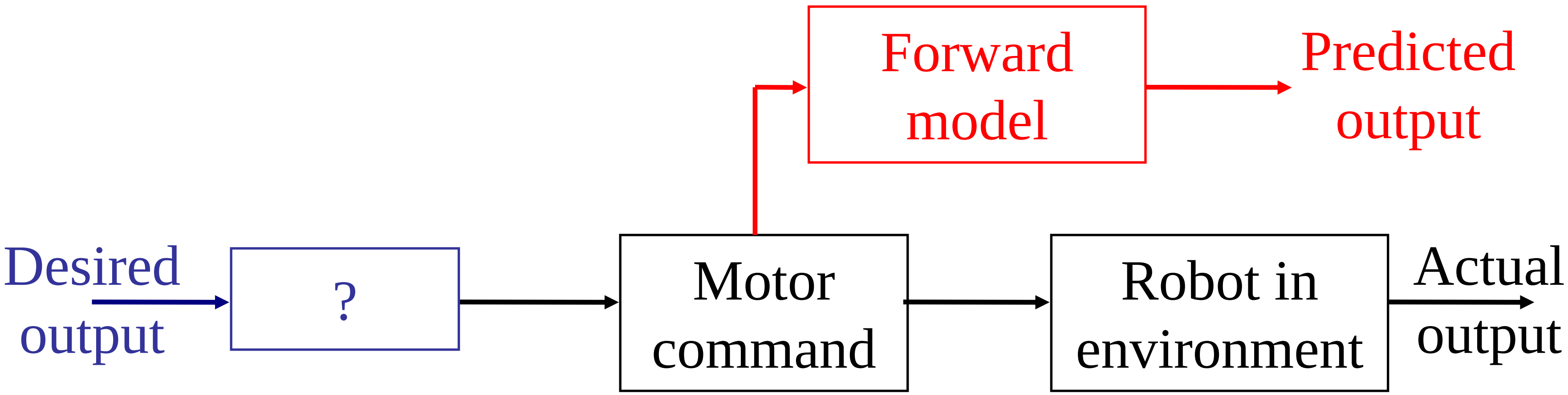
Control 2

Keypoints:

- Given desired behaviour, determine control signals
- Inverse models:
  - Inverting the forward model for simple linear dynamic system
  - Problems for more complex systems
- Open loop control: advantages and disadvantages
- Feed forward control to deal with disturbances

The control problem

- Forward: Given the control signals, can we predict the motion of the robot?



- Inverse: Given the desired motion of the robot can we determine the right control signals?

- Often no

  unique or easy exact solution (non-linearities, noise).

Open loop control

Examples:

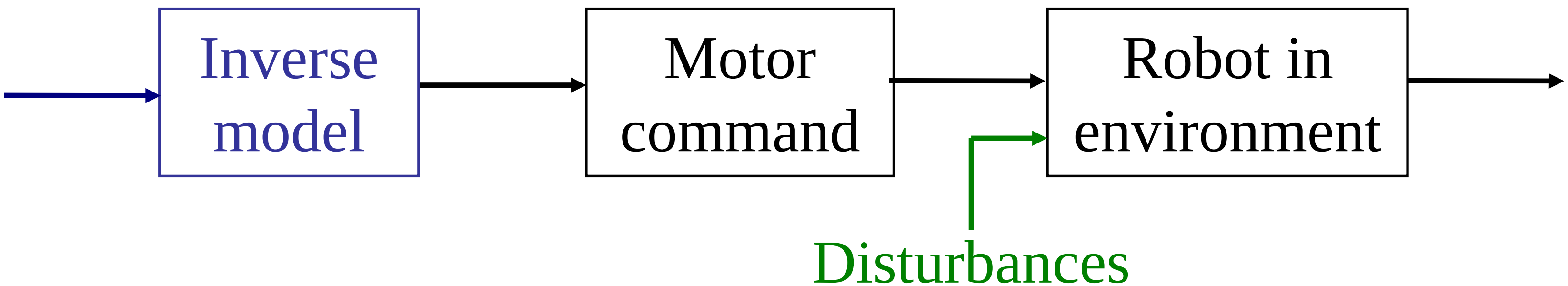
- To execute memorised trajectory, produce appropriate sequence of motor torques
- To obtain a goal, make a plan and execute it
  - (means-ends reasoning could be seen as inverting a forward model of cause-effect)
- ‘Ballistic’ movements such as saccades

Open loop control

- Potentially cheap and simple to implement e.g. if solution is already known.
- Fast, e.g. useful if feedback would come too late.
- Benefits from calibration e.g. tune parameters of approximate model.
- If model unknown, may be able to use statistical learning methods to find a good fit e.g. neural network.

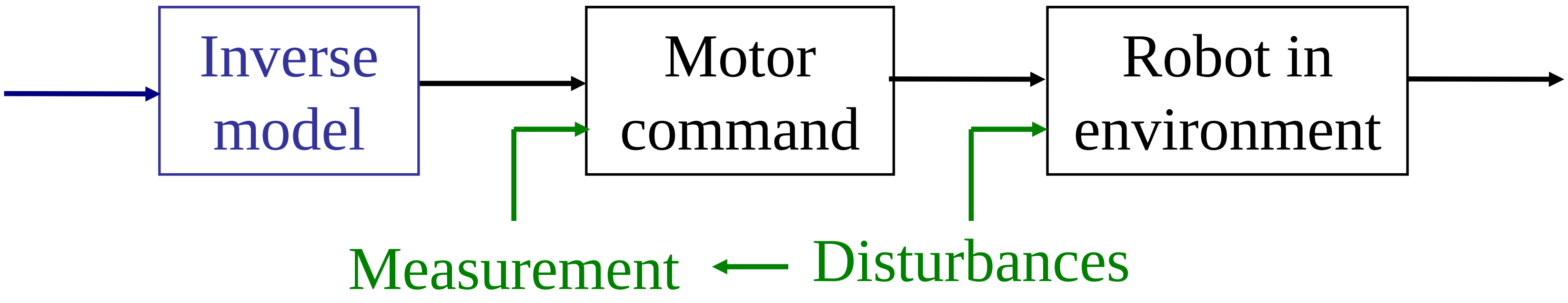
Open loop control

- Neglects possibility of disturbances, which might affect the outcome.



- For example:
  - change in temperature may change the friction in all the robot joints.
  - Or unexpected obstacle may interrupt trajectory

Feed-forward control

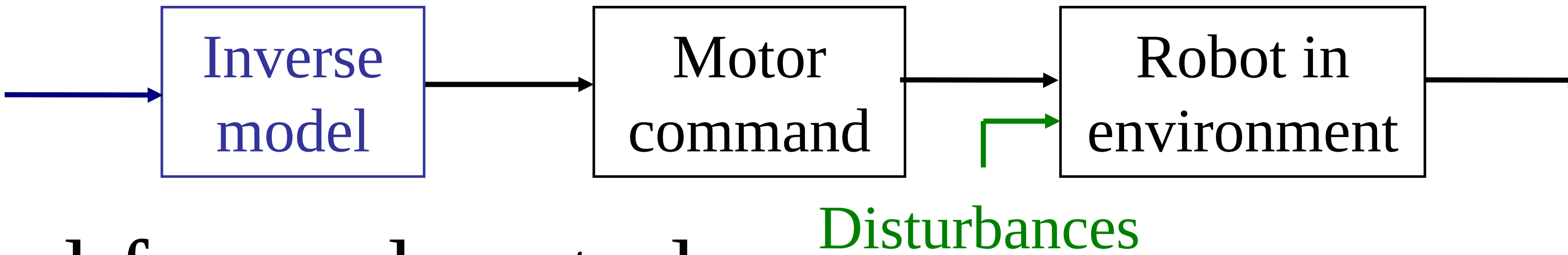


- One solution is to measure the (potential) disturbance and use this to adjust the control signals.
- For example
  - thermometer signal alters friction parameter.
  - obstacle detection produces alternative trajectory.

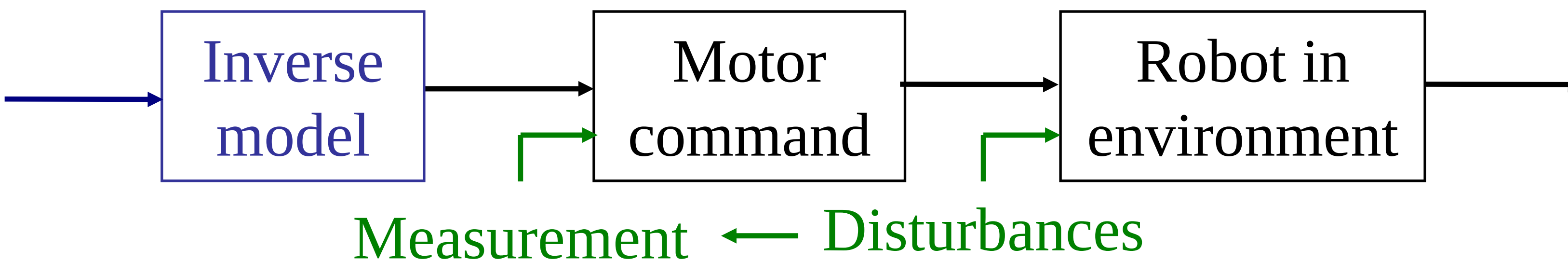
Feed-forward control

- Can sometimes be effective and efficient.
- Requires anticipation, not just of the robot process characteristics, but of possible changes in the world.
- Does not provide or use knowledge of actual output – for this need to use **feedback** control

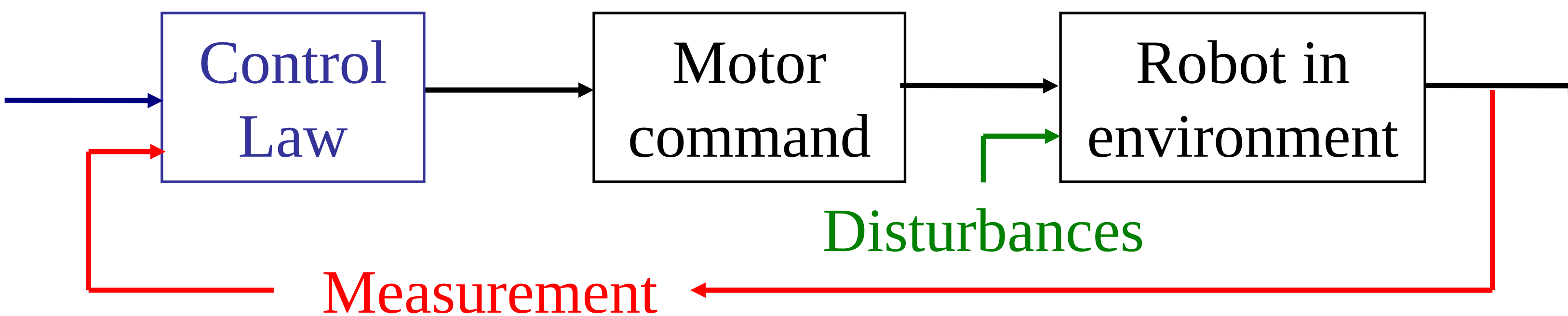
Open loop control:



Feed-forward control:

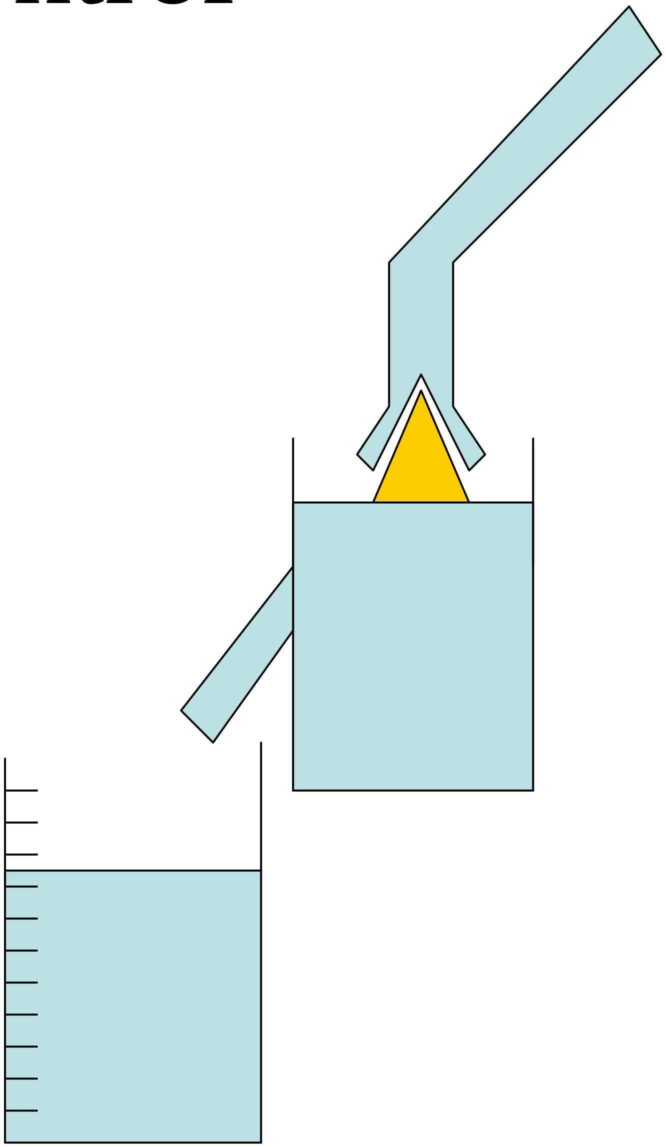


Feed-back control:



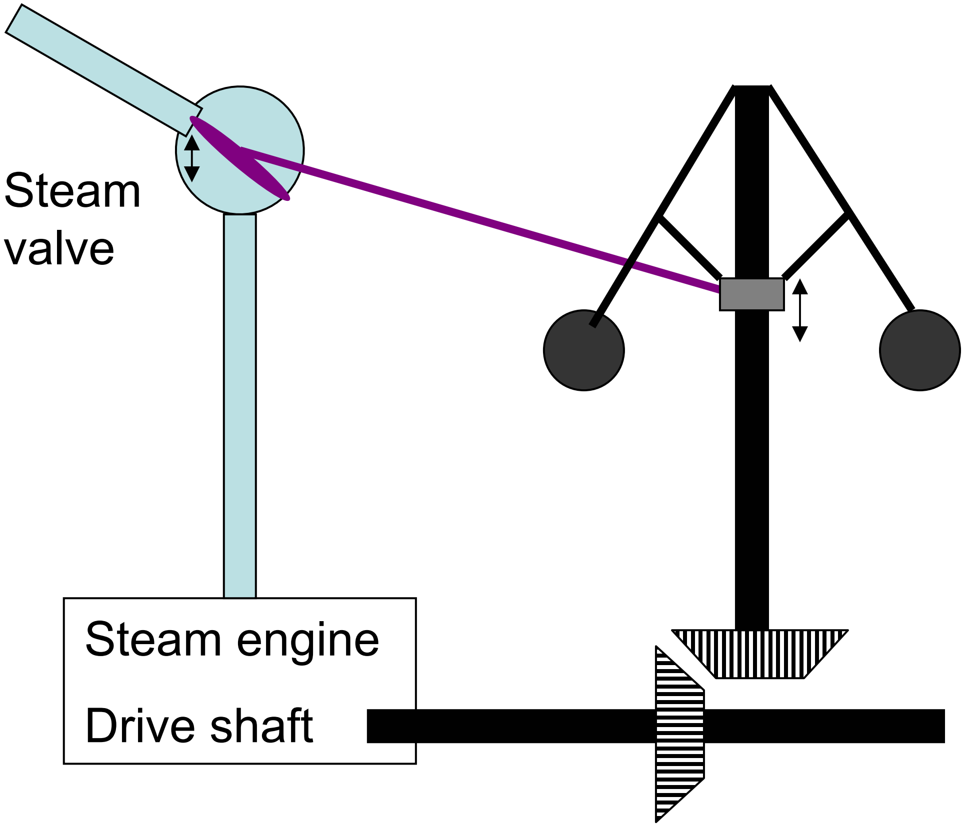
Feedback control

- Example: Greek water clock
- Require constant flow to signal time
- Obtain by controlling water height
- Float controls inlet valve



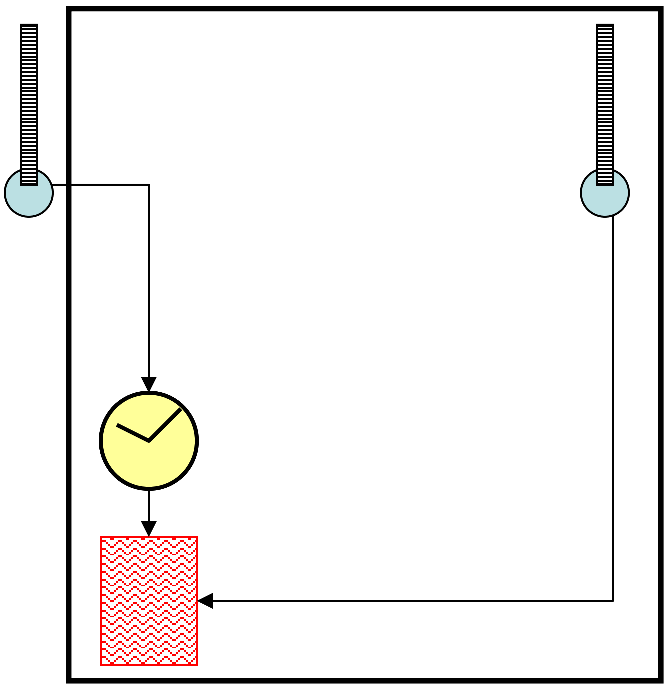
Feedback control

- Example: Watt governor



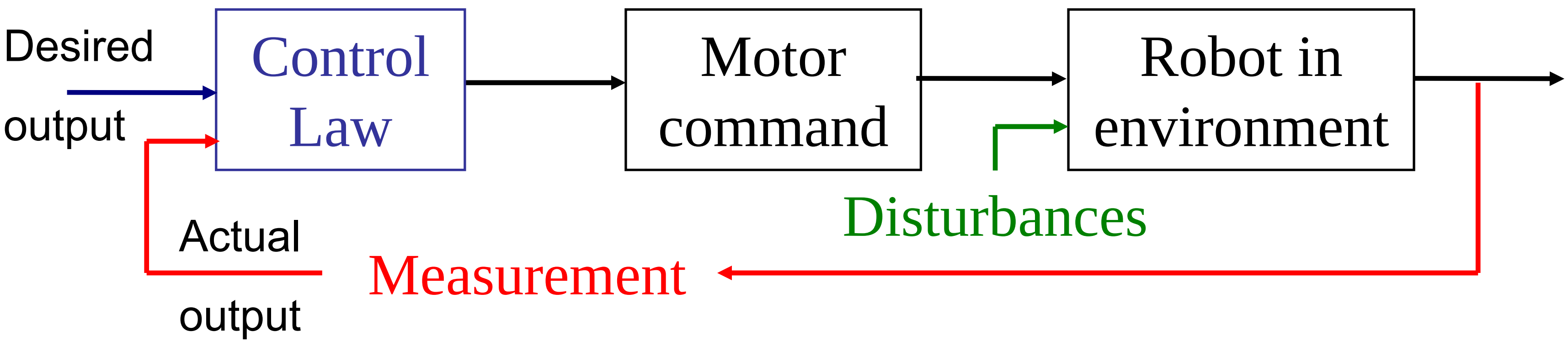
Compare: room heating

- Open loop: for desired temperature, switch heater on, and after pre-set time, switch off.
- Feed forward: use thermometer outside room to compensate timer for external temperature.
- Feedback: use thermometer inside room to switch off when desired temperature reached.

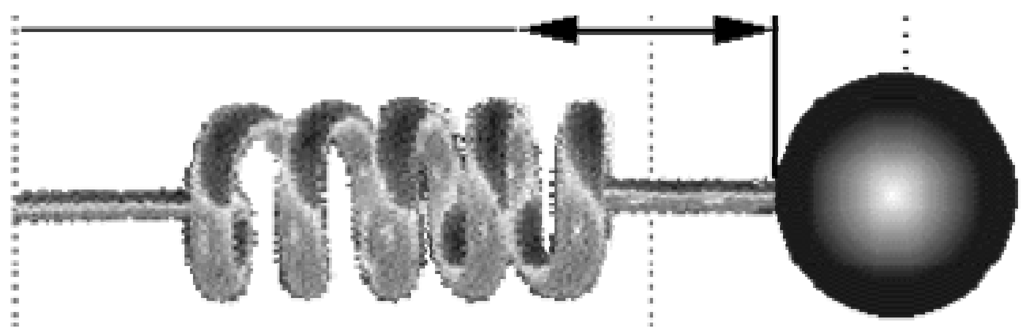


NO PREDICTION REQUIRED!

Control Laws



- On-off: switch system if desired ≠ actual
- Servo: control signal proportional to difference between desired and actual, e.g. spring:



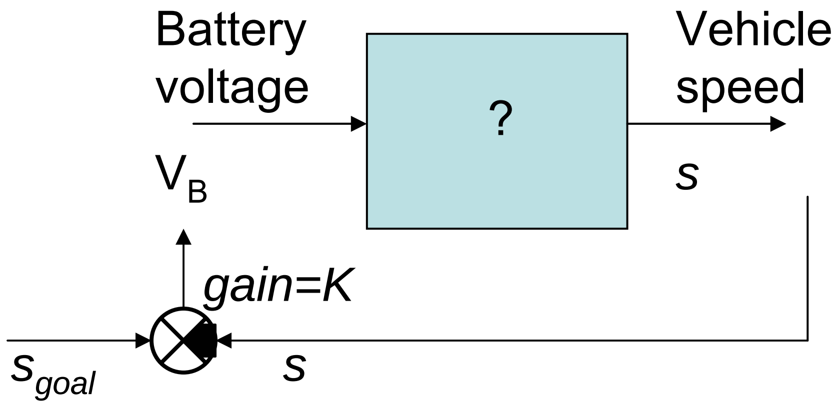
Servo control

Simple dynamic example:

$$V_B = k_1 s + \frac{MR}{k_2}\frac{ds}{dt}$$

Control law:

$$V_B = K(s_{\text{goal}} - s)$$



So now have new process:

$$K(s_{\text{goal}} - s) = k_1 s + \frac{MR}{k_2}\frac{ds}{dt}$$

$$Ks_{\text{goal}} = (K + k_1)s + \frac{MR}{k_2}\frac{ds}{dt}$$

With steady state:

$$s_\infty = {Ks_{\text{goal}}} \big/ {K + k_1}$$

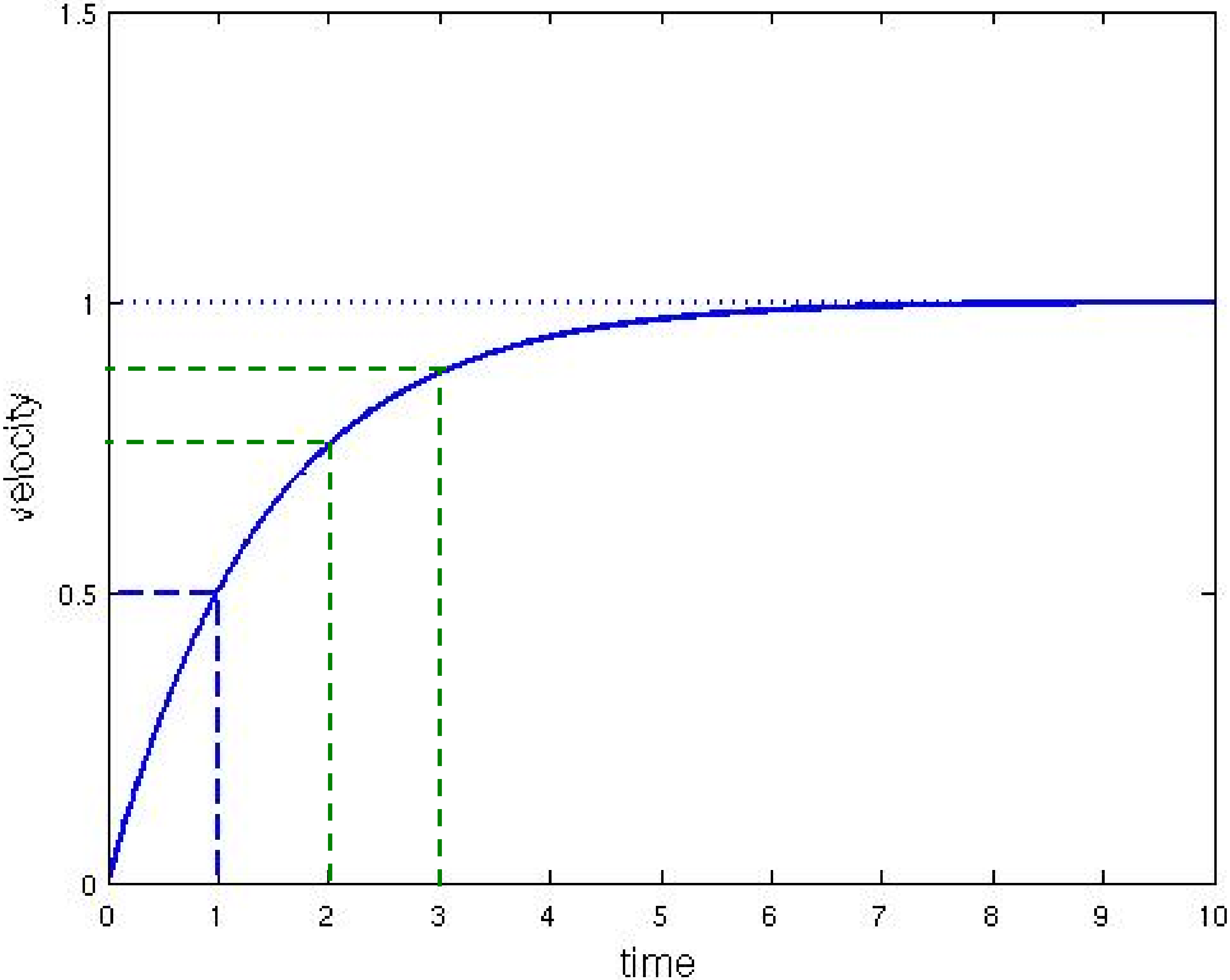
And half-life:

$$\tau_{1/2} = 0.7\frac{MR}{(K + k_1)k_2}$$

- Say we have s_{goal} =10. What does K need to be for s_∞ = 10?

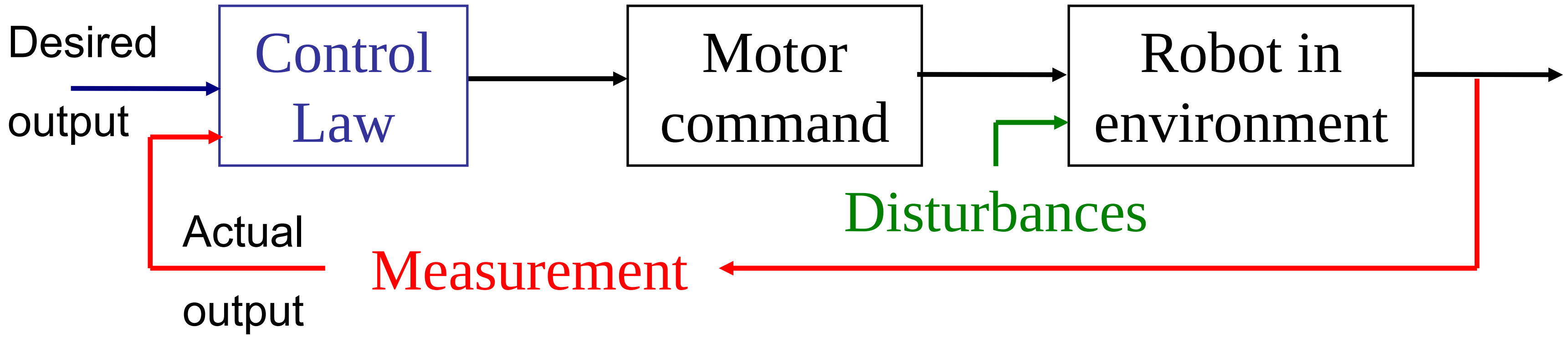
- If K=5, and s_∞ = 8, and the system takes 14 seconds to reach s=6, what is the process equation?

$$Ks_{\text{goal}} = \quad ? \quad s + \ ? \ \frac{ds}{dt}$$



1.5
1
0.5
0
0
1
2
3
4
5
6
7
8
9
10
time
velocity

Complex control law



- May involve multiple inputs and outputs
- E.g. ‘homeostatic’ control of human body temperature
  - Multiple temperature sensors linked to hypothalamus in brain
  - Depending on difference from desired temperature, regulates sweating, vasodilation, piloerection, shivering, metabolic rate, behaviour…
  - Result is reliable core temperature control

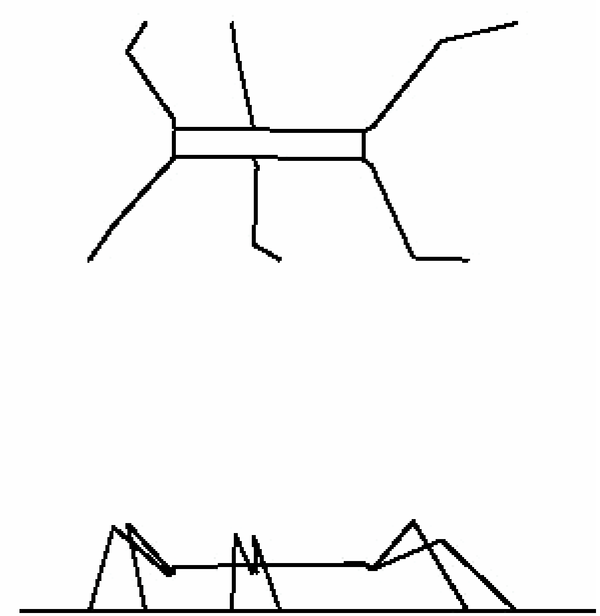
Negative vs. Positive Feedback

- Examples so far have been *negative* feedback: control law involves subtracting the measured output, acting to decrease difference.
- *Positive* feedback results in amplification:
  – e.g. microphone picking up its own output.
  - e.g. ‘runaway’ selection in evolution.
- Generally taken to be undesirable in robot control, but sometimes can be effective
  – e.g. in model of stick insect walking (Cruse et al 1995)

• 6-legged robot has 18 degrees of mobility.

• Difficult to derive co-ordinated control laws

• But have linked system: movement of one joint causes appropriate change to all other joints.



• Can use signal in a feed-forward loop to control 12 joints (remaining 6 use feedback to resist gravity).

Advantages

- Major advantage is that (at least in theory) feedback control does not require a model of the process.
  - E.g. thermostats work without any knowledge of the dynamics of room heating.
- Thus controller can be very simple and direct
  - E.g. hardware governor does not even need to do explicit measurement, representation and comparison
- Can (potentially) produce robust output in the face of unknown and unpredictable disturbances
  - E.g. homeostatic body temperature control keeps working in unnatural environments

Issues

- Requires sensors capable of measuring output
  - Not required by open-loop or feed-forward
- Low gain is slow, high gain is unstable
- Delays in feedback loop will produce oscillations (or worse)
- In practice, need to understand process to obtain good control:
  - E.g. James Clerk Maxwell's analysis of dynamics of the Watt governor
- …more next lecture

Cybernetics

- Feedback control advanced in post WW2 years (particularly by Wiener) as general explanatory tool for all ‘systems’: mechanical, biological, social…
- E.g. Powers –

  “*Behaviour: the control of perception*”
- Forrester –

  “*World dynamics*” – modelling the global economic-ecological network

Combining control methods

- In practice most robot systems require a combination of control methods
  - Robot arm using servos on each joint to obtain angles required by geometric inverse model
  - Forward model predicts feedback, so can use in fast control loop to avoid problems of delay
  - Feed-forward measurements of disturbances can be used to adjust feedback control parameters
  - Training of an open-loop system is essentially a feedback process

Further reading:

Most standard robotics textbooks (e.g. McKerrow) discuss forward and inverse models in great detail.

For the research on saccades see:

Harris, C.M. & Wolpert, D.M. (1998) Signal dependent noise determines motor planning. *Nature*, 394:780-184.

For an interesting discussion of forward and inverse models in relation to motor control in humans, see: Wolpert, DM & Ghahramani, Z. (2000) “Computational principles of movement neuroscience” Nature Neuroscience 3:1212-1217

Further reading:

Most standard robotics textbooks (e.g. McKerrow) discuss feedback control in great depth.

For the research on stick insect walking see:

Cruse, H., Bartling, Ch., Kindermann, T. (1995) High-pass filtered positive feedback for decentralized control of cooperation. In: F. Moran, A. Moreno, J. J. Merelo, P. Chacon (eds.), Advances in Artificial Life, pp. 668-678. Springer 1995

Classic works on cybernetics:

Wiener, Norbert: (1948) *Cybernetics. or Control and Communication in the Animal and Machine*, MIT Press, Cambridge

Powers, WT: (1973) *Behavior, the Control of Perception*, Aldine, Chicago

Forrester, JW (1971) *World Dynamics*, Wright and Allen, Cambridge