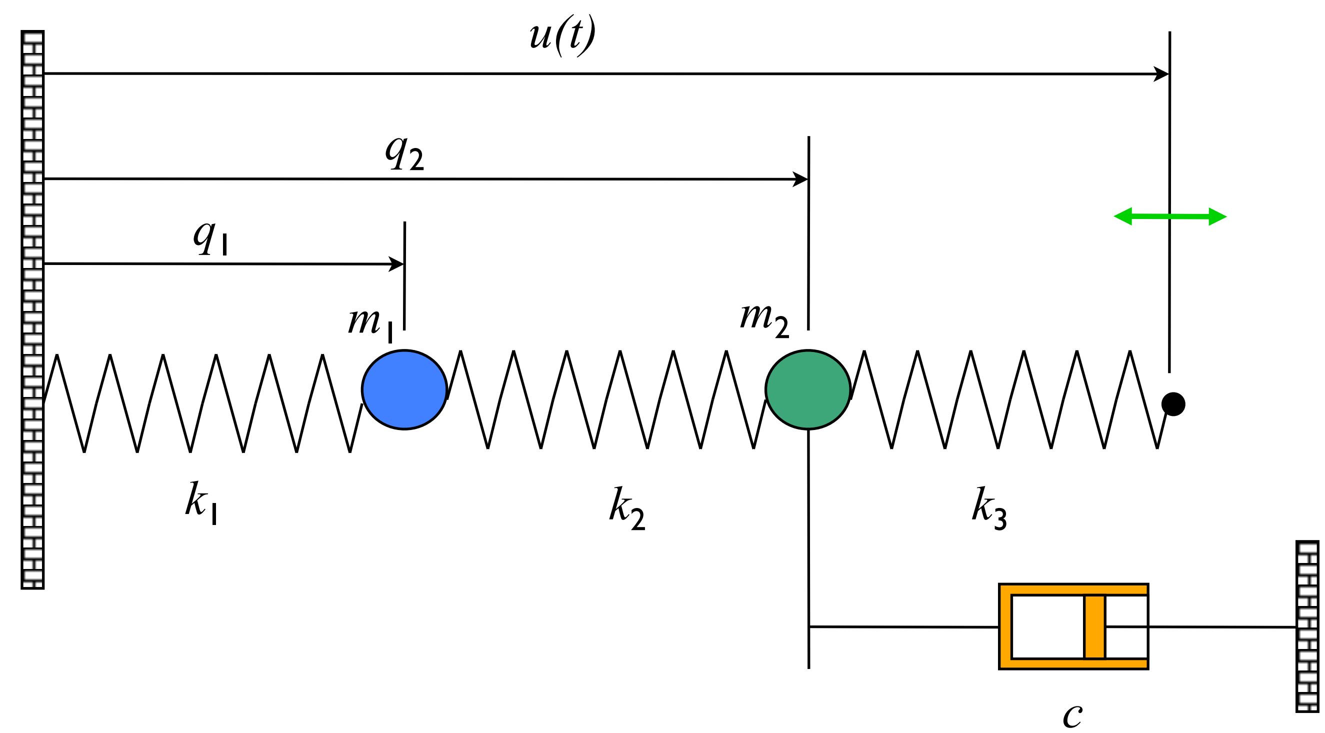
- Inputs are *extrinsic* to the system dynamics (externally specified)

***Dynamics* describes state evolution**

- update rule for system state
- function of current state and any external inputs

***Outputs* describe measured quantities**

- Outputs are function of state and inputs ⇒ not independent variables
- Outputs are often *subset* of state



Example: spring mass system

- State: position and velocities of each mass: $q_1, q_2, \dot{q}_1, \dot{q}_2$
- Input: position of spring at right end of chain: $u(t)$
- Dynamics: basic mechanics
- Output: measured positions of the masses: q_1, q_2

Modeling Properties

Choice of state is not unique

- There may be *many* choices of variables that can act as the state
- Trivial example: different choices of units (scaling factor)
- Less trivial example: sums and differences of the mass positions

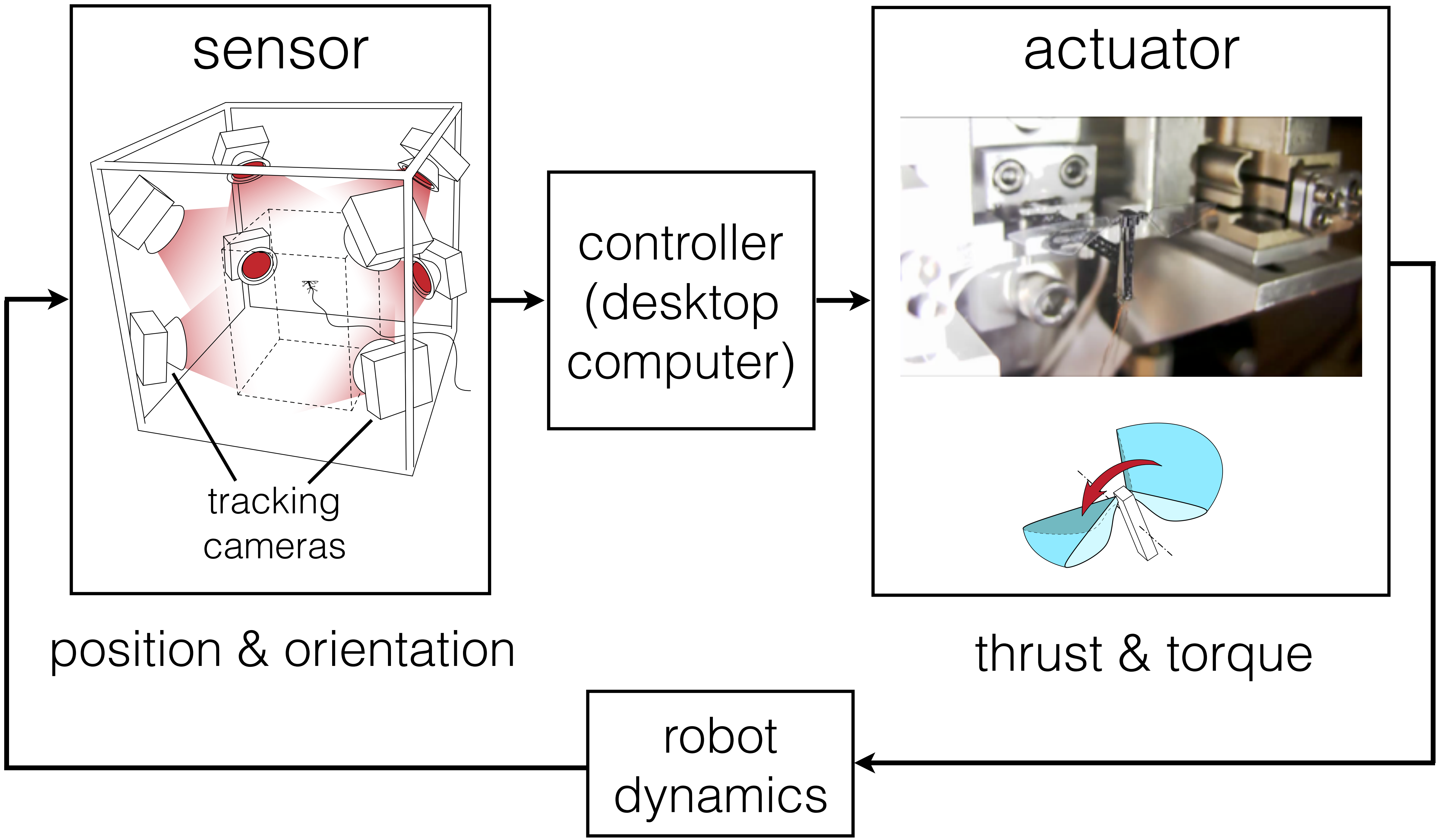
Choice of inputs, outputs depends on point of view

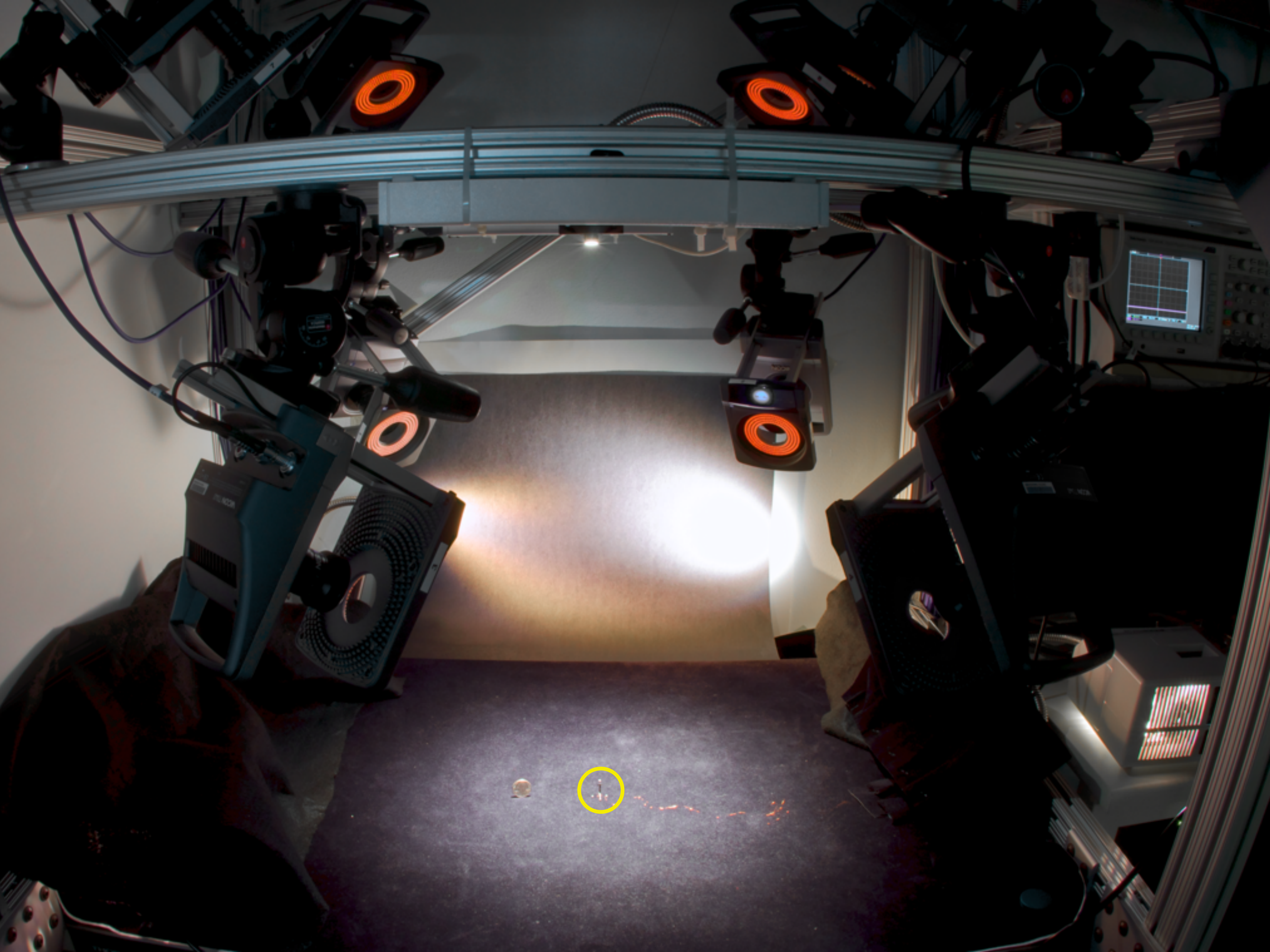
- Inputs: what factors are *external* to the model that you are building
  - Inputs in one model might be outputs of another model (eg, the output of a cruise controller provides the input to the vehicle model)
- Outputs: what physical variables (often states) can you *measure*
  - Choice of outputs depends on what you can sense and what parts of the component model interact with other component models

Example 3: insect-robot flight control

Ma K, Chirarattananon P, Fuller SB, and Wood RJ, *Science* 2013

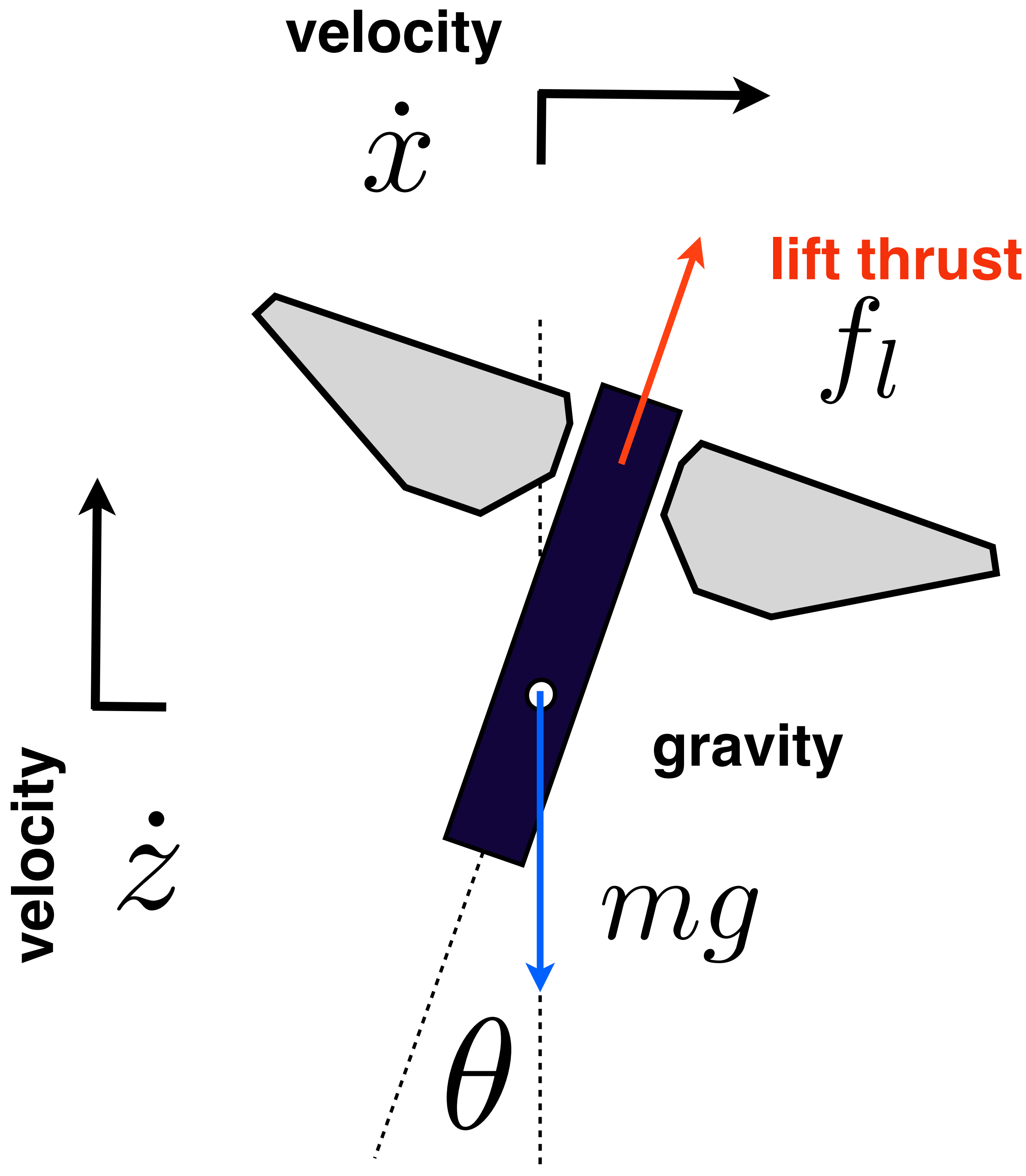
motion capture feedback control





lateral maneuver, real time

flight model



Simulation and modeling resources

- Modeling and simulation: Chapters 1 & 2 of *Feedback Systems* by Astrom and Murray, available online at http://www.cds.caltech.edu/~murray/amwiki/index.php

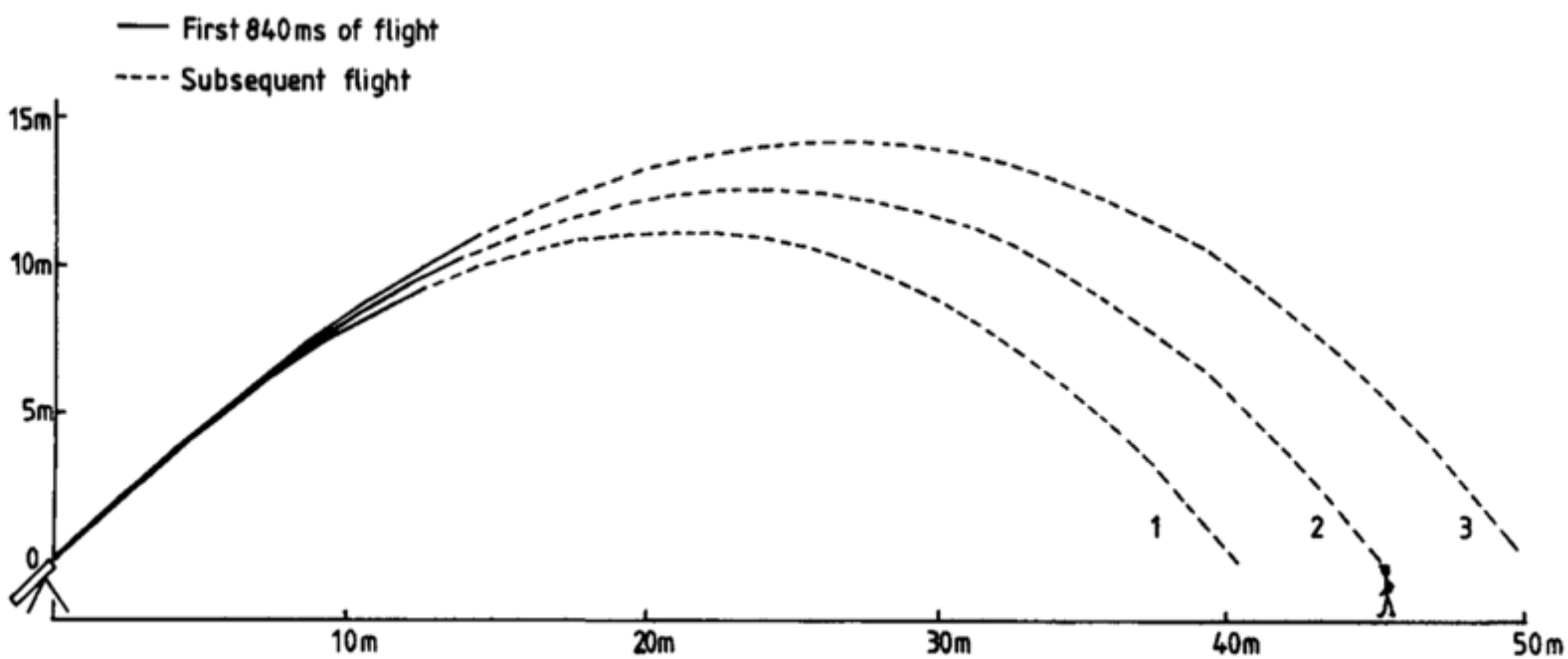
- Online tutorial of MATLAB http://www.cyclismo.org/tutorial/matlab/

- Online tutorial of python and python notebook: http://nbviewer.ipython.org/gist/rpmuller/5920182 (note: slightly out of date, install python using anaconda https://www.continuum.io/downloads)

Paper 0: McLeod & Dienes

"Do baseball fielders know where to go to catch the ball or only how to get there?"

- answer is an example of "reflexive" control: results indicate good catchers use a specific algorithm to intercept the ball
- paper 0 review due on Canvas by Tuesday (9pm)



how to read a paper

1. read the abstract - 2-5 min
2. look through the figures - 5-10 min
3. read the introduction - 5-20 min
4. read the conclusion - 10 min
5. read the rest of the paper - 1-10 hrs
   (depending on difficulty and detail desired)

Wednesday

- example paper presentation of paper 0
- paper 0 review due day before, on canvas

Friday

- problem set 1 due in class (to be posted on canvas monday)
- guest speaker: Prof. Sam Burden