Systems Neuroscience CISC 3250

Motor control

Professor Daniel Leeds
dleeds@fordham.edu
JMH 332

Classes of motion

Voluntary

Somatic		Skeletal muscle
Autonomic	Sympathetic Fight or Flight	Smooth muscle
	Parasympathetic Resting state	Cardiac muscle

Involuntary

Pathways to motion in (typically) 2 synaptic steps

0 Command from primary motor cortex (M1)

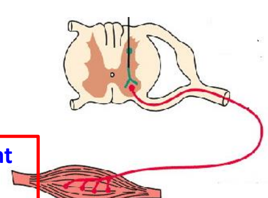
1 Synapse onto neuron in spinal cord/cranial nerve

2 Synapse onto muscle

Efferent – motor message **out**

Afferent – perceptual message **in**

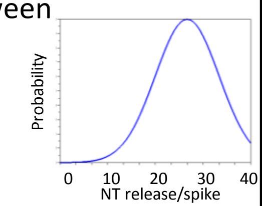
Cortical commands sent to contralateral side of body



Precise motion in an imprecise world

Imprecise neurons

- Efferent signal for motion will present variable number of NT molecules per spike
- Number of spikes may vary between movement repetitions

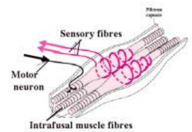


Unreliable world

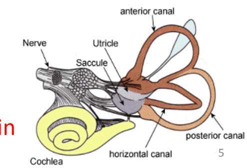
- Wind blows while you pick up a bag
- You trip on unseen object while walking

Monitoring body motion

- Seeing body move (covered in later lecture)
- Skin stretch
- Muscle stretch/contraction – muscle spindles



- Head rotations – inner ear; semi-circular canals



Anterior: Sagittal spin **Posterior**: Coronal spin
Horizontal: Axial spin

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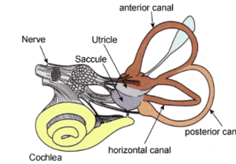
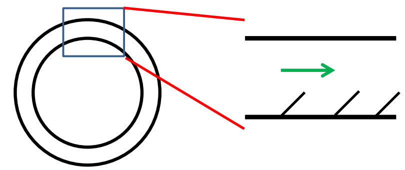
Vestibular system

Three canals on left and right side of head: anterior, posterior, horizontal





1. Head rotates
2. Fluid flows
3. Hairs displaced

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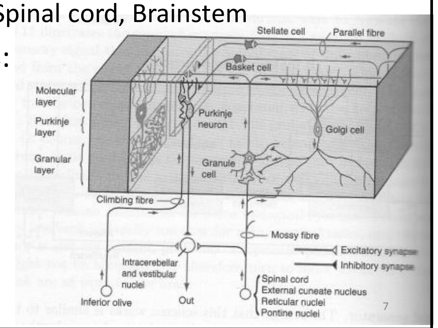
Adjusting motion with the cerebellum

- Compare motor commands to actual motion
- Cerebellar inputs:
  - Climbing fiber from Inferior Olive (brainstem)
  - Mossy fiber from Spinal cord, Brainstem
- Cerebellar outputs:
  - Purkinje cells – inhibition to brainstem



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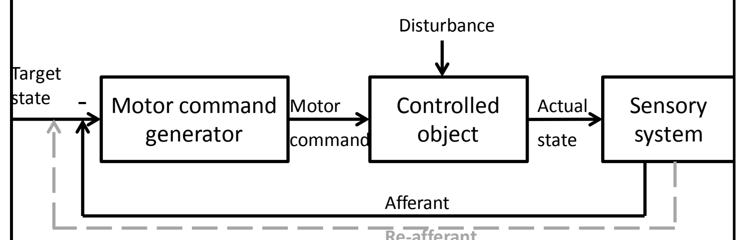
Control theory

Correcting errors in motion



Afferant – muscle sensors

Re-afferant – visual sensors

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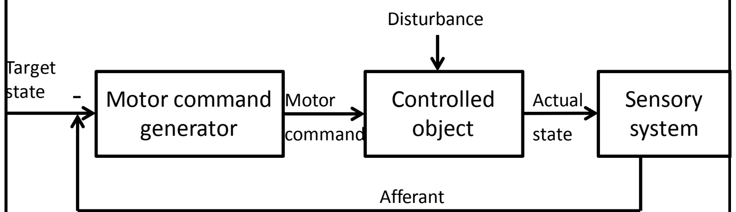
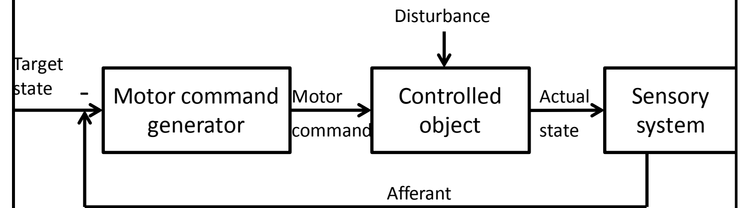
Motor command generation

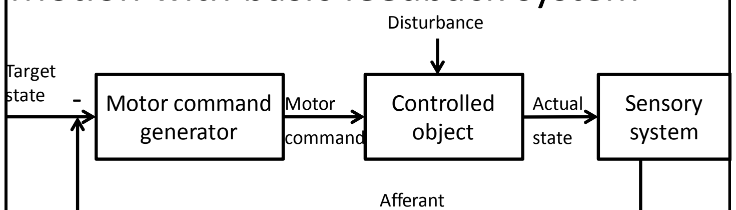
swing leg forward -> rotate leg using muscle force



Motion with basic feedback system

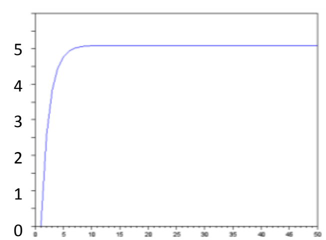


Motion with basic feedback system



Move = 1/2 x (**T**arget-**C**urrent)

Target: 5
t=1 Start at 0



Motion strategy

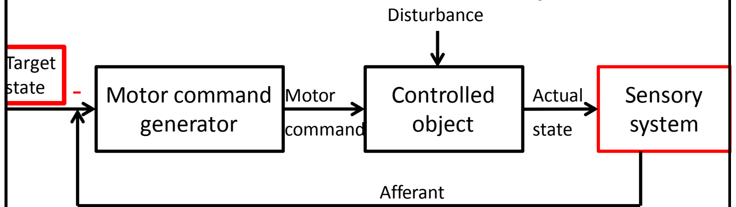
Move = 1/2 x (**T**arget-**C**urrent)

	t=1	t=2	t=3	t=4	t=5
Sense	0	2.5	3.75	4.38	4.69
Move	+2.5	+1.25	+.63	+.31	...
Actual	0	2.5	3.75	4.38	4.69

Target: 5
t=1 Start at 0

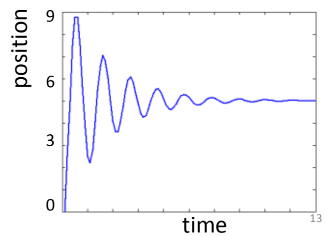
$Actual_t = Actual_{t-1} + Move_{t-1}$
$Sense_t = Actual_{t-delay}$

Motion with basic feedback system



Move = 1/2 x (**T**arget-**S**ensed)

Target: 5
t=1 Start at 0
Sense delay: 2 time points



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Motion strategy

Move = 1/2 x (**T**arget-**S**ensed)

	t=1	t=2	t=3	t=4	t=5	t=6
Sense	0	0	0	2.5	5	7.5
Move	+2.5	+2.5	+2.5	+1.25	0	-1.25
Actual	0	2.5	5	7.5	8.75	8.75

Target: 5
t=1 Start at 0
2 time point sensation delay

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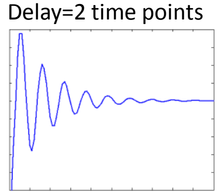
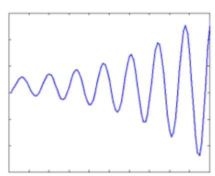
Delay-based Oscillations

- If sense delay and update fraction (**1/2**x(Targ-Sens)) are small, oscillations will converge to target

Update: ½
Delay=2 time points



- If sense delay and/or update fraction (**1/2**x(Targ-Sens)) are large, oscillations will get larger and NOT converge to target



Update: ½
Delay=3 time points

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Simulating in Matlab

`actual(n)` is actual at time n-2

```
target=5;
actual(1)=0;
actual(2)=0;
actual(3)=0;
sens(3)=actual(1);
mov=0.5*(target-sens(3));
actual(4)=actual(3)+mov;
sens(4)=actual(2);
mov=0.5*(target-sens(4));
actual(5)=actual(4)+mov;
...
sens(31)=actual(29);
mov=0.5*(target-sens(31));
actual(32)=actual(31)+mov
```

$Sen_t=Act_{t-2}$
$Mov=.5x(Tar-Sen)$
$Act_{t+1}=Act_t+Mov$

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Simulating in Matlab

```
target=5;
actual(1)=0;
actual(2)=0;
actual(3)=0;
for n=3:31,
  sens(n)=actual(n-2);
  mov=0.5*(target-sens(n));
  actual(n+1)=actual(n)+mov;
end;
```

delay

fract

Expanded control theory

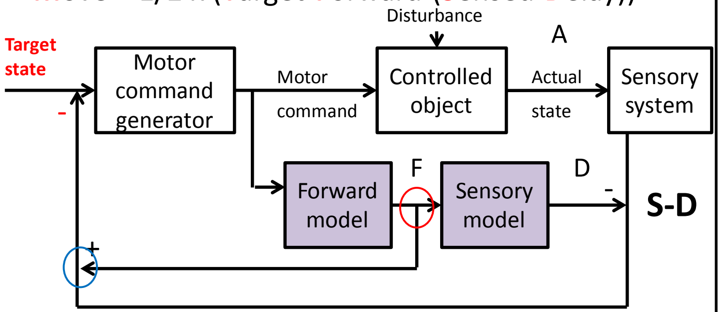
Challenge: Waiting for afferent feedback is slow

Solutions:

- Anticipate typical motion progress – **forward model**
- Account for typical motion progress from the beginning – **inverse model**

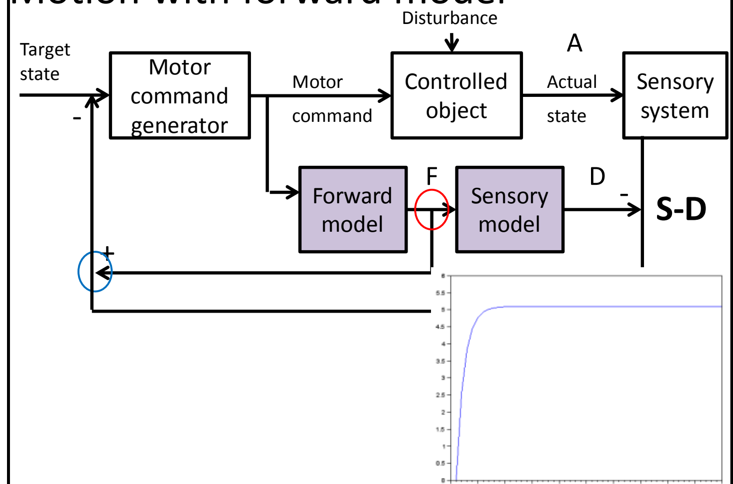
Forward model

Move = 1/2 x (**T**arget-**F**orward-(**S**ensed-**D**elay))



- Forward: Adjust motion based on predicted position
- Delay: Predicted motion with time delay
- Sense: Adjust predicted error based on actual position
- Adjust models (over longer experience)

Motion with forward model



Motion strategy

How you expect you'll move if nothing unusual happens

Normally == 0 if nothing unusual happens

Move = 1/2 x (**T**arget-**F**orward-(**S**ensed-**D**elay))

	t=1	t=2	t=3	t=4	t=5	t=6
Sense	0	0	0	2.5		
Forward	0	2.5	3.75			
Delay	0	0	0	2.5		
Actual	0	2.5	3.75			
Move	**+2.5**	**+1.25**	**+0.625**			

Target: 5

t=1 Start at 0

2 time point sensation delay

$Forward_t = Forward_{t-1} + Move_{t-1}$

$Delay_t = Forward_{t-delay}$

$Actual_t = Actual_{t-1} + Move_{t-1}$

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Motion strategy

Move = 1/2 x (**T**arget-**F**orward-(**S**ensed-**D**elay))

	t=1	t=2	t=3	t=4	t=5	t=6
Sense	0	0	0	2.5	3.75	4.38
Forward	0	2.5	3.75	4.38	4.69	4.85
Delay	0	0	0	2.5	3.75	4.38
Actual	0	2.5	3.75	4.38	4.69	4.85
Move	**+2.5**	**+1.25**	**+.63**	**+.31**	**+.16**	**+.08**

Target: 5

t=1 Start at 0

2 time point sensation delay

$Forward_t = Forward_{t-1} + Move_{t-1}$

$Delay_t = Forward_{t-delay}$

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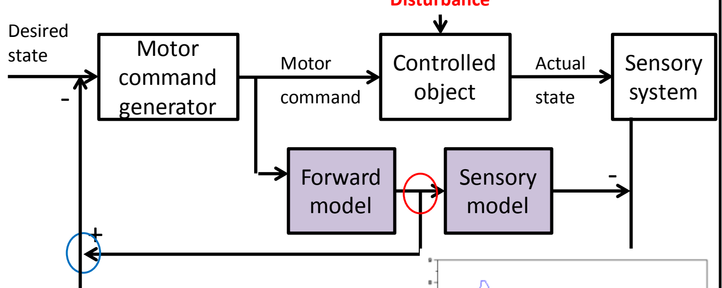
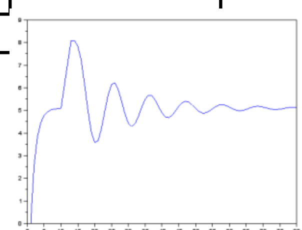
Motion with forward model + push





desired location = 5 starting location = 0 **sensory delay = 2**

push forward by 2 at time 1 no other

	1	2	3	4	5
Act	0	4.5	**5.75**	6.38	
For	0	2.5	3.75	4.38	
Sen	0	0	0	4.5	
Del	0	0	0	2.5	
Mov	**+2.5**	**+1.25**	**+0.625**	**-0.69**	

Moved by +2.5, Pushed by +2 (1→2); Moved by +1.25 (2→3); Moved by +0.63 (3→4); Moved by +(0.62-**2**)/2 (4→5)

Move = 1/2 x (**T**arg-**F**orw-(**S**ens-**D**el))

Compare model motion and actual motion after 2 time step delay

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desired location = 5 starting location = 0 sensory delay = 2
push forward by 2 at time 1 no other

Moved by +2.5 / Pushed by +2 (1→2); Moved by +1.25 (2→3); Moved by +0.63 (3→4); Moved by +0.32-**2/2** (4→5)

	1	2	3	4	5
A	0	4.5	5.75	6.38	5.7
F	0	2.5	3.75	4.38	4.7
S	0	0	0	4.5	5.75
D	0	0	0	2.5	3.75

Compare model motion and actual motion after 2 time step delay

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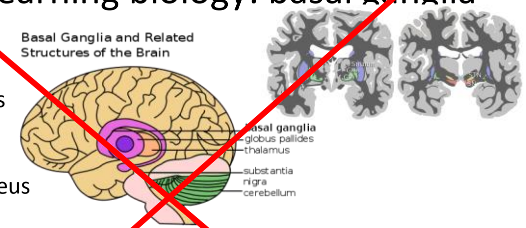
Motor learning biology: basal ganglia

Striatum
- Putamen
- Caudate nucleus

Globus pallidus
Substantia nigra
Sub-thalamic nucleus (STN)



Nat Revw Neuro
Bostan and Strick 2018
https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6503669/

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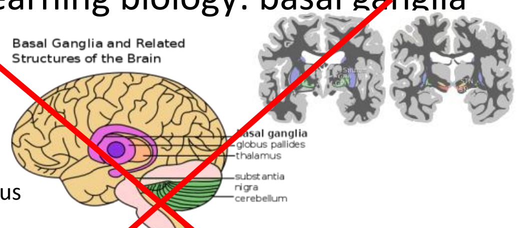

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