普遍法则与架构

Universal laws and architectures:

Theory and lessons from

brains, hearts, cells, grids, nets, bugs,
fluids, bodies, planes, docs, fire, fashion,
earthquakes, music, buildings, cities, art, running,
cycling, throwing, Synesthesia, spacecraft, statistical mechanics and zombies

John Doyle 道耀
Jean-Lou Chameau Professor
Control and Dynamical Systems, EE, & BioE
Ca#1tech
https://www.cds.caltech.edu/~doyle

普遍法则与架构

Universal laws and architectures: The videos

The following preview is approved for all audiences. ~~and zombies~~

https://www.cds.caltech.edu/~doyle

Thanks to

- **Yorie Nakahira,** Nikolai Matni,Yuh Shiang Wang, James Anderson, Yoke Peng Leong, Quanying Liu, …
- **Terry Sejnowski, Marie Csete**, Simon Laughlin, Richard Murray
- ARO (MURI), NSF, AFOSR, DARPA
- Google, Cisco, Northrup-Grumman, Huawei

In attendance

Reading

Theoretical foundations for layered architectures and speed-accuracy tradeoffs in sensorimotor control

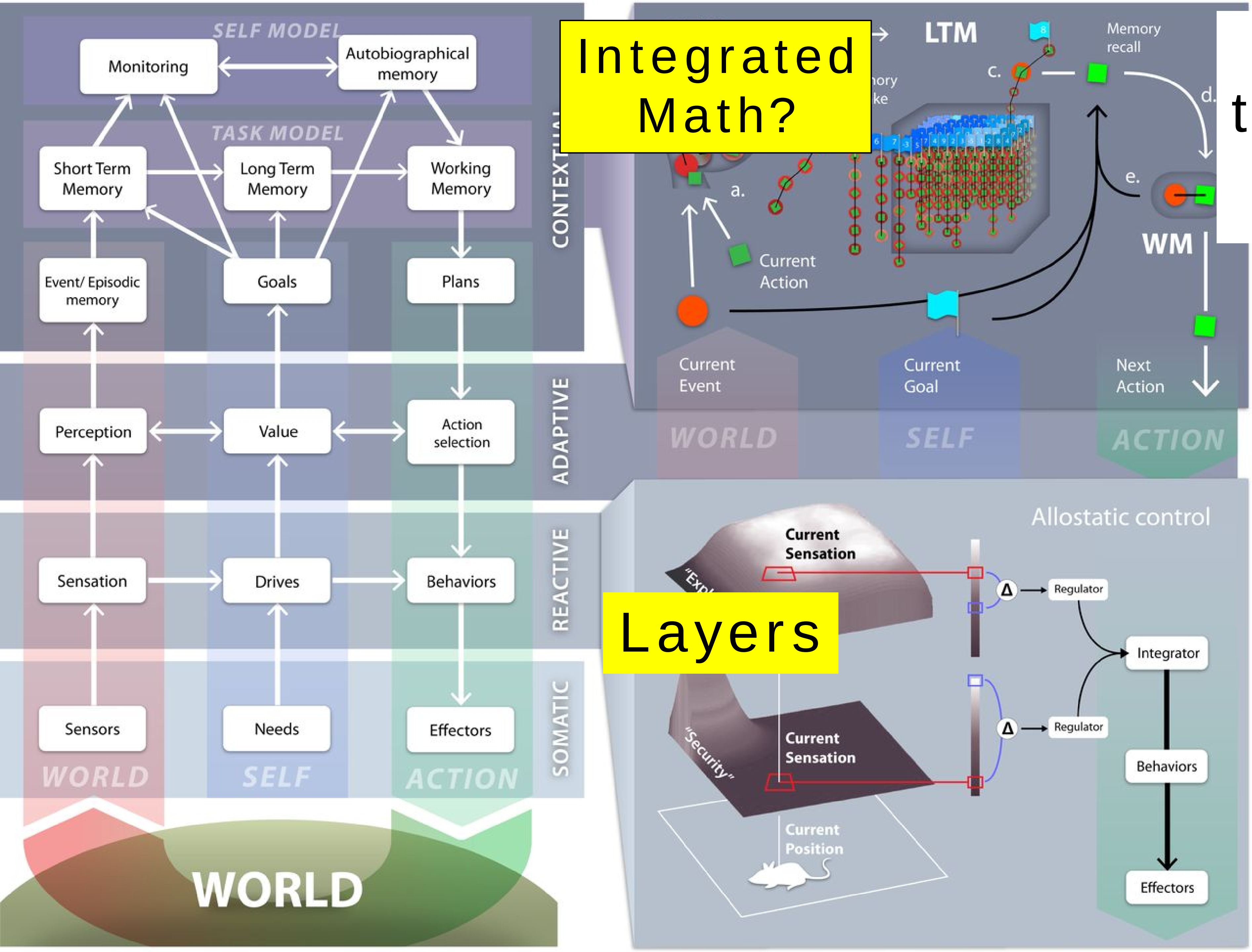
Yorie Nakahira[1], Quanying Liu[1], Natalie Bernat[1], Terry Sejnowski[2], John Doyle[1]

Experimental and educational platforms for studying architecture and tradeoffs in human sensorimotor control

Quanying Liu[1], Yorie Nakahira[1], Ahkeel Mohideen[1], Adam Dai[1],
Sunghoon Choi[1], Angelina Pan[1], Dimitar M. Ho[1] and John C. Doyle[1]

System Level Synthesis: A Tutorial

John C. Doyle, Nikolai Matni, Yuh-Shyang Wang, James Anderson, and Steven Low

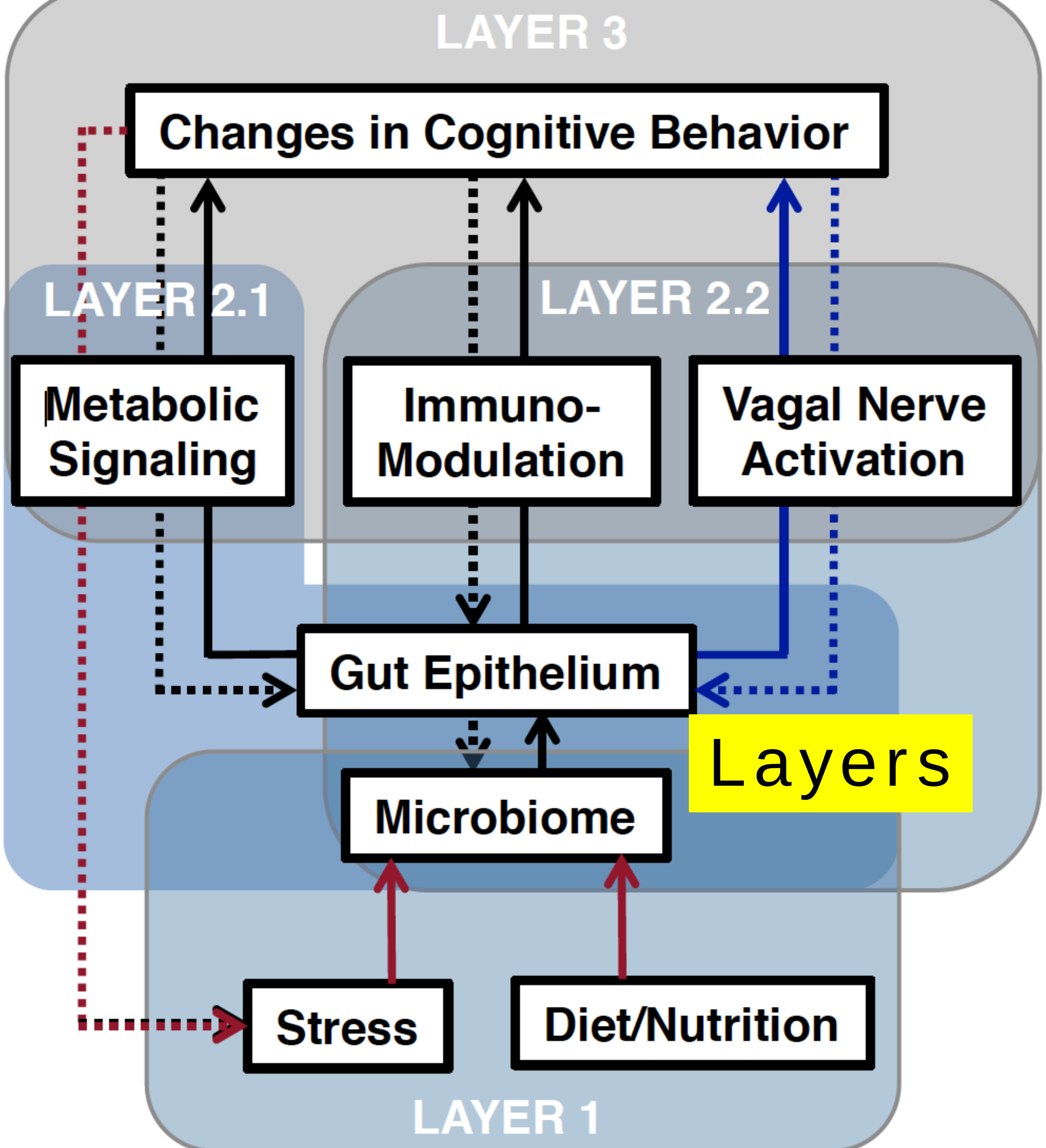


Integrated Math?

The DAC theory of mind and brain

The why, what, where, when and how of goal-directed choice: neuronal and computational principles

Paul F. M. J. Verschure et al. Phil. Trans. R. Soc. B 2014;369:20130483

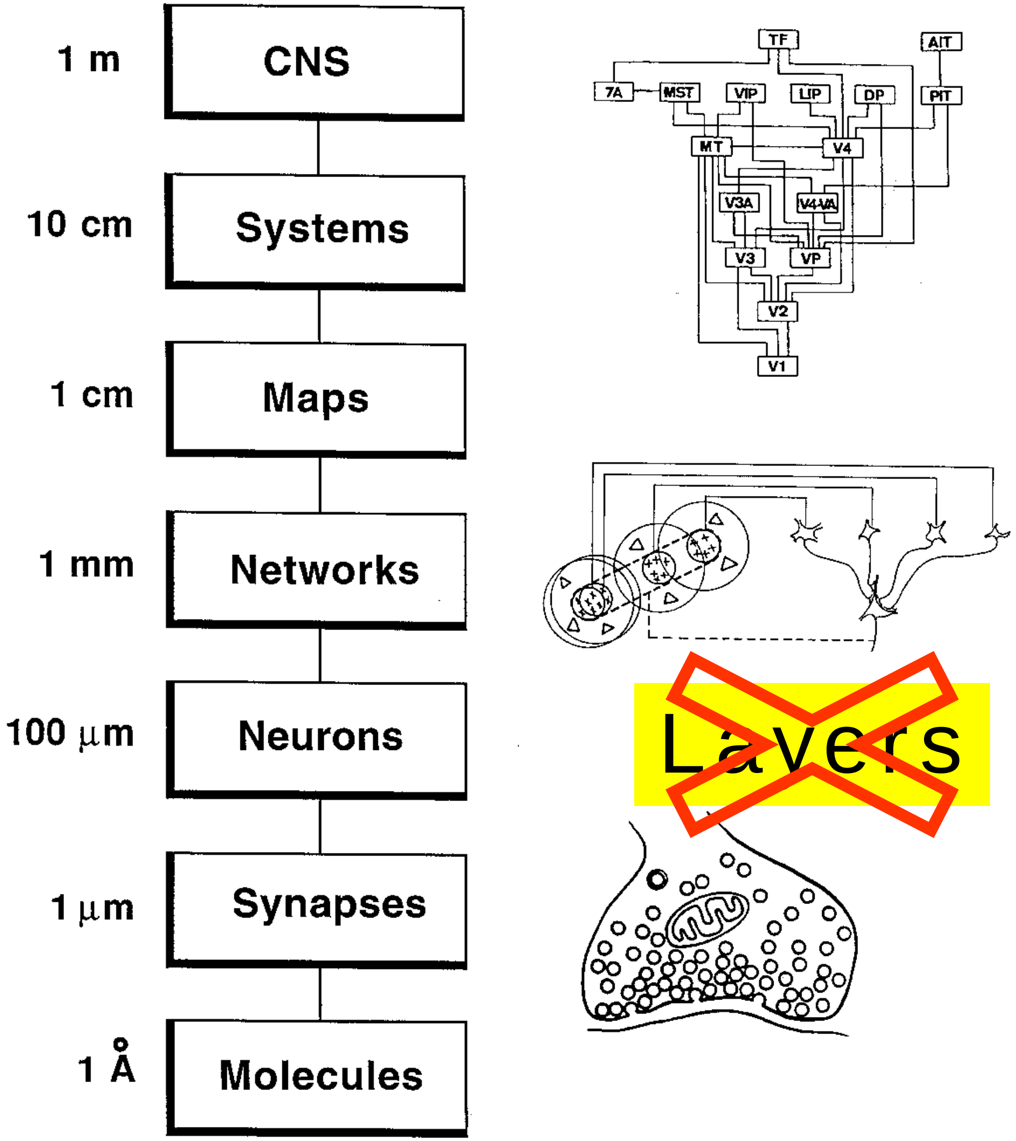


Extreme diversity

What is done?
Where?
How?
Why?
Necessary?

Elaine Hsiao, UCLA

Levels of Investigation

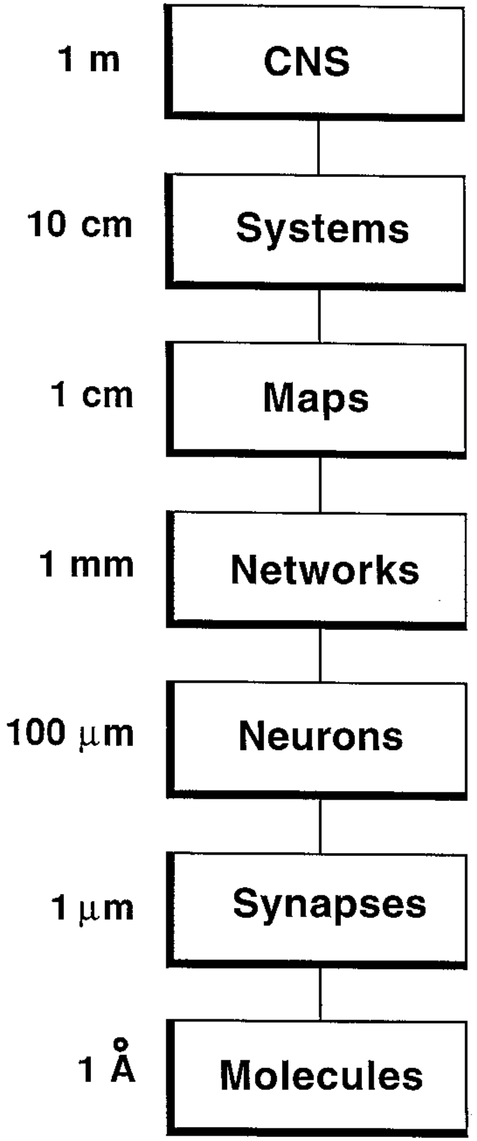


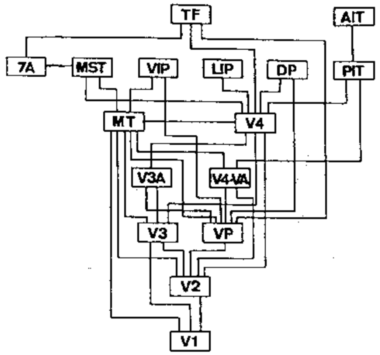
Extreme diversity

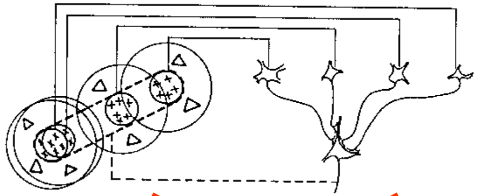
Levels
+
Layers

Sejnowski

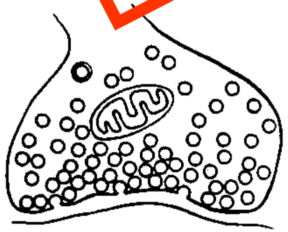
Levels of Investigation



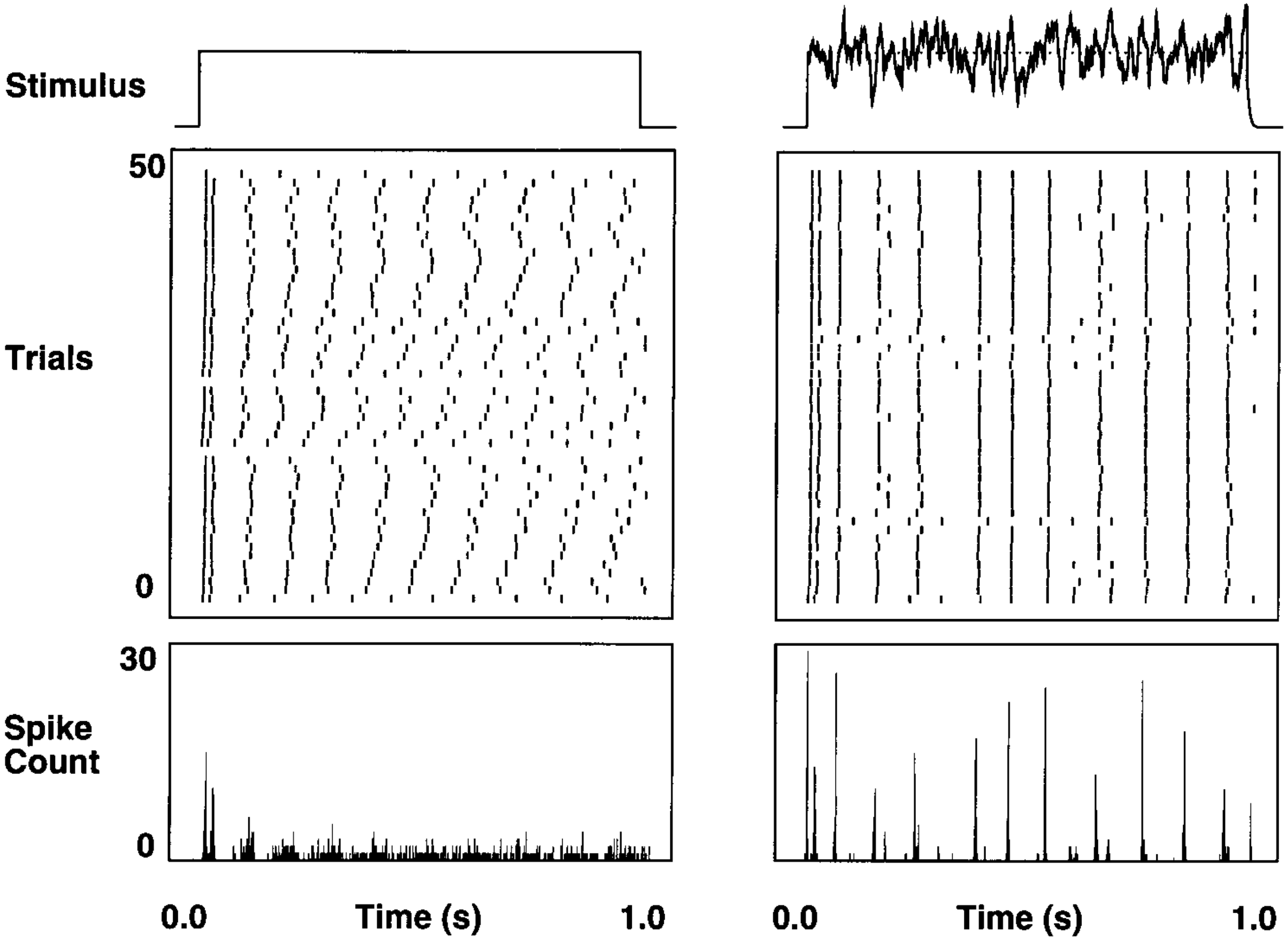




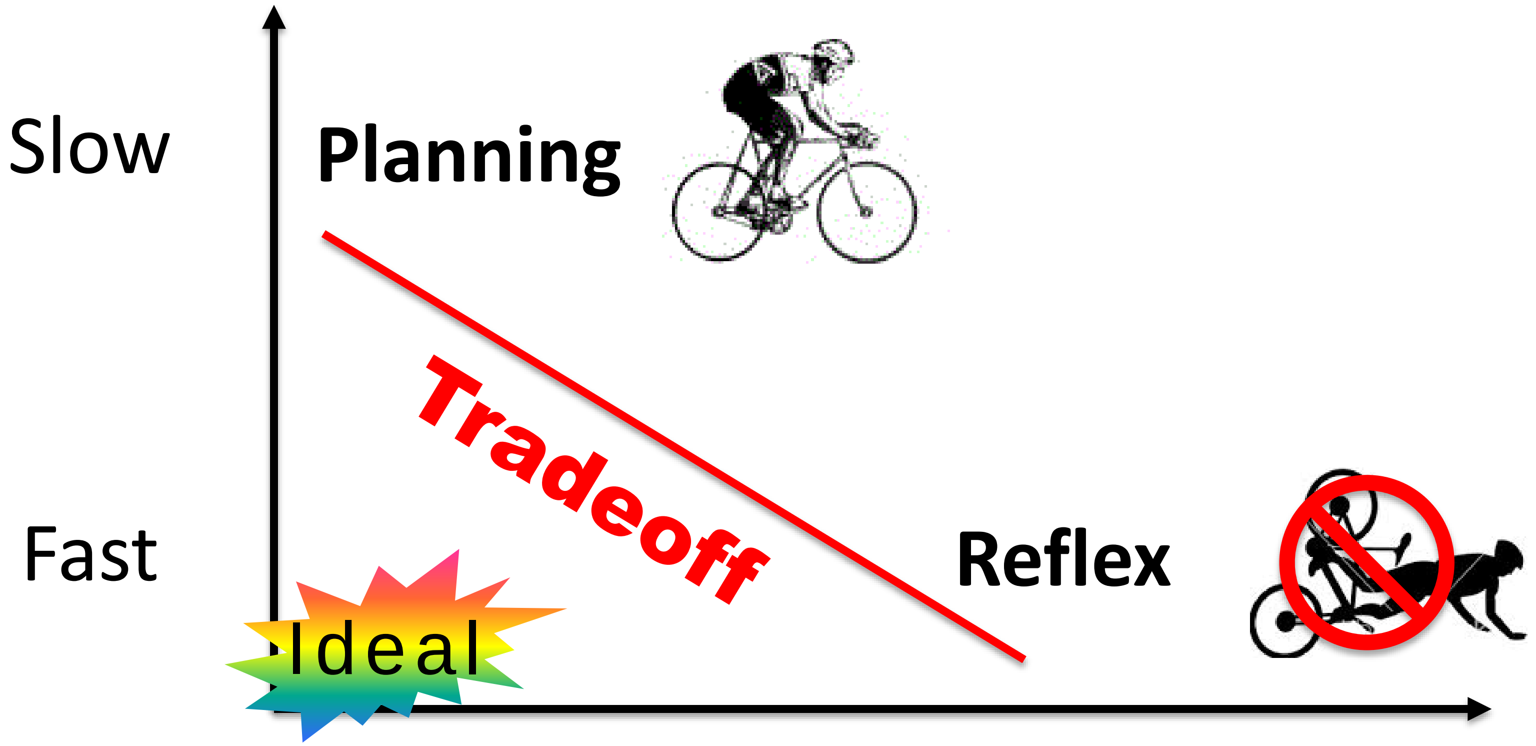
~~Layers~~



Spike Timing Reliability

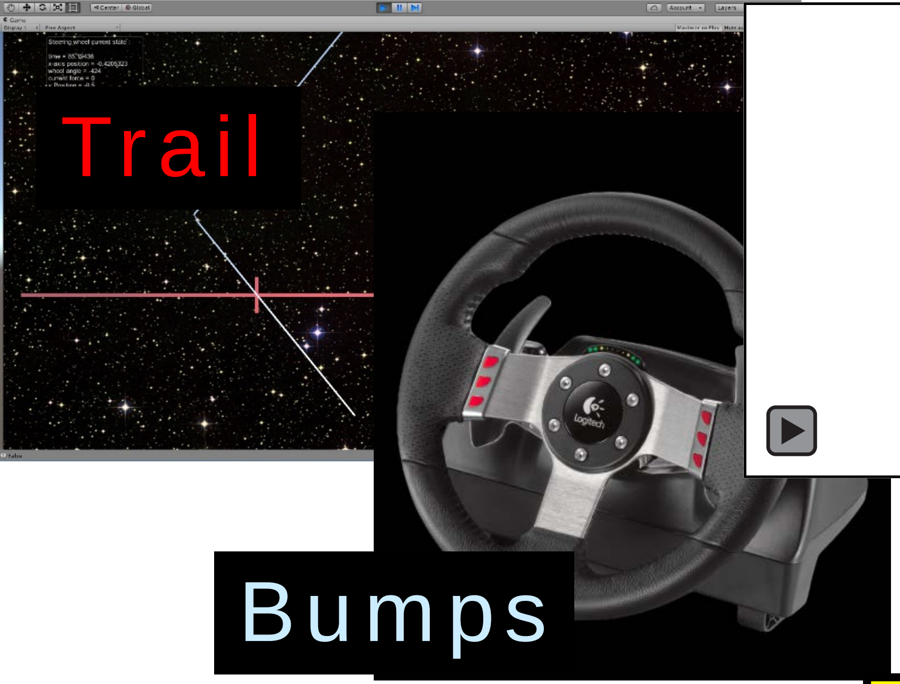


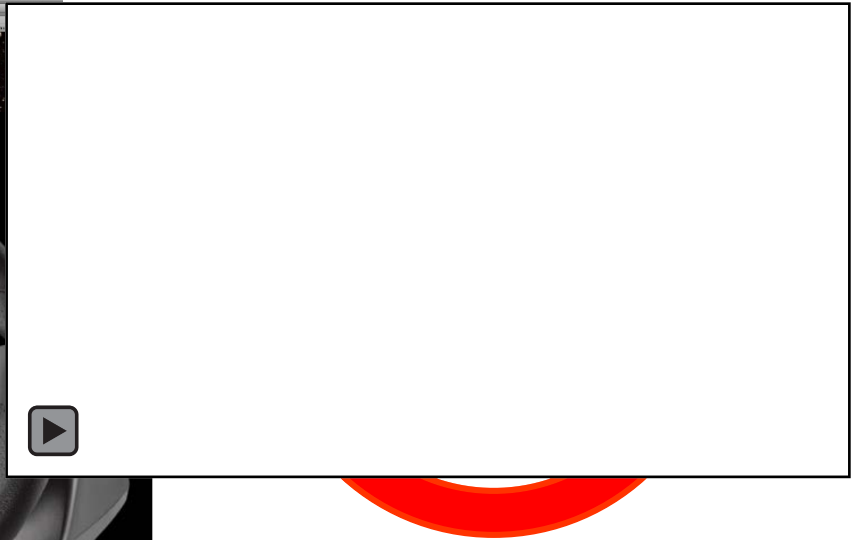
Mainen and Sejnowski, 1995



Accurate	Inaccurate
Flexible	Rigid
Centralized	Localized, distributed
Conscious	Unconscious
Deliberate	Automatic
Stable virtual	Unstable real dynamics

Layers



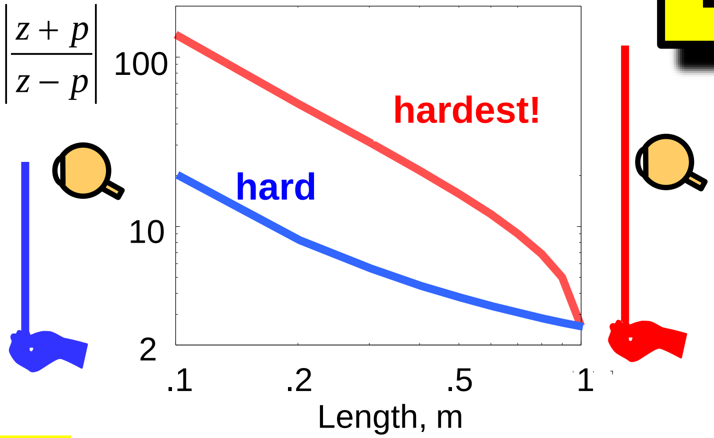


Object motion

Slow

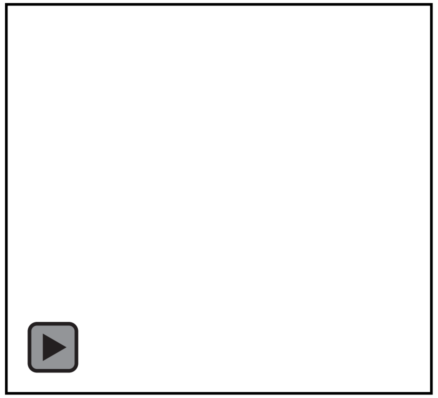
Experiments

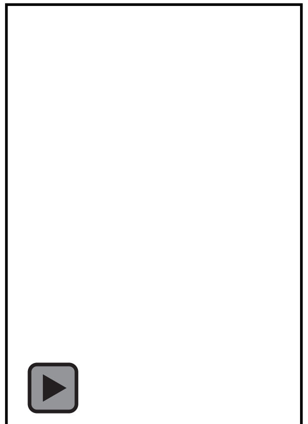
$$\exp(p\tau)\left|\frac{z+p}{z-p}\right|$$



Waterbed

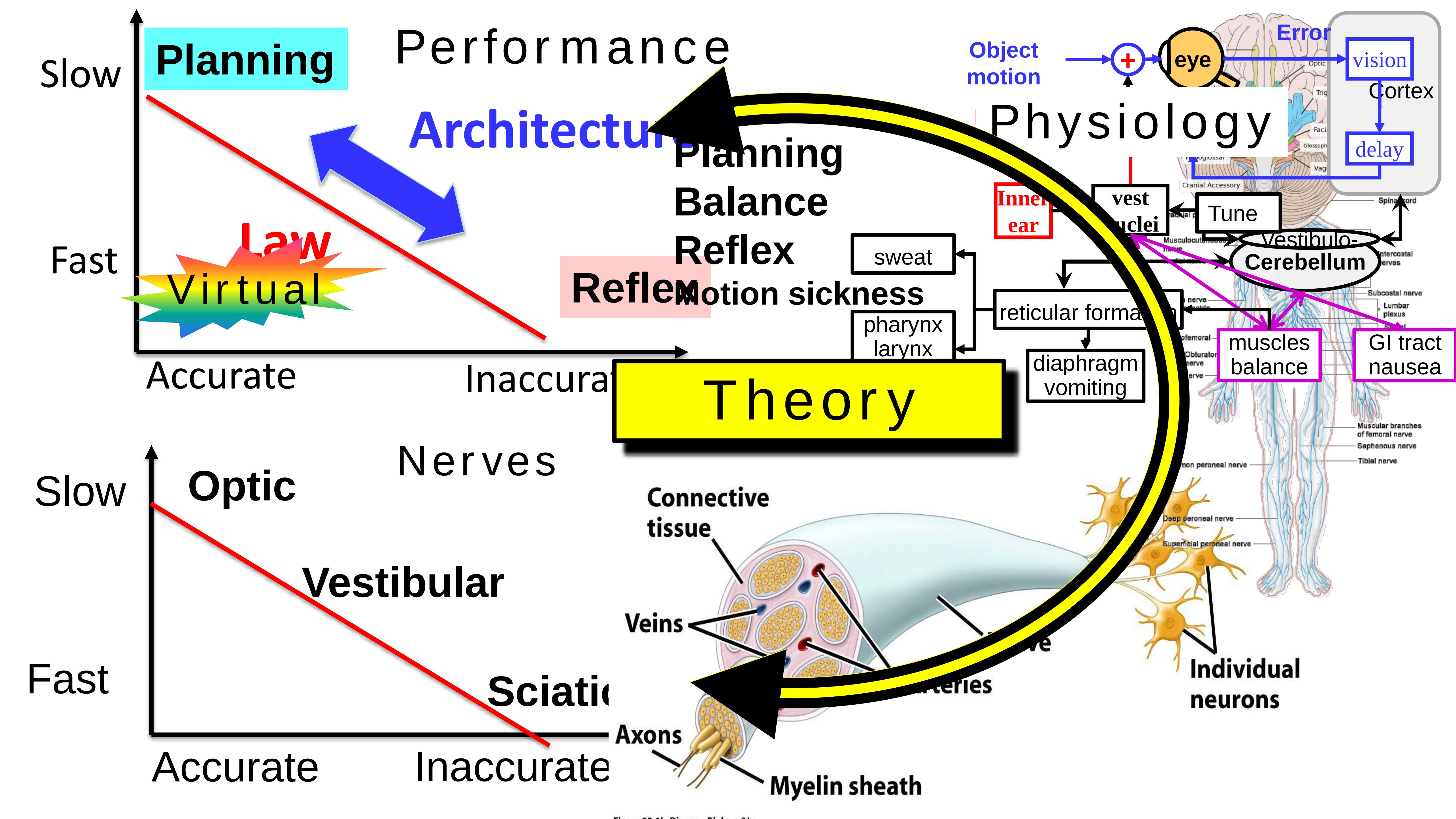
$$\left.\begin{array}{c}\exp\left(\int \ln|T|\right)\\ \|T\|_\infty\end{array}\right\} \geq \exp(p\tau)\left|\frac{z+p}{z-p}\right|$$



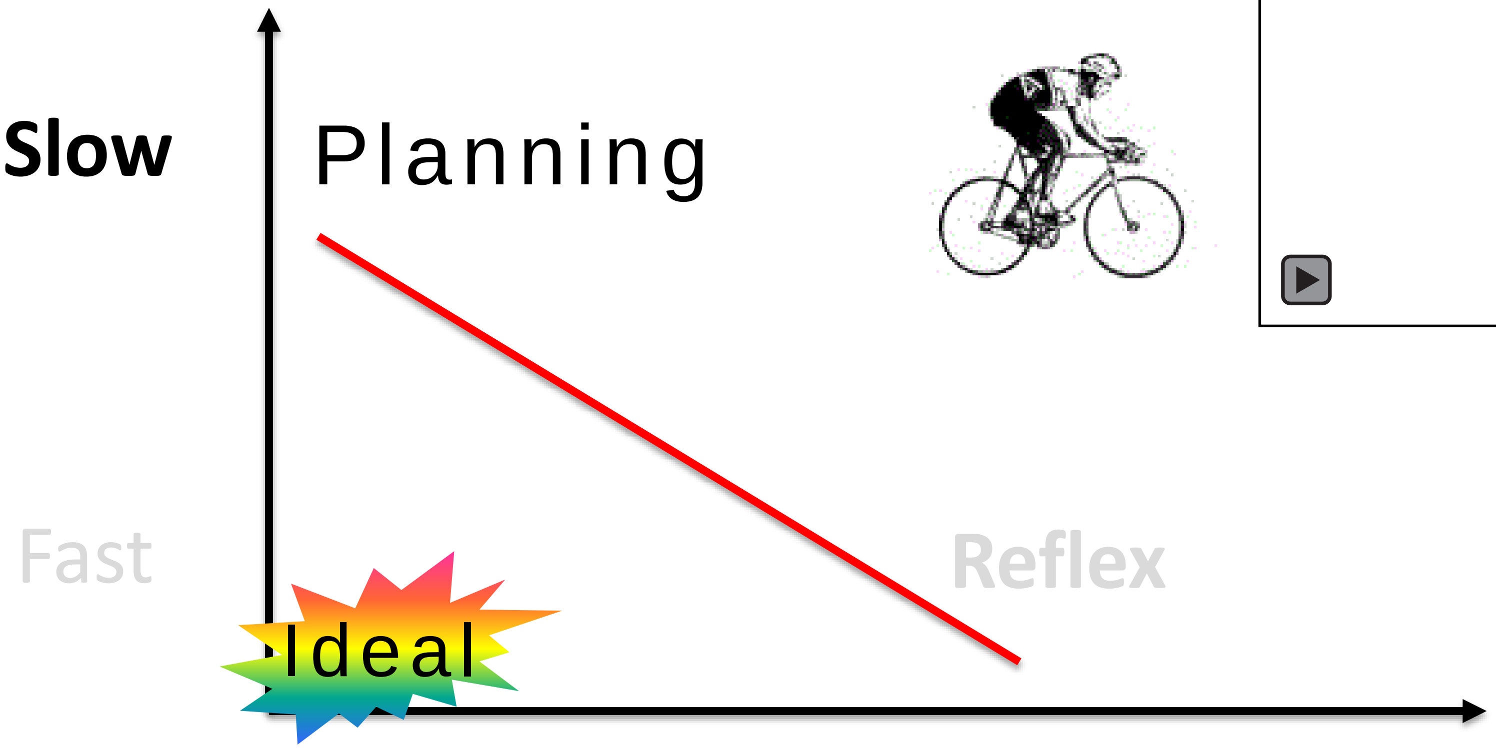


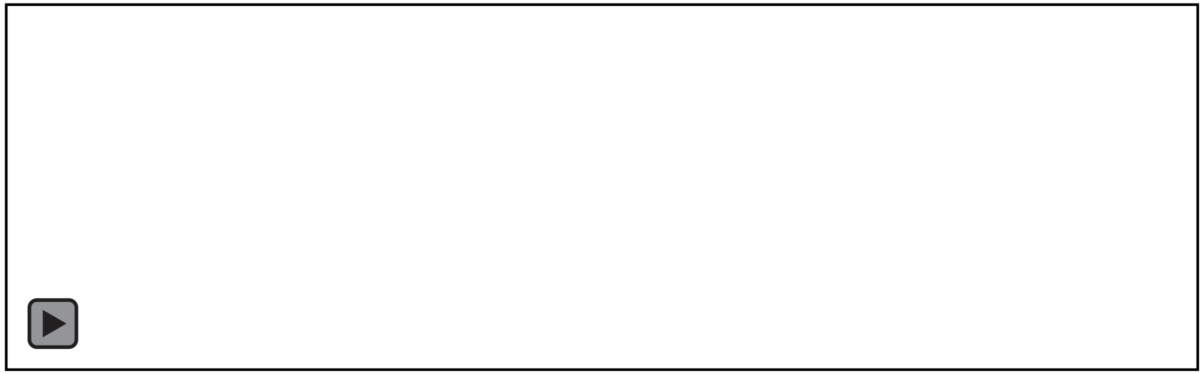
Head motion

Fast



Performance
Slow
Fast
Planning
Architecture
Law
Virtual
Reflex
Accurate
Inaccurate
Planning
Balance
Reflex
Motion sickness
Theory
Object motion
Error
eye
vision
Cortex
delay
Physiology
Inner ear
vest nuclei
Tune
Vestibulo-
Cerebellum
sweat
reticular formation
pharynx larynx
diaphragm vomiting
muscles balance
GI tract nausea
Nerves
Slow
Fast
Optic
Vestibular
Sciatic
Accurate
Inaccurate
Connective tissue
Veins
Arteries
Axons
Myelin sheath
Individual neurons



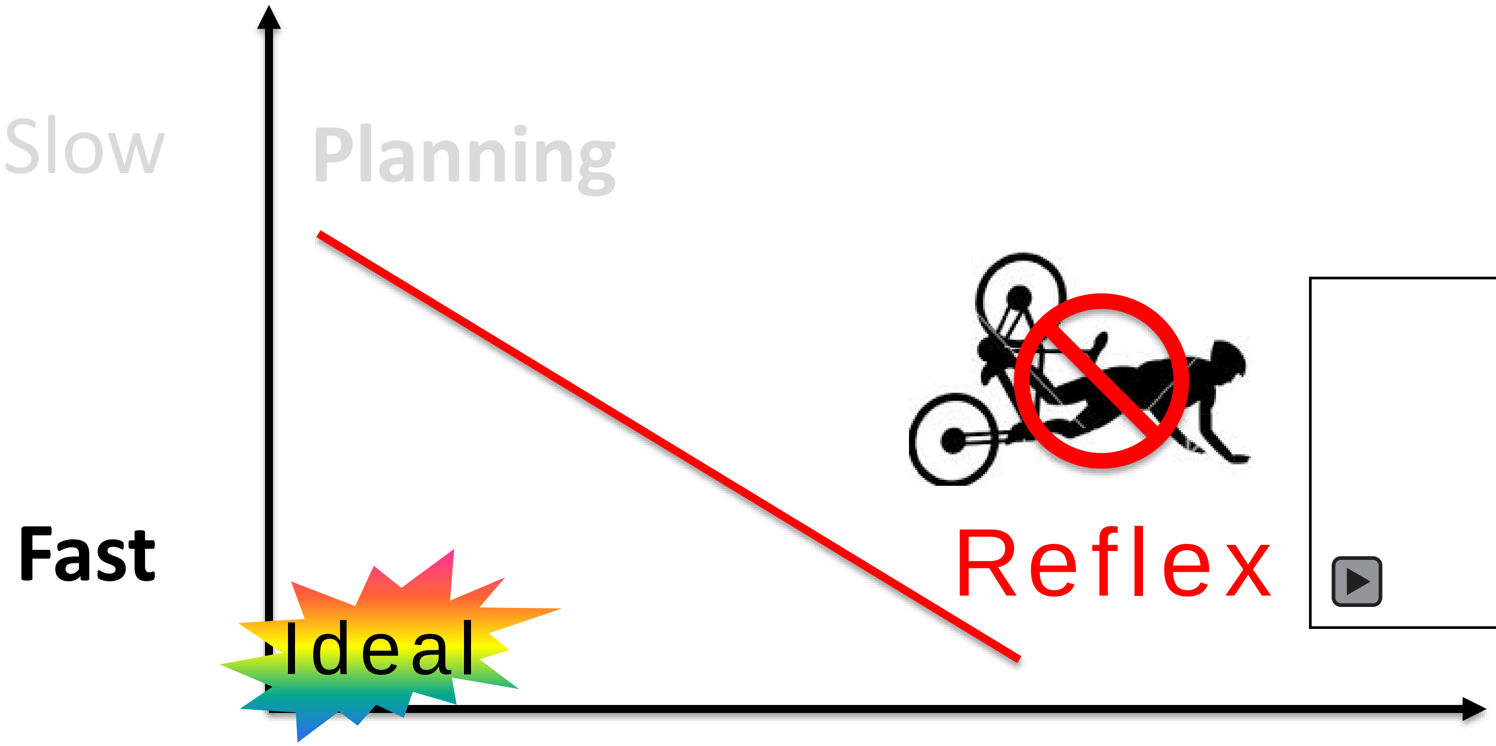


Trail
Vision

Layers

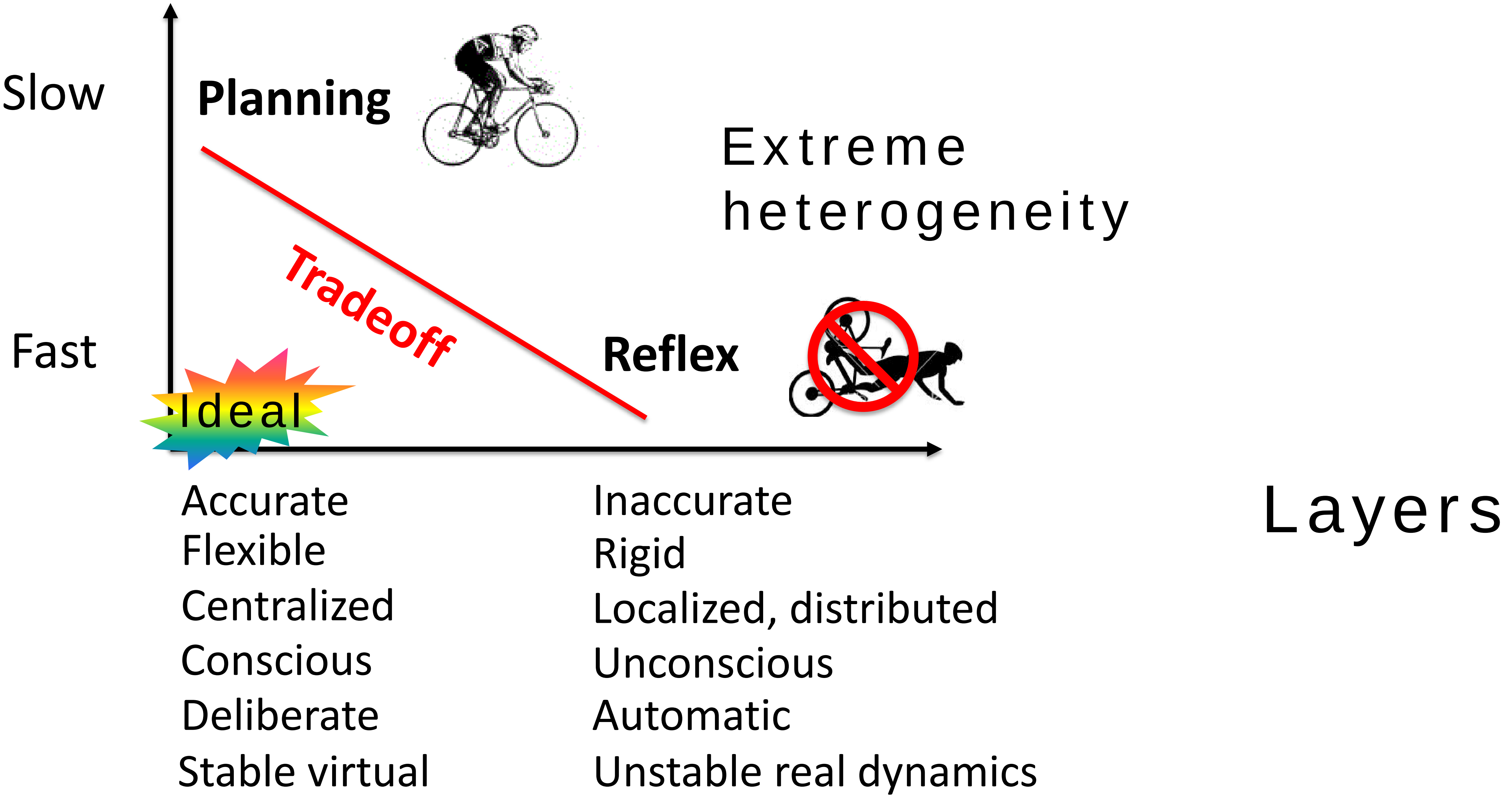
Accurate	Inaccurate
Flexible	Rigid
Centralized	Localized, distributed
Conscious	Unconscious
Deliberate	Automatic
Stable virtual	Unstable real dynamics

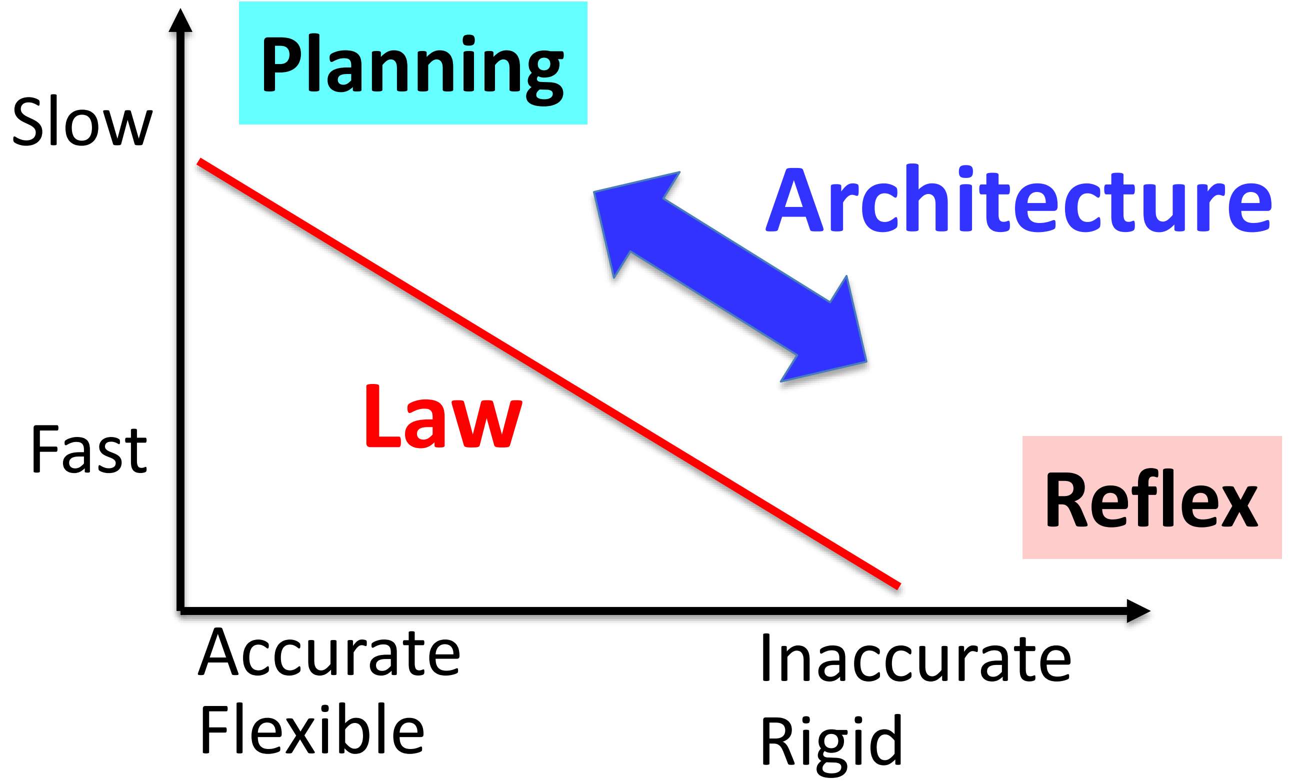
Bumps
Reflex



Layers

Accurate	**Inaccurate**
Flexible	**Rigid**
Centralized	**Localized, distributed**
Conscious	**Unconscious**
Deliberate	**Automatic**
Stable virtual	**Unstable real dynamics**

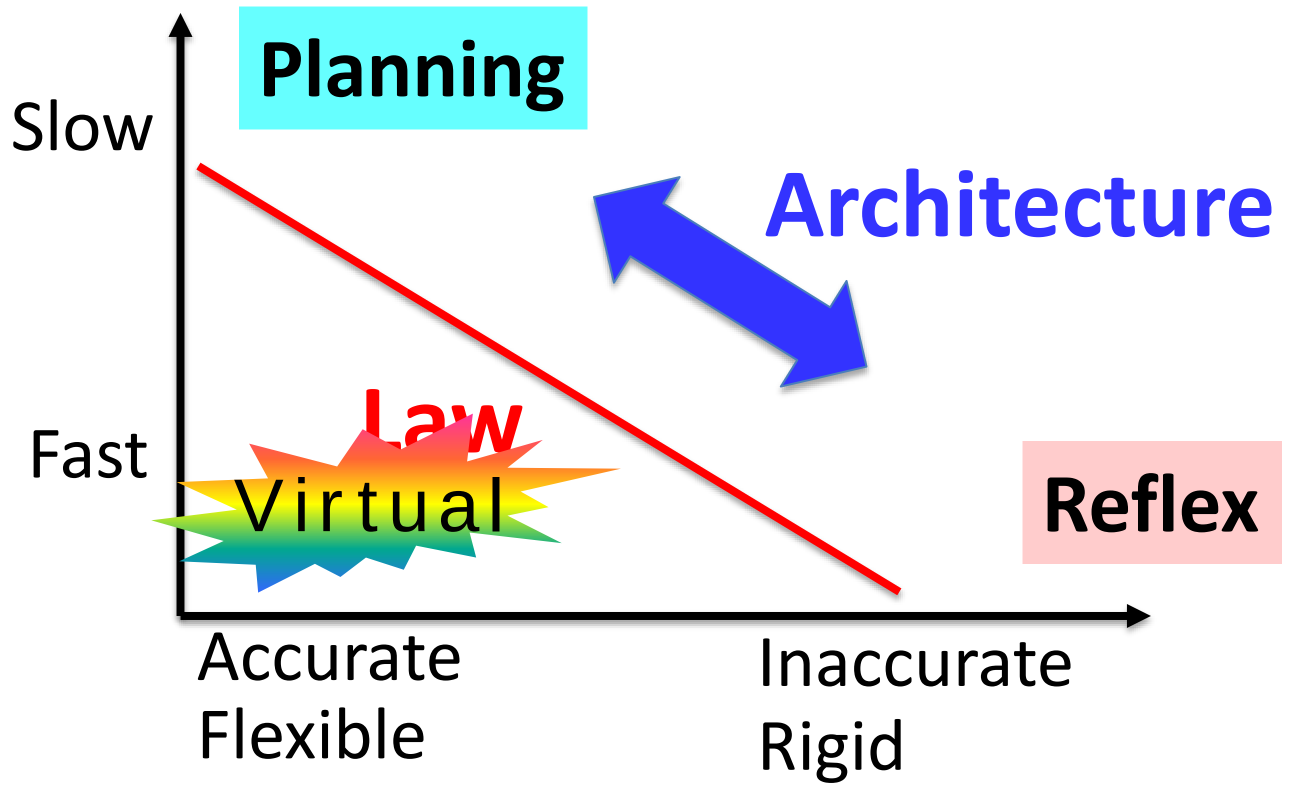

Slow
Planning
Extreme heterogeneity
Tradeoff
Fast
Reflex
Ideal
Accurate
Flexible
Centralized
Conscious
Deliberate
Stable virtual
Inaccurate
Rigid
Localized, distributed
Unconscious
Automatic
Unstable real dynamics
Layers



Universal laws and architectures

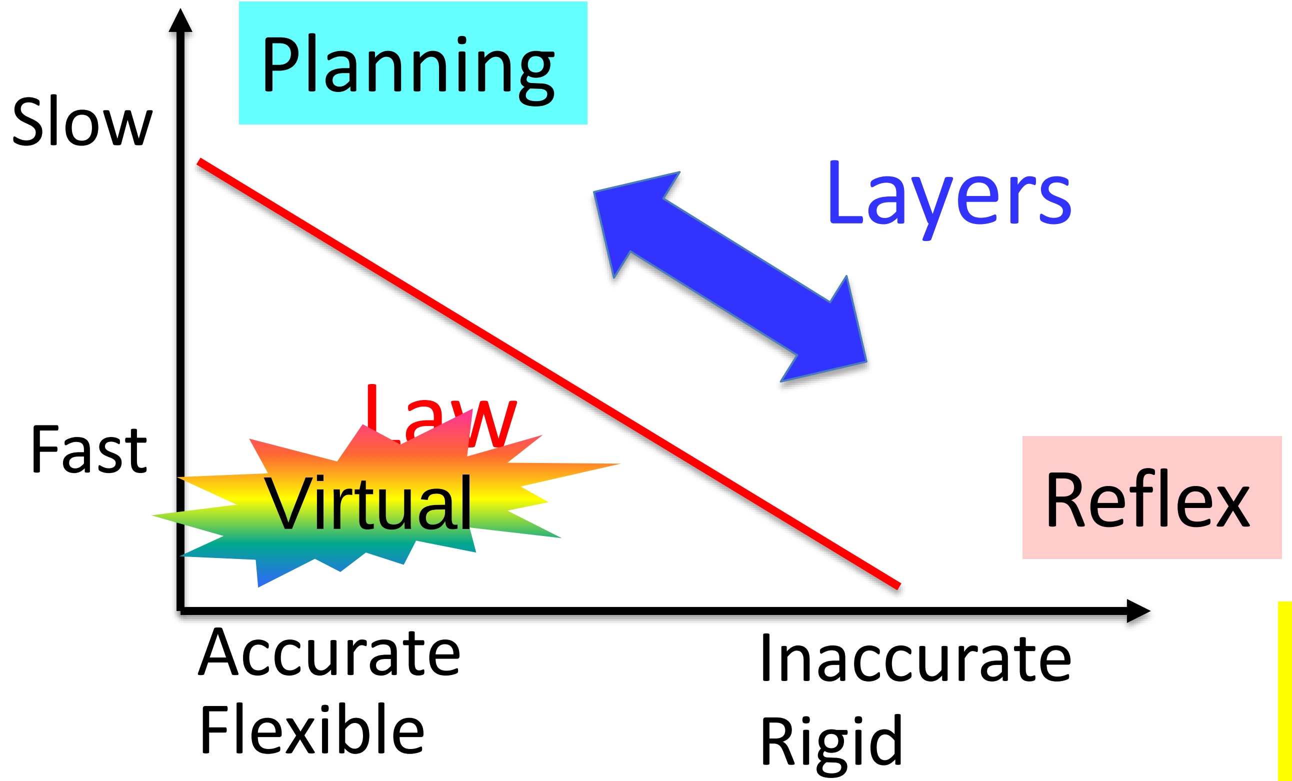
"constraints that deconstrain"
Gerhart & Kirschner

Laws: constrains the possible
Architectures: deconstrains the lawful



Universal laws
and
virtual
architectures

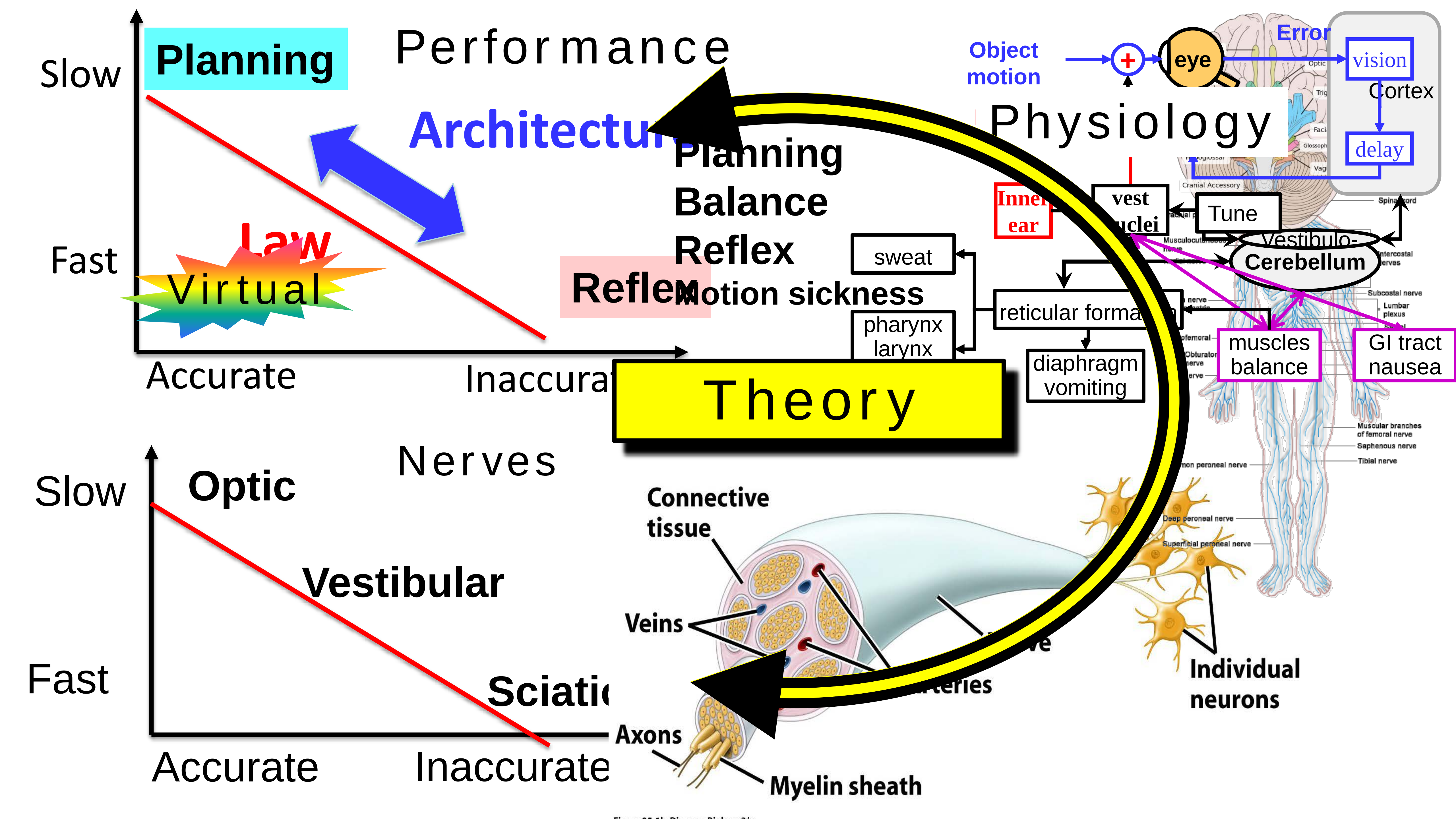
Laws: **constrains the possible**
Architectures: **deconstrains the lawful**
Virtualization: **create sweet spot**



Universal laws
and
virtual
architectures

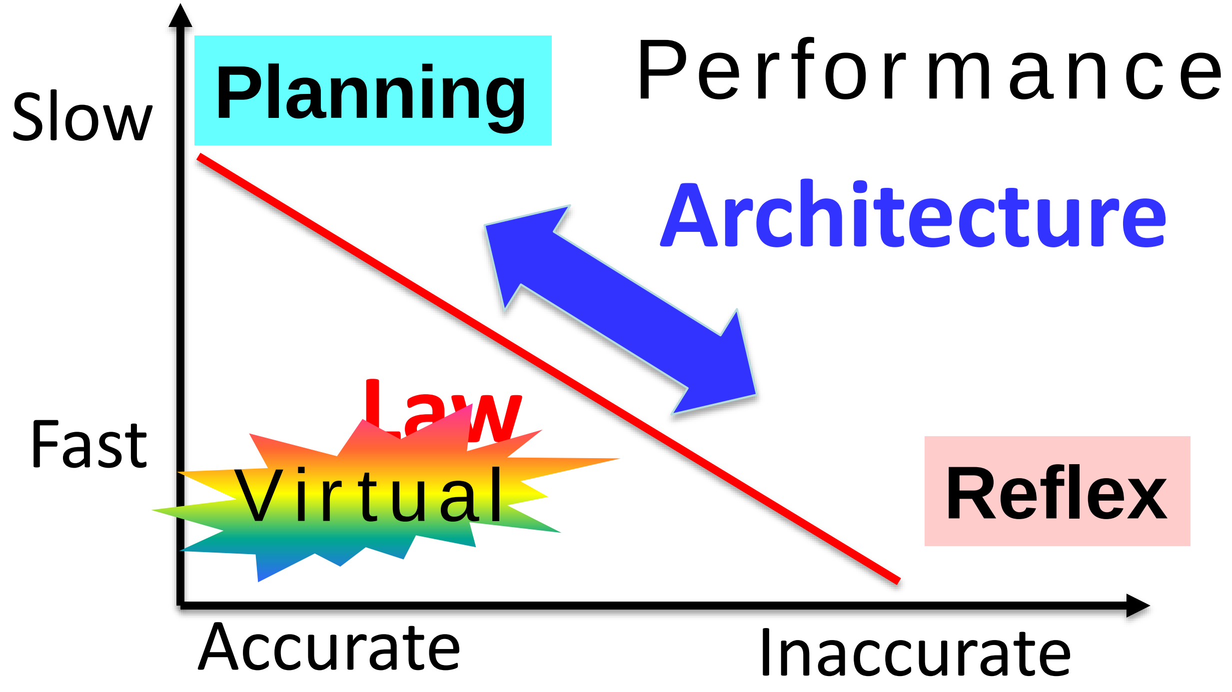
Levels
+
Layers

Laws:	constrains the possible
Architectures:	deconstrains the lawful
Virtualization:	create sweet spot

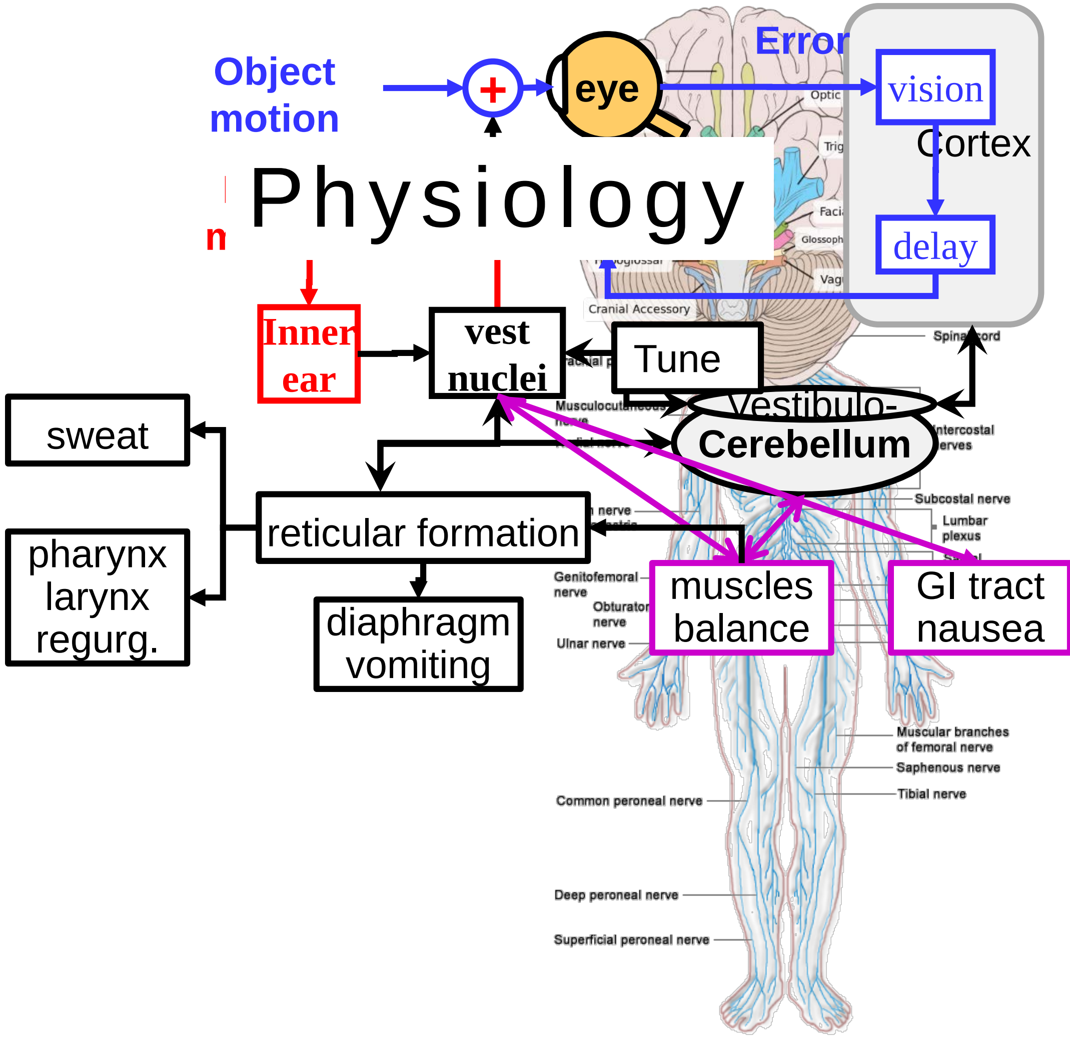


Slow
Planning
Performance
Architecture
Fast
Law
Virtual
Accurate
Inaccurate
Reflex
Planning
Balance
Reflex
Motion sickness
Theory
Object motion
Error
eye
vision
Cortex
delay
Physiology
Inner ear
vest nuclei
Tune
Vestibulo-
Cerebellum
sweat
pharynx larynx
reticular formation
diaphragm vomiting
muscles balance
GI tract nausea
Nerves
Slow
Optic
Vestibular
Fast
Sciatic
Accurate
Inaccurate
Connective tissue
Veins
Axons
Arteries
Myelin sheath
Individual neurons

Performance

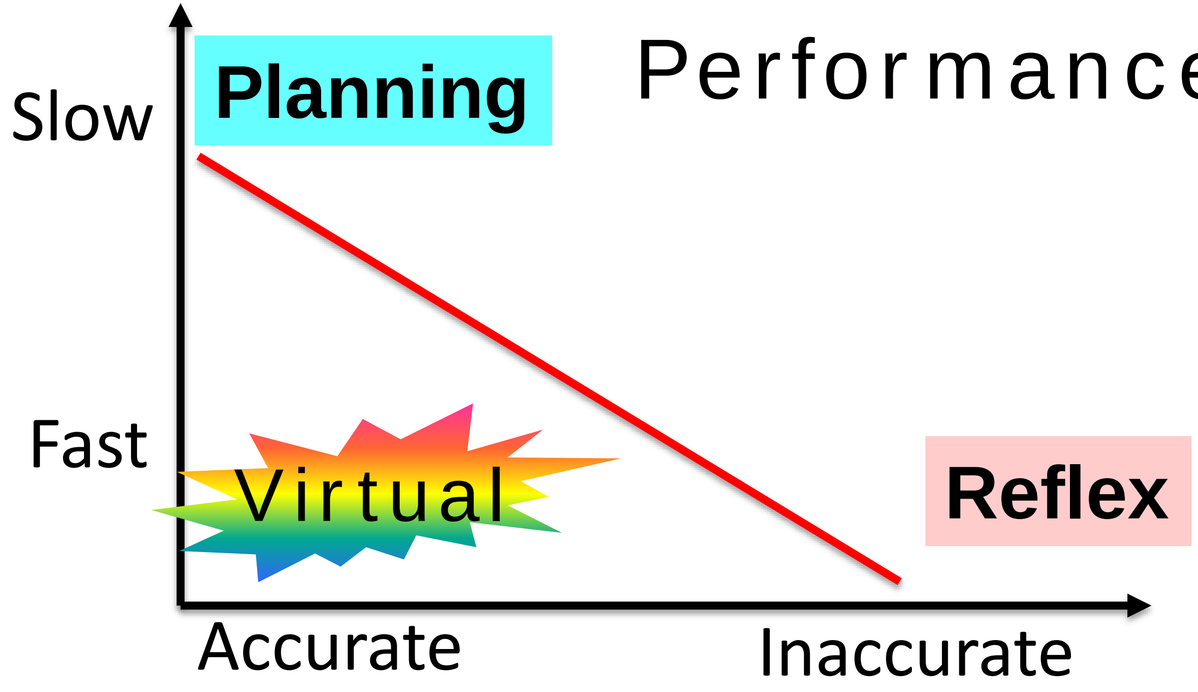


Physiology



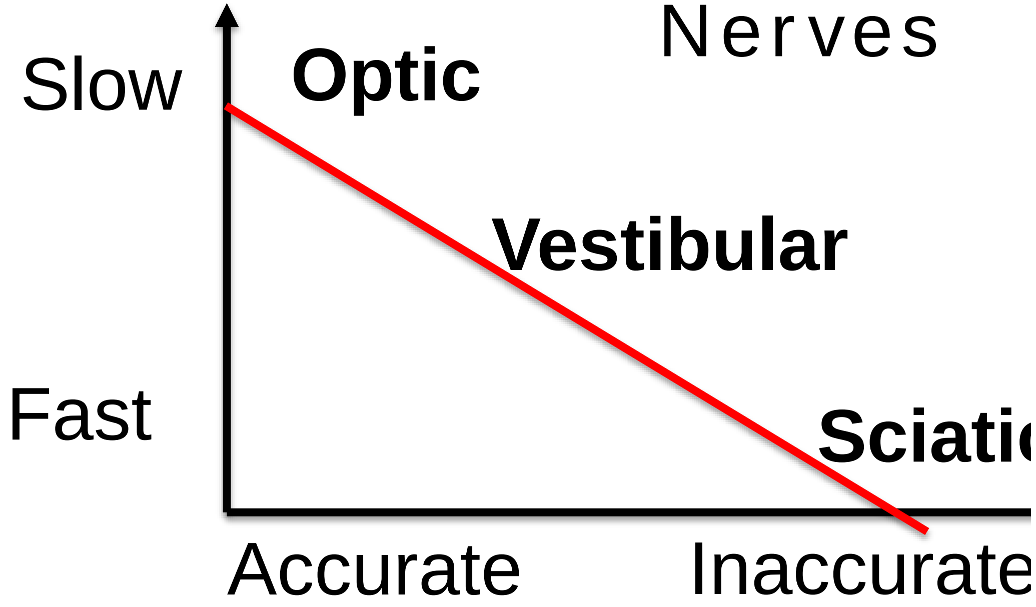
Layers

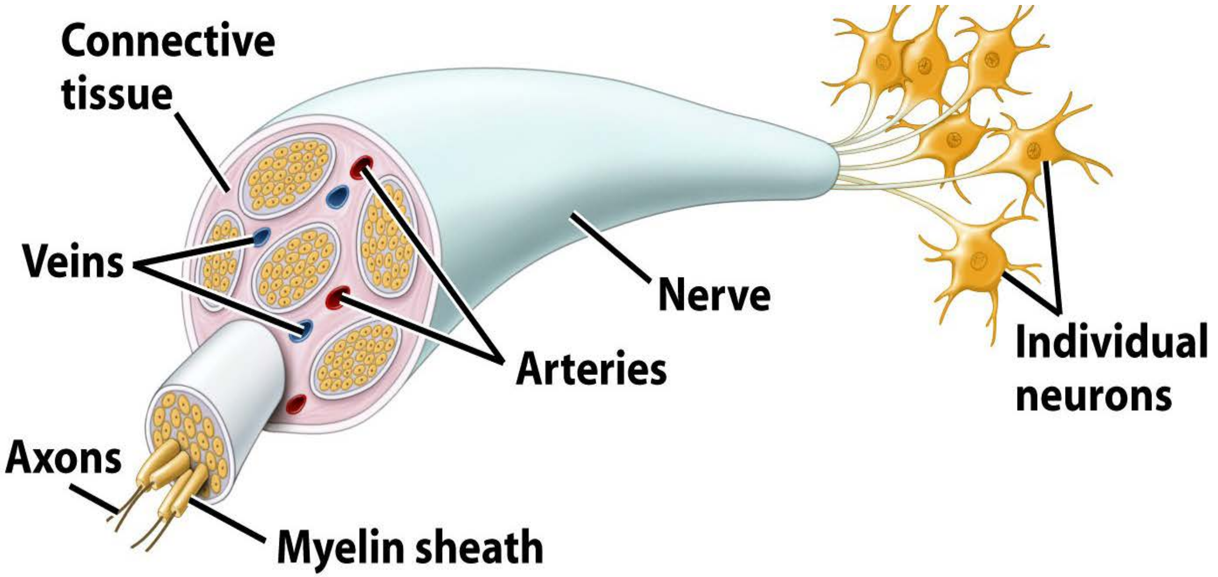
Performance

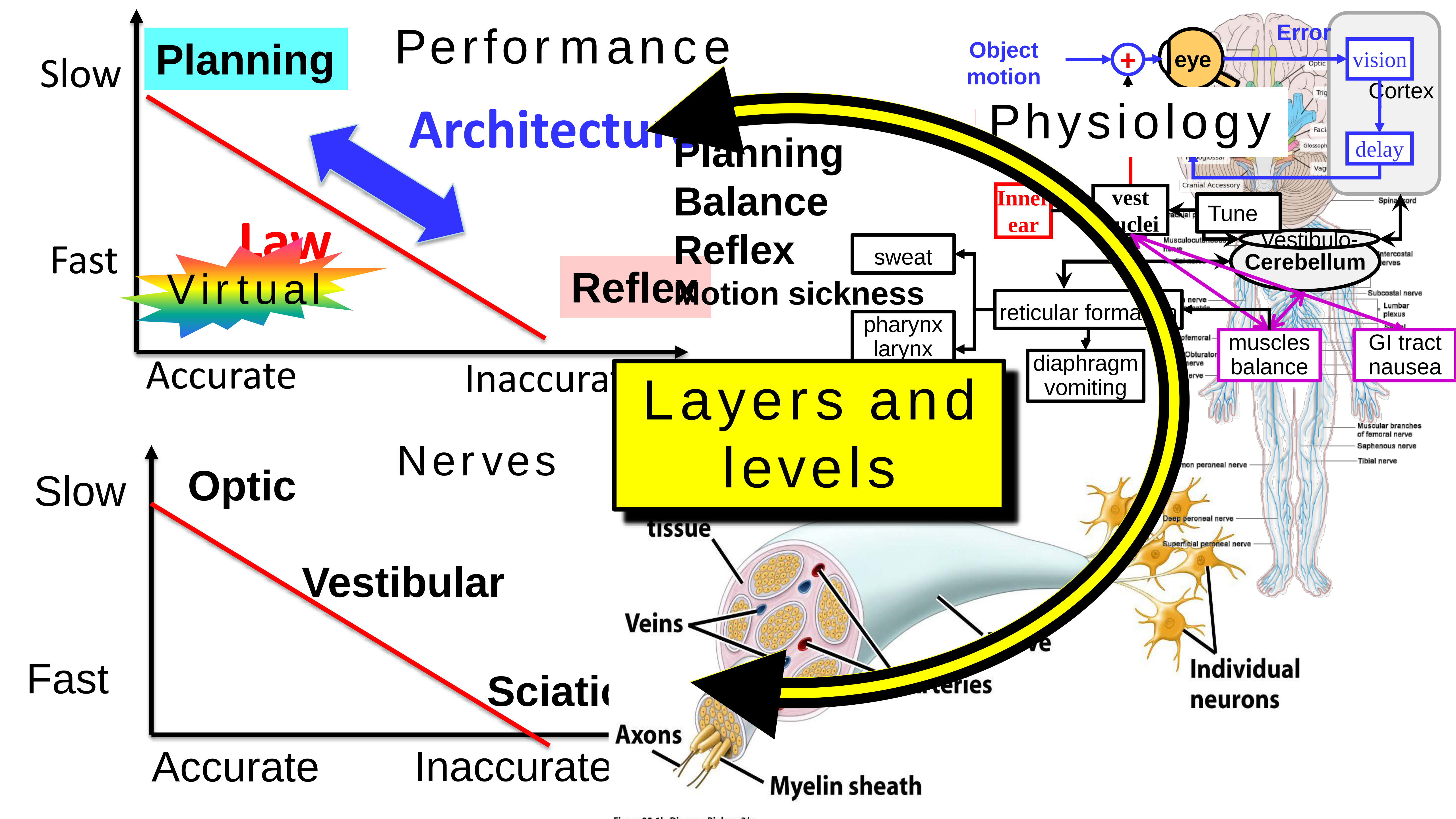


Levels

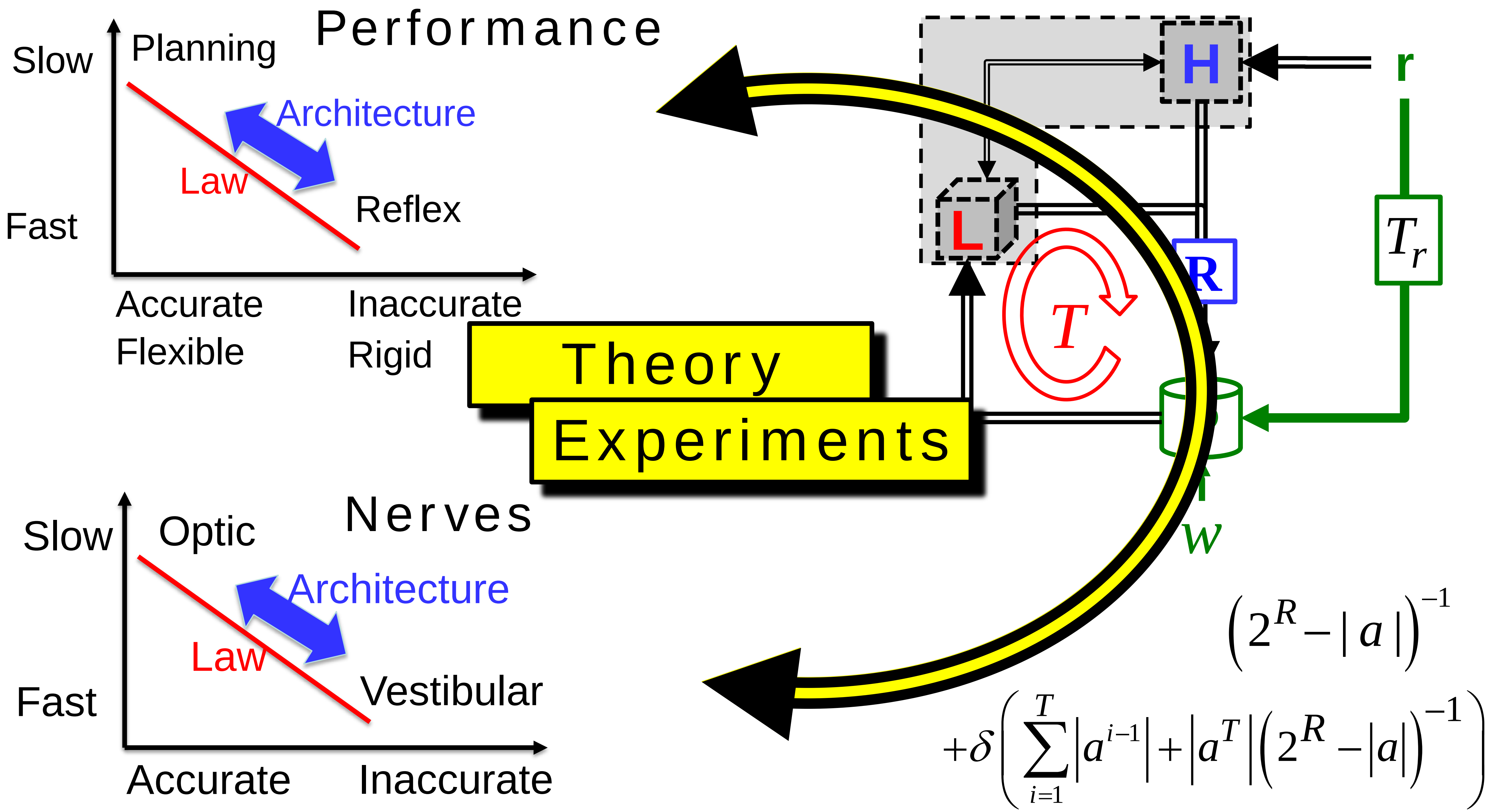
Nerves



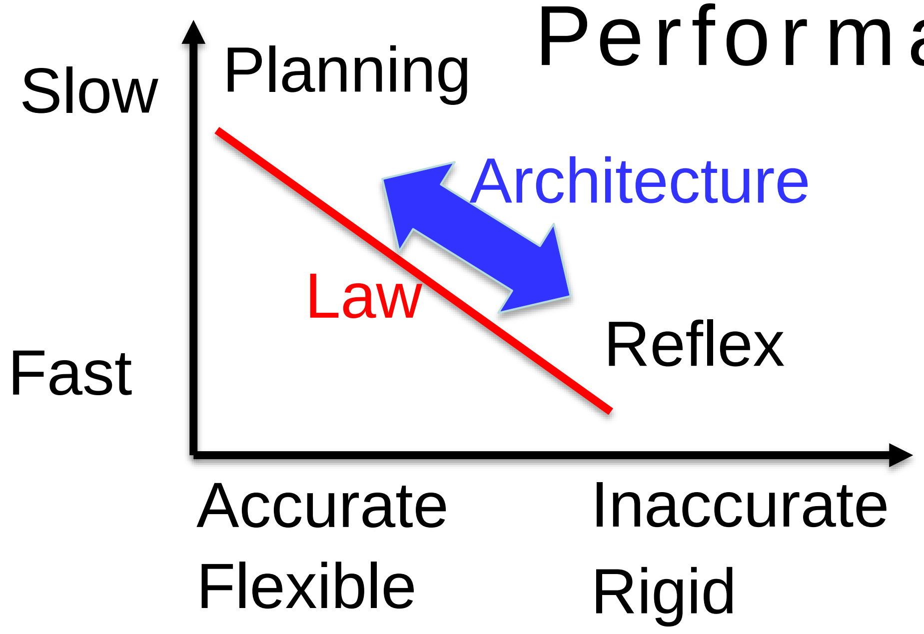




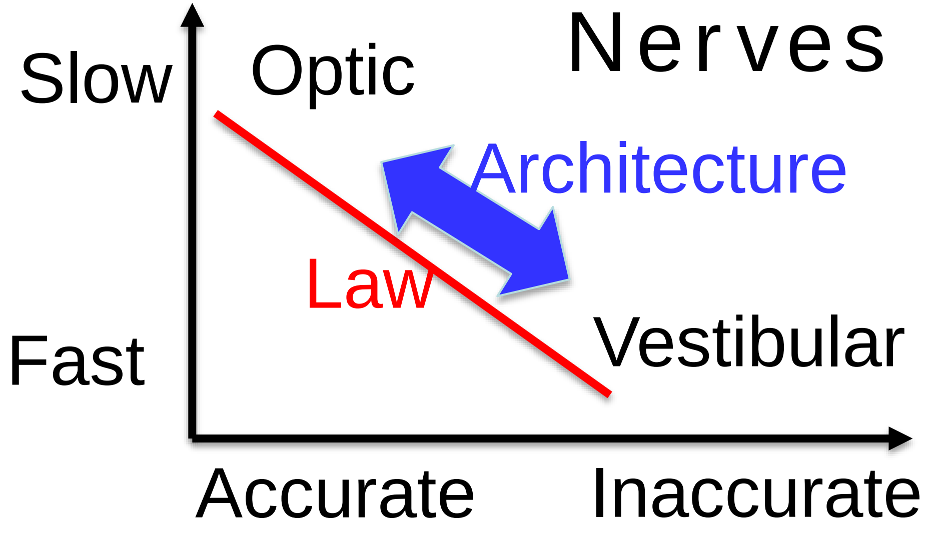
Performance
Planning
Slow
Fast
Architecture
Law
Virtual
Reflex
Accurate
Inaccurate
Nerves
Optic
Vestibular
Sciatic
Slow
Fast
Accurate
Inaccurate
Planning
Balance
Reflex
Motion sickness
Physiology
Object motion
Error
eye
vision
Cortex
delay
Inner ear
vest nuclei
Tune
Vestibulo-
Cerebellum
sweat
reticular formation
pharynx larynx
diaphragm vomiting
muscles balance
GI tract nausea
Layers and levels
tissue
Veins
Arteries
Axons
Myelin sheath
Individual neurons

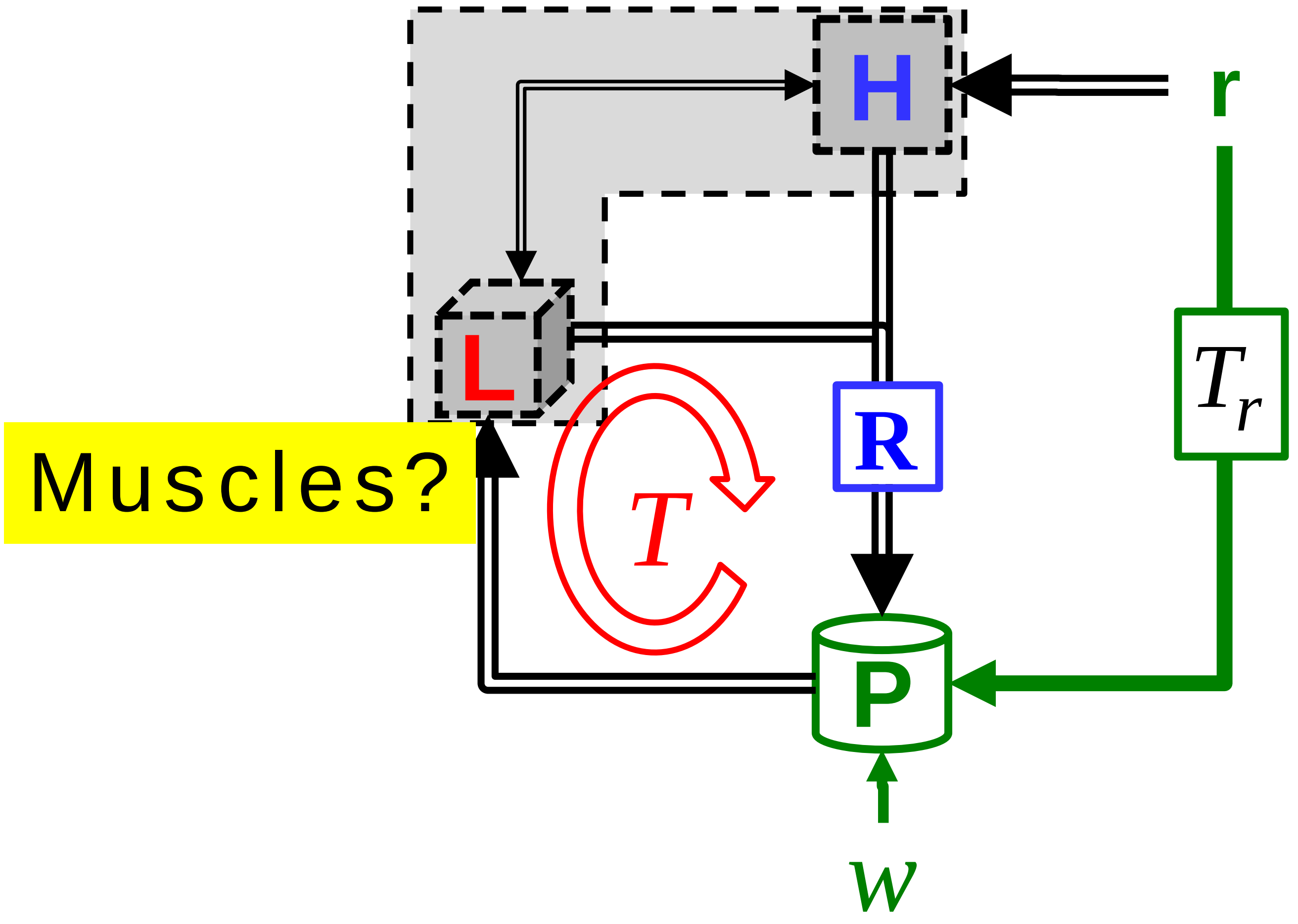

Performance
Slow
Planning
Architecture
Law
Reflex
Fast
Accurate
Flexible
Inaccurate
Rigid
Theory
Experiments
Nerves
Slow
Optic
Architecture
Law
Vestibular
Fast
Accurate
Inaccurate
H
r
L
R
T
T_r
w
$\left(2^R - |a|\right)^{-1}$
$+\delta\left(\sum_{i=1}^{T}\left|a^{i-1}\right| + \left|a^T\right|\left(2^R - |a|\right)^{-1}\right)$

Performance



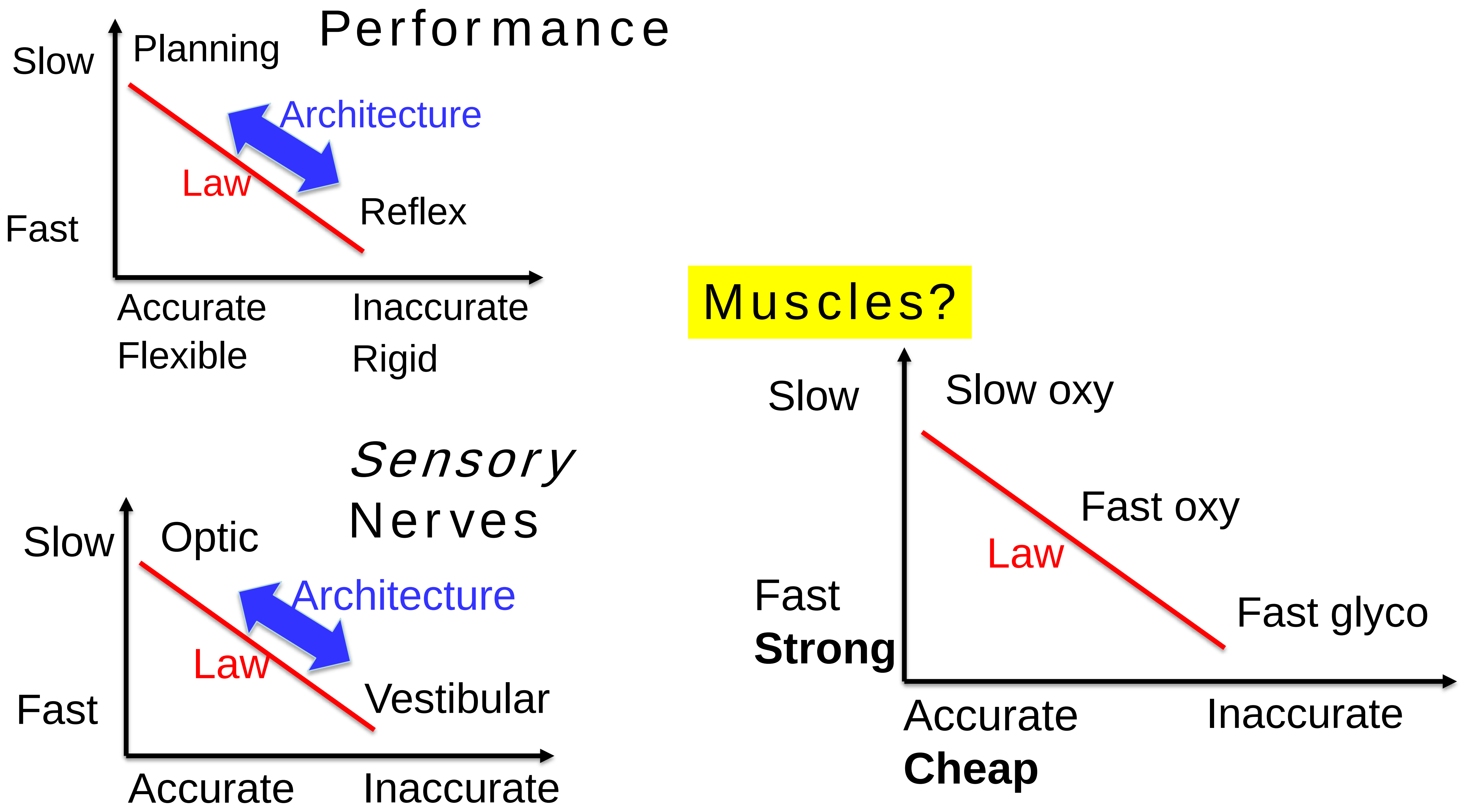
Sensory Nerves

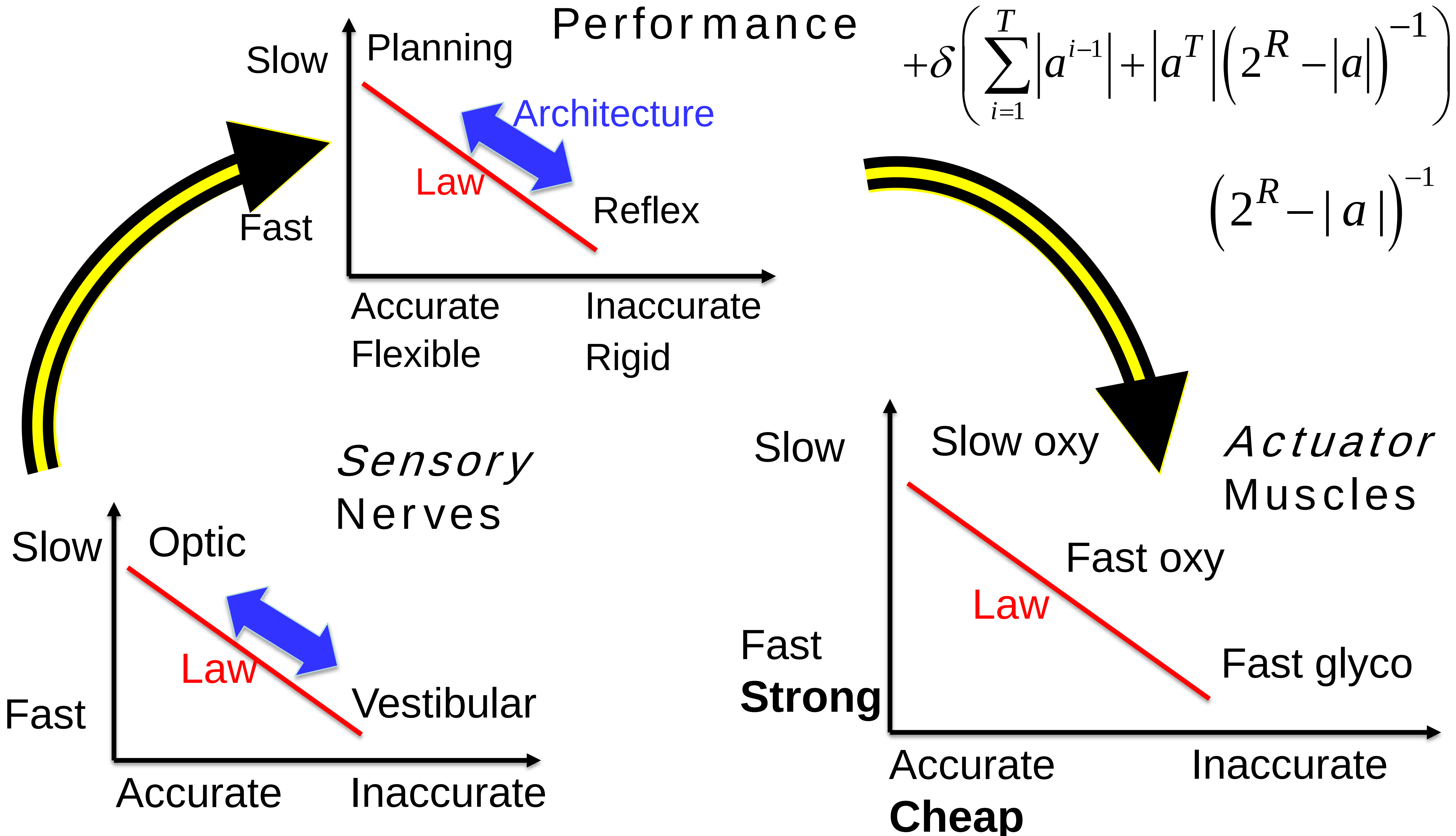




$$\left(2^R - |a|\right)^{-1}$$

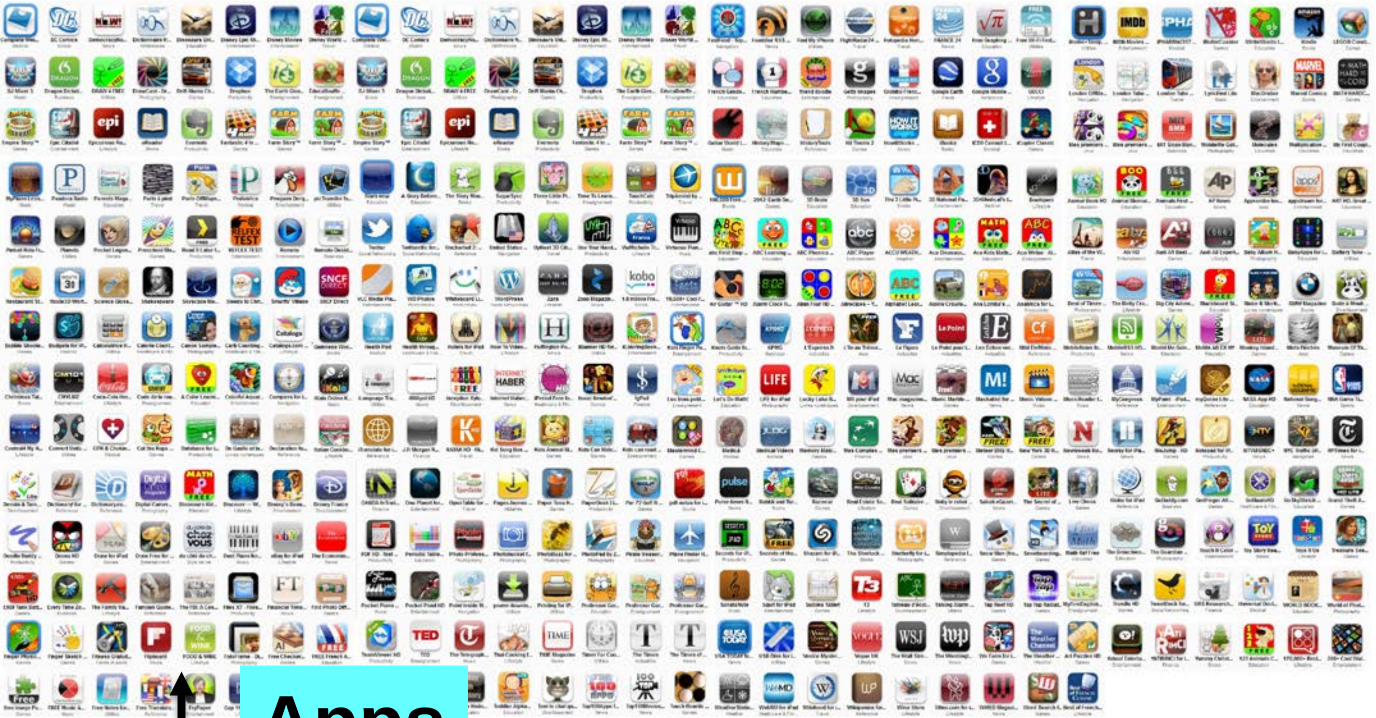
$$+\delta\left(\sum_{i=1}^{T}\left|a^{i-1}\right| + \left|a^T\right|\left(2^R - |a|\right)^{-1}\right)$$

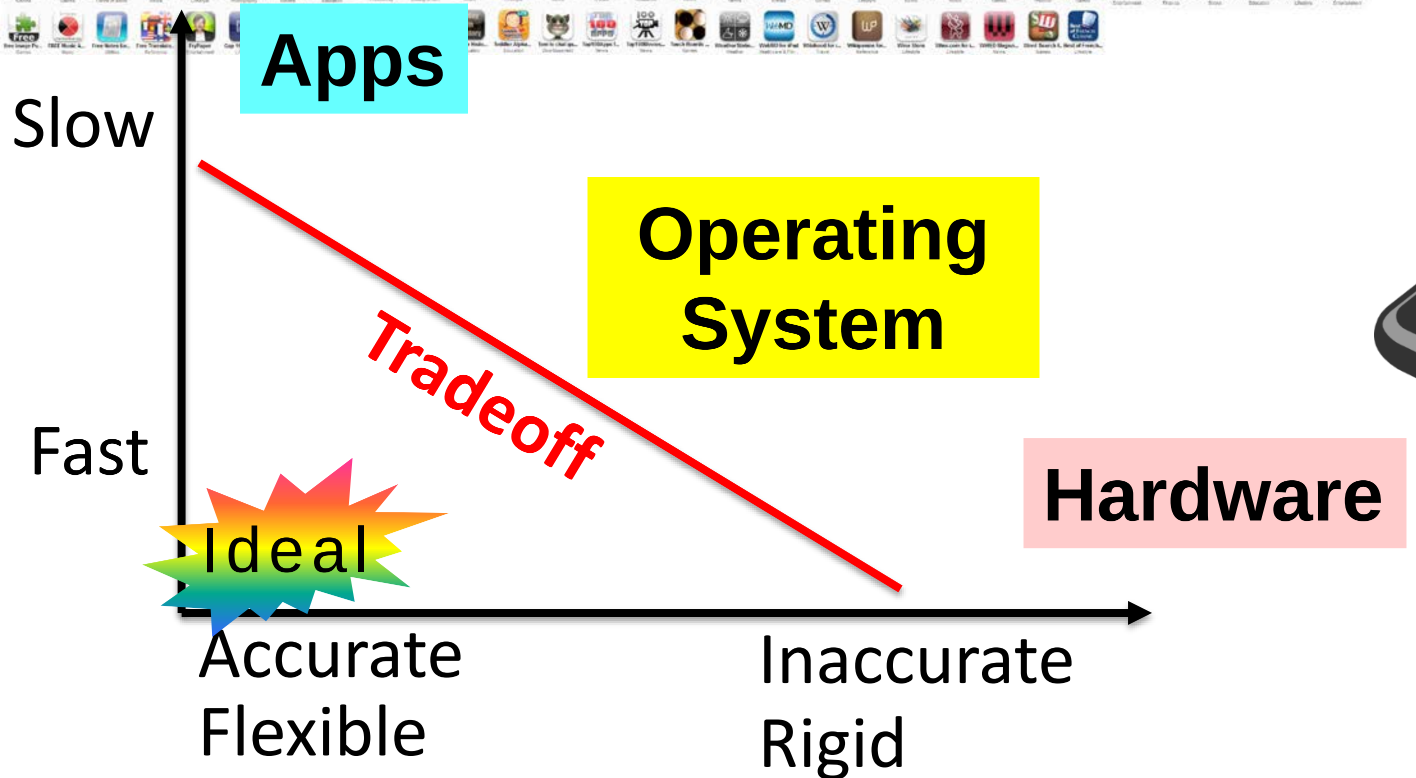

Performance
Slow
Planning
Architecture
Law
Reflex
Fast
Accurate
Flexible
Inaccurate
Rigid
Sensory
Nerves
Slow
Optic
Architecture
Law
Vestibular
Fast
Accurate
Inaccurate
Muscles?
Slow
Slow oxy
Fast oxy
Law
Fast
Strong
Fast glyco
Accurate
Cheap
Inaccurate



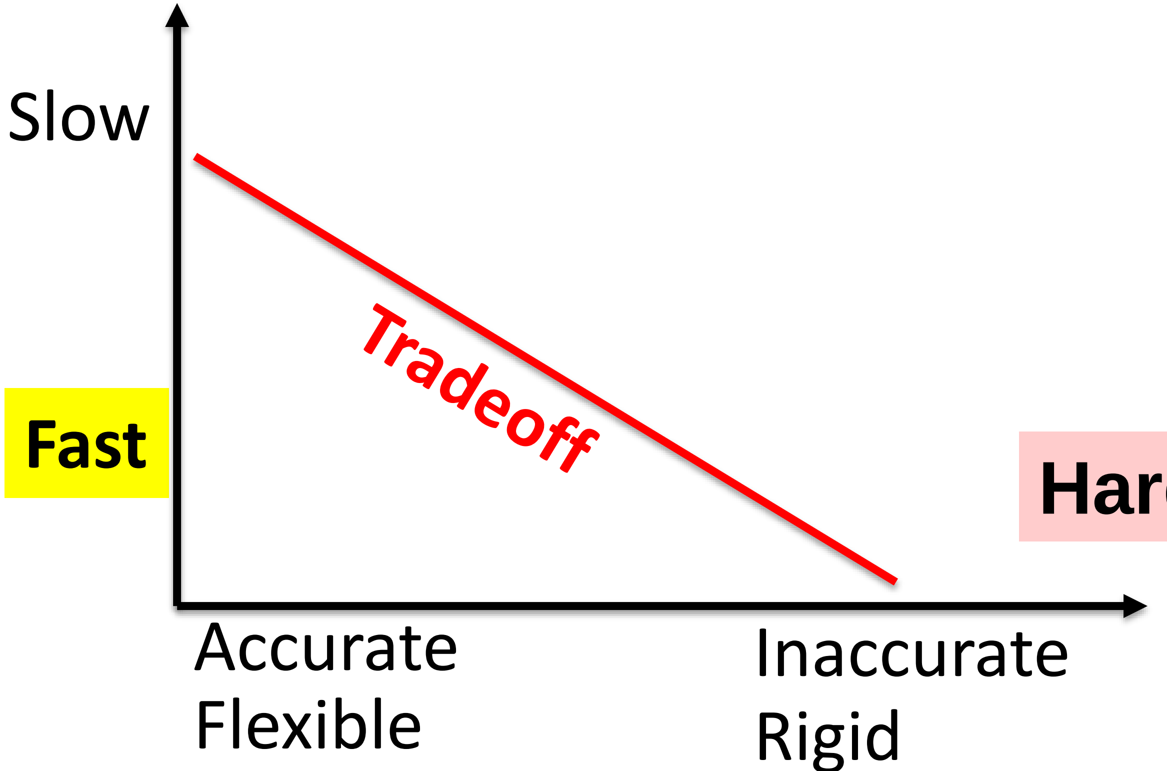
Performance
$+\delta\left(\sum_{i=1}^{T}\left|a^{i-1}\right|+\left|a^{T}\right|\left(2^{R}-\left|a\right|\right)^{-1}\right)$
$\left(2^{R}-|a|\right)^{-1}$
Slow
Planning
Architecture
Law
Reflex
Fast
Accurate
Flexible
Inaccurate
Rigid
Sensory
Nerves
Slow
Optic
Law
Vestibular
Fast
Accurate
Inaccurate
Actuator
Muscles
Slow
Slow oxy
Fast oxy
Law
Fast
Strong
Fast glyco
Accurate
Cheap
Inaccurate

Layered architecture



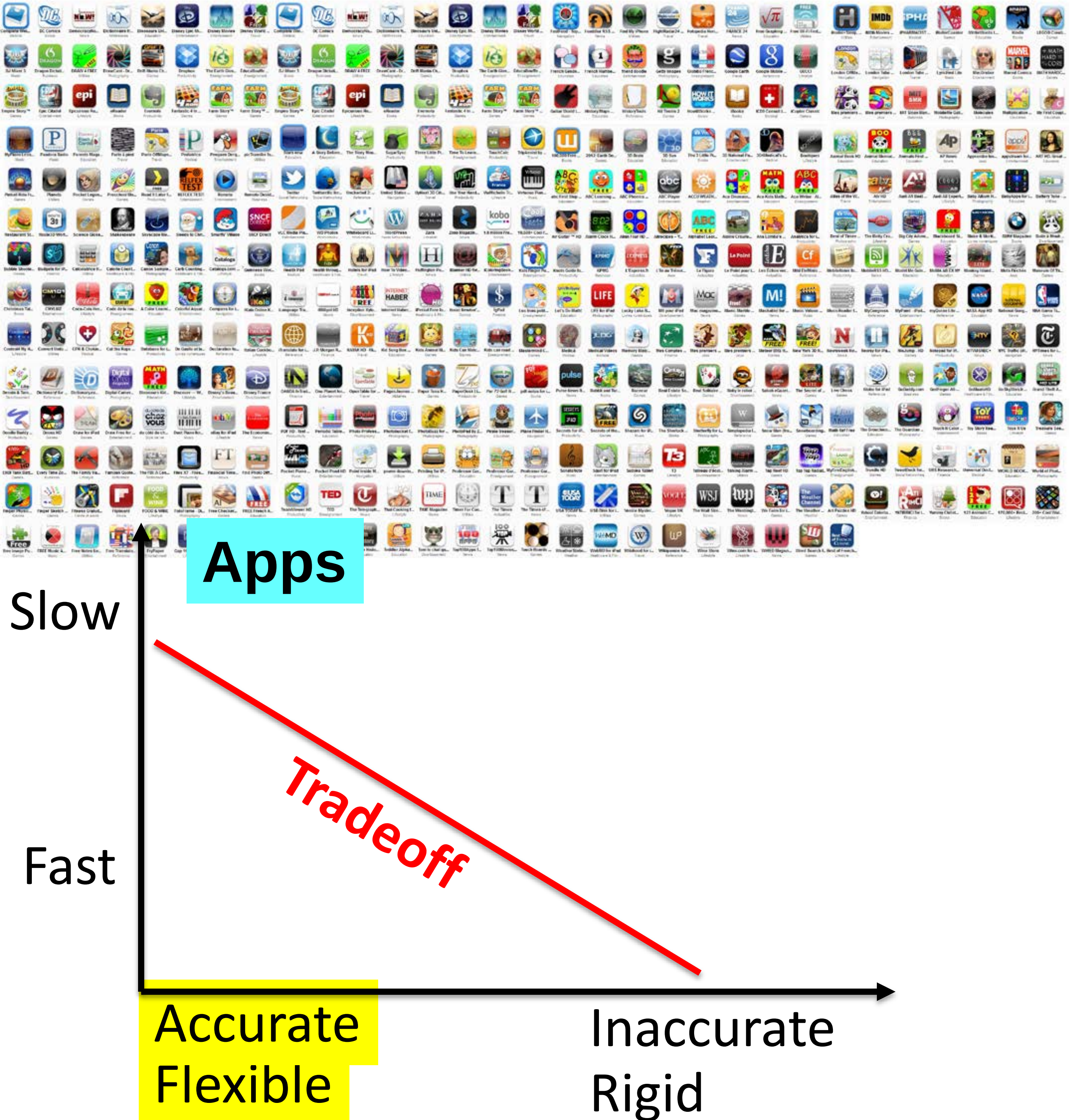


Layered architecture

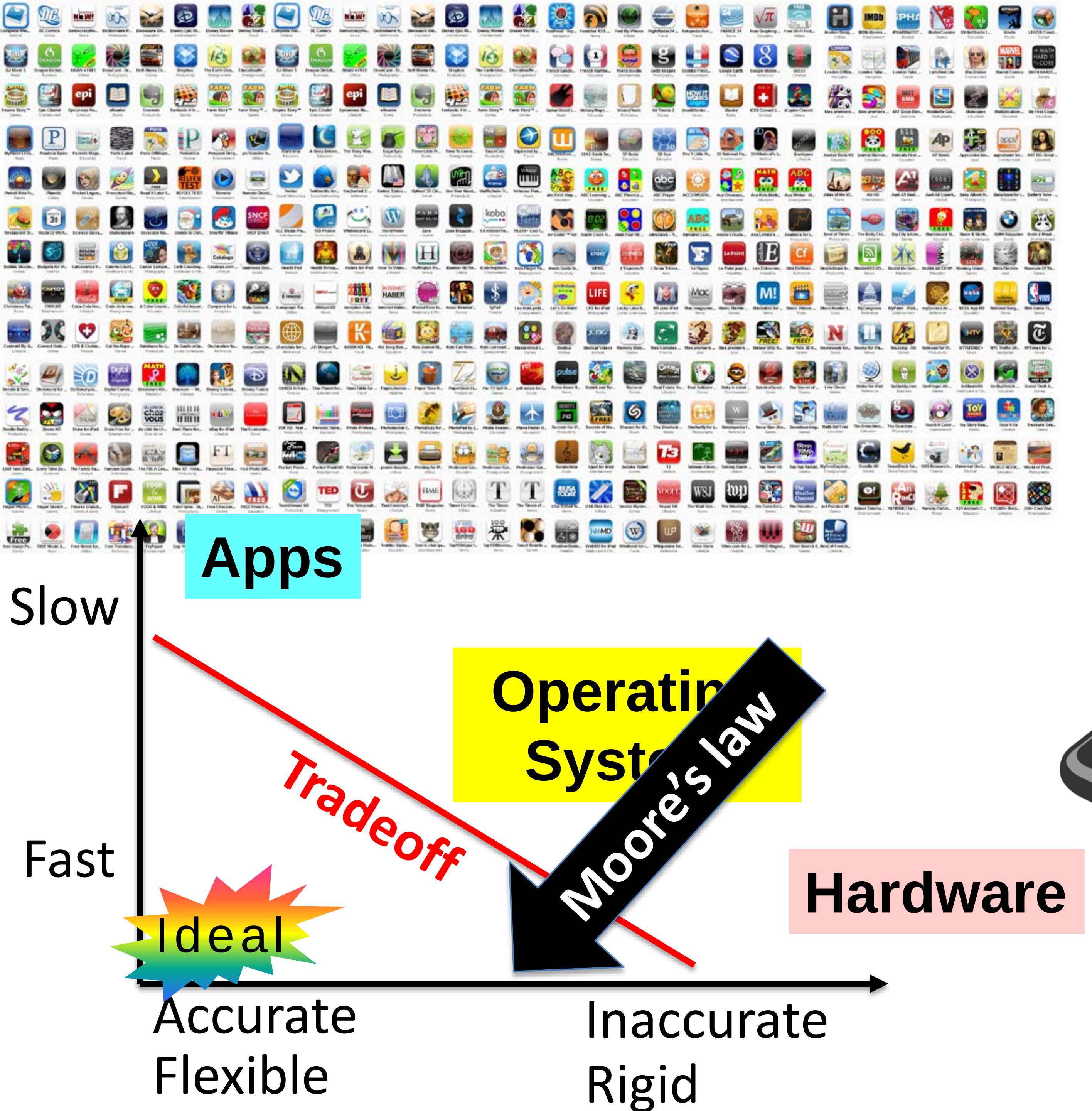


Hardware

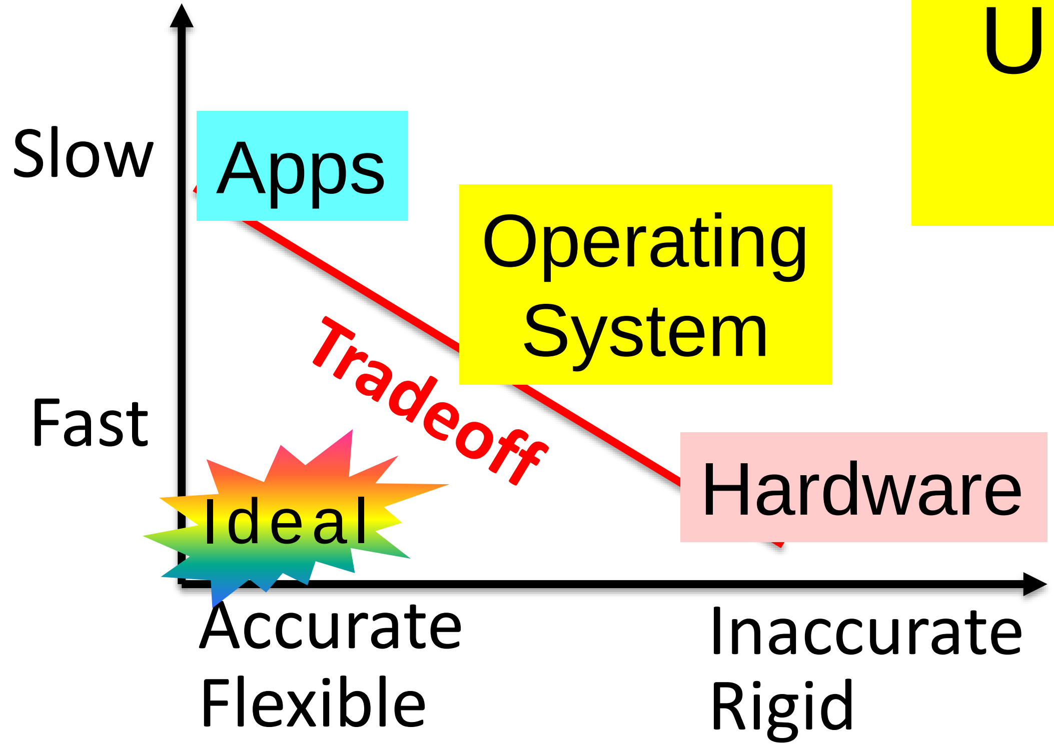
Layered architecture



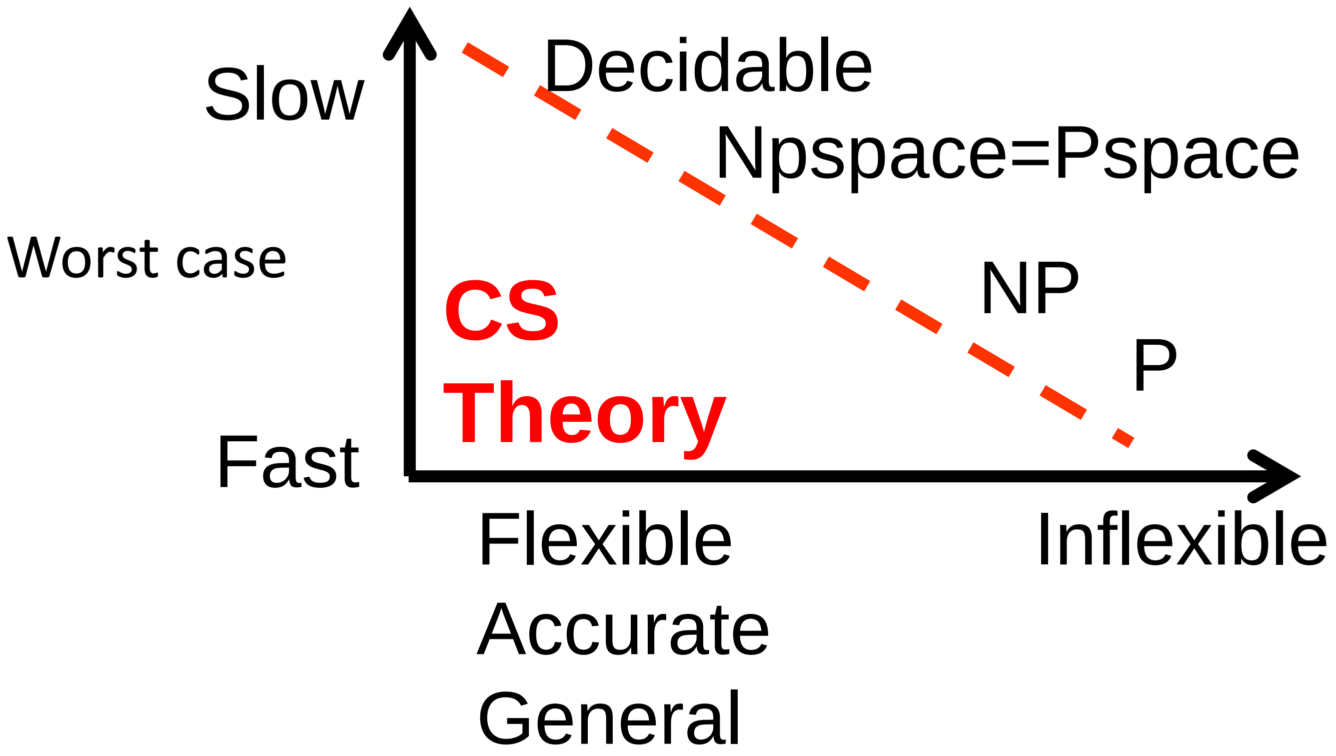
Layered architecture

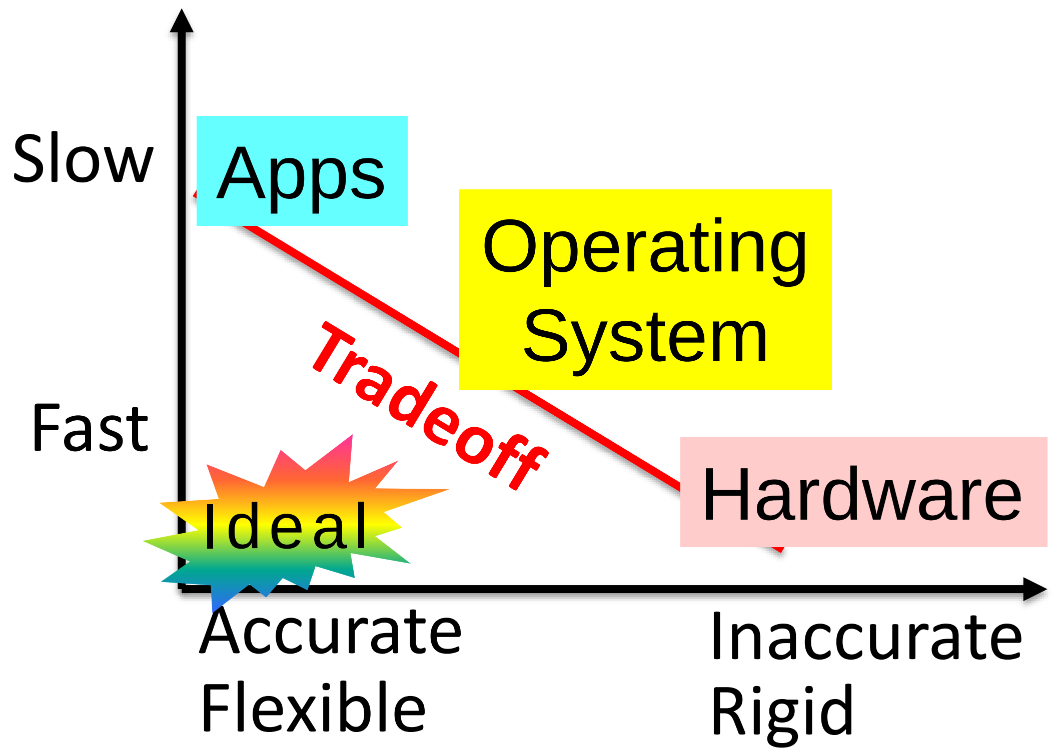


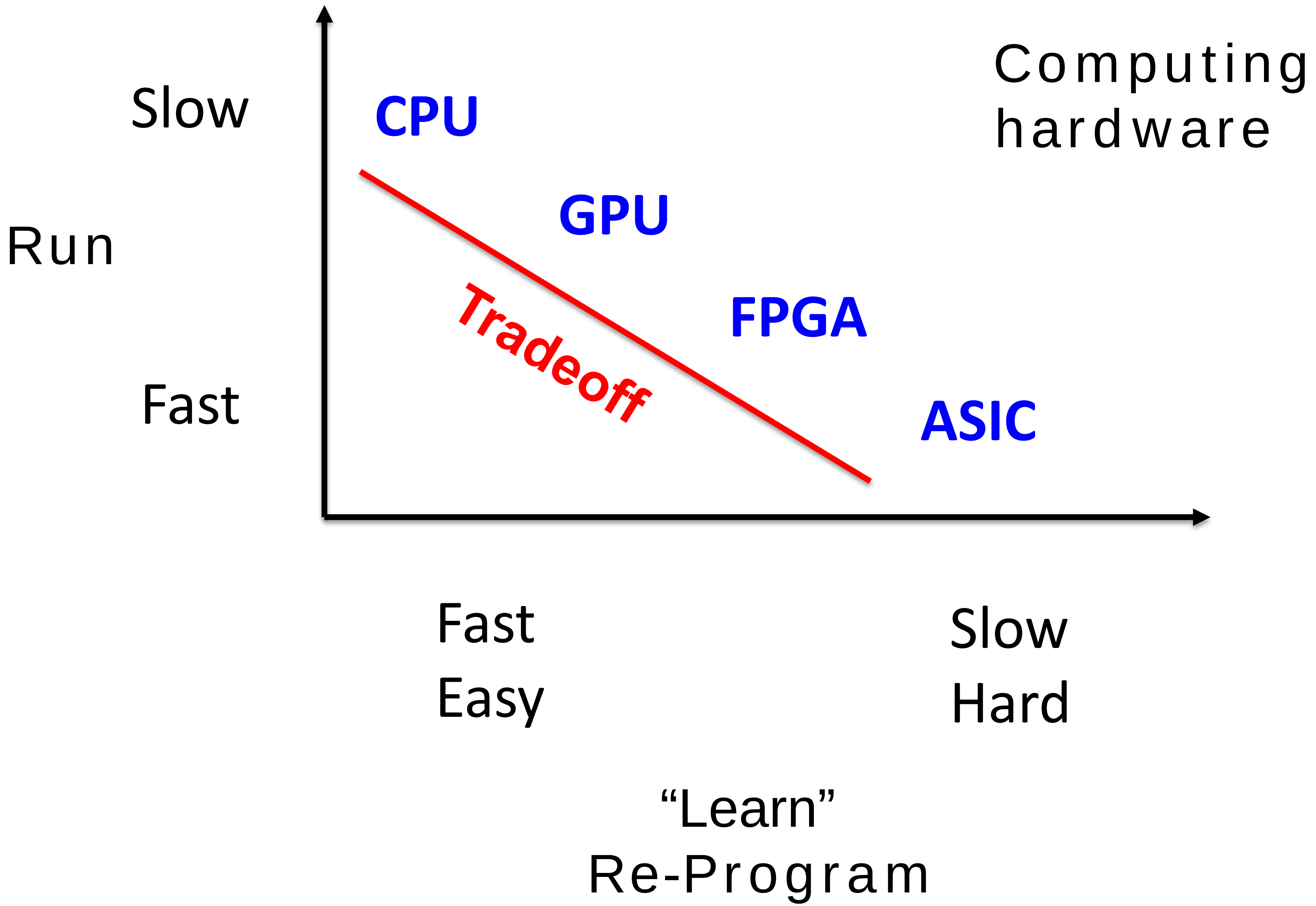
Constraints
that
deconstrain

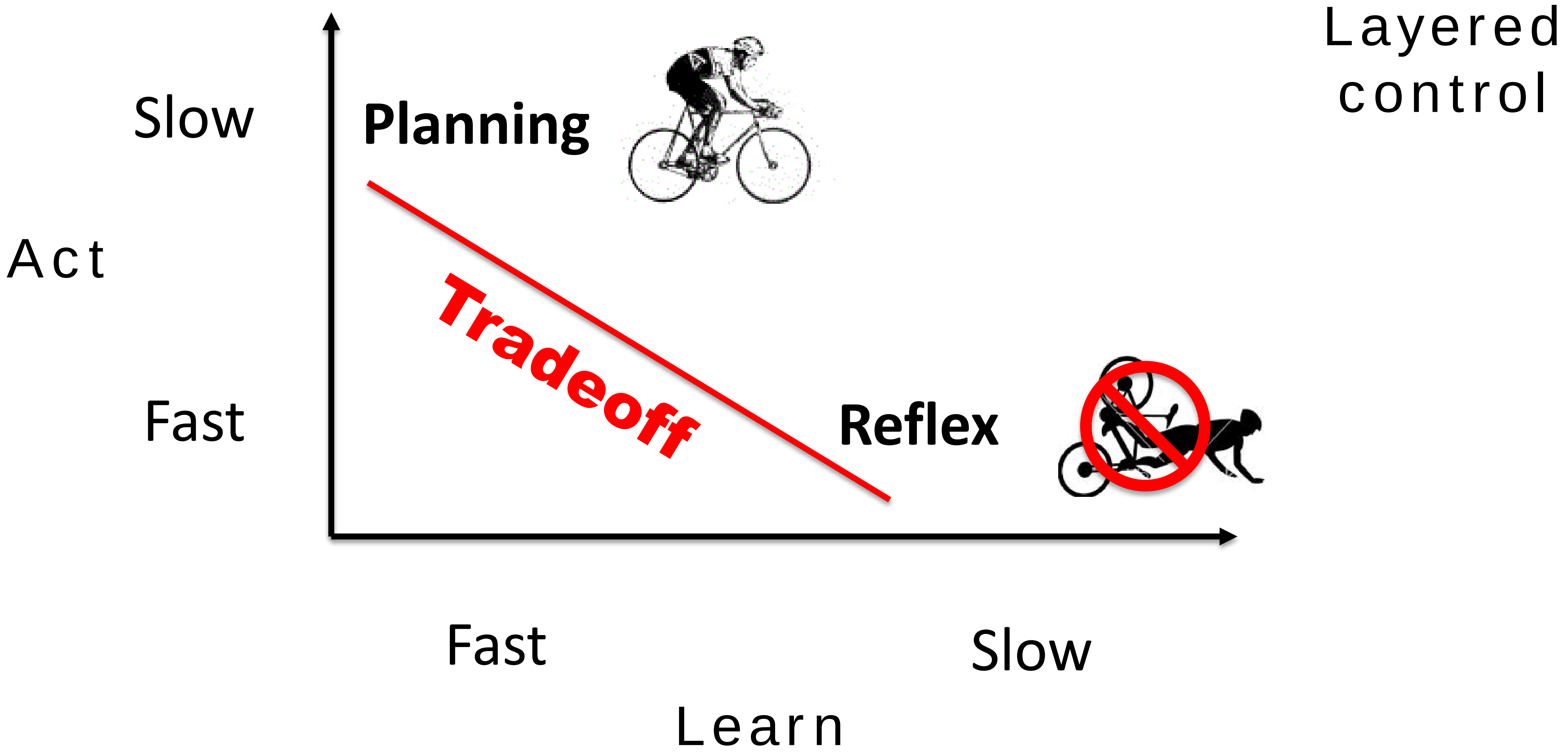


Uniform
OSes

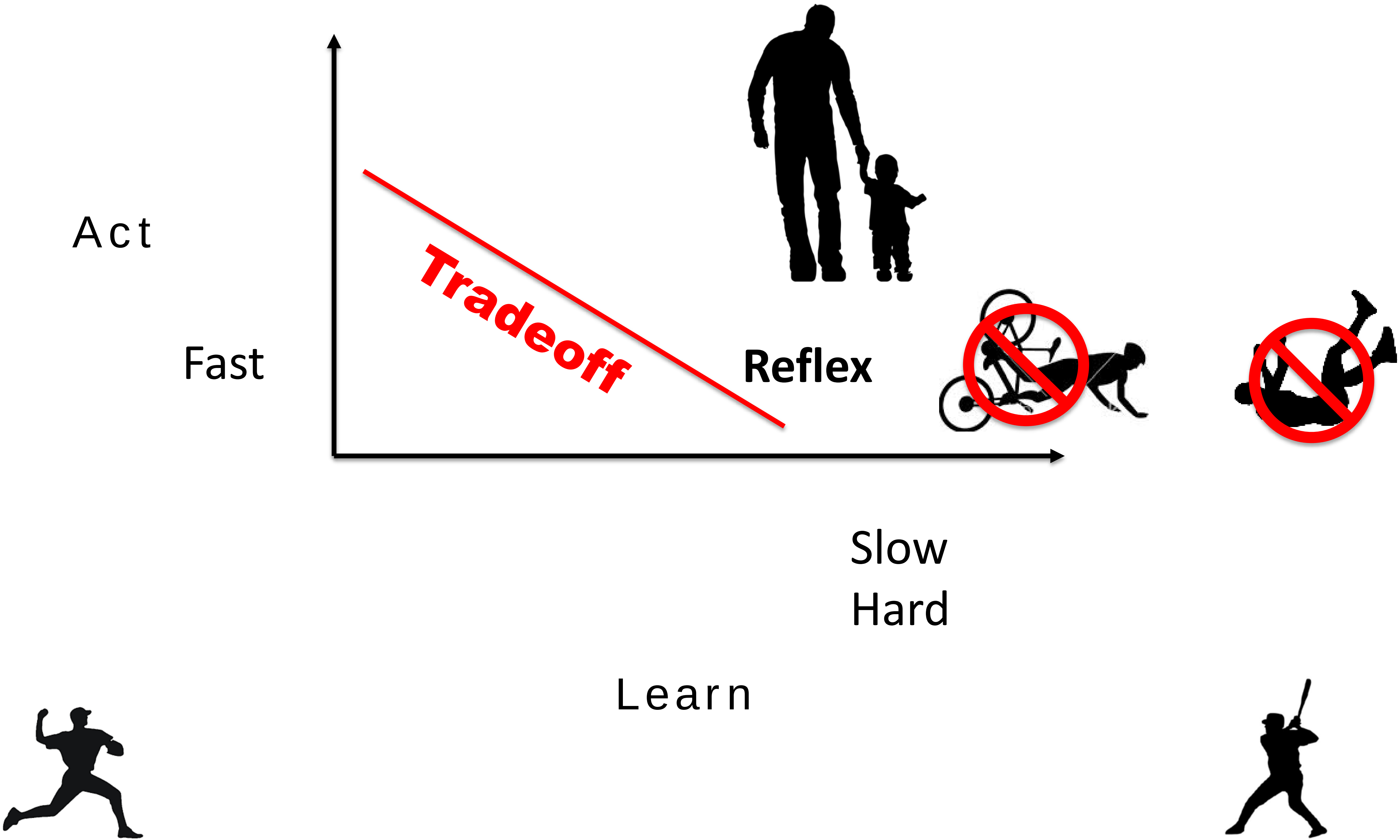

Slow
Decidable
Npspace=Pspace
Worst case
NP
CS
Theory
P
Fast
Flexible
Accurate
General
Inflexible


Slow
Apps
Operating
System
Tradeoff
Fast
Hardware
Ideal
Accurate
Flexible
Inaccurate
Rigid


Computing hardware
Slow
Run
Fast
CPU
GPU
FPGA
ASIC
Tradeoff
Fast
Easy
Slow
Hard
“Learn”
Re-Program

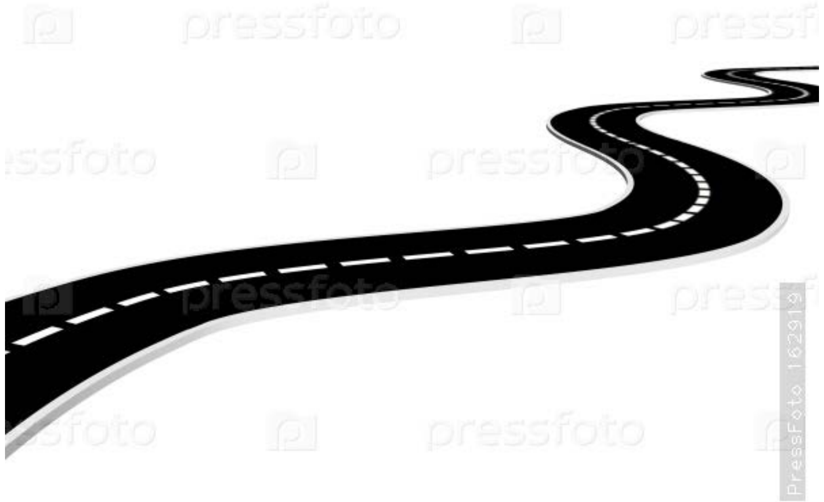


Layered control
Slow
Planning
Act
Tradeoff
Fast
Reflex
Fast
Slow
Learn


Act
Fast
Tradeoff
Reflex
Slow
Hard
Learn

Slow

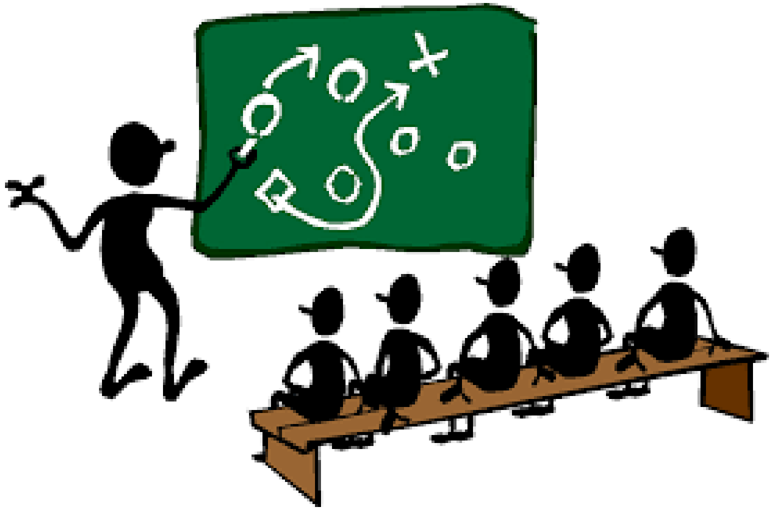
Act

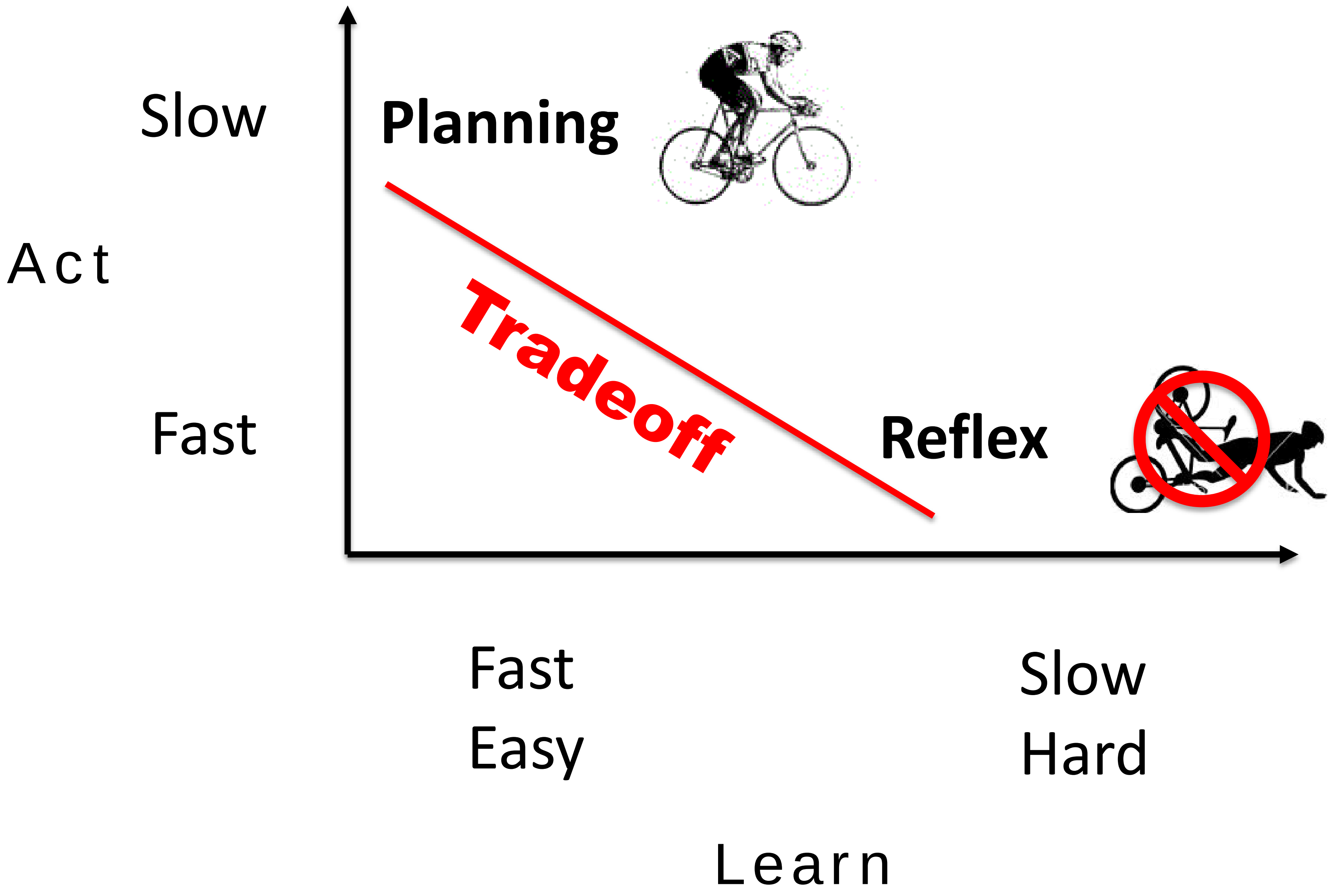


Fast

Easy

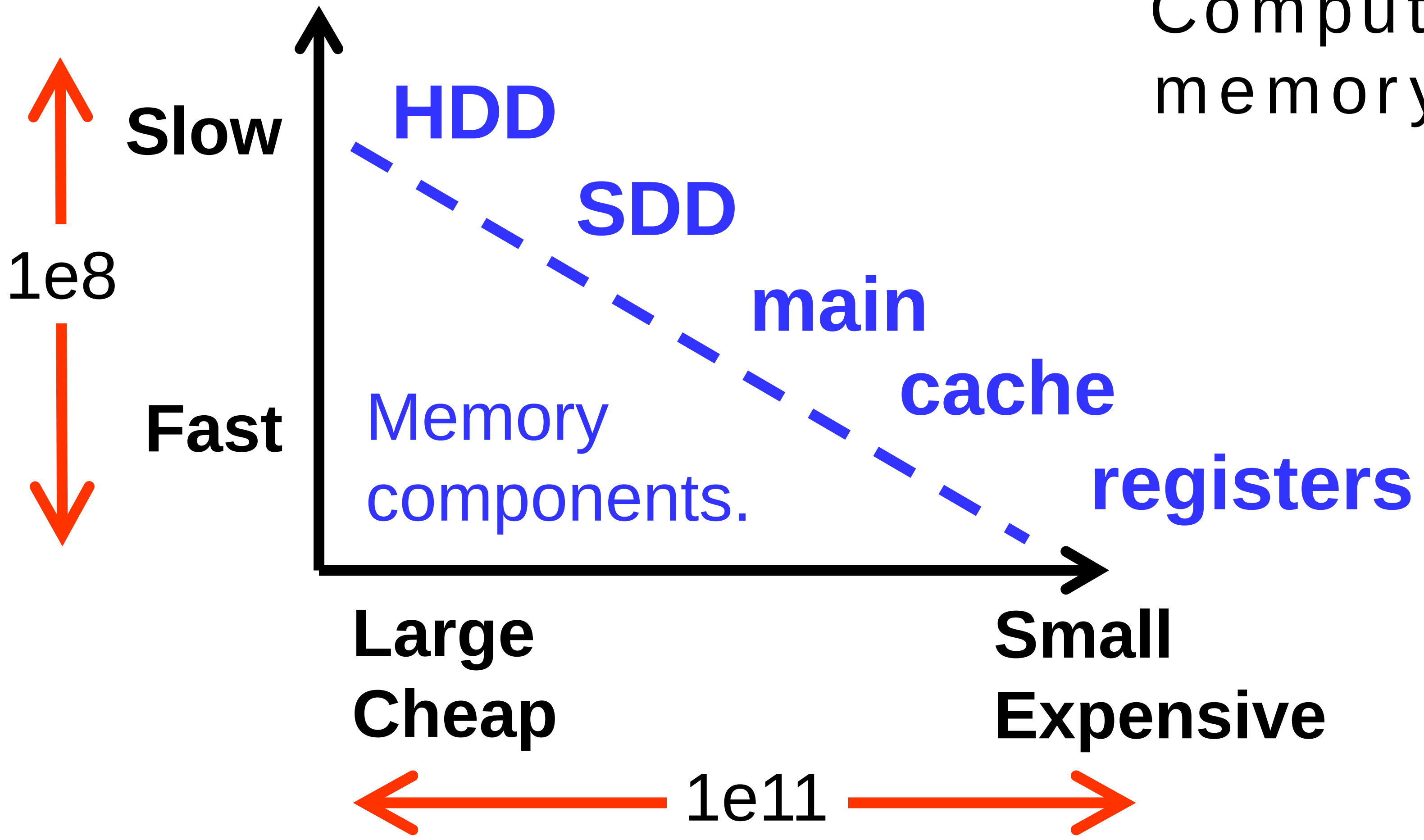
Learn



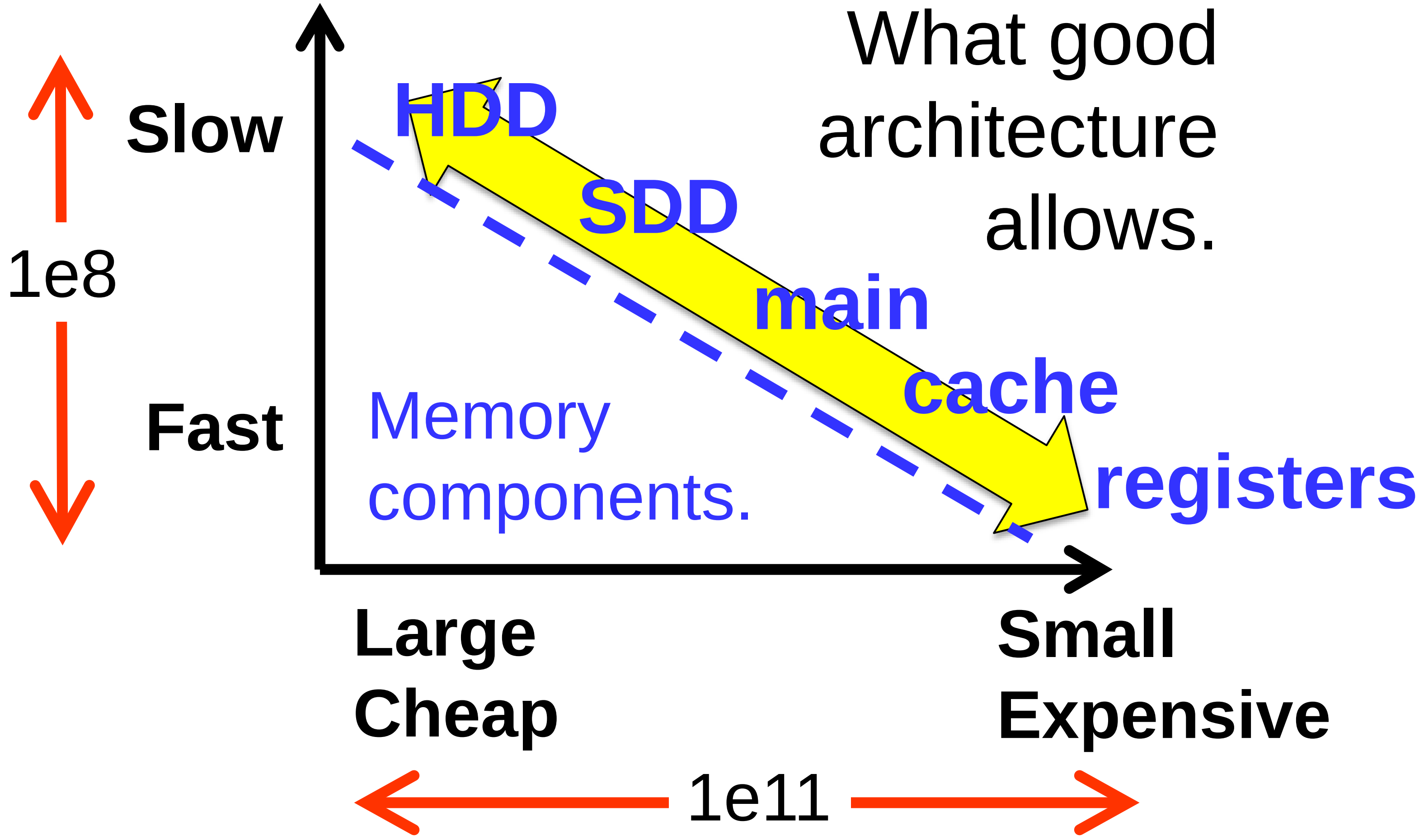


Slow
Planning
Act
Tradeoff
Fast
Reflex
Fast
Easy
Slow
Hard
Learn

Computing memory



What good architecture allows.

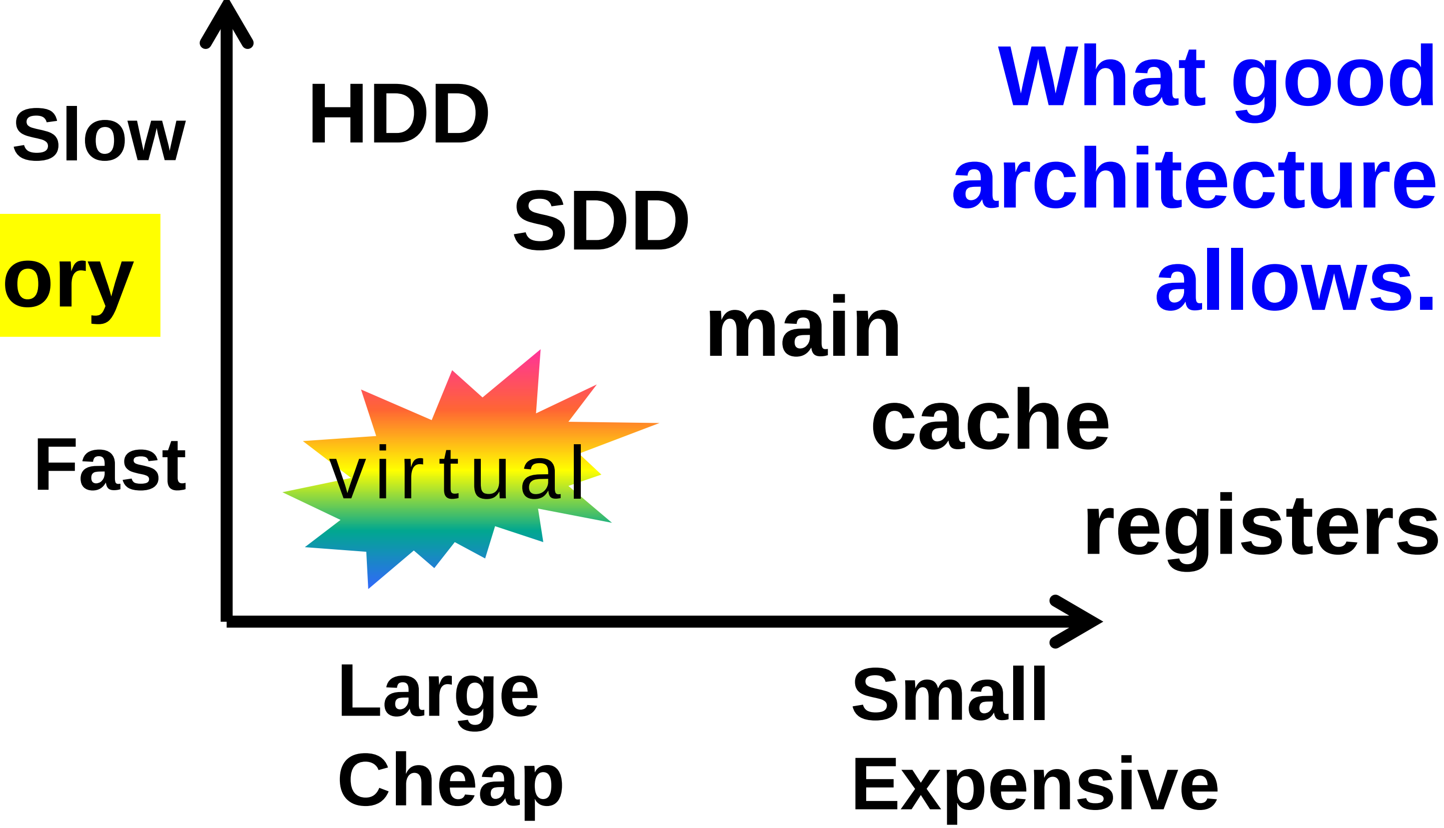


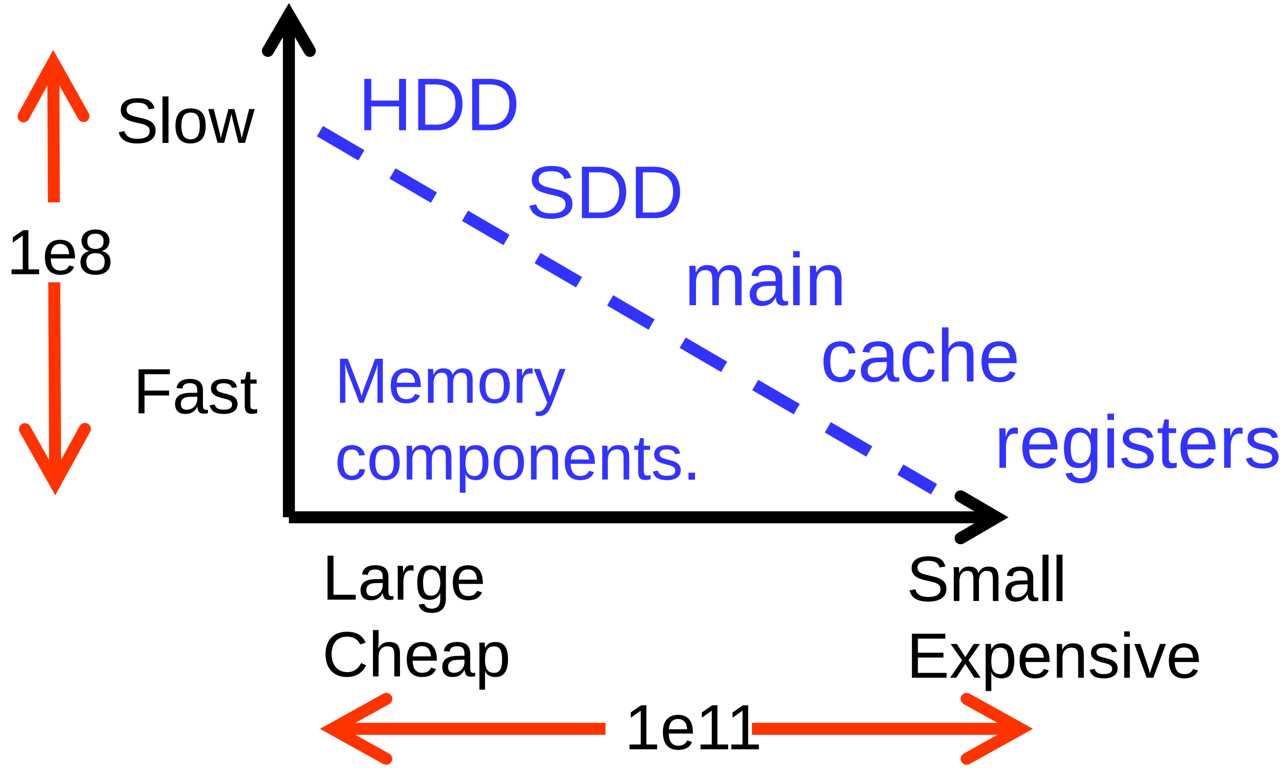
What good architecture allows.

Flexibly build what is possible.

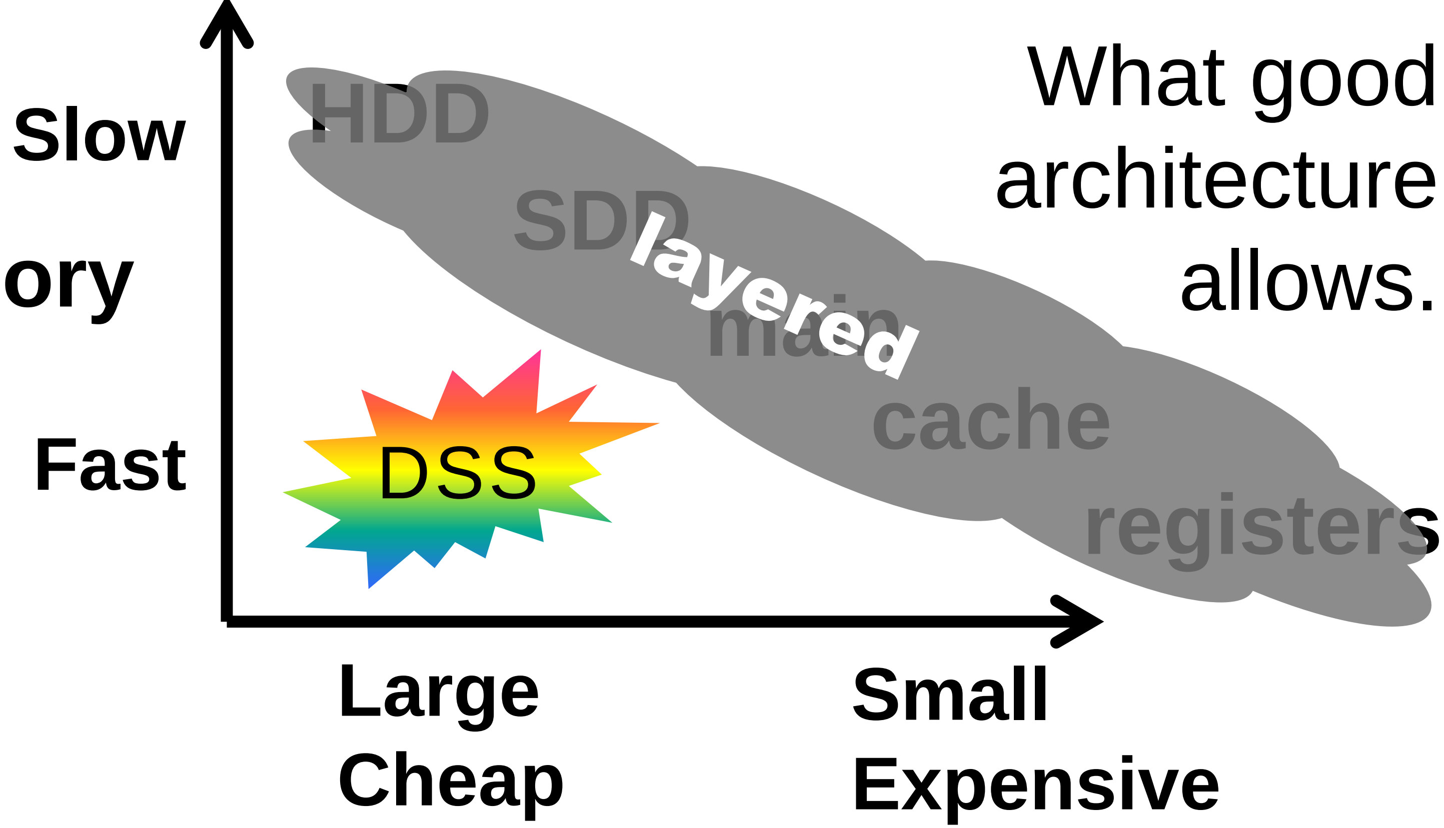
Virtual memory

What good architecture allows.



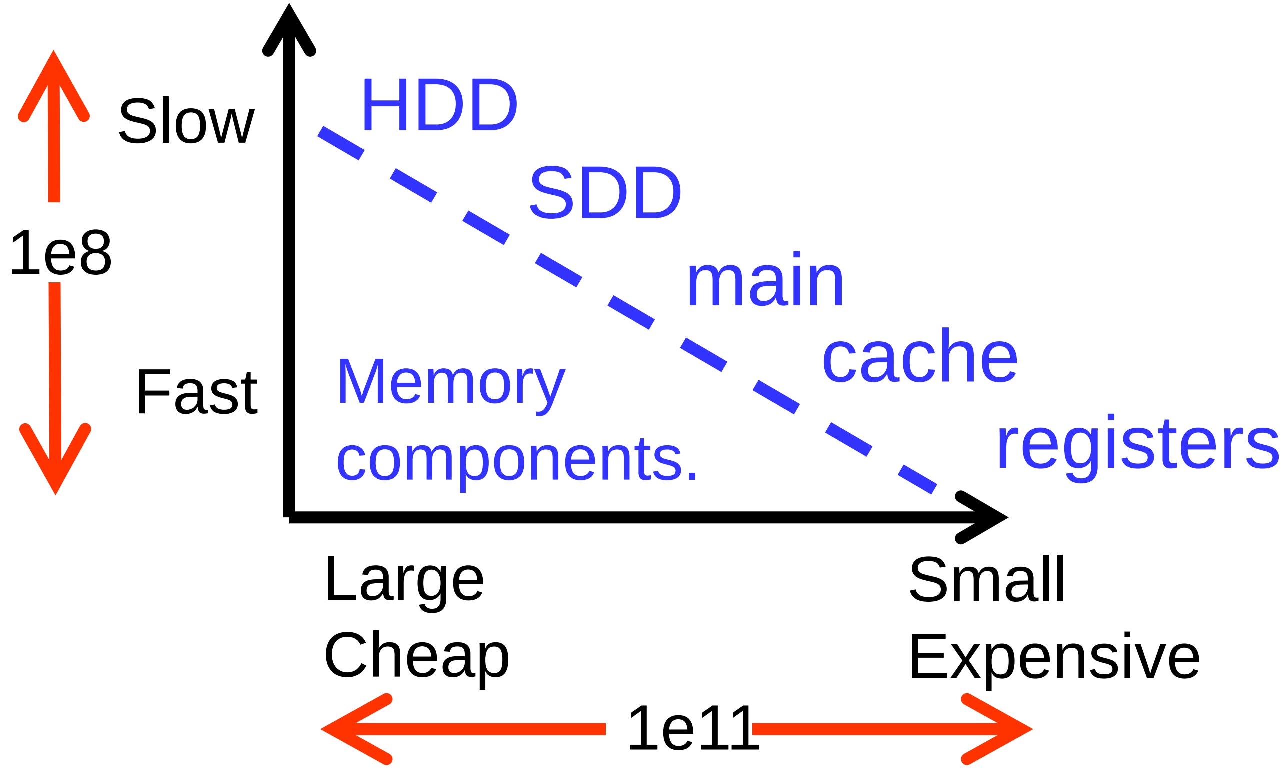


Virtual memory

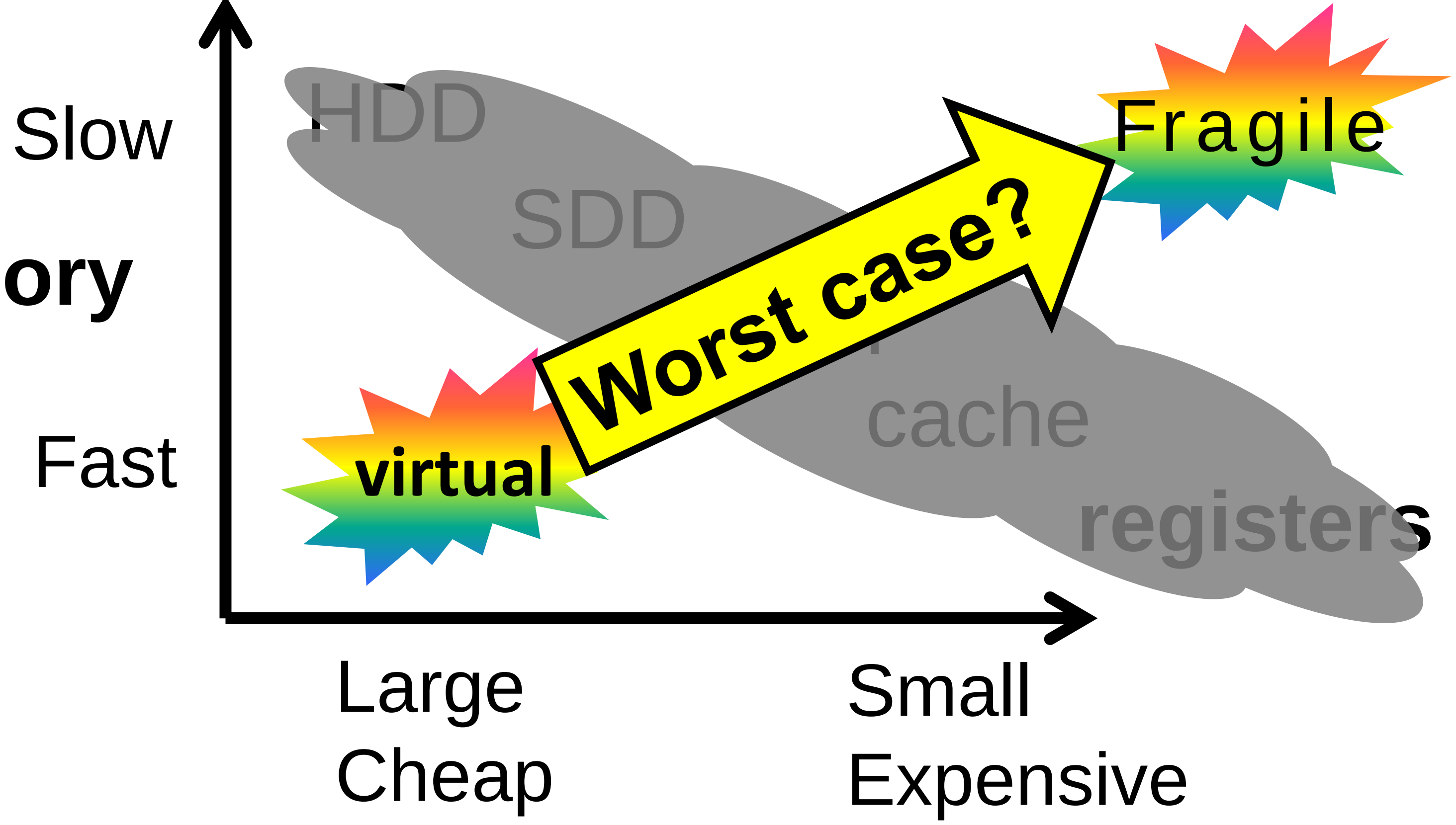


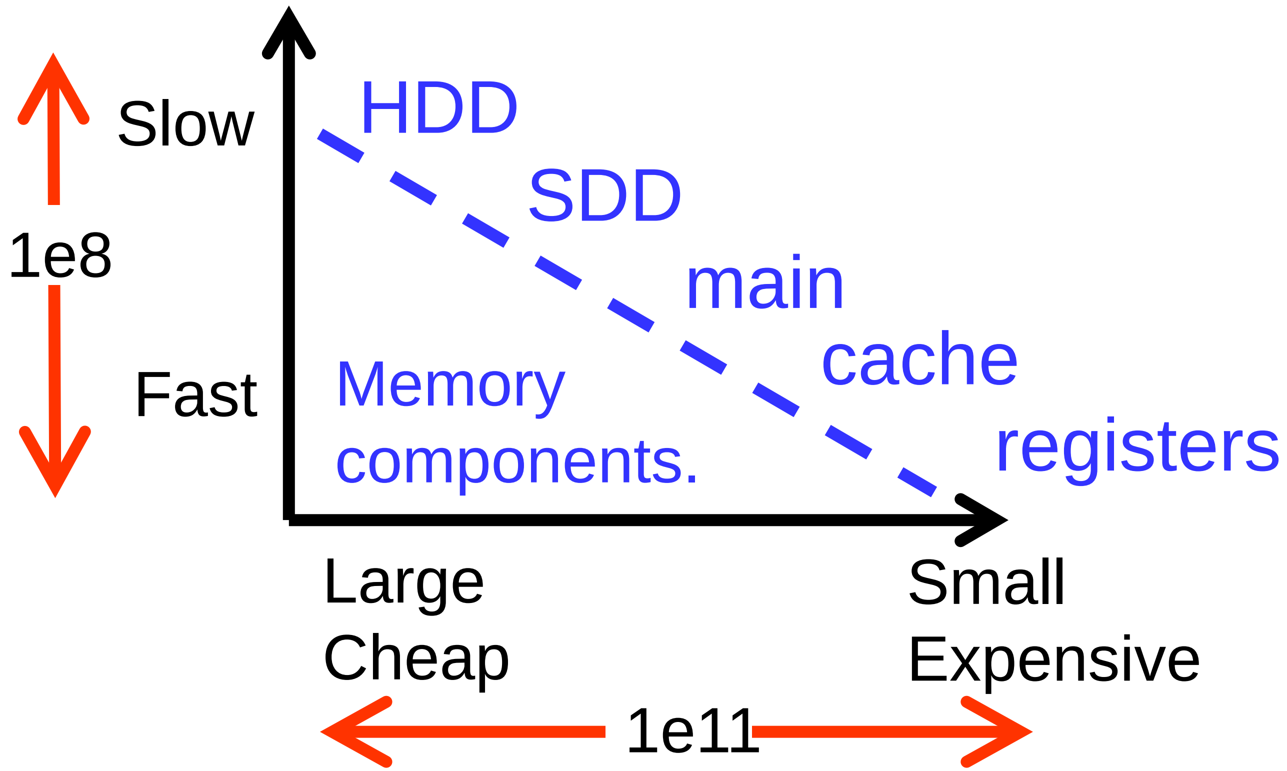
What good architecture allows.

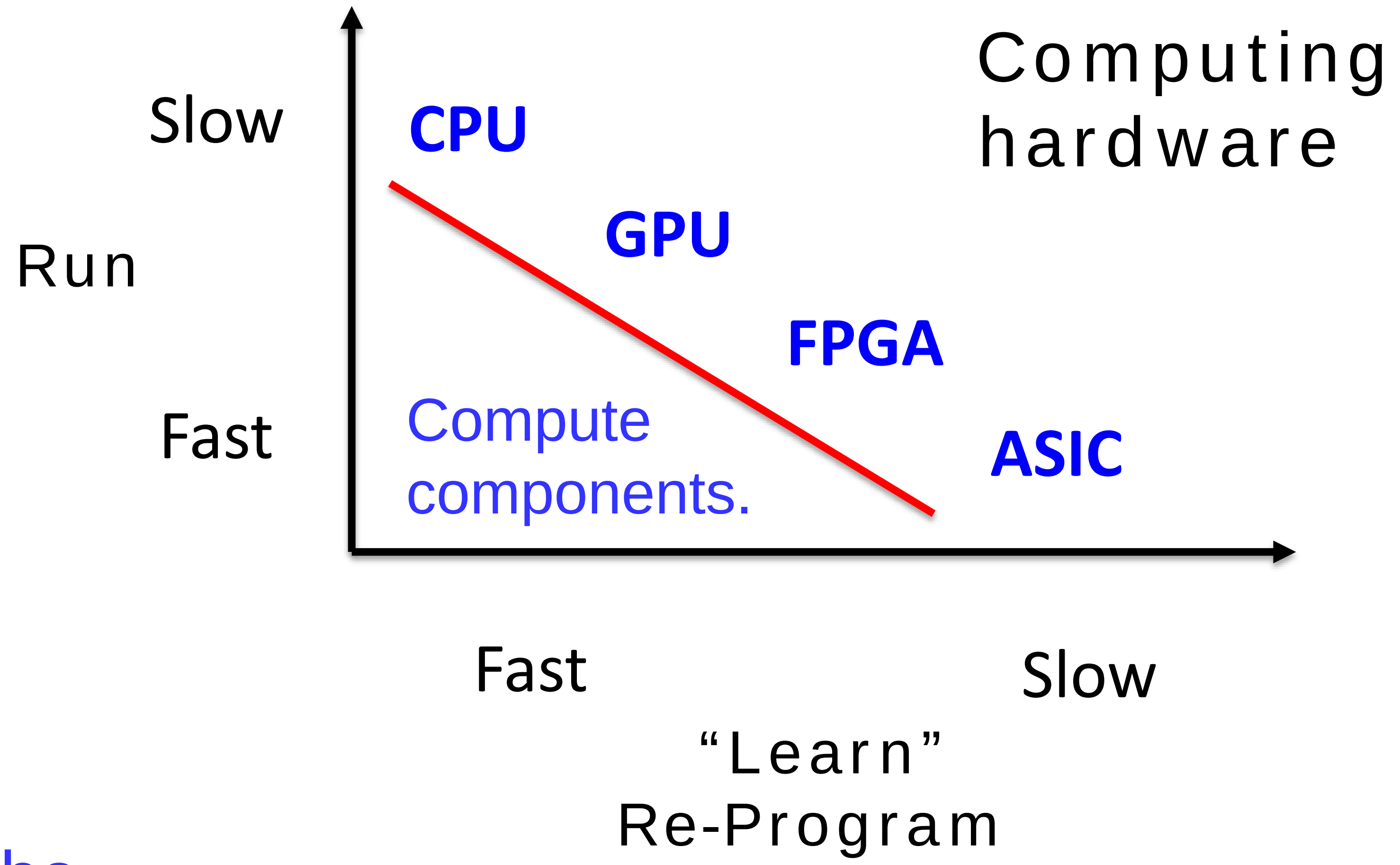
Diversity Sweet Spot

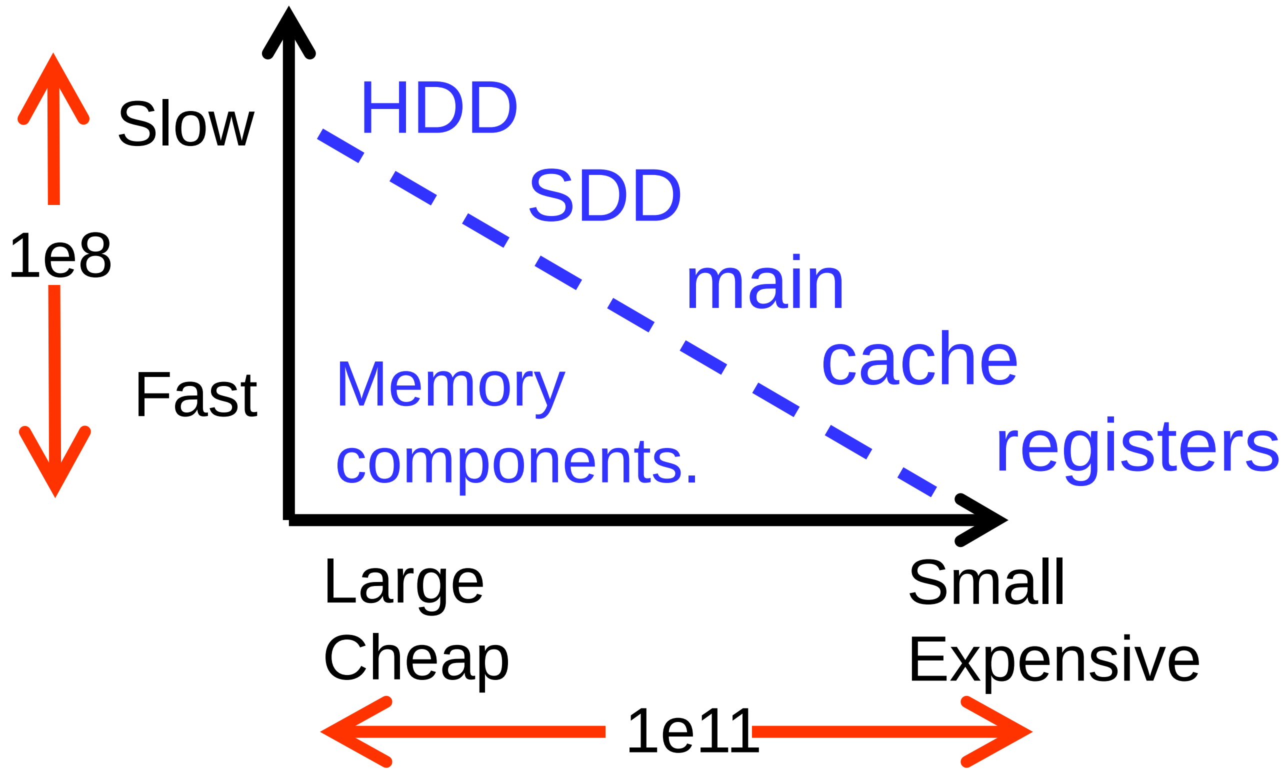


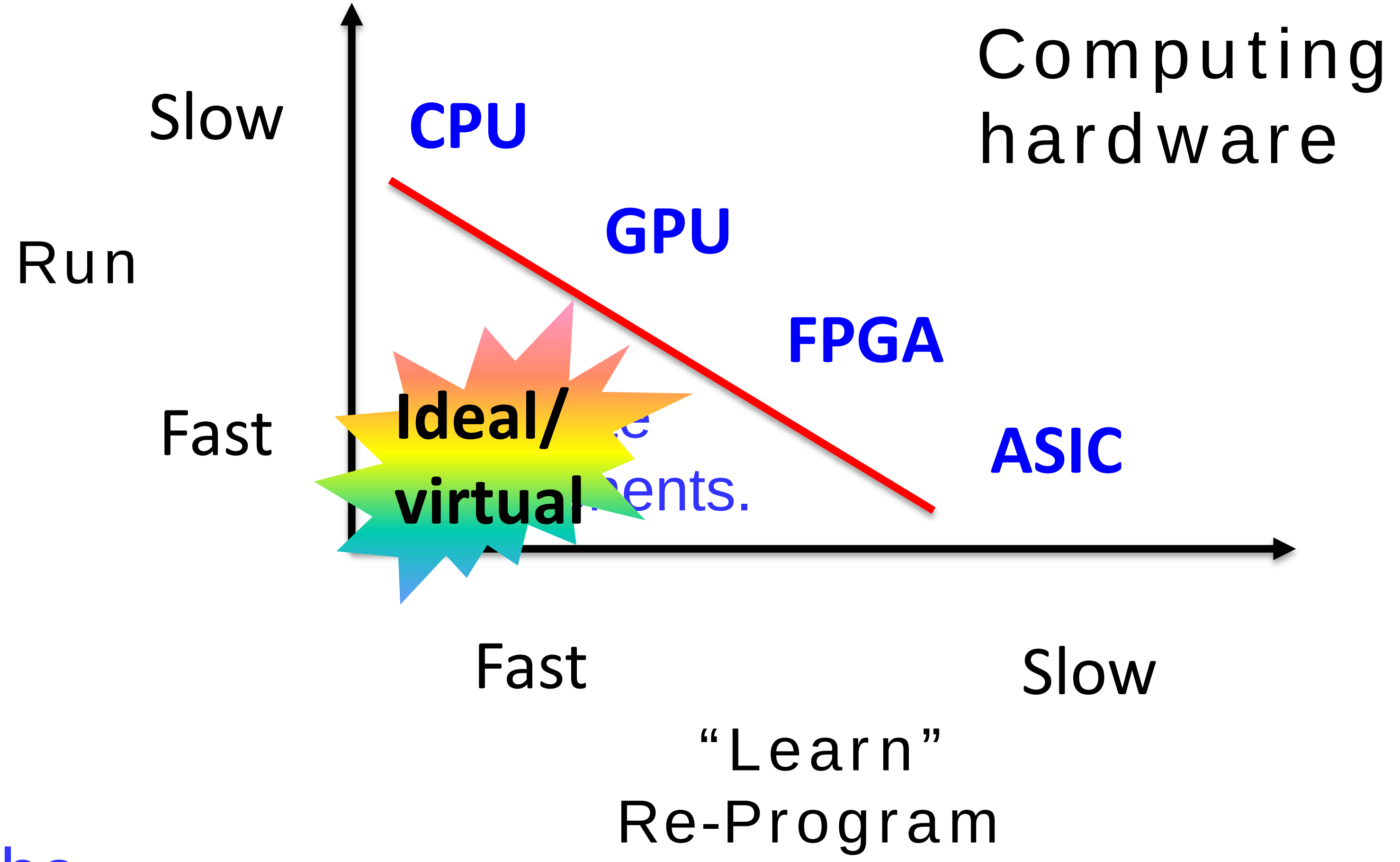
Virtual memory

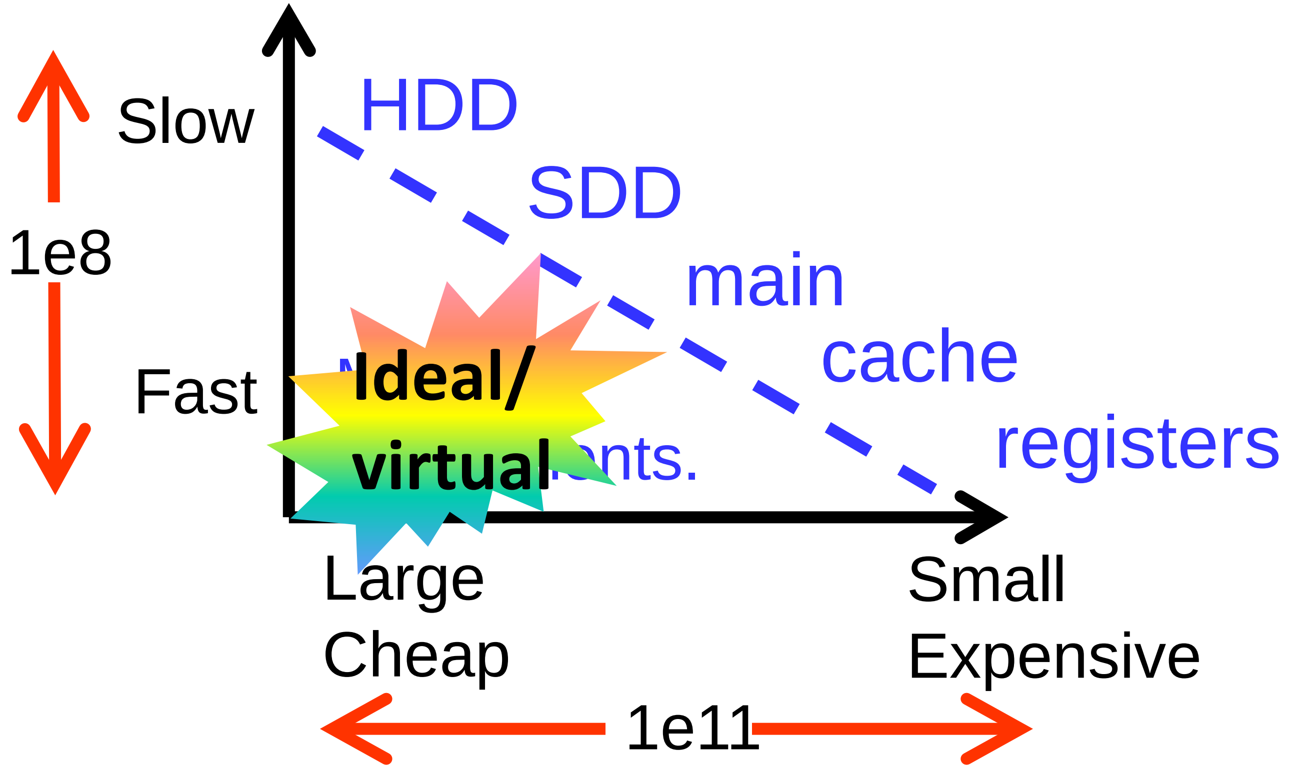




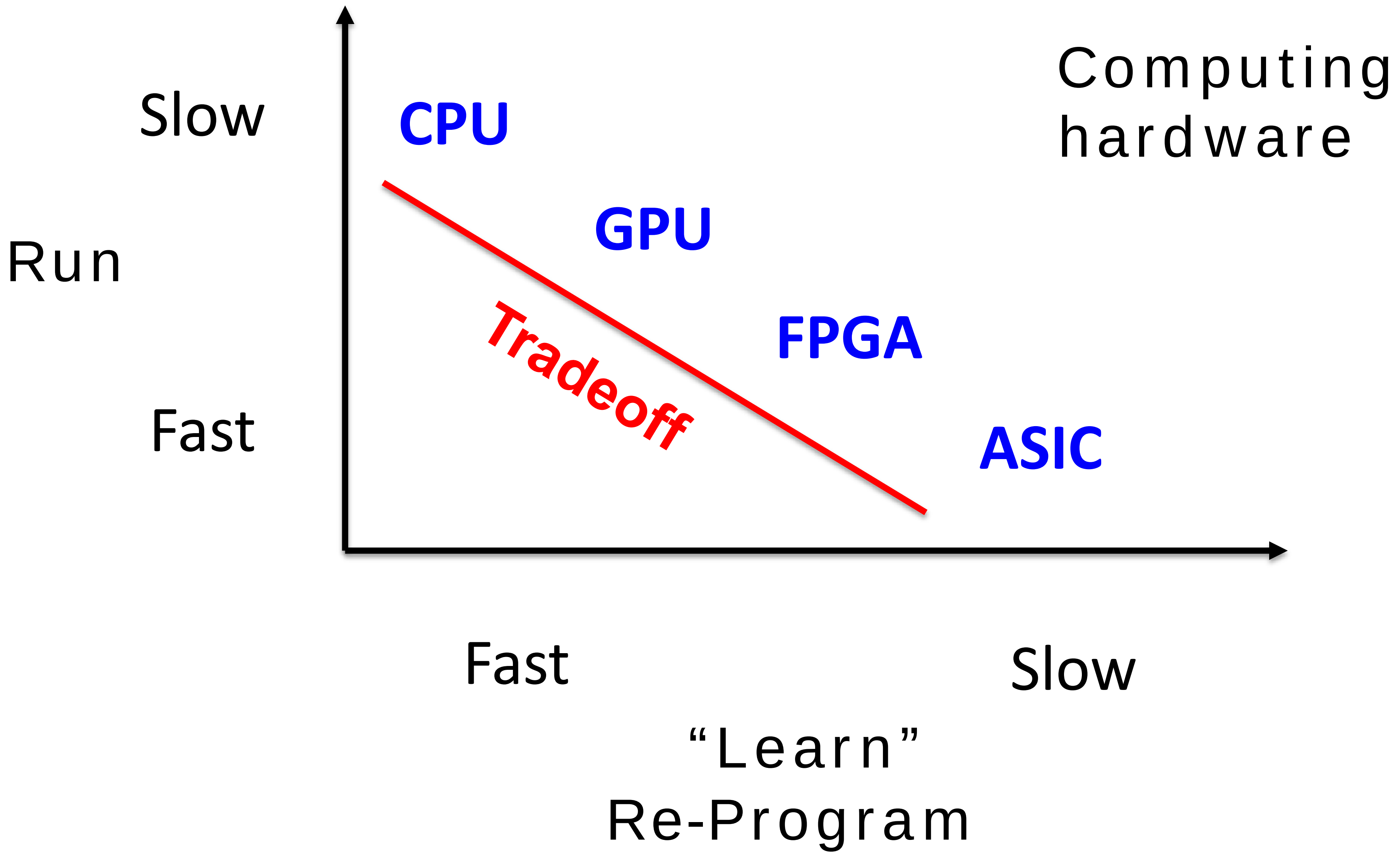

Computing
hardware
Slow
Run
Fast
CPU
GPU
FPGA
ASIC
Compute
components.
Fast
Slow
"Learn"
Re-Program

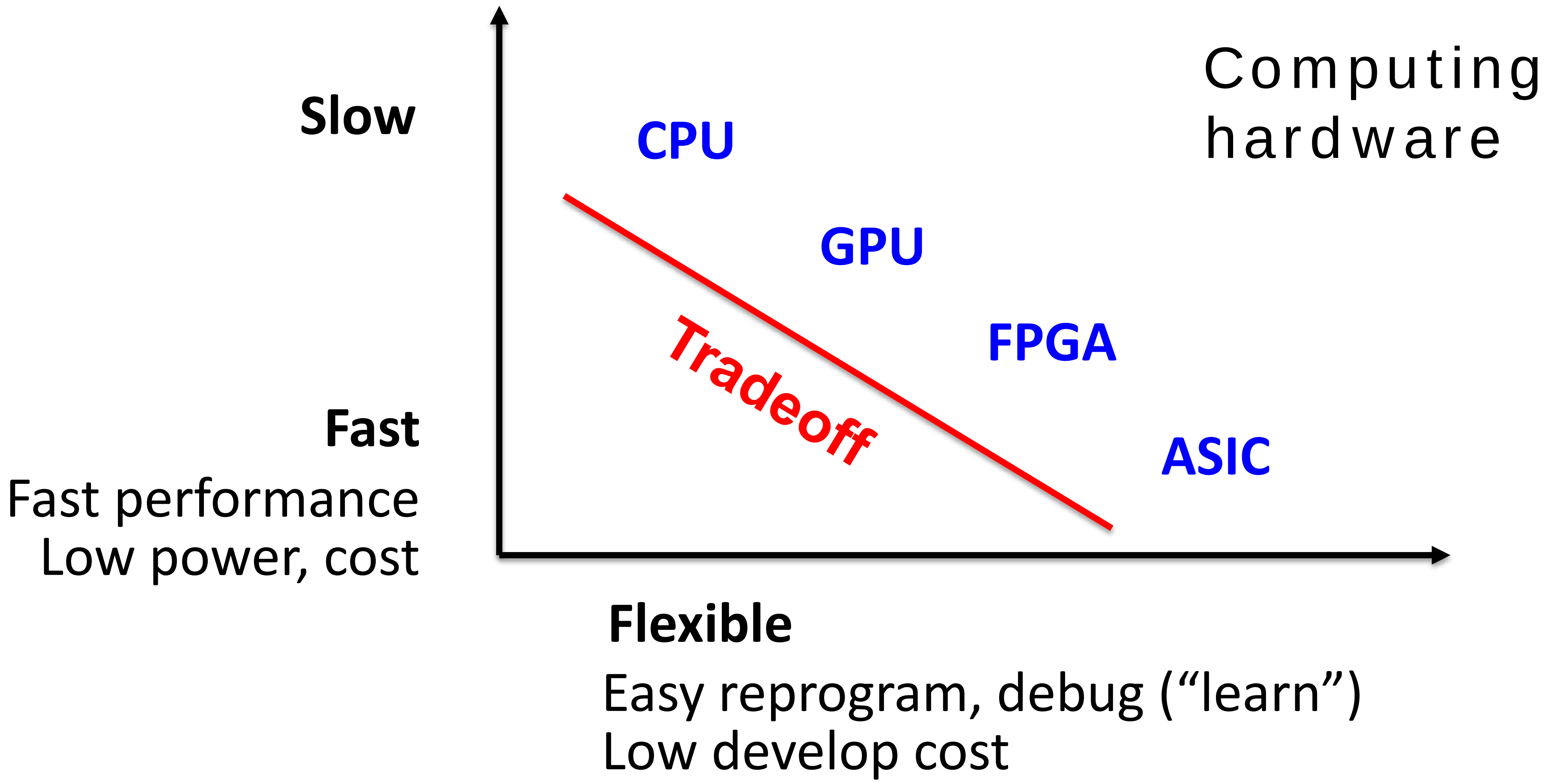

1e8
Slow
Fast
HDD
SDD
main
cache
registers
Memory
components.
Large
Cheap
Small
Expensive
1e11

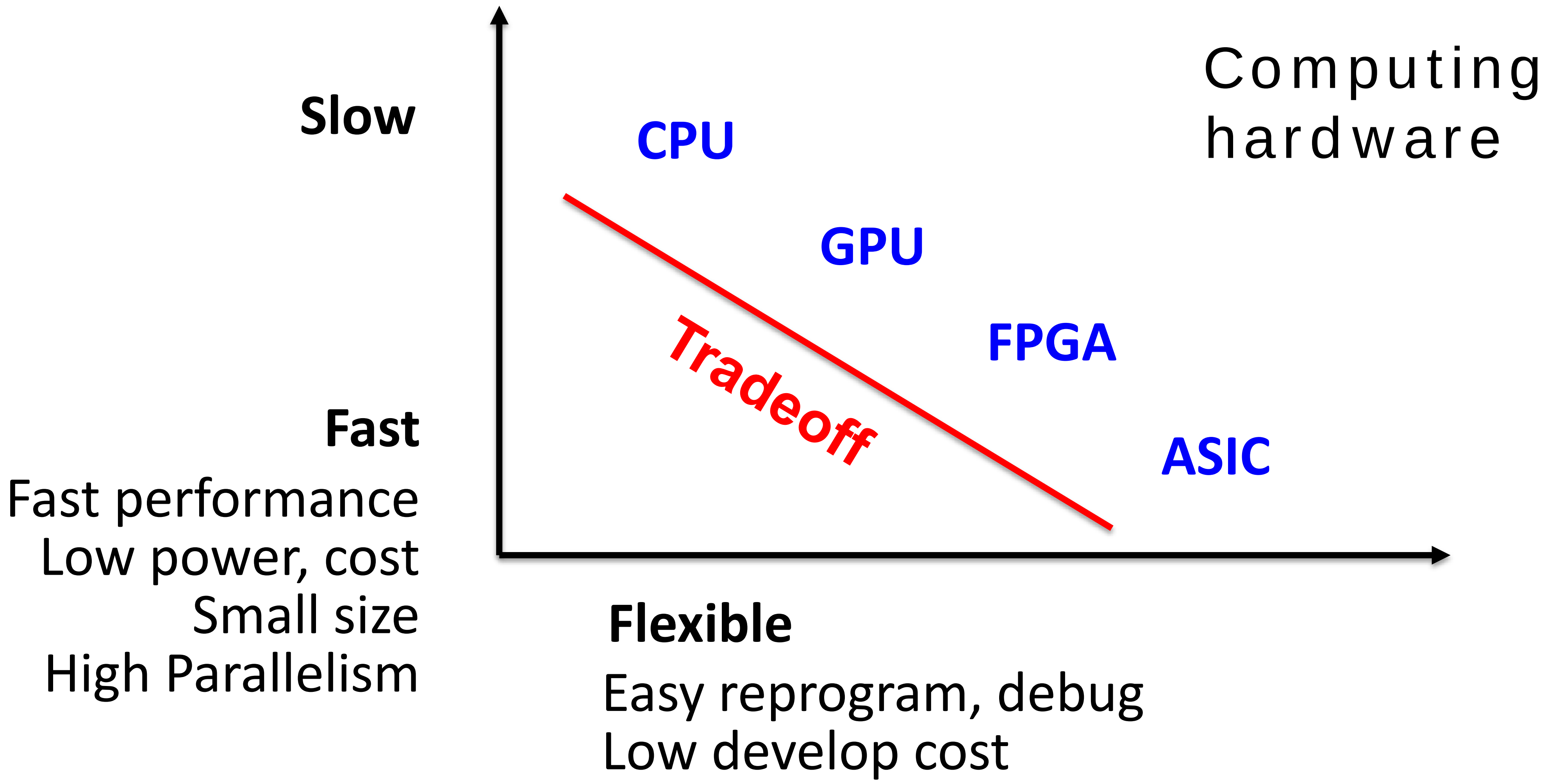




Diversity Sweet Spots


Computing
hardware
Slow
Run
Fast
CPU
GPU
FPGA
ASIC
Tradeoff
Fast
Slow
"Learn"
Re-Program


Computing
hardware
Slow
Fast
Fast performance
Low power, cost
CPU
GPU
FPGA
ASIC
Tradeoff
Flexible
Easy reprogram, debug ("learn")
Low develop cost

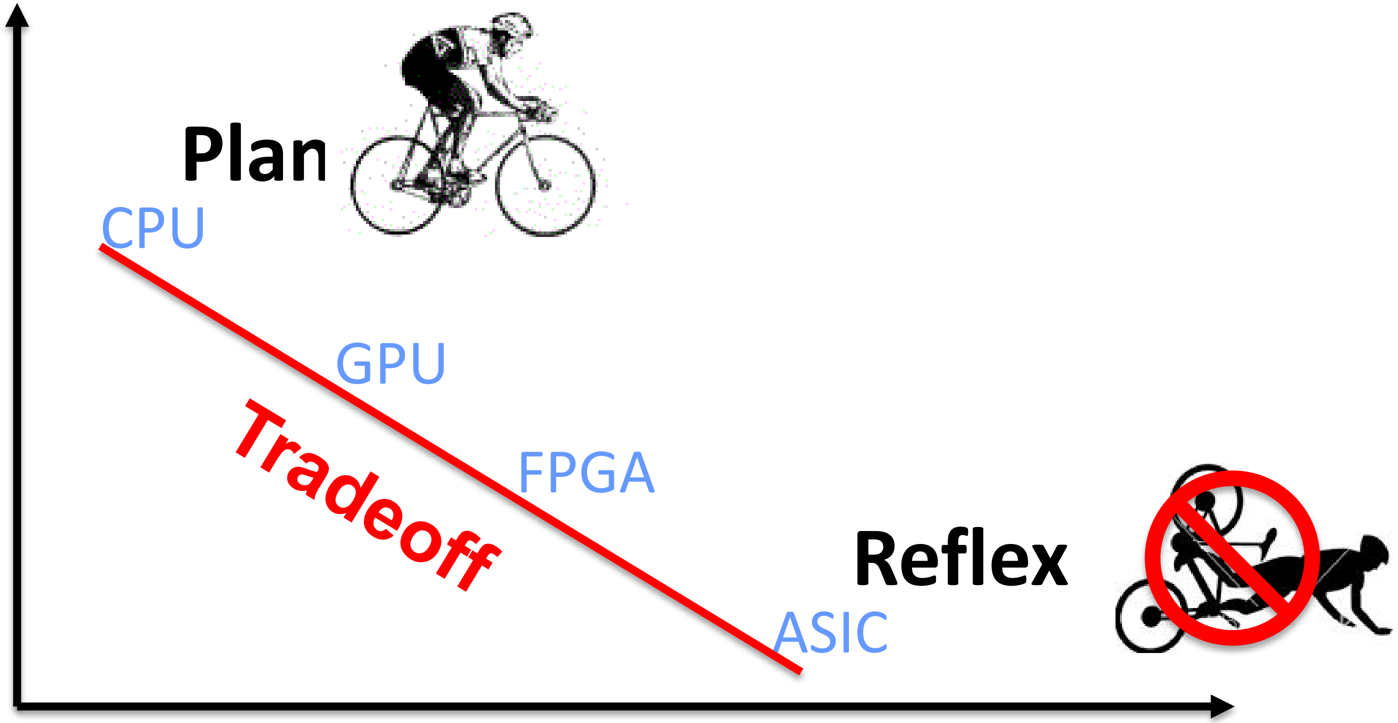


Computing hardware
Slow
CPU
GPU
FPGA
ASIC
Tradeoff
Fast
Fast performance
Low power, cost
Small size
High Parallelism
Flexible
Easy reprogram, debug
Low develop cost

Slow

Fast

Fast performance
Low power, cost
Small size
High Parallelism



Flexible

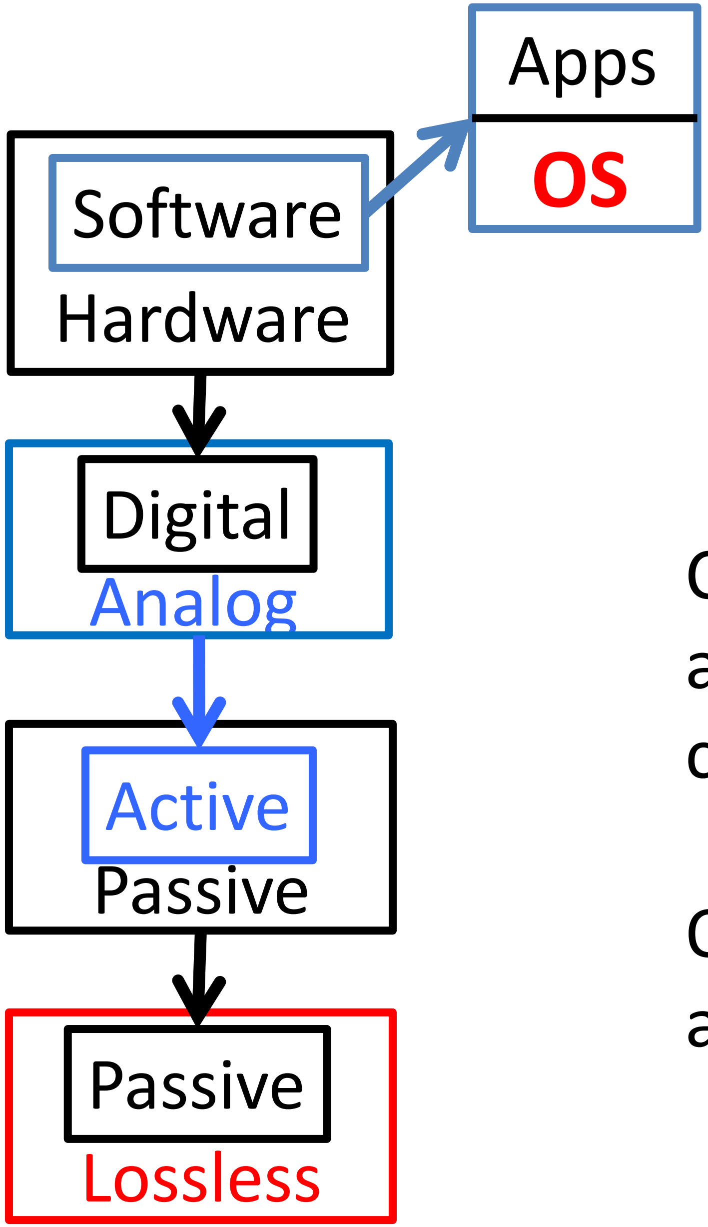
Reprogram, debug
Accurate
Centralized
Conscious
Deliberate
Stable virtual

Virtualization

Mechanistic
Concrete

Networks
- Socio
- Techno
- Neuro
- Bio

- Physics



Math?
Abstract?

Claim: there are universal laws and architectures that this cartoon hints at

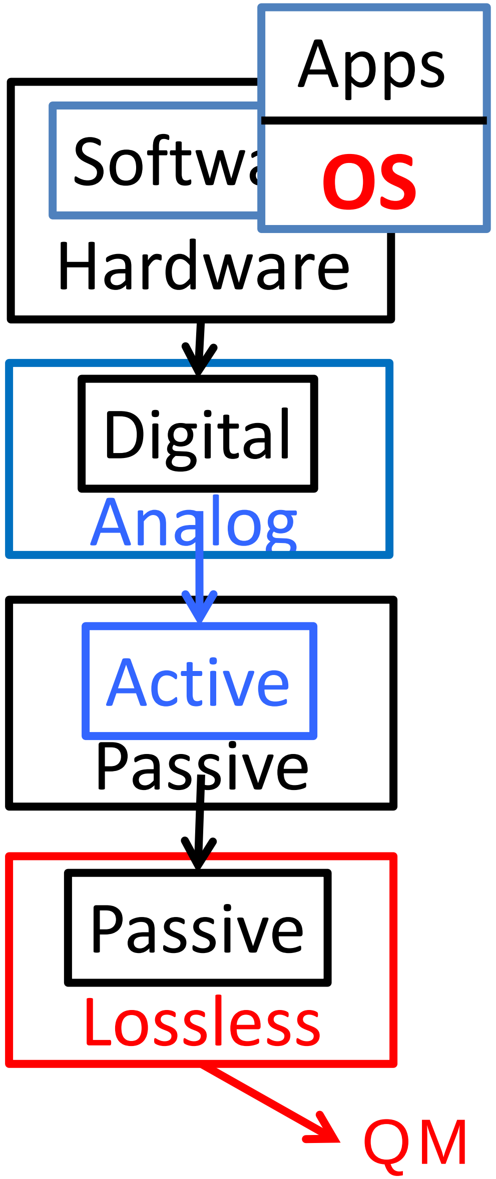
Question: What are the right abstractions and mathematics?

Virtualization

Mechanistic
Concrete

Networks
- Socio
- Techno
- Neuro
- Bio

- Physics



Turing

Kalman
Bode

Shannon
Nyquist

Boltzmann
Carnot

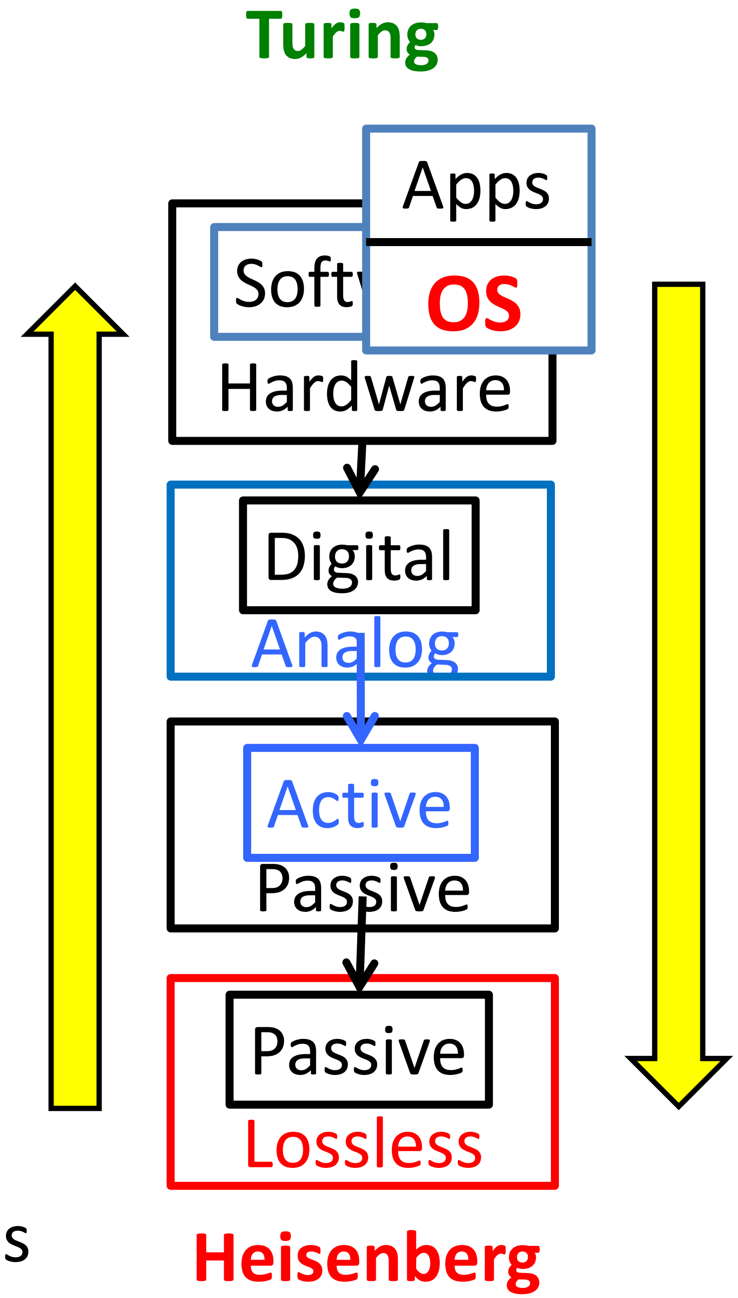
Newton

Heisenberg

Math
Abstract

- Incoherent, disconnected, models, abstractions, “laws”
- Historical artefacts
- No overall architecture

Virtualization



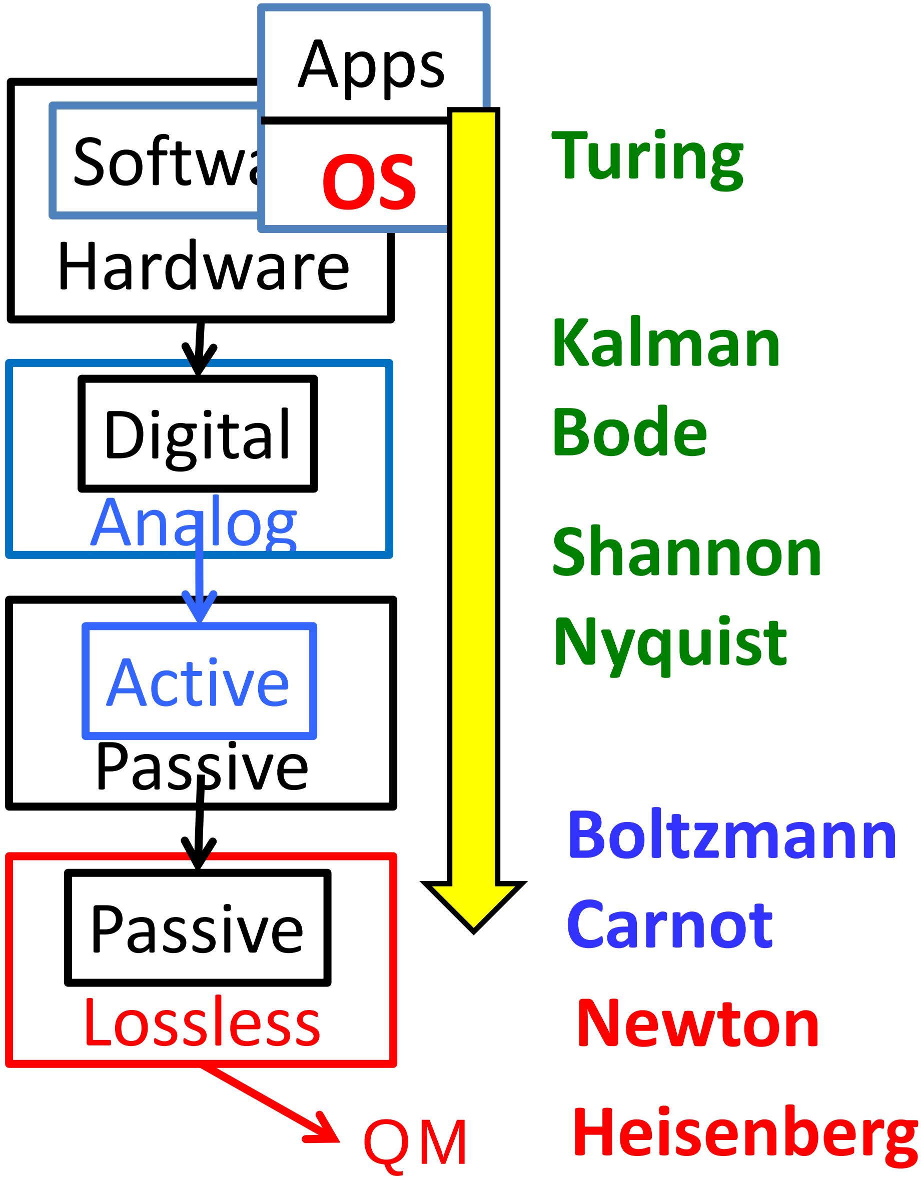
Physics

- "new sciences"
- No tradeoffs
- Minimally architectural
- Large, thick, convex
- Order for free
- Self-organization
- Emergence, edge of…
- Chaos, criticality, fractals

Engineering/math

- Tradeoffs everywhere
- Maximally architectural
- Large, thin, nonconvex

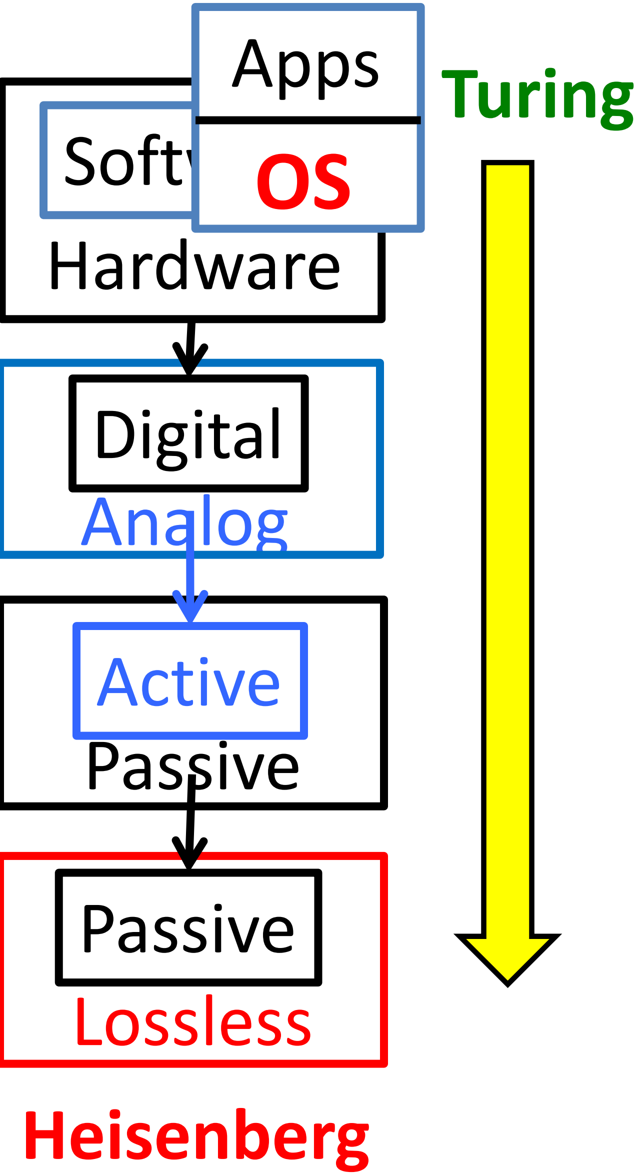
Virtualization reboot

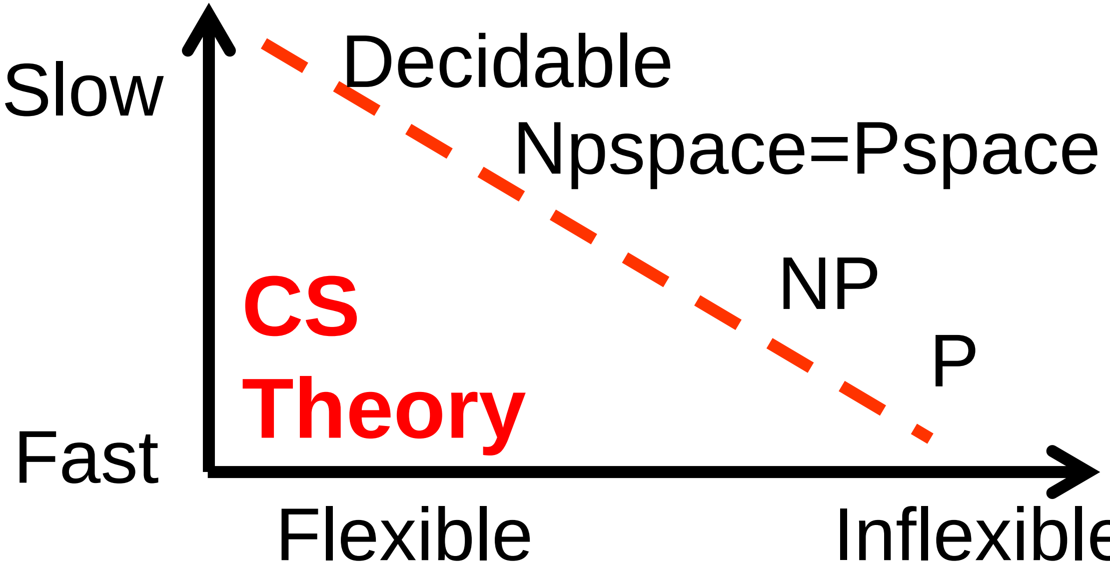


Math Abstract

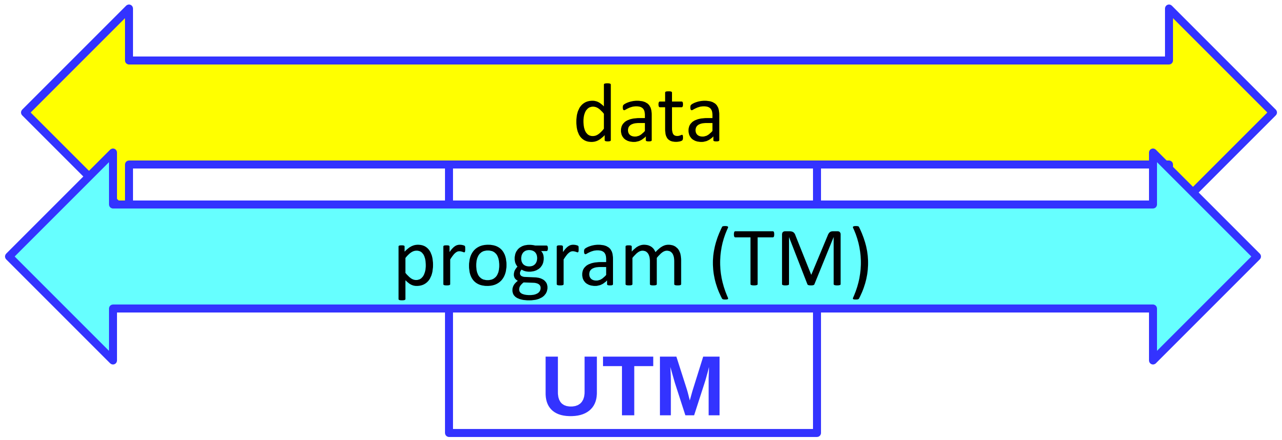
- Top down, start with Turing
- Redo "classical" laws (and architectures) but coherent and integrated
- And formulate new laws (and architectures) but…
- Motivated by "new" networks in tech and bio

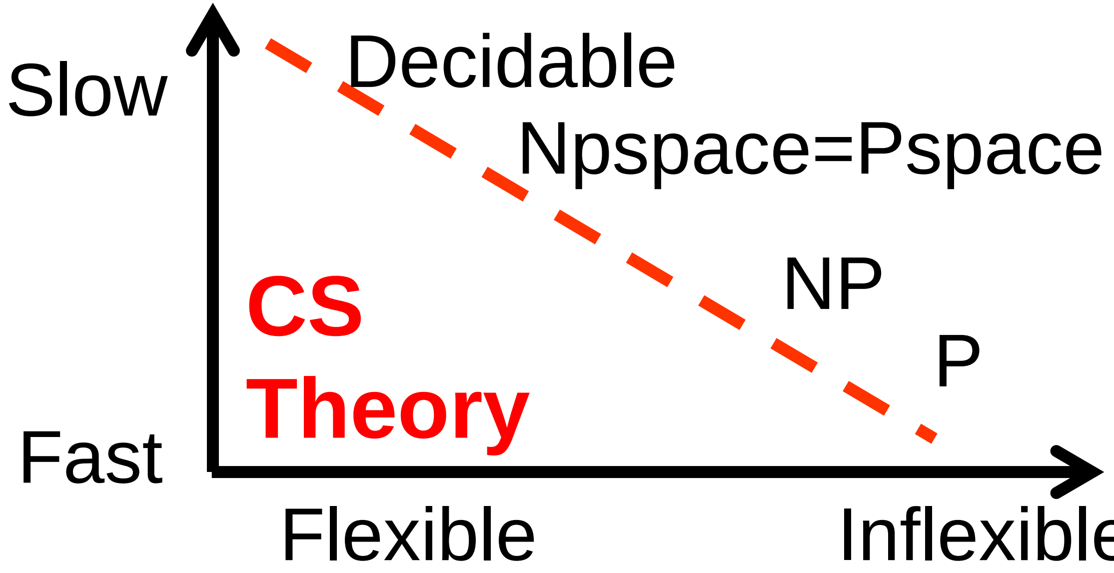
Virtualization





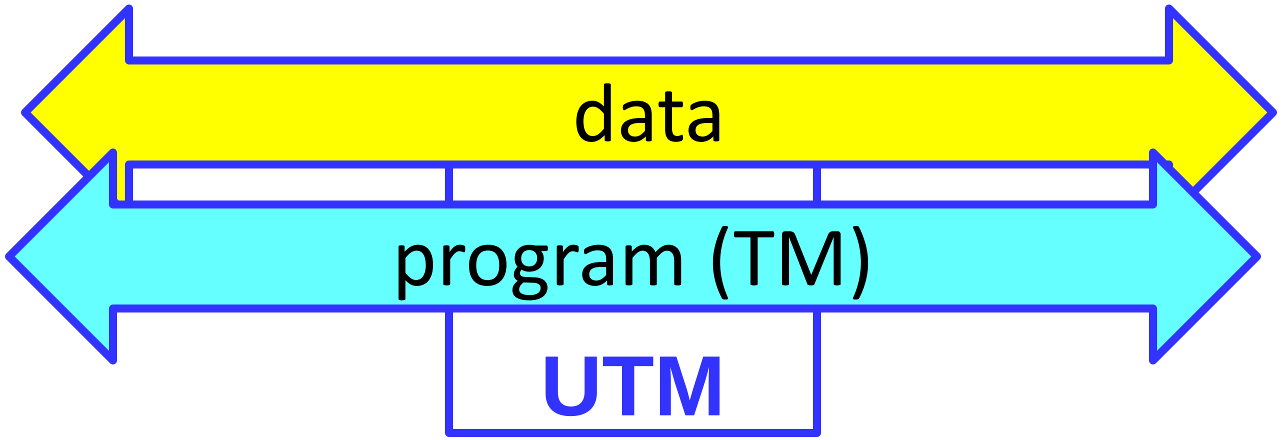
- Tradeoffs everywhere
- Maximally architectural
- Large, thin, nonconvex

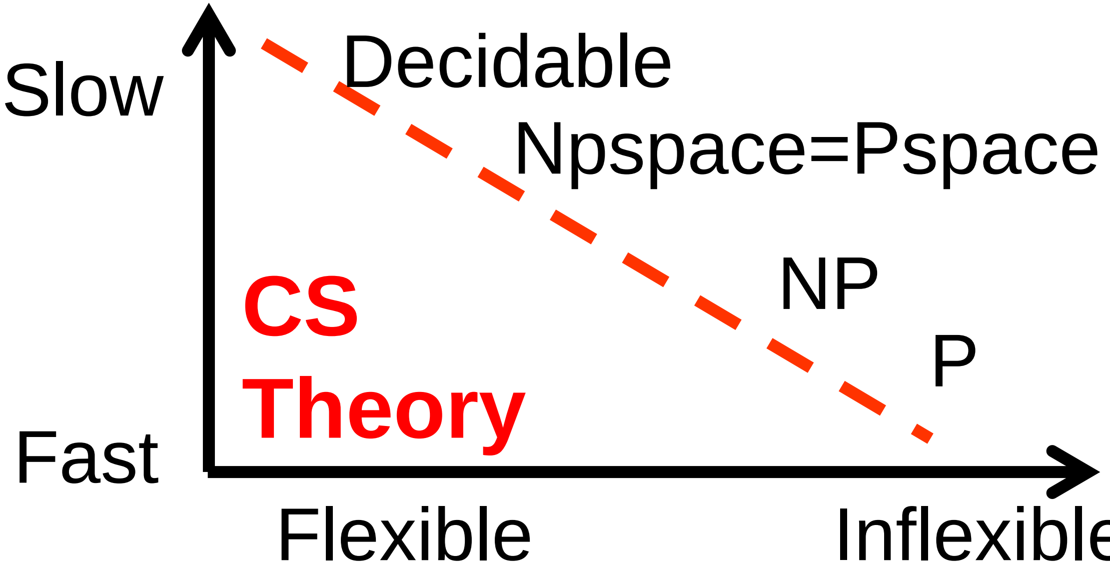




Turing's 3 step research:

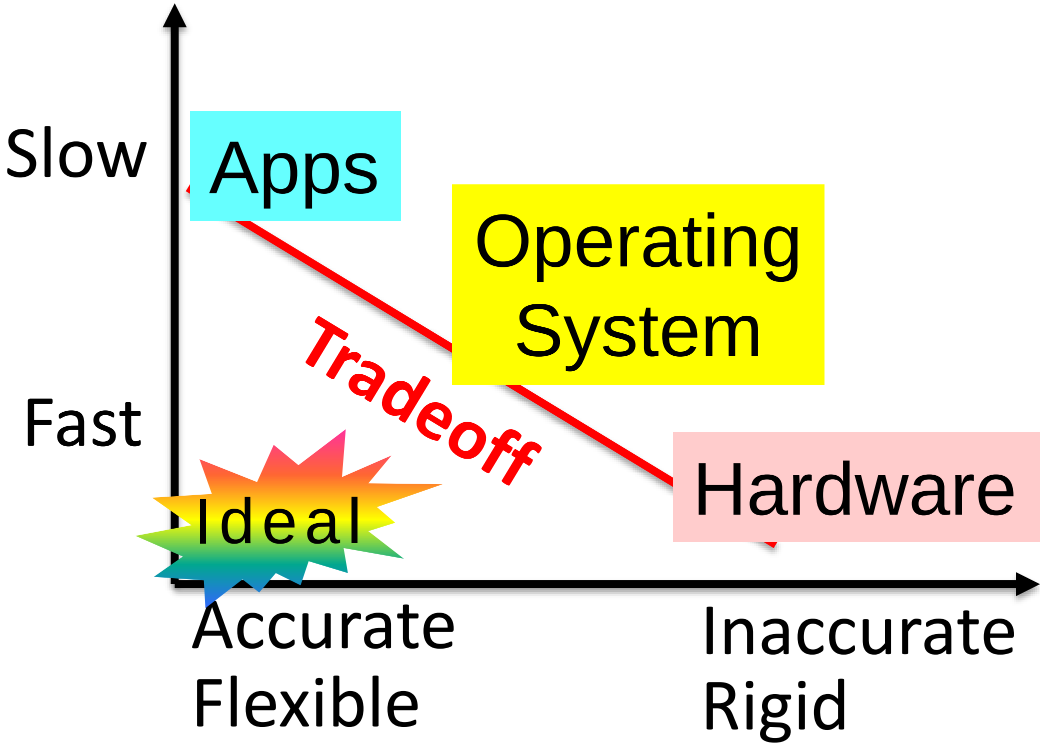
0. Virtual (TM) machines
1. hard limits, (un)decidability using standard model (TM)
2. **Universal architecture achieving hard limits (UTM)**
3. Practical implementation in digital electronics (biology?)



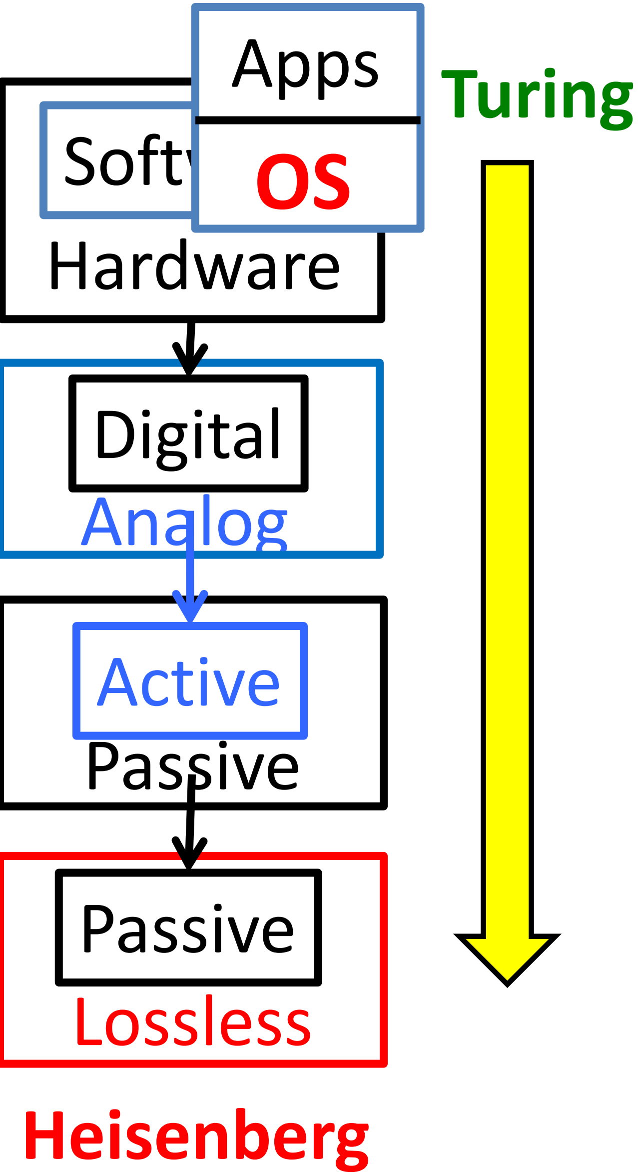


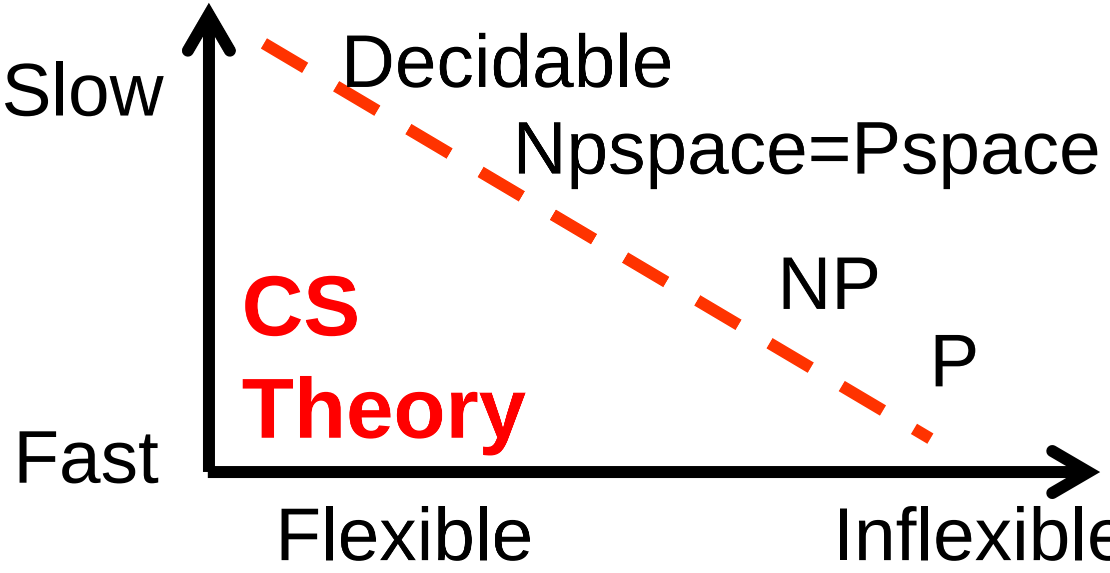
Implications

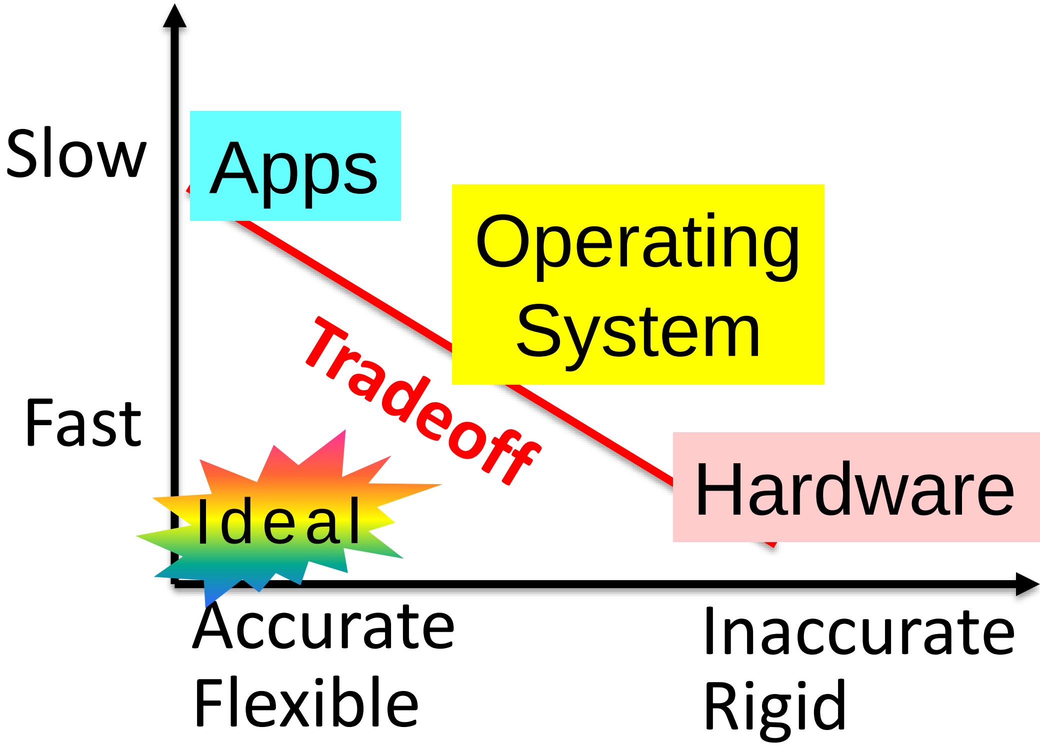
- Large, thin, nonconvex everywhere…
- TMs and UTMs are perfectly repeatable
- But perfectly unpredictable
- Undecidable: Will a TM halt? Is a TM a UTM? Does a TM do X (for almost any X)?
- Easy to make UTMs, but hard to recognize.
- Is anything decidable? Yes, NOT about TMs.
- Time/delay/latency is most precious resource (expensive and limiting)

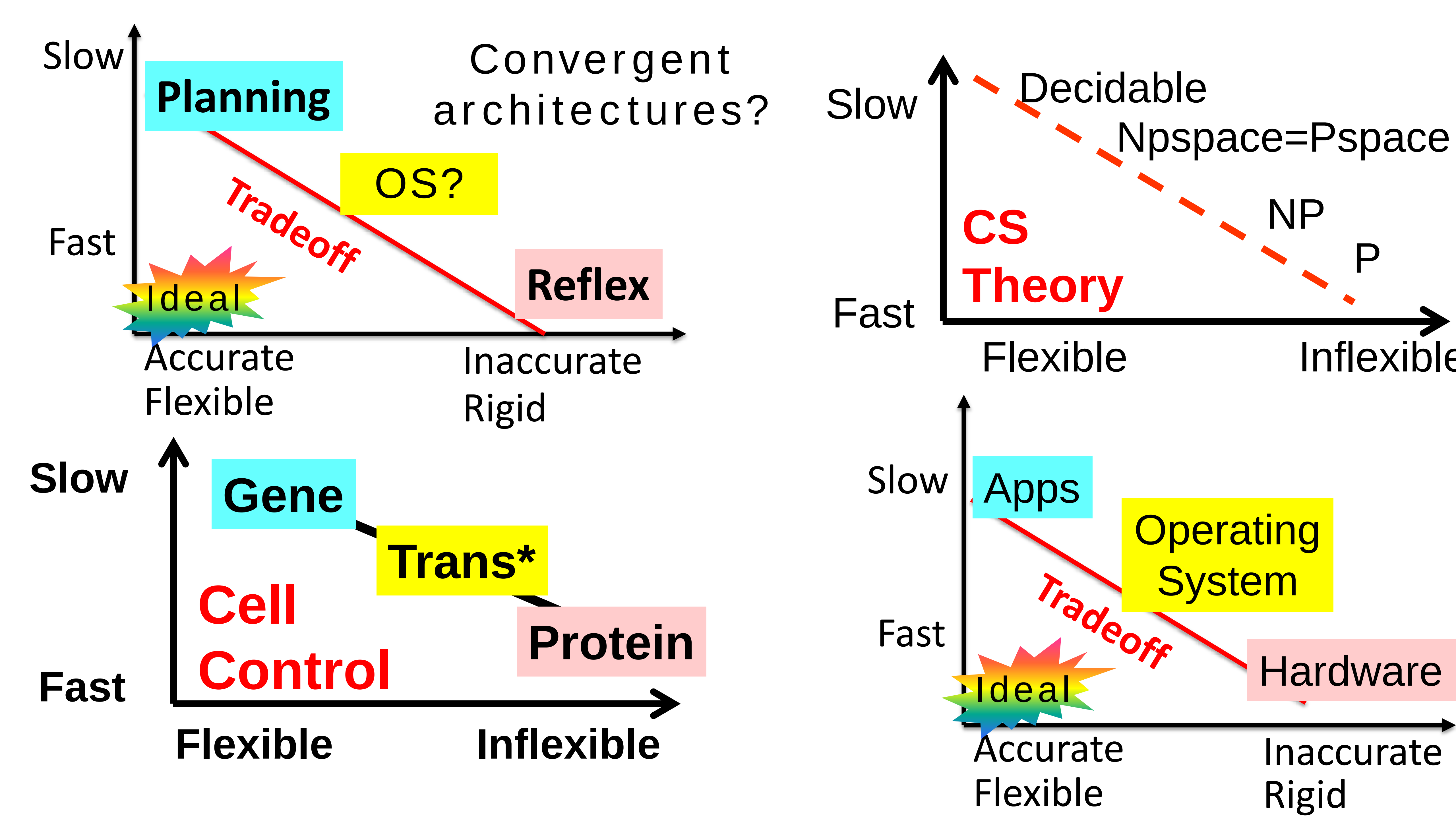


Virtualization



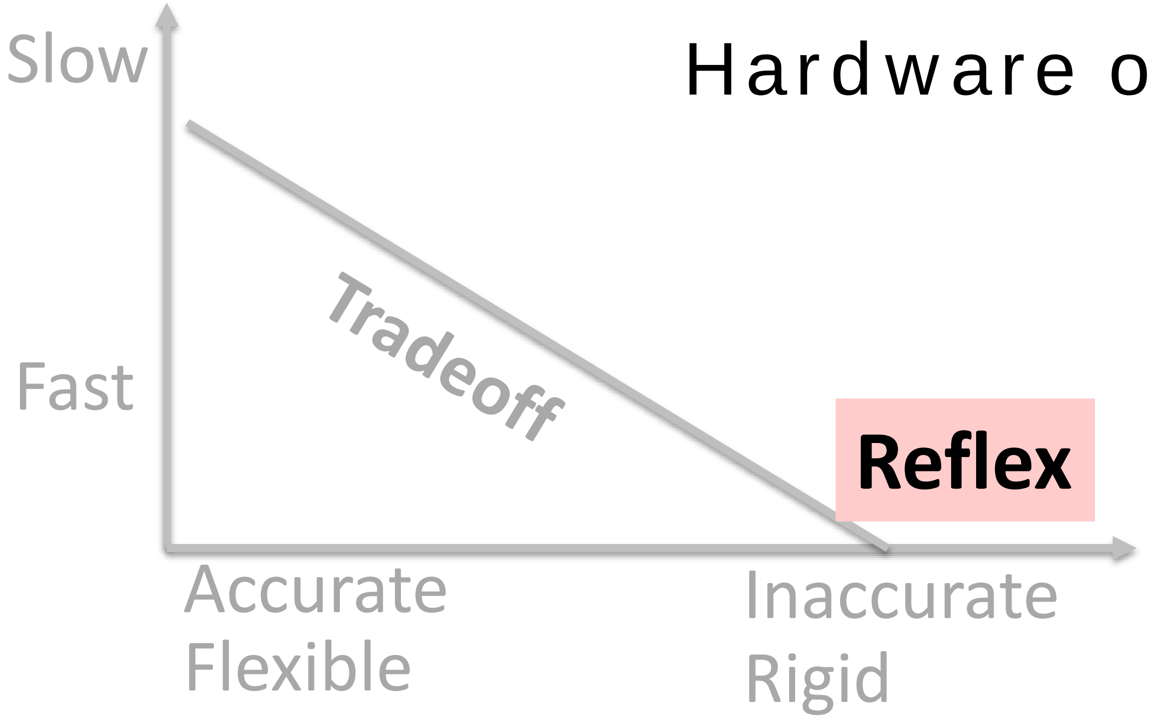


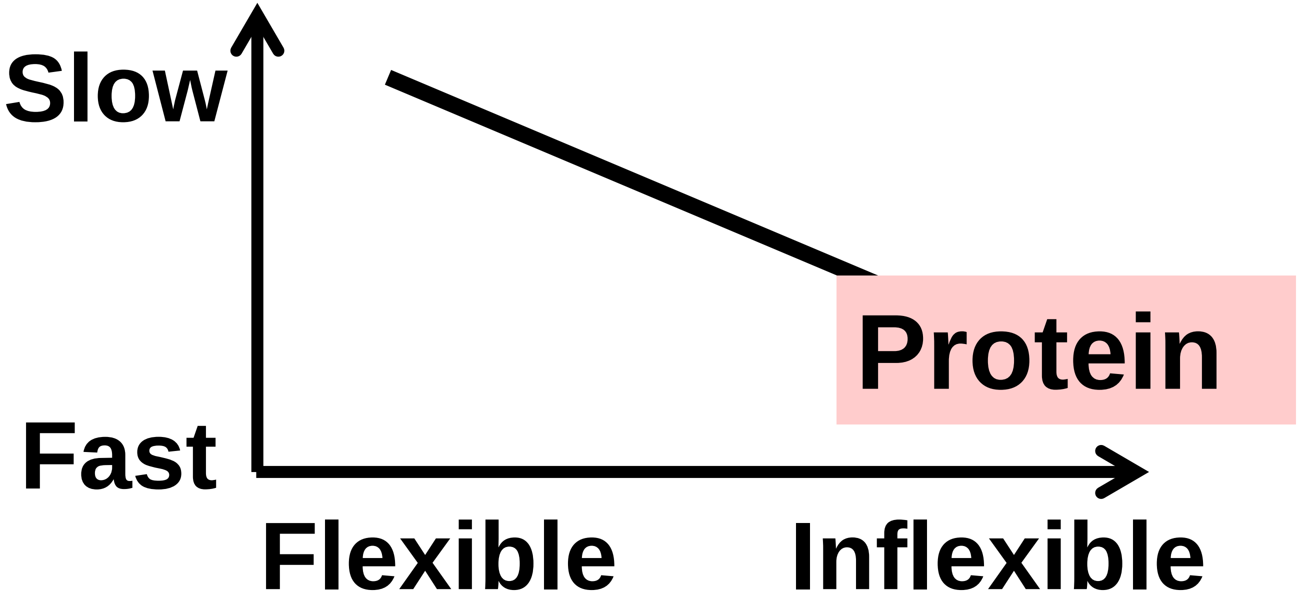


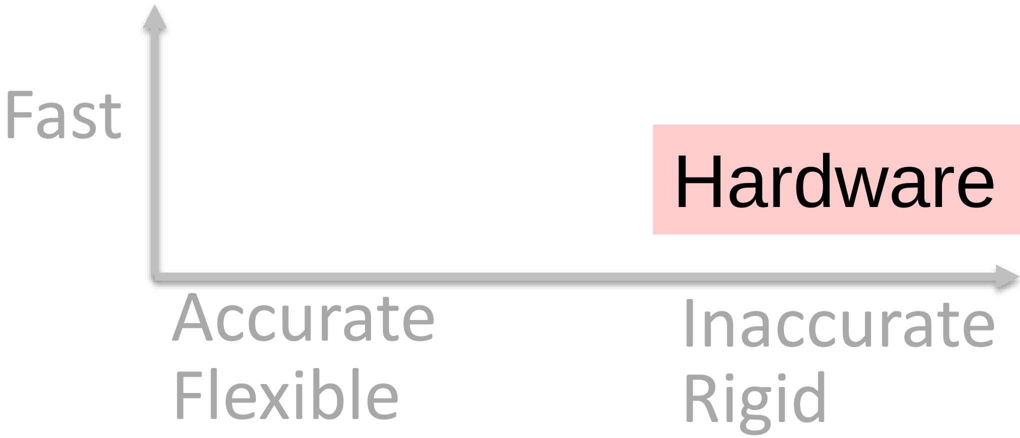


Convergent architectures?
Slow
Fast
Planning
OS?
Tradeoff
Reflex
Ideal
Accurate
Flexible
Inaccurate
Rigid
Slow
Fast
Decidable
Npspace=Pspace
NP
P
CS
Theory
Flexible
Inflexible
Slow
Fast
Gene
Trans*
Cell
Control
Protein
Flexible
Inflexible
Slow
Fast
Apps
Operating
System
Tradeoff
Hardware
Ideal
Accurate
Flexible
Inaccurate
Rigid

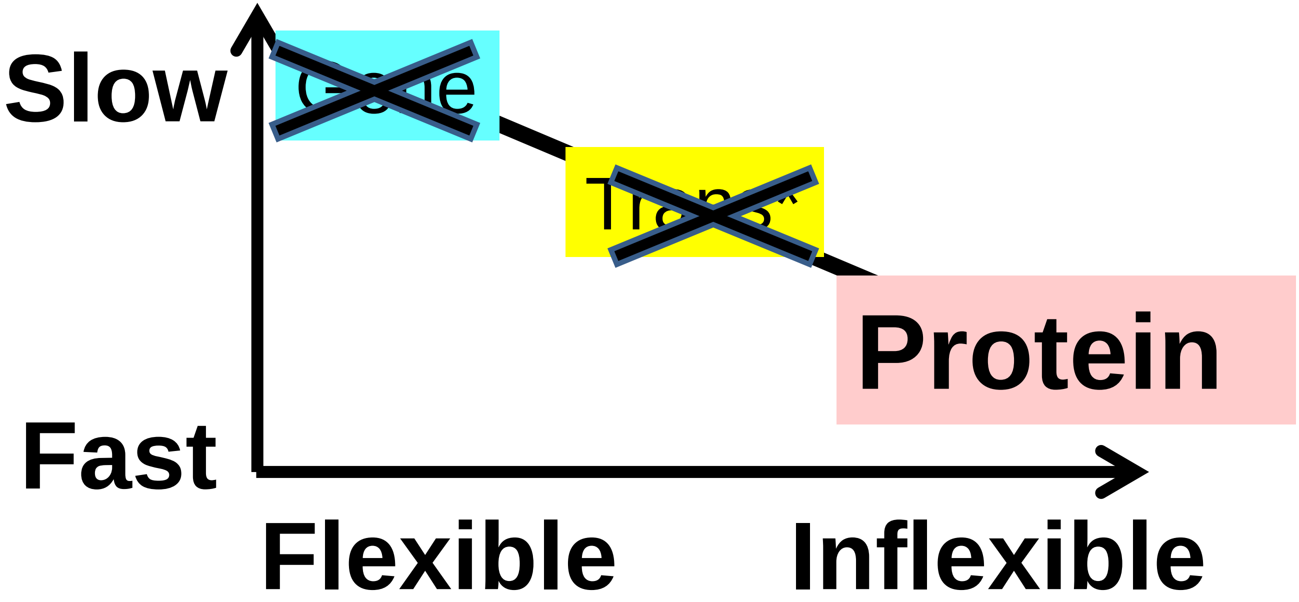
Hardware only







Hardware only



Mammals

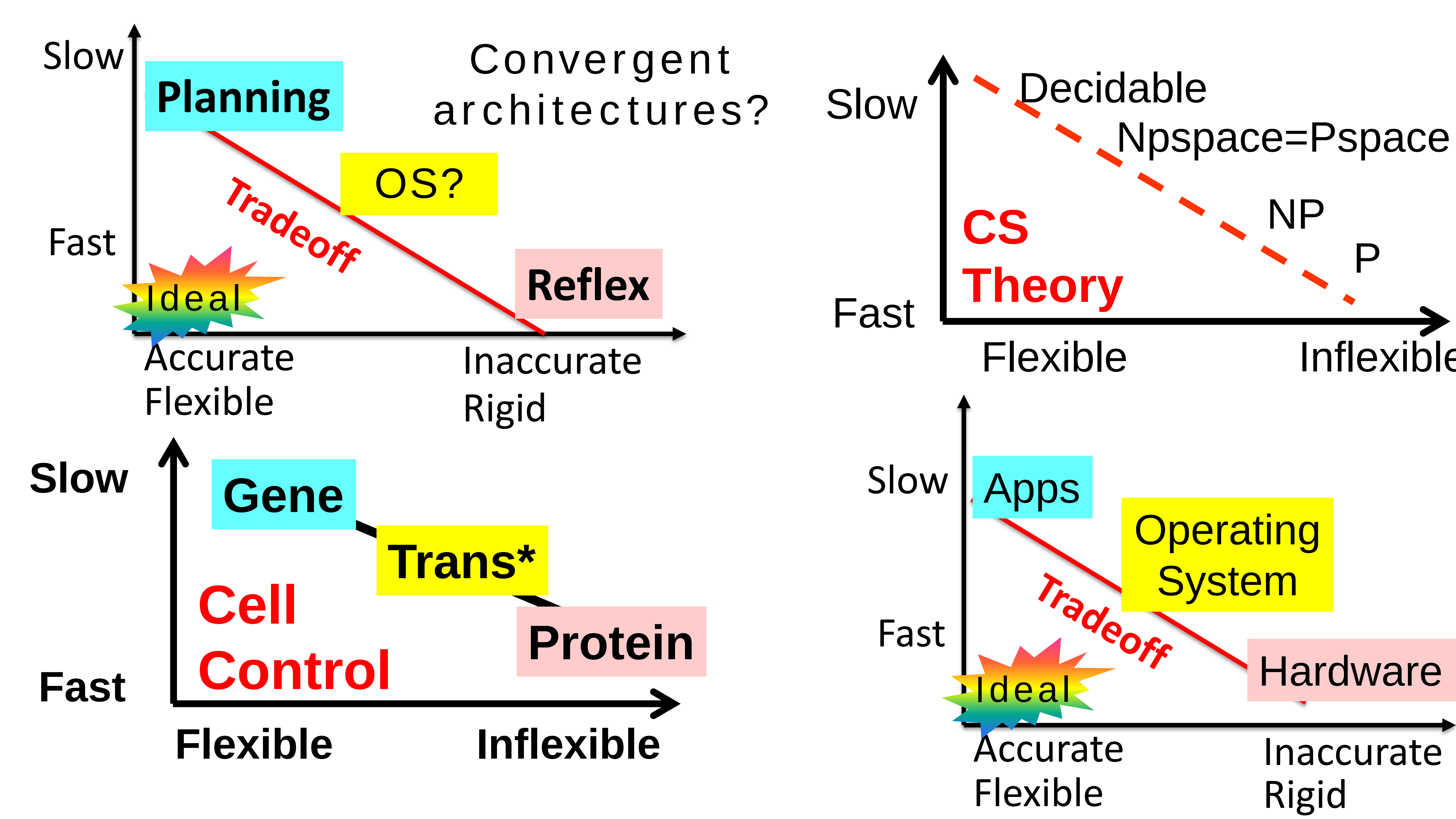
- Erythrocytes (RBC)
- Platelets
- Eye lens fibers
- Skin periphery

Micro-wasps

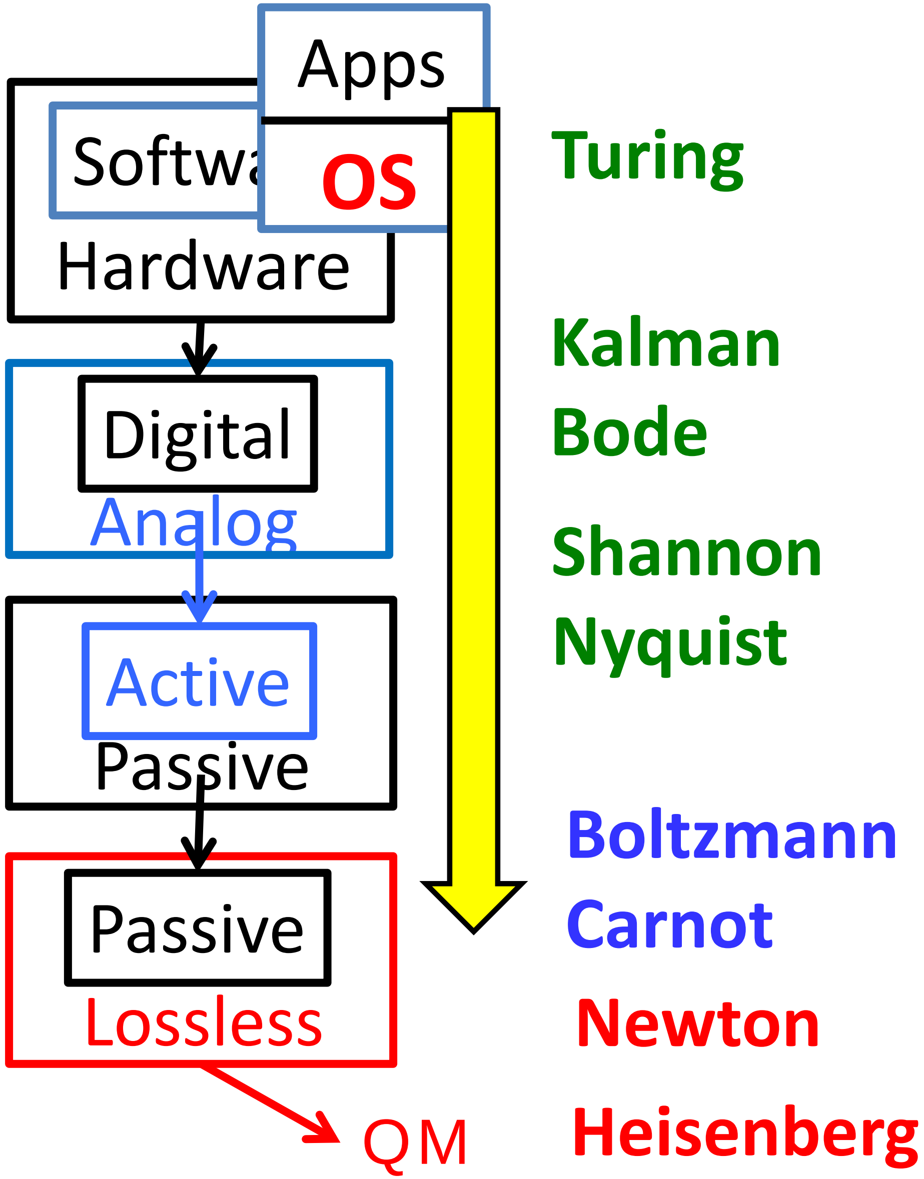
- Neurons

Plants

- Sieve tubes of phloem


Convergent architectures?
Slow
Fast
Planning
OS?
Tradeoff
Reflex
Ideal
Accurate
Flexible
Inaccurate
Rigid
Slow
Fast
Decidable
Npspace=Pspace
NP
P
CS
Theory
Flexible
Inflexible
Slow
Fast
Gene
Trans*
Cell
Control
Protein
Flexible
Inflexible
Slow
Fast
Apps
Operating
System
Tradeoff
Hardware
Ideal
Accurate
Flexible
Inaccurate
Rigid

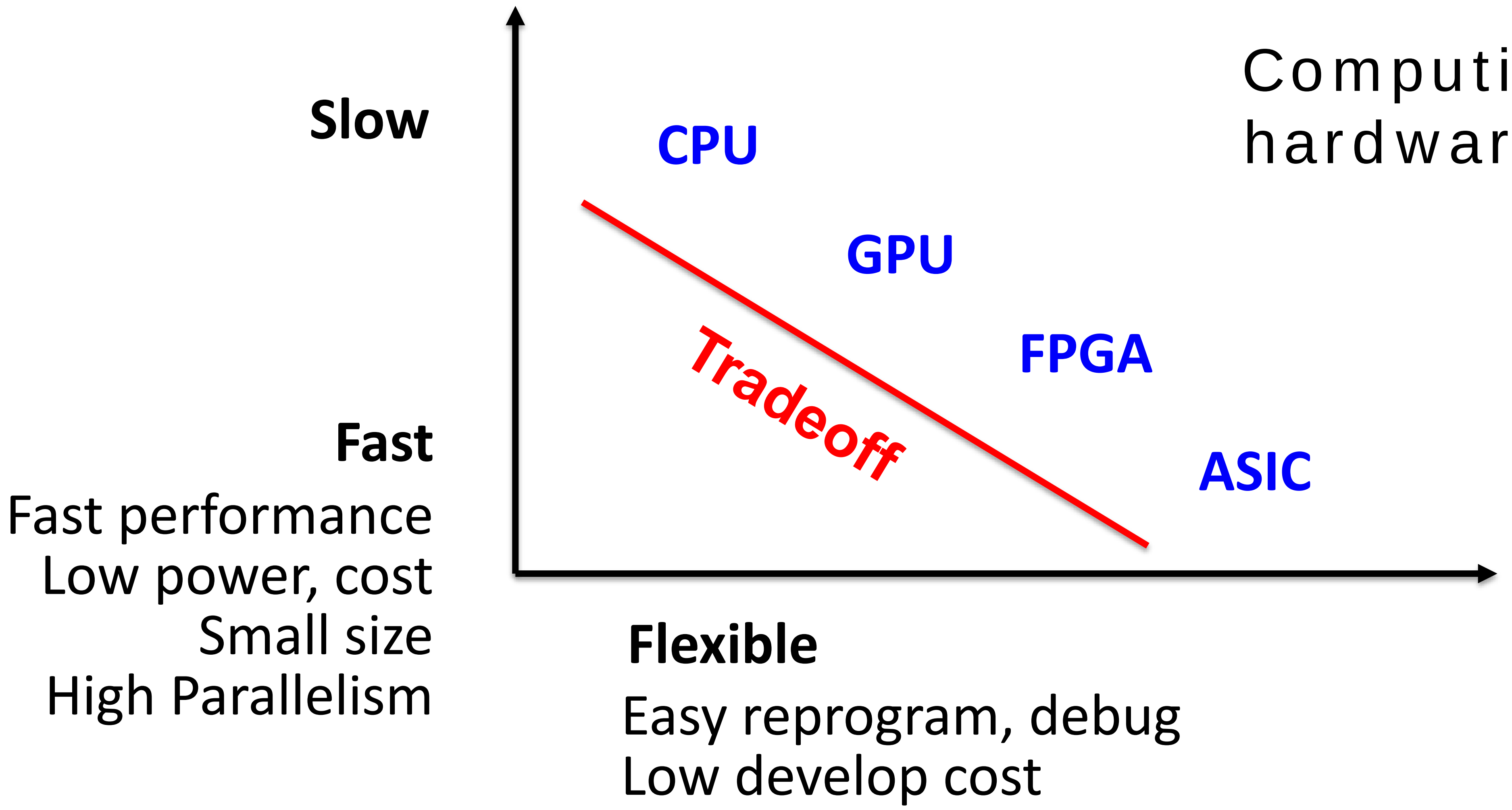
Virtualization education

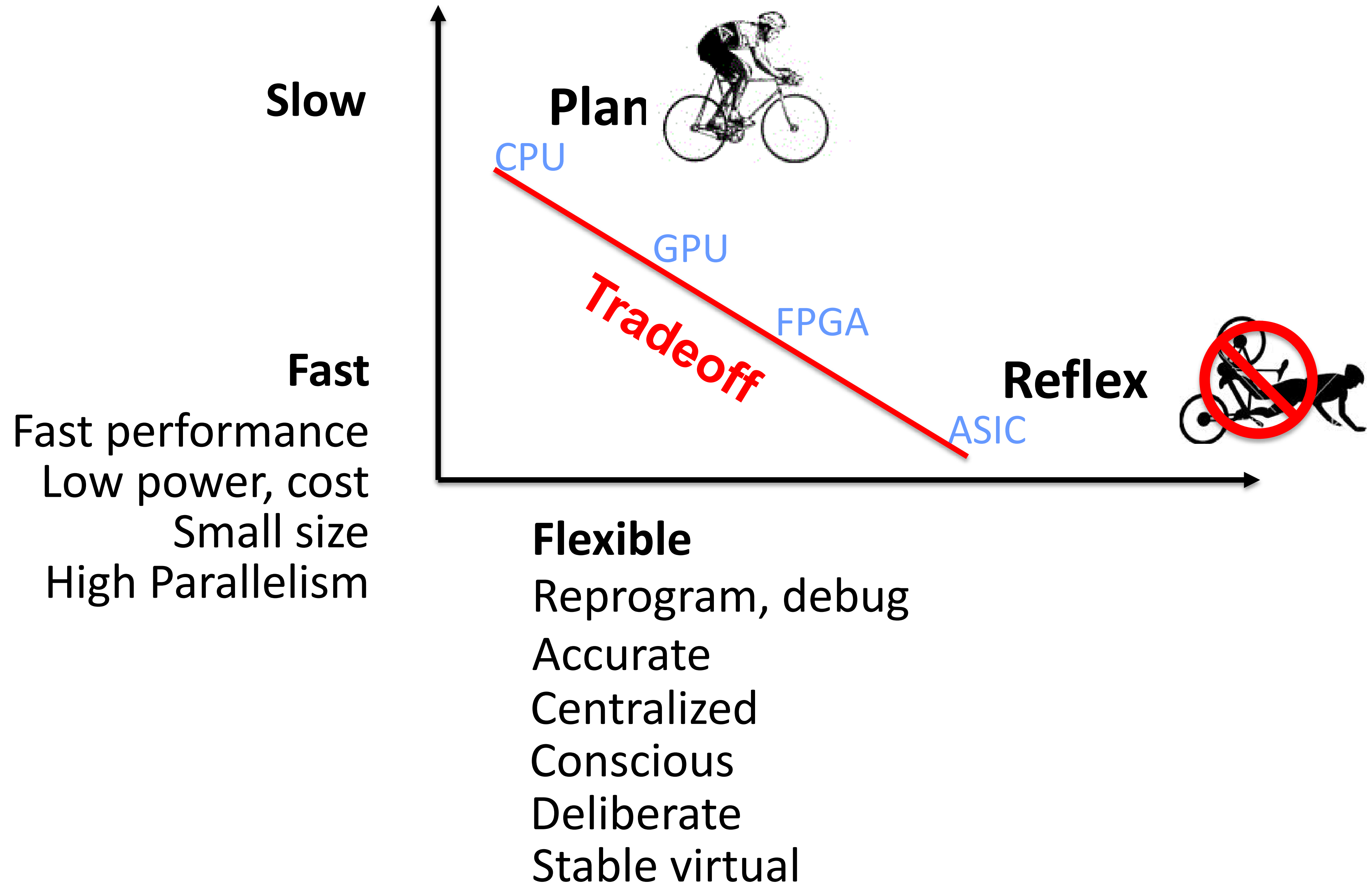


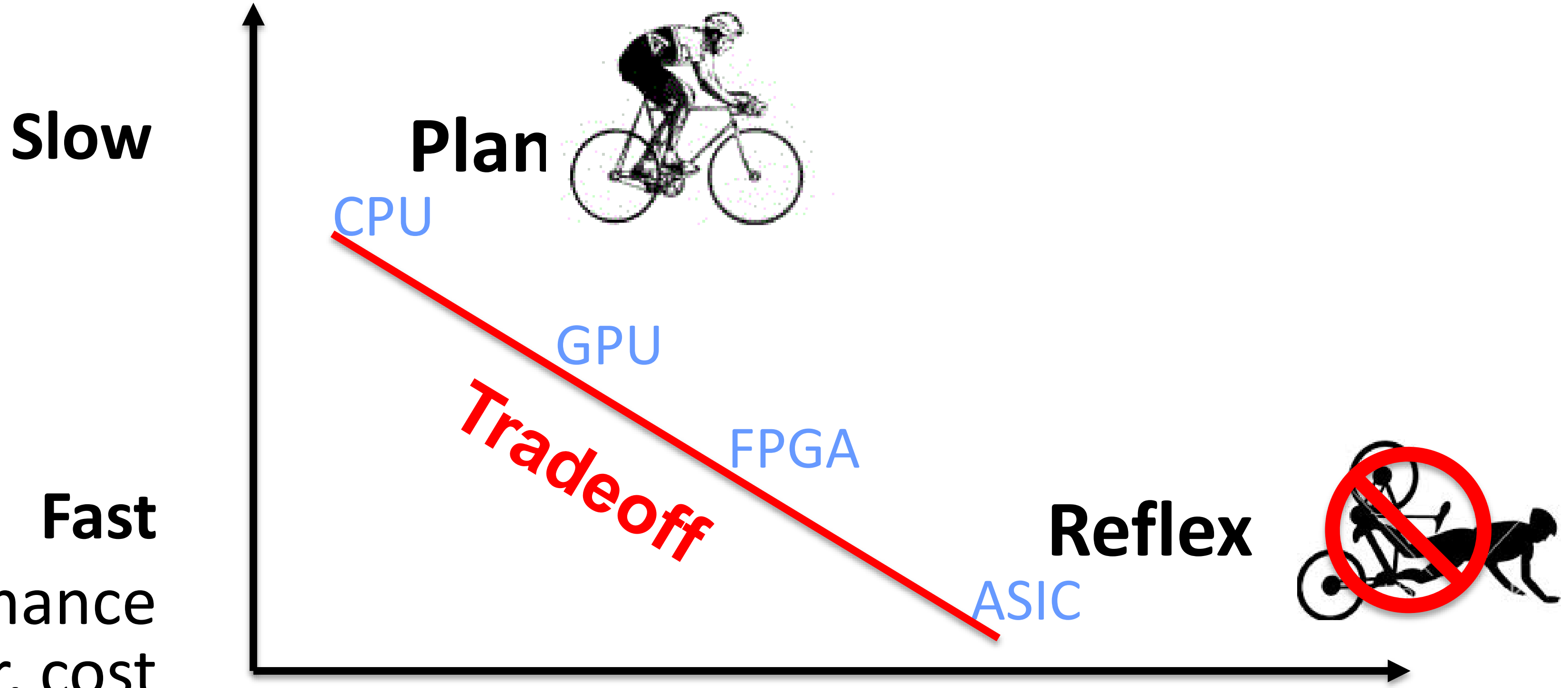
Math
Abstract

- Start with Turing
- A lot has already been done
- A few gaps near the bottom
- Have time domain versions of Bode and extensions
- Have redo of stat mech: lossless to passive
- Have classical version of Heisenberg using Kalman
- Need more work on passive to active

Computing hardware



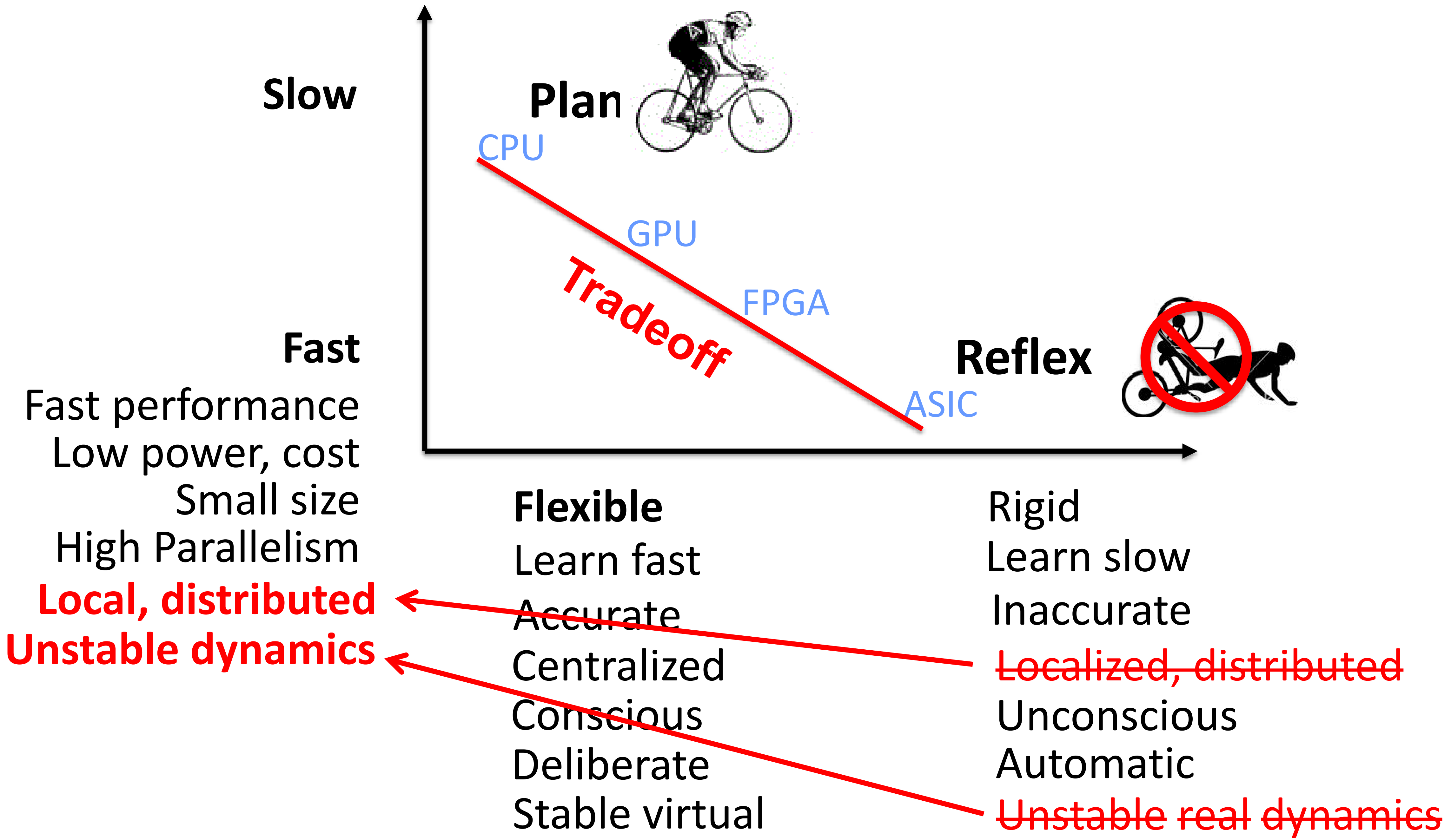

Slow
Plan
CPU
GPU
Tradeoff
FPGA
ASIC
Reflex
Fast
Fast performance
Low power, cost
Small size
High Parallelism
Flexible
Reprogram, debug
Accurate
Centralized
Conscious
Deliberate
Stable virtual



Fast performance
Low power, cost
Small size
High Parallelism

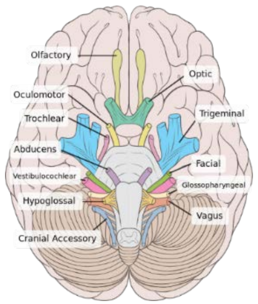
Flexible
Learn fast
Accurate
Centralized
Conscious
Deliberate
Stable virtual

Rigid
Learn slow
Inaccurate
Localized, distributed
Unconscious
Automatic
Unstable real dynamics


Slow
Plan
CPU
GPU
Tradeoff
FPGA
Fast
Reflex
ASIC
Fast performance
Low power, cost
Small size
High Parallelism
Local, distributed
Unstable dynamics
Flexible
Learn fast
Accurate
Centralized
Conscious
Deliberate
Stable virtual
Rigid
Learn slow
Inaccurate
~~Localized, distributed~~
Unconscious
Automatic
~~Unstable real dynamics~~

Slow

Plan

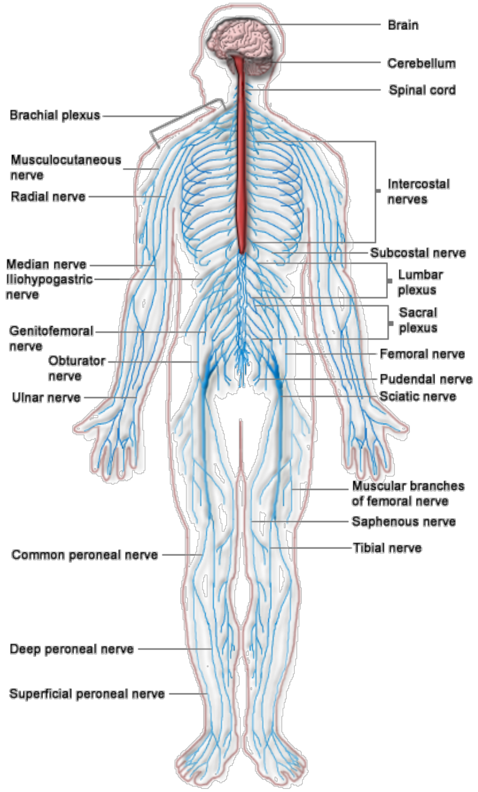


Tradeoff

OS?

Fast

Reflex

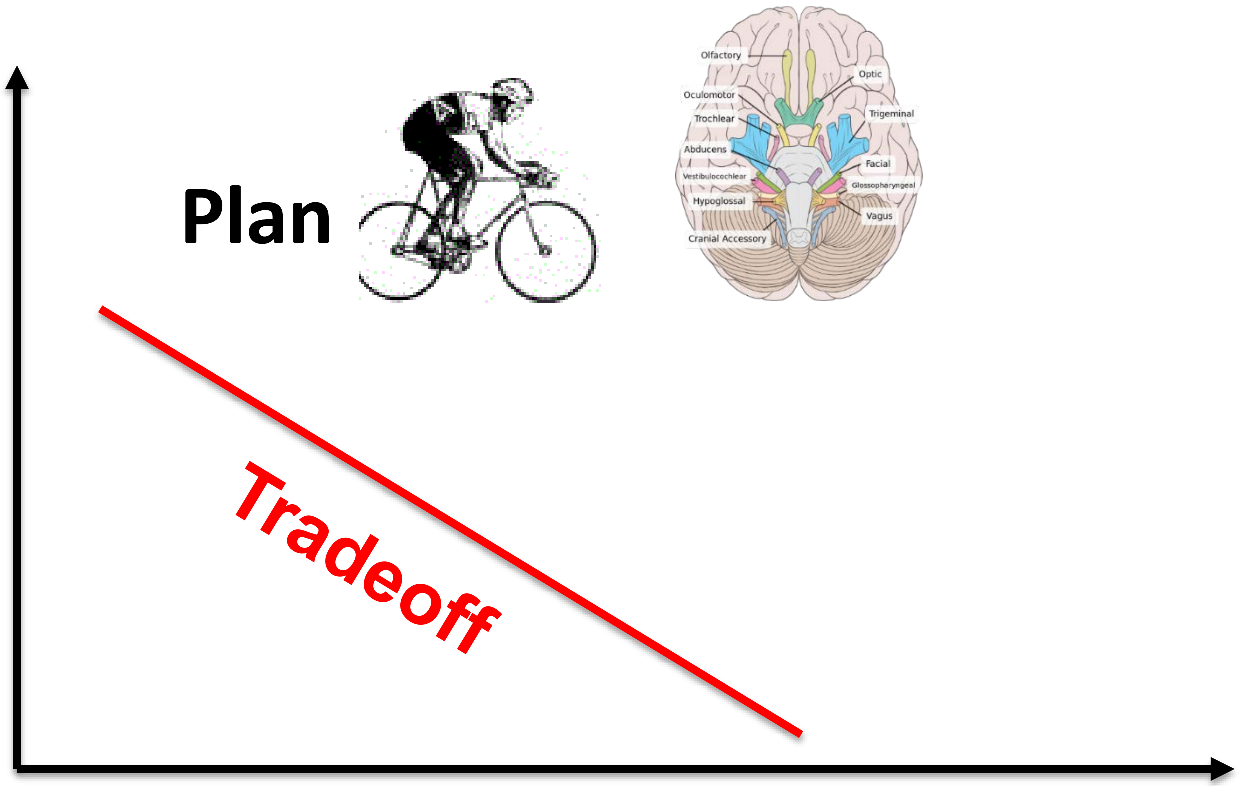


Fast performance
Low power, cost
Small size
High Parallelism
Local, distributed
Unstable dynamics

Flexible
Learn fast
Accurate
Conscious
Deliberate
Centralized
Stable virtual

Rigid
Learn slow
Inaccurate
Unconscious
Automatic

Slow



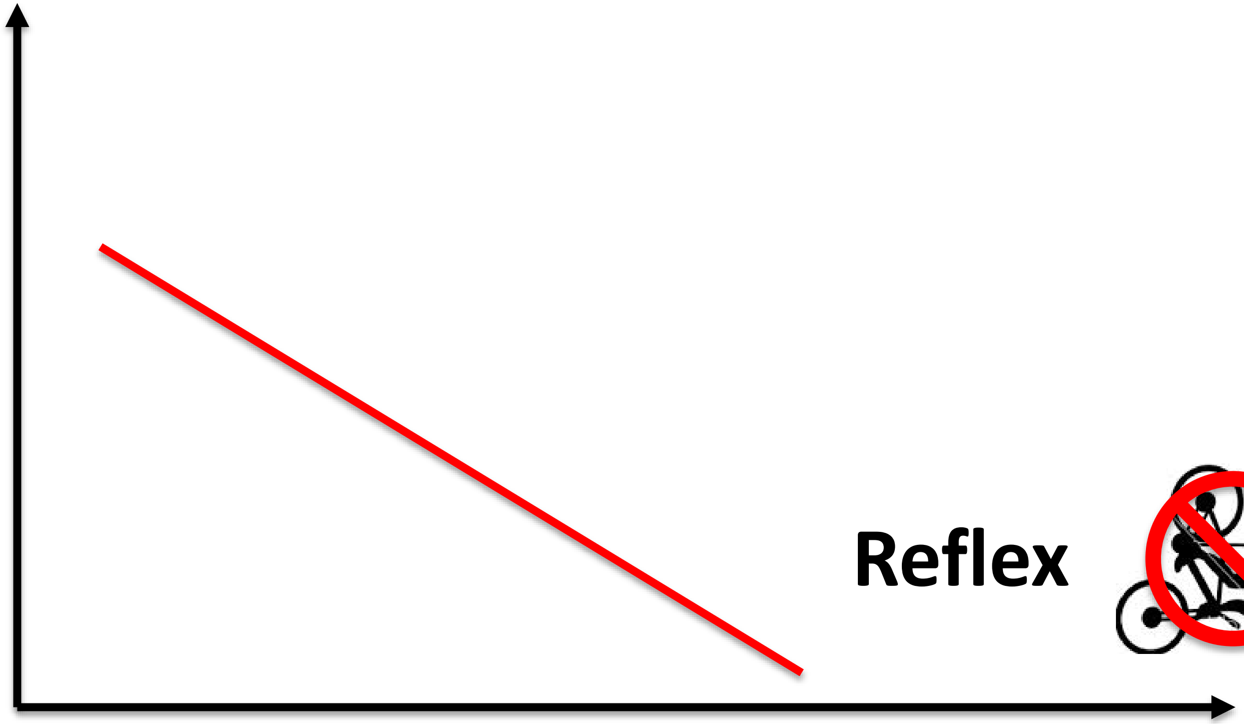
Fast

Fast performance
Low power, cost
Small size
High Parallelism
Local, distributed
Unstable dynamics

Flexible

Learn fast
Accurate
Conscious
Deliberate
Centralized
Stable virtual

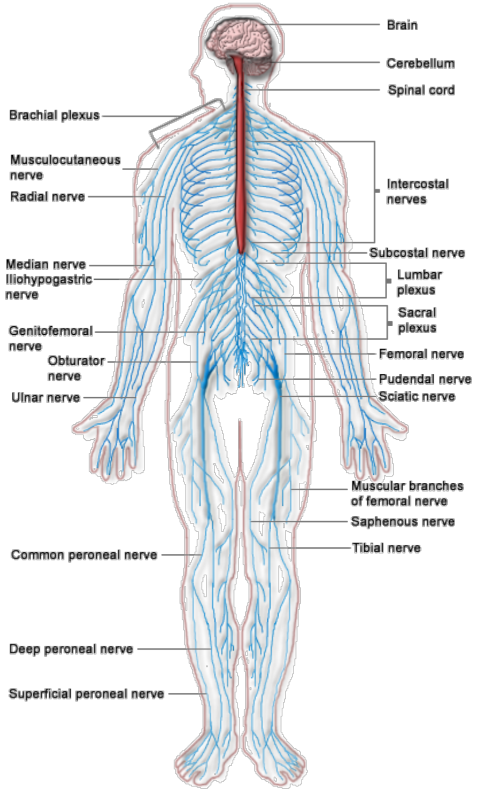
Slow



Fast

Fast performance
Low power, cost
Small size
High Parallelism
Local, distributed
Unstable dynamics

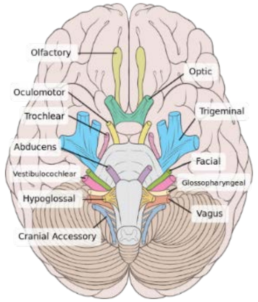
Reflex



Rigid
Learn slow
Inaccurate
Unconscious
Automatic

Slow

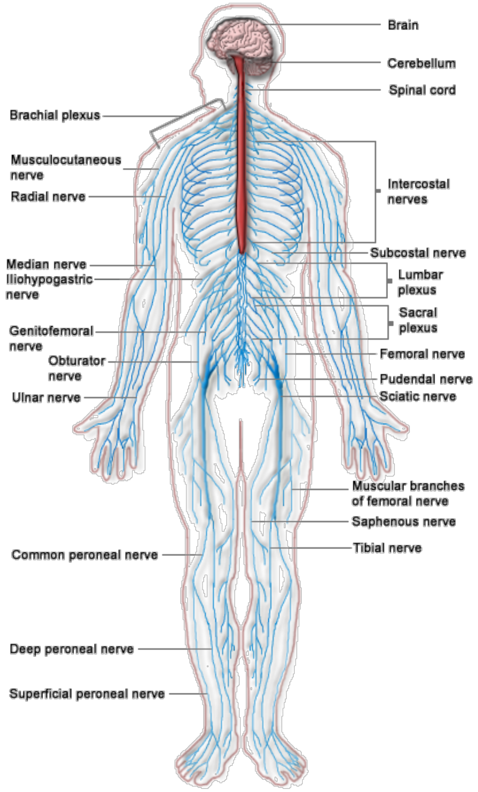
Plan



OS?

Tradeoff

Reflex



Fast

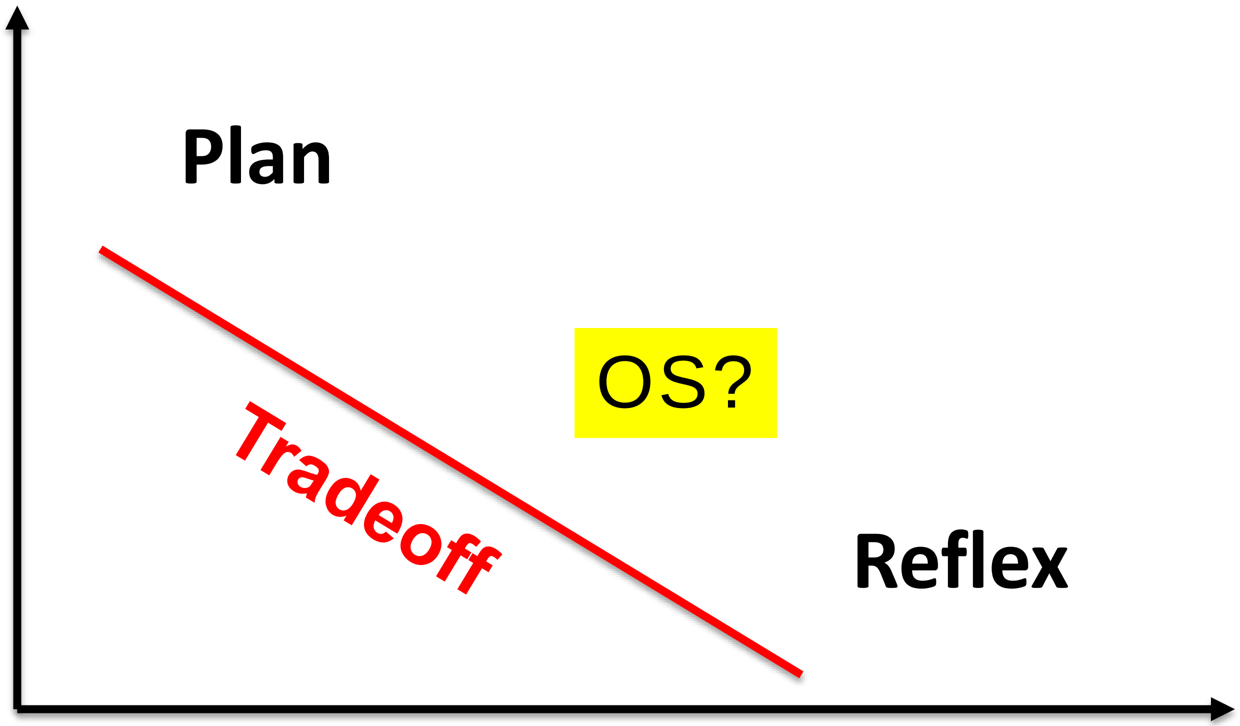
Fast performance
Low power, cost
Small size
High Parallelism
Local, distributed
Unstable dynamics

Flexible

Learn fast
Accurate
Conscious
Deliberate
Centralized
Stable virtual

Rigid
Learn slow
Inaccurate
Unconscious
Automatic

Slow

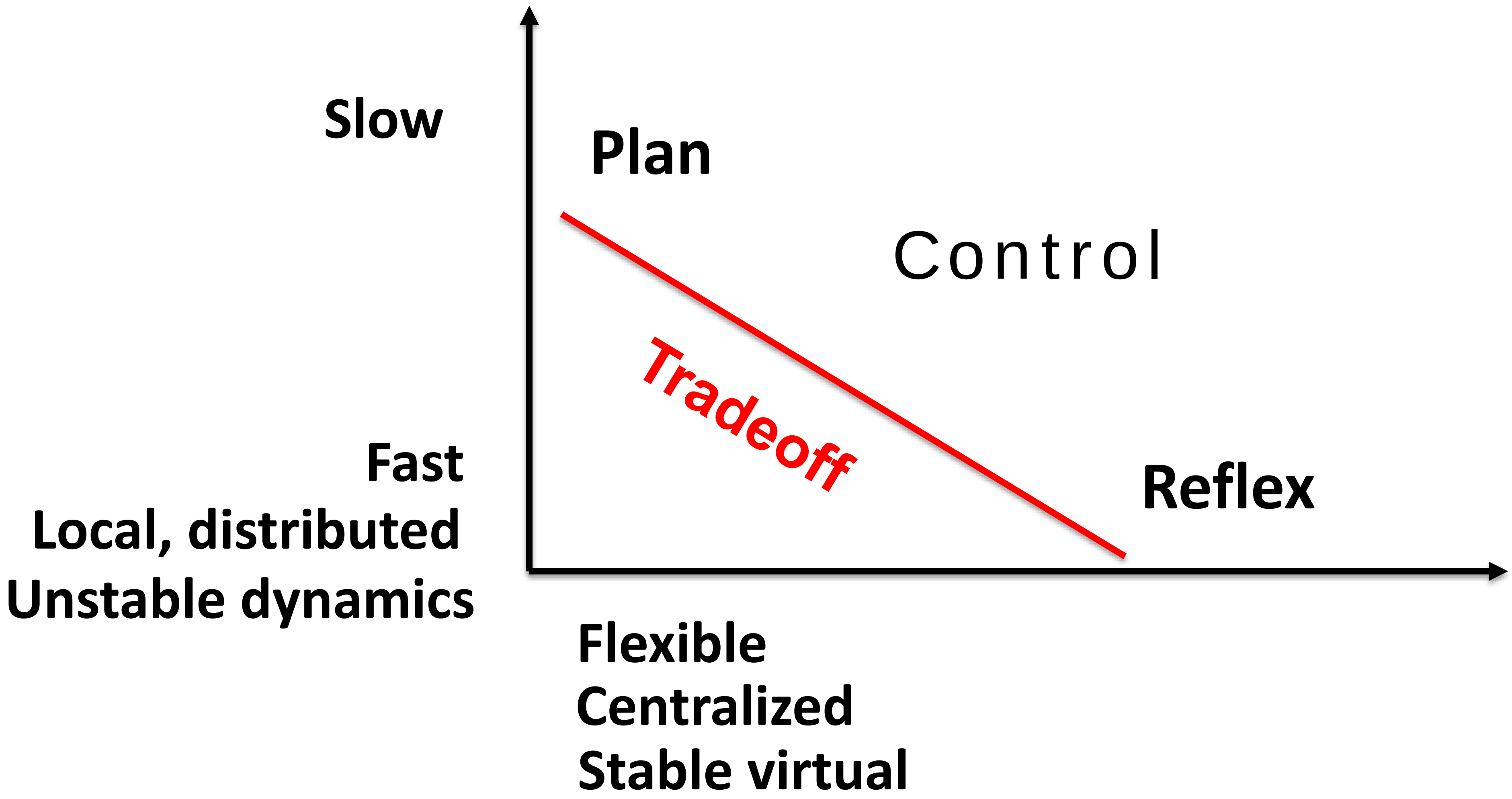


Fast

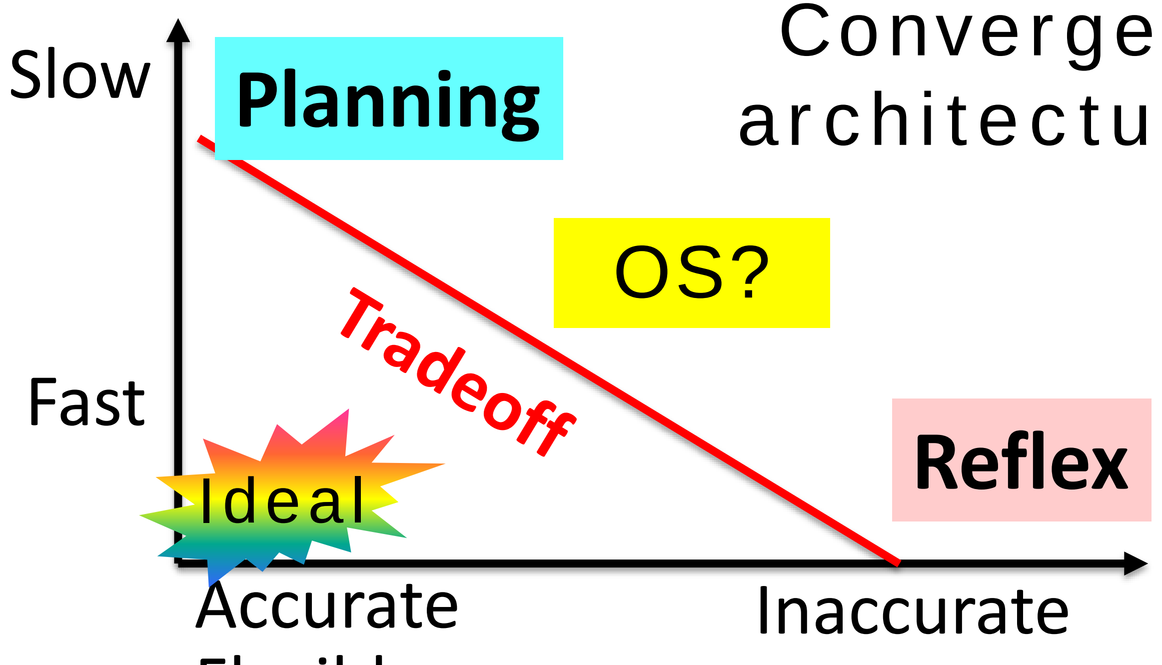
Fast performance
Low power, cost
Small size
High Parallelism
Local, distributed
Unstable dynamics

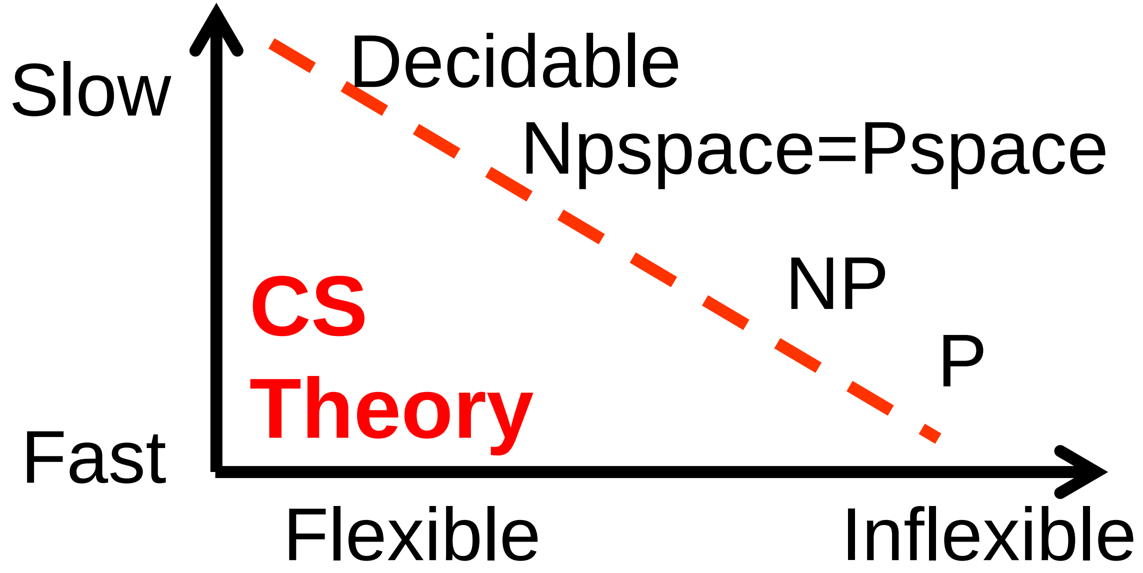
Flexible

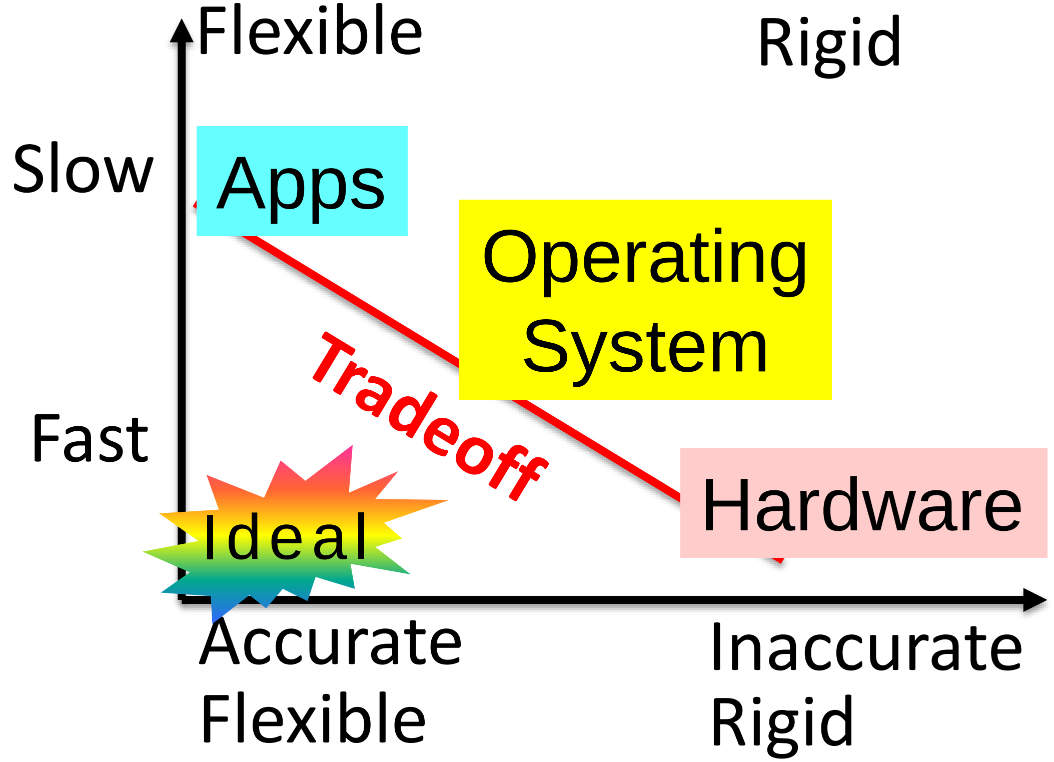
Learn fast
Accurate
Conscious
Deliberate
Centralized
Stable virtual

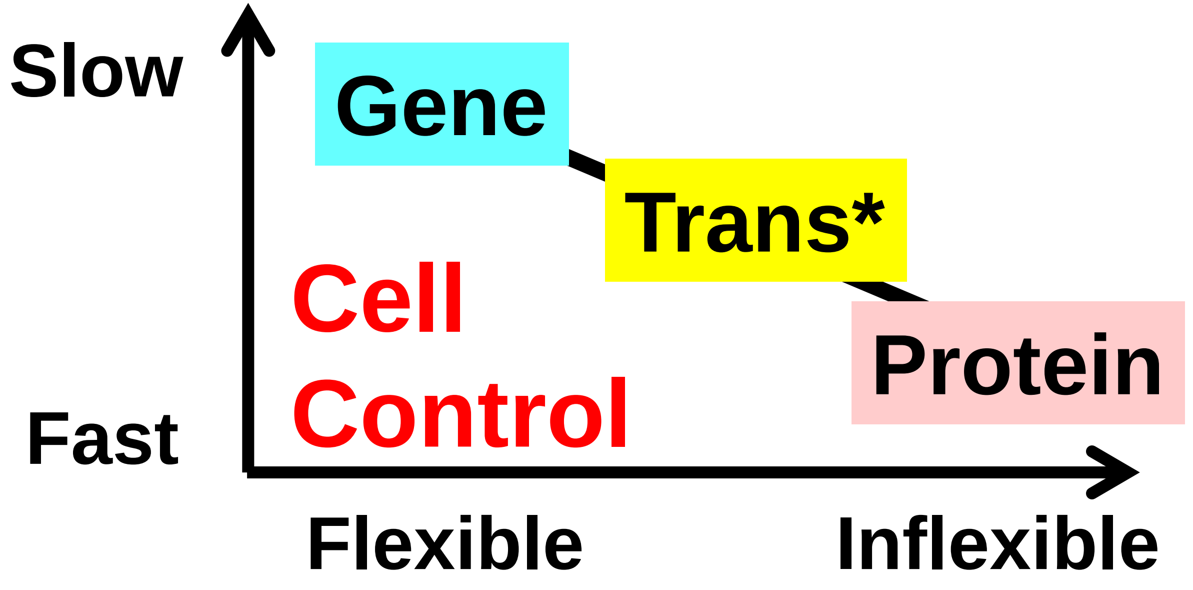

Slow
Plan
Control
Tradeoff
Reflex
Fast
Local, distributed
Unstable dynamics
Flexible
Centralized
Stable virtual

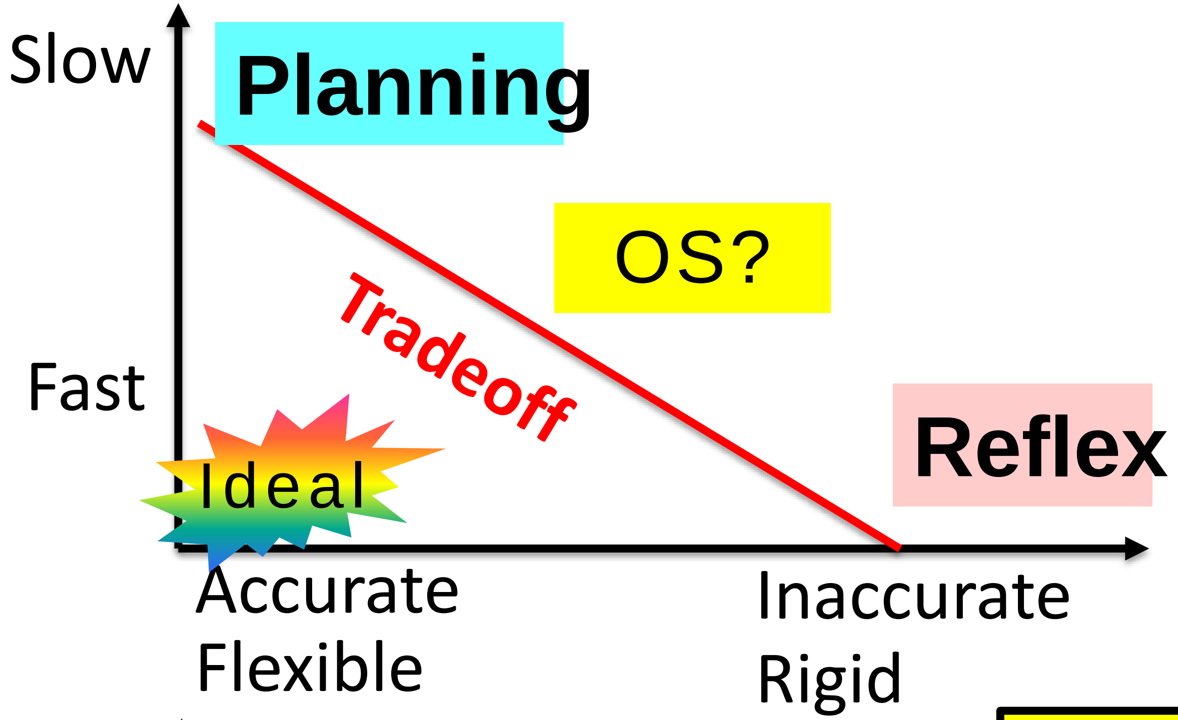
Convergent architecture?

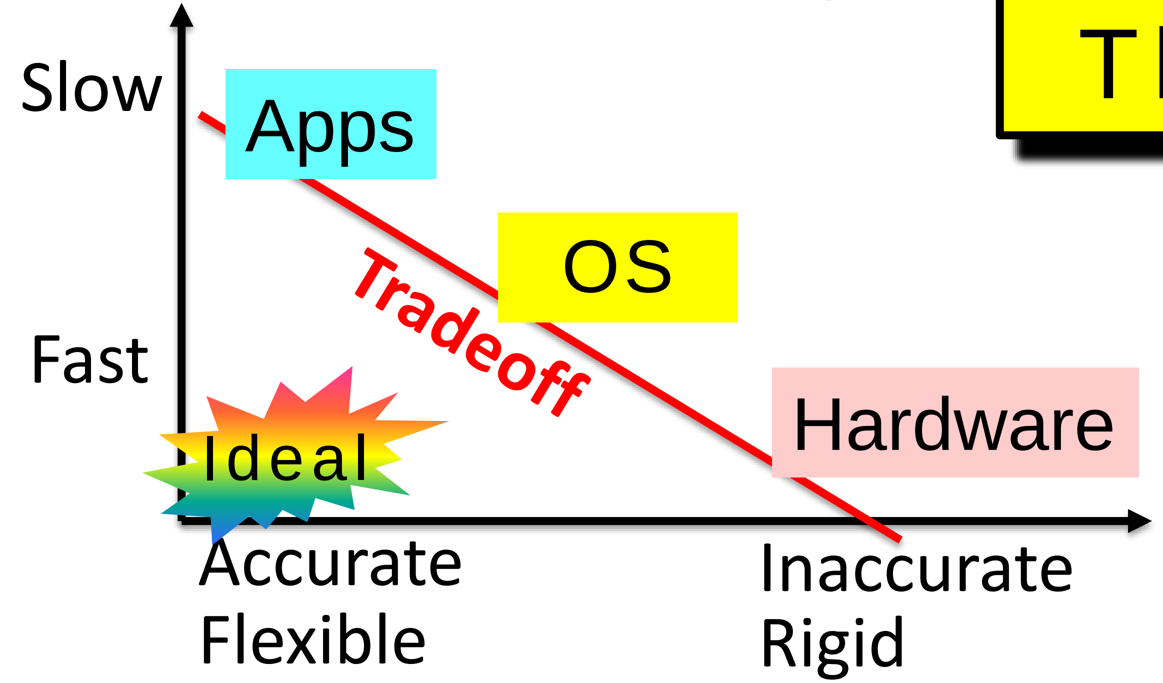


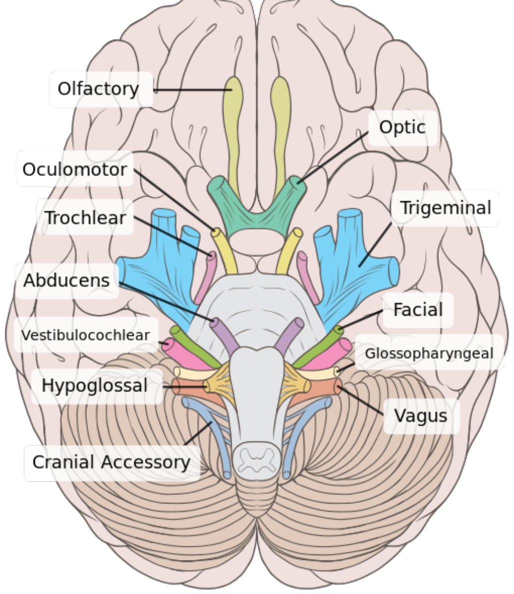






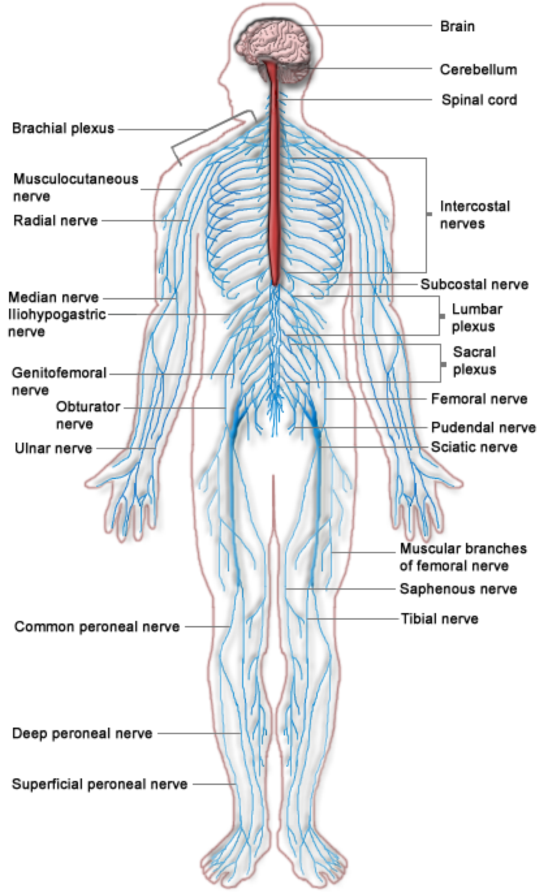




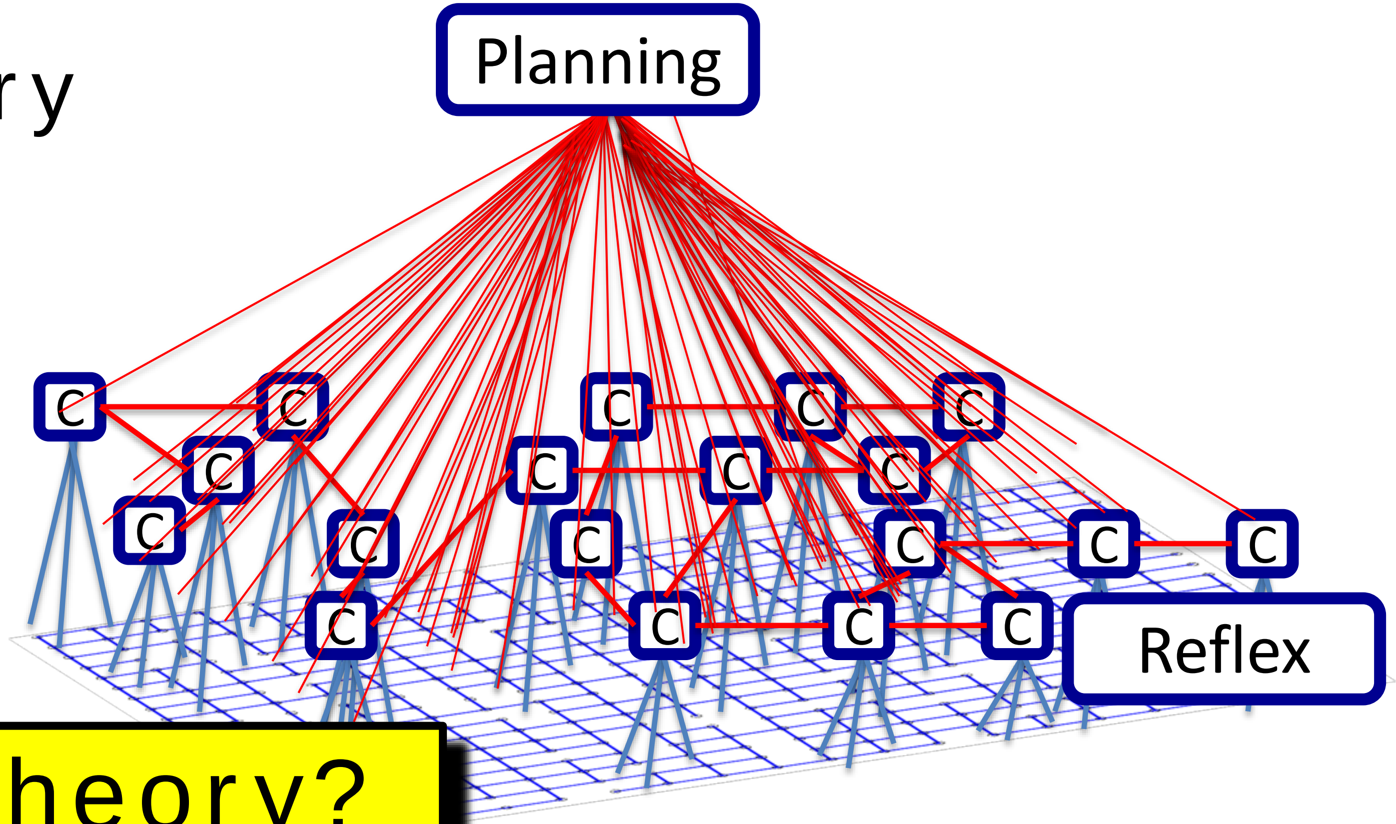


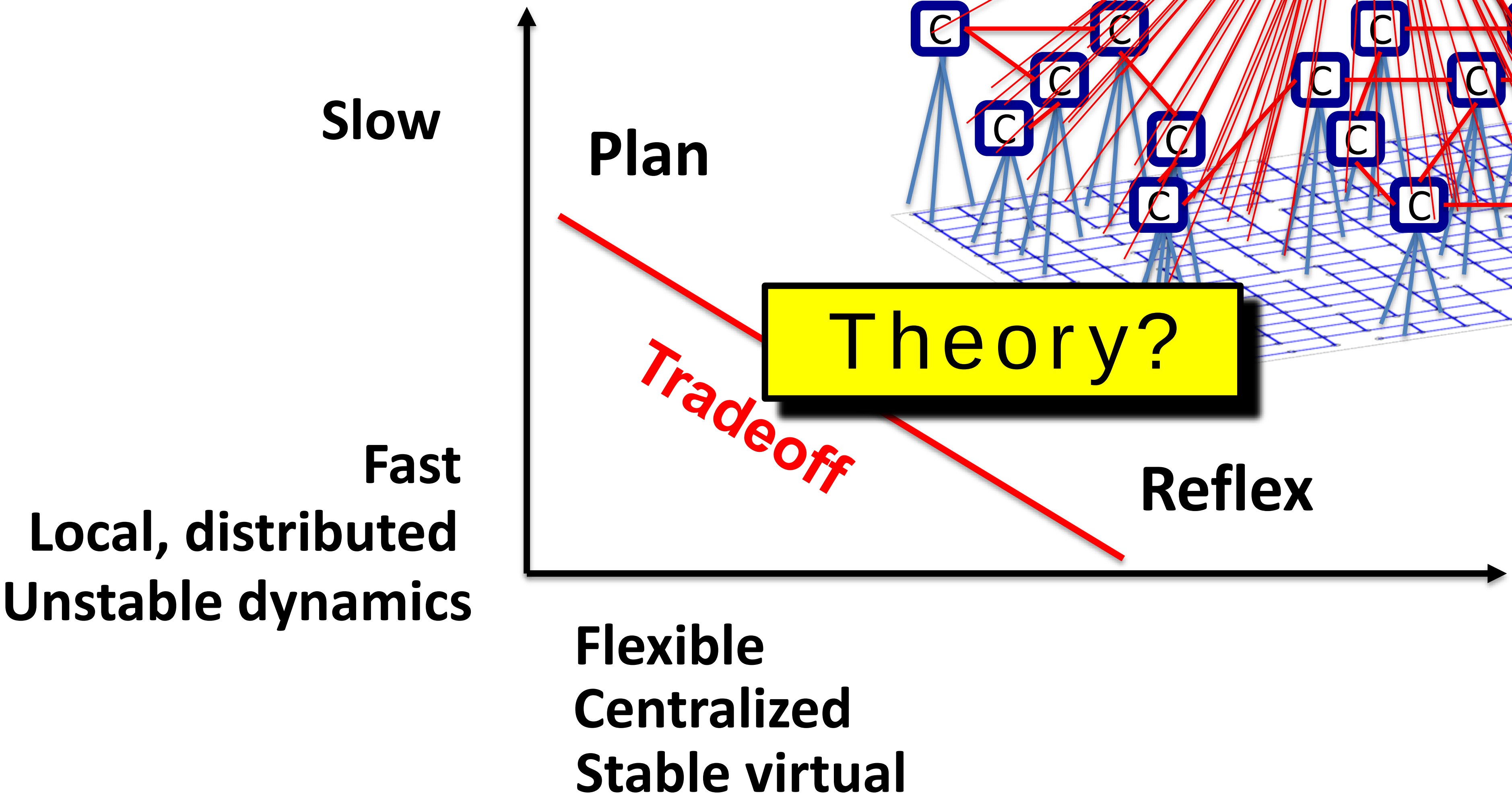
Convergent architecture?

Theory?

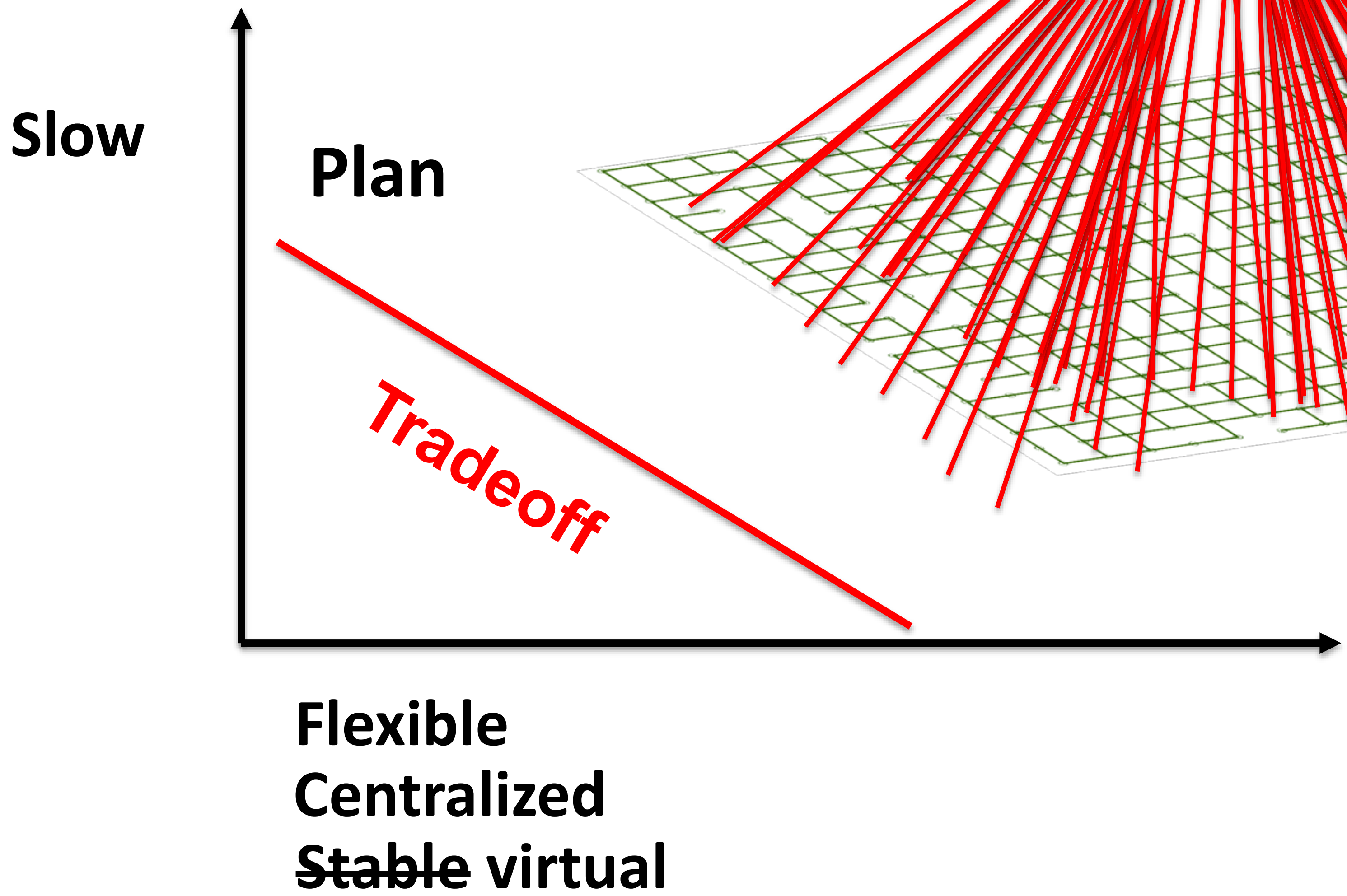


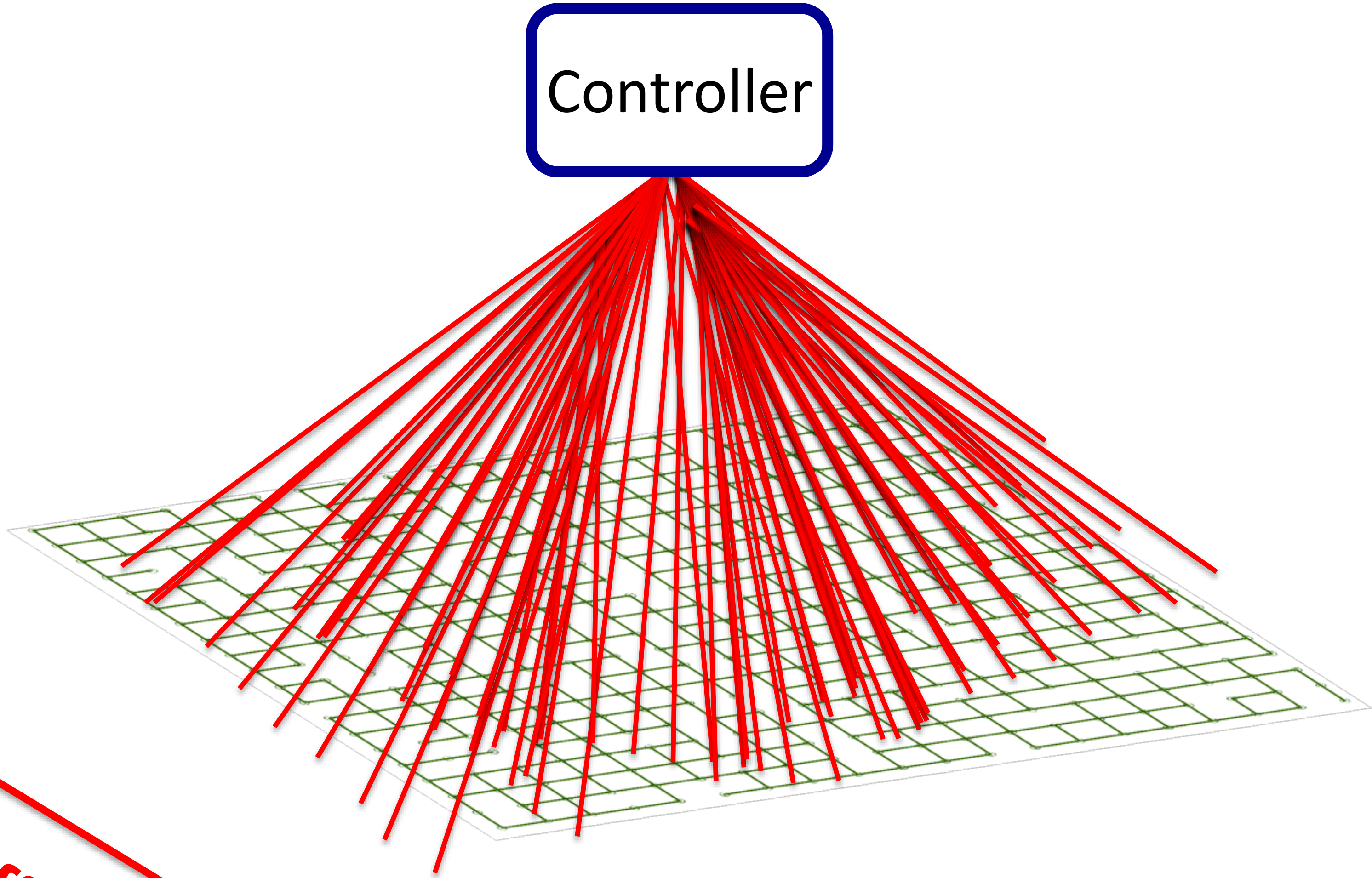
New Control theory



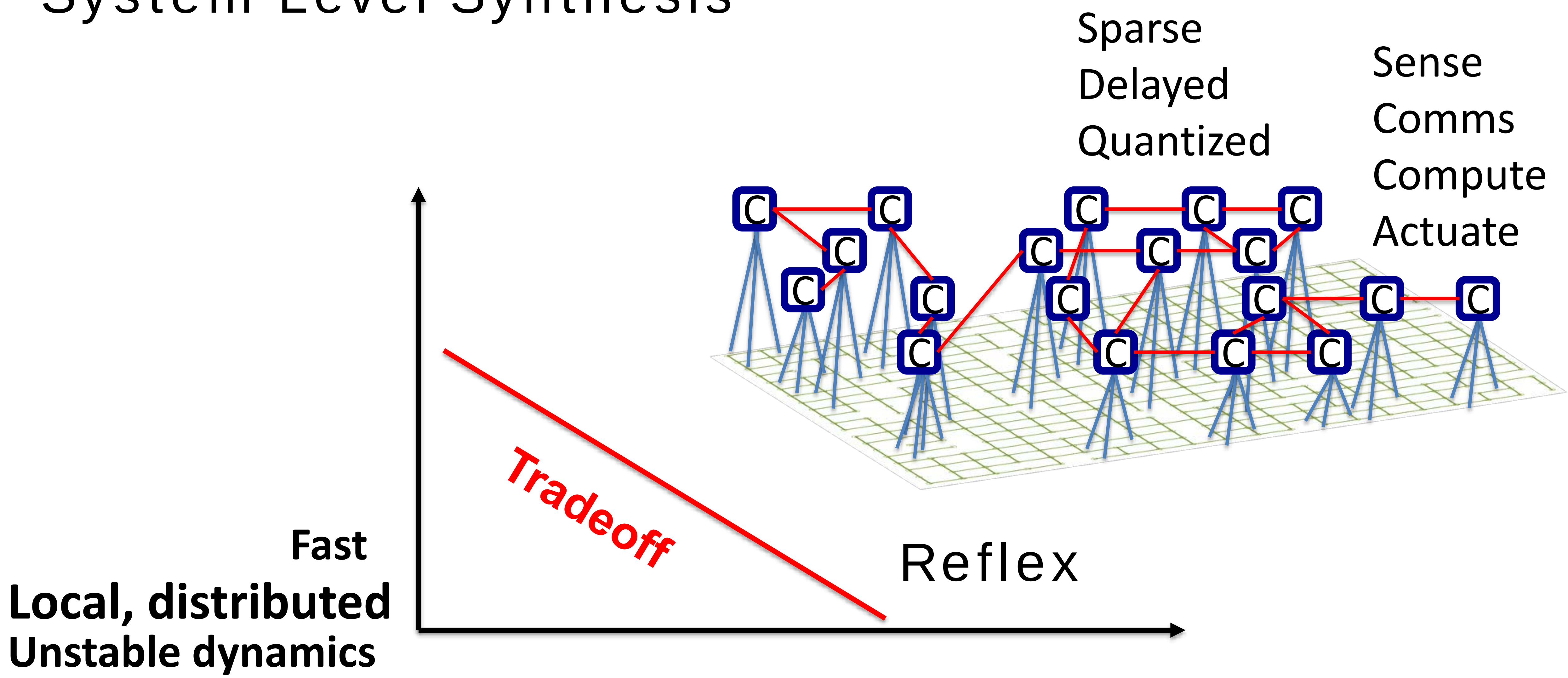


Control


Slow
Plan
Tradeoff
Flexible
Centralized
~~Stable~~ virtual


Controller

System Level Synthesis



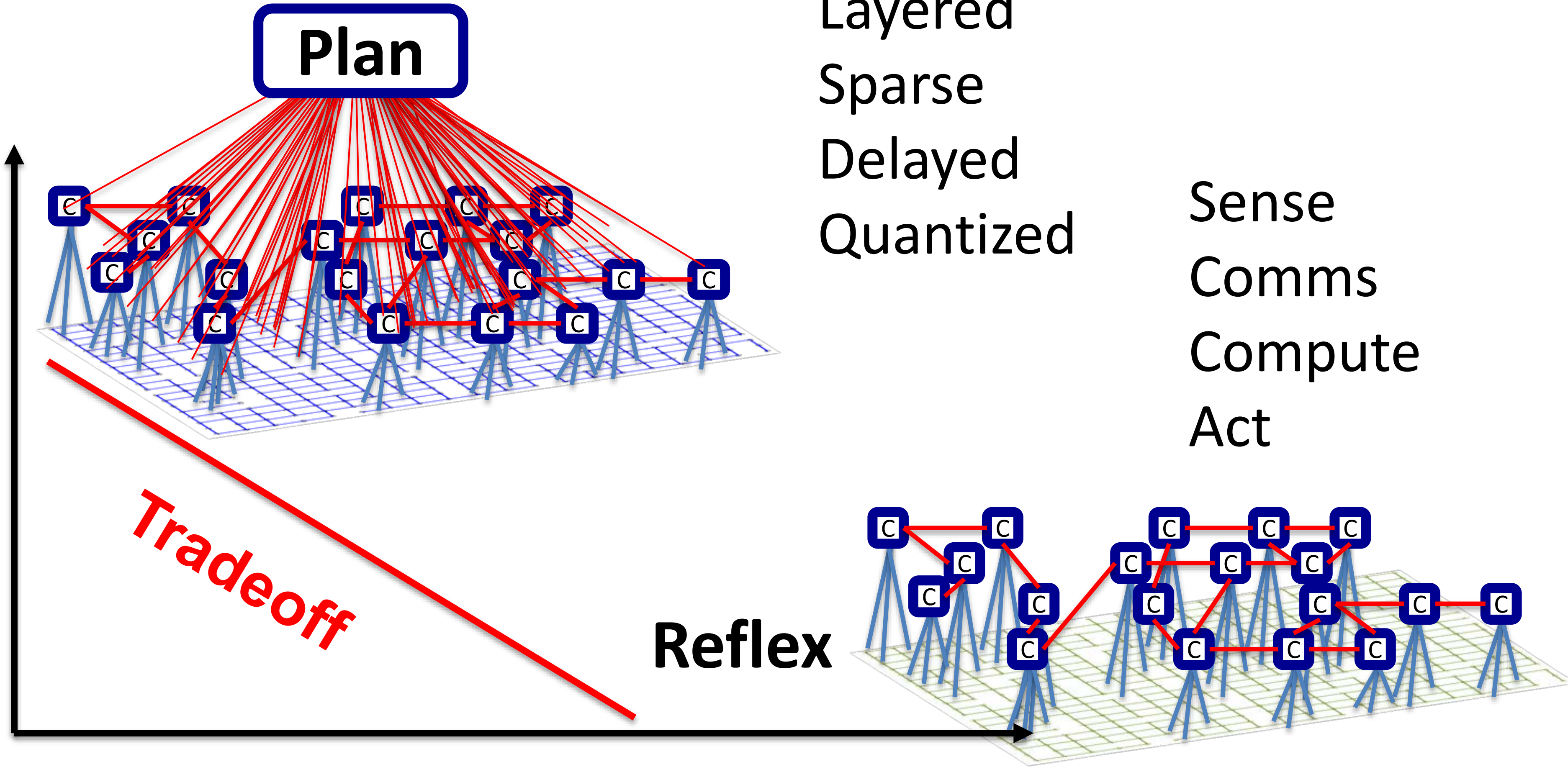
System Level Synthesis

Wang and Matni

Layered
Sparse
Delayed
Quantized

Sense
Comms
Compute
Act

Slow

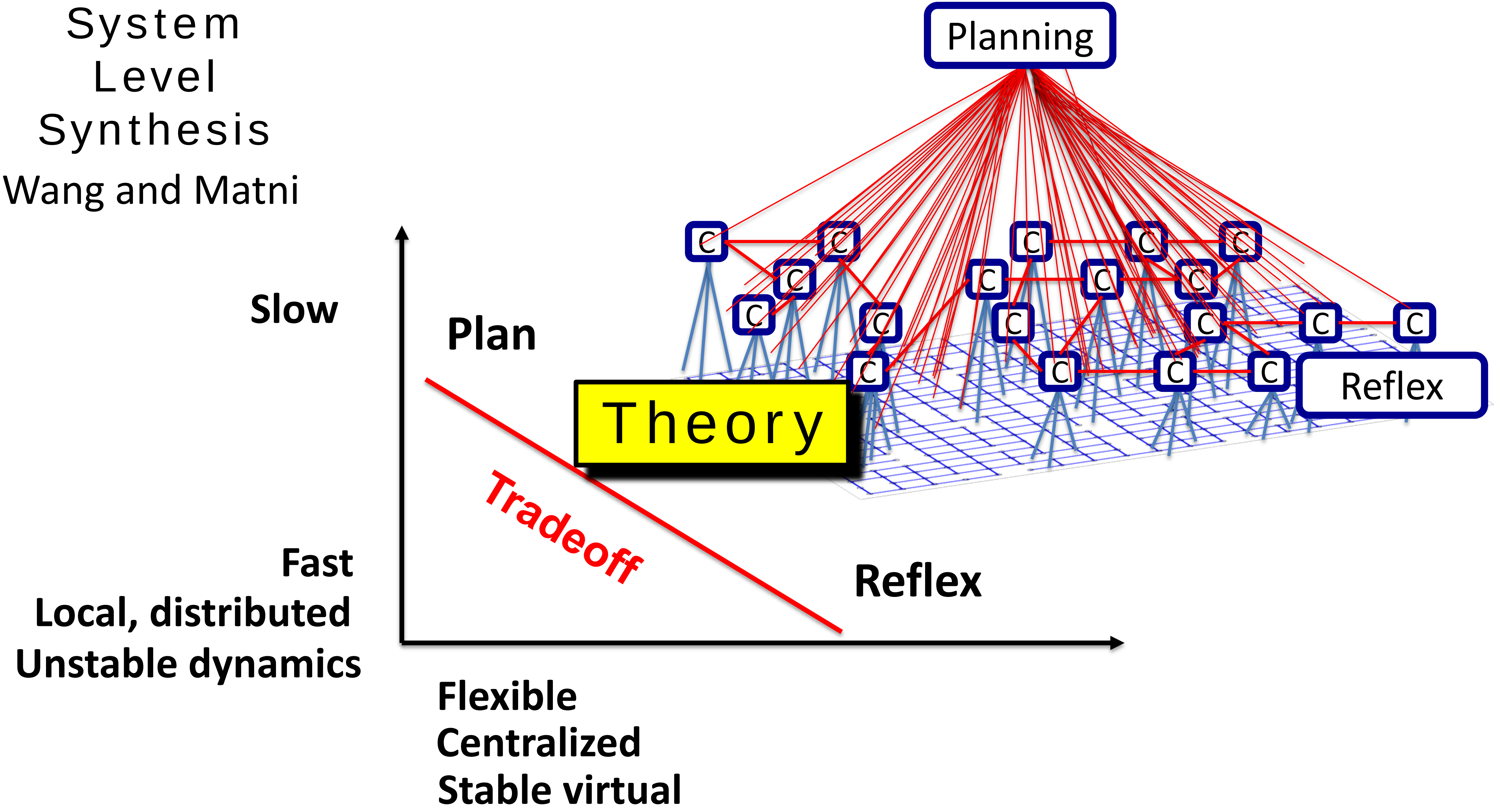


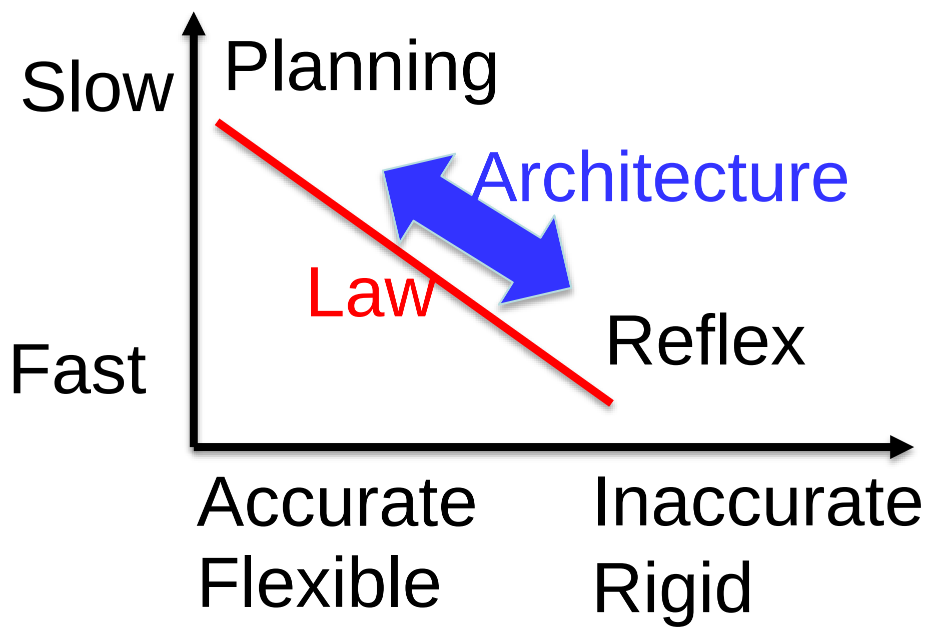
Fast
Local, distributed
Unstable dynamics

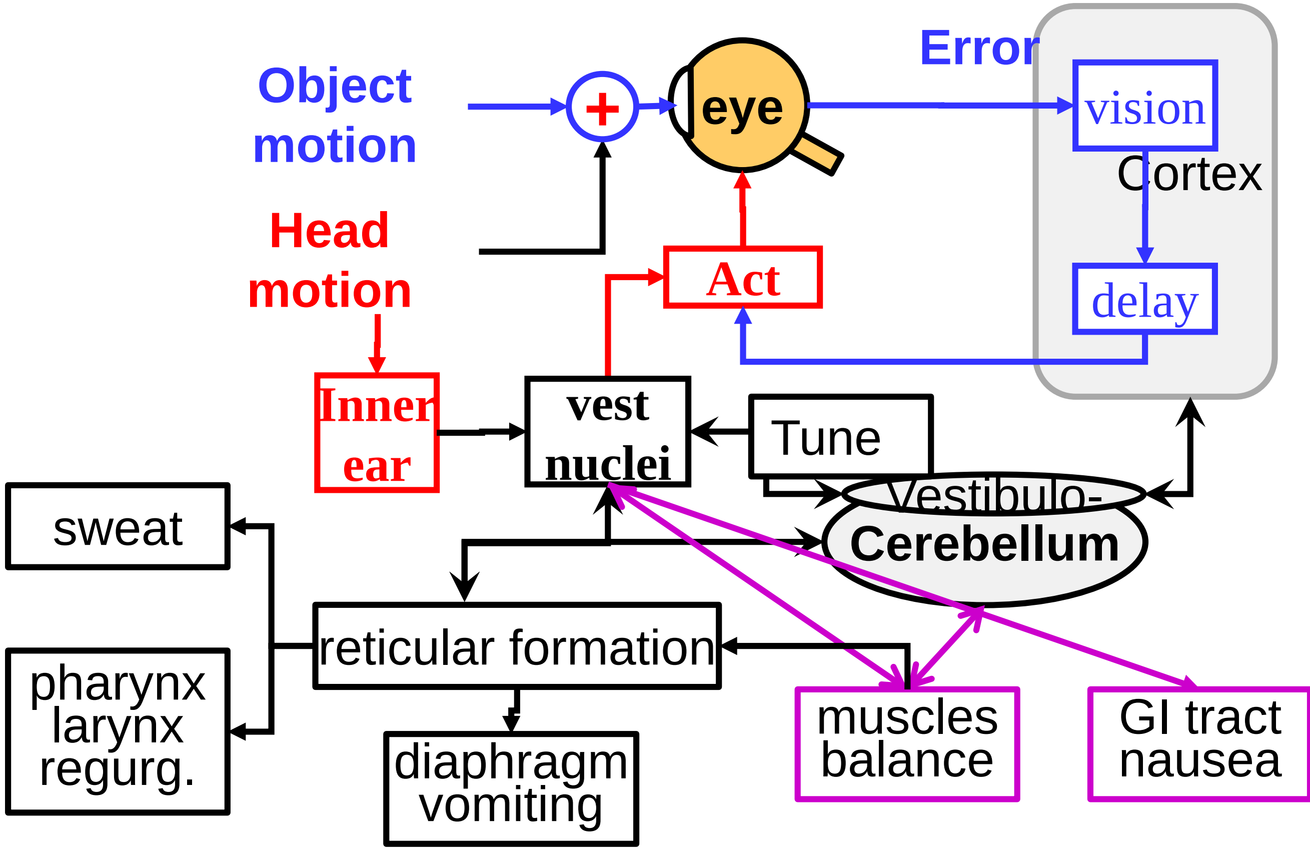
Flexible
Centralized
Stable virtual

System Level Synthesis

Wang and Matni





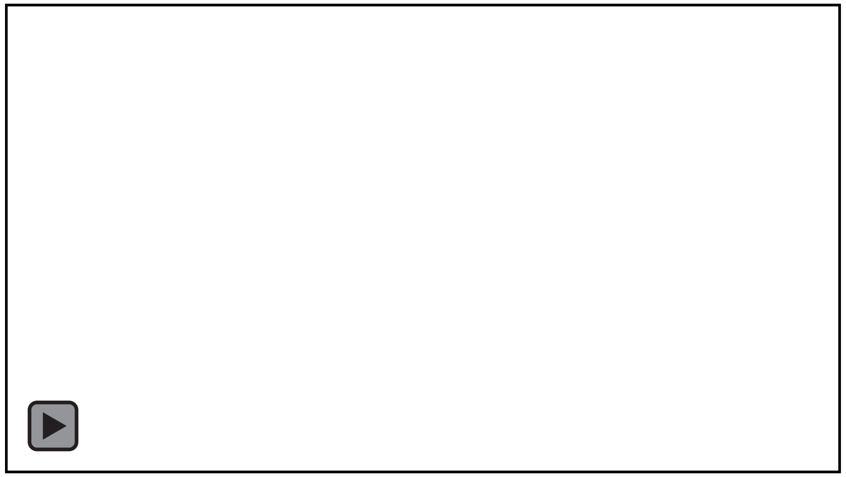


Planning

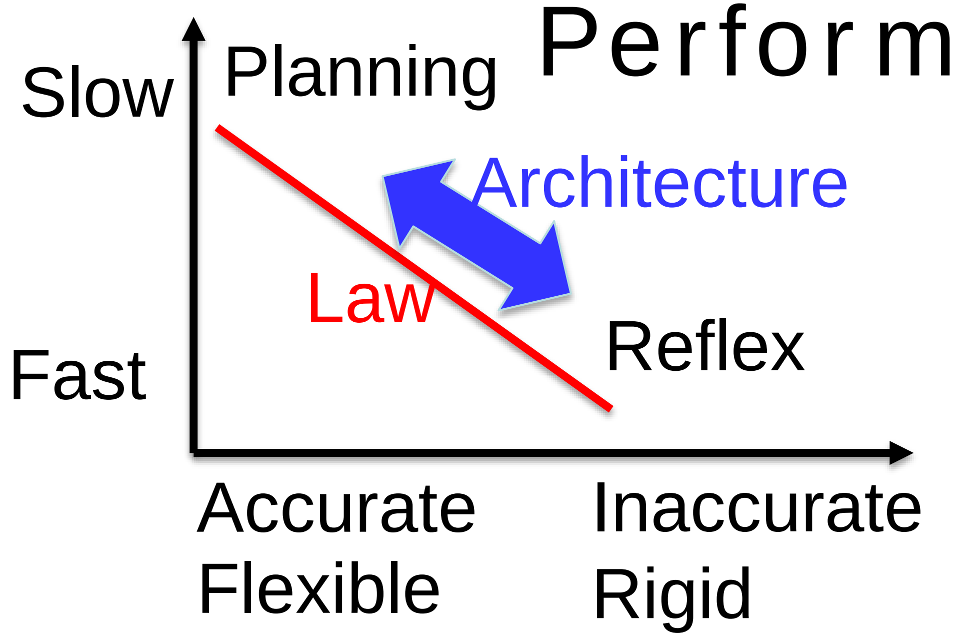
Balance

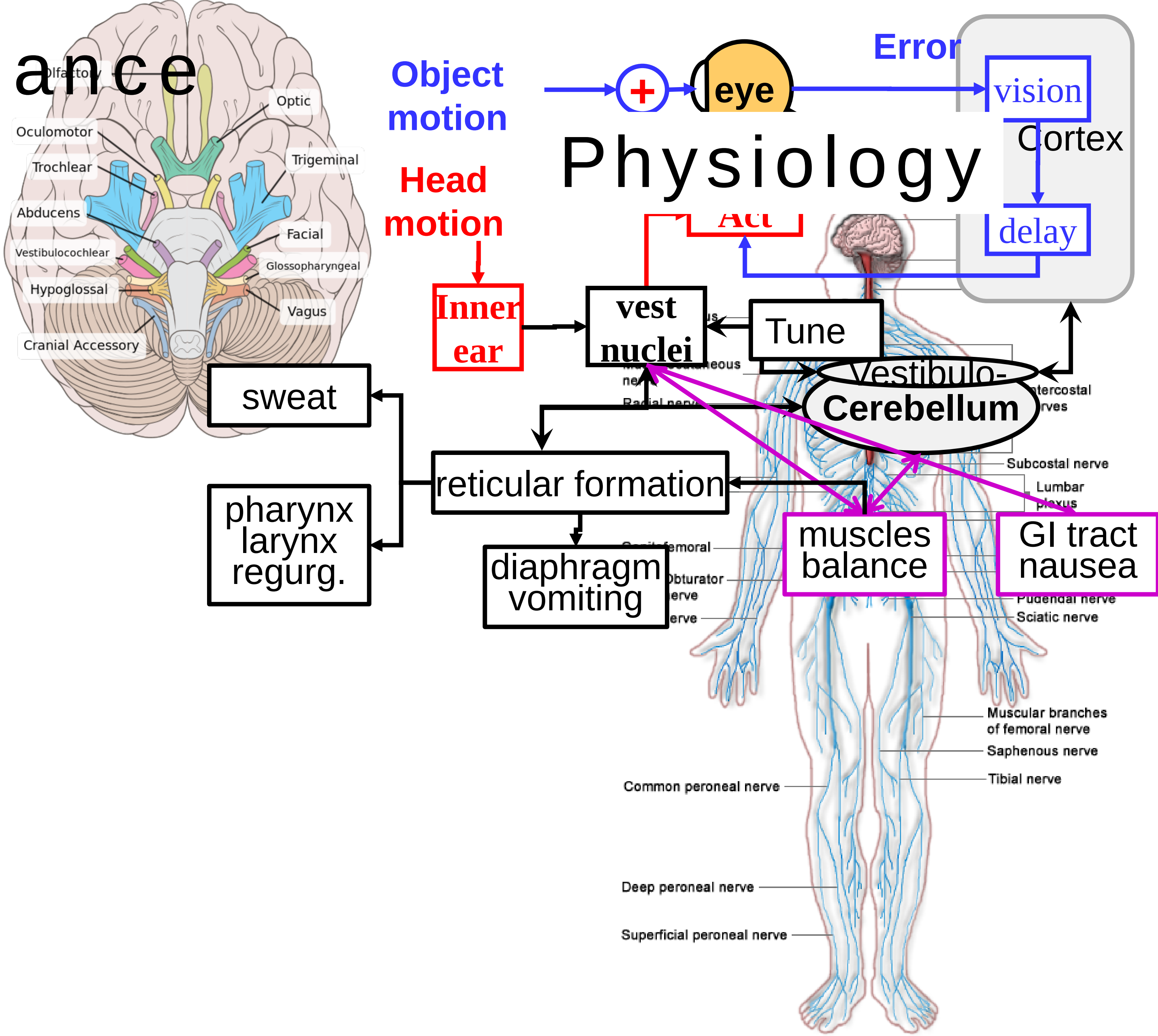
Reflex

Motion sickness



Performance

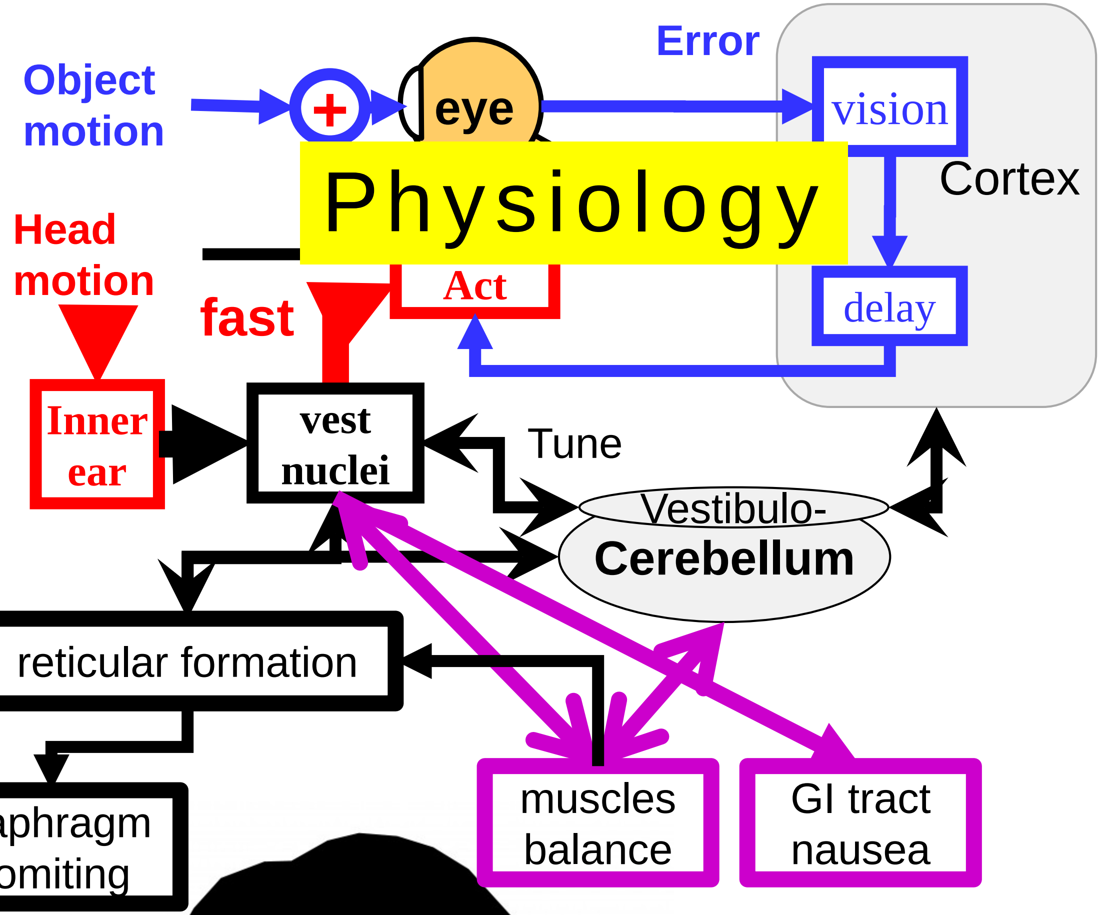


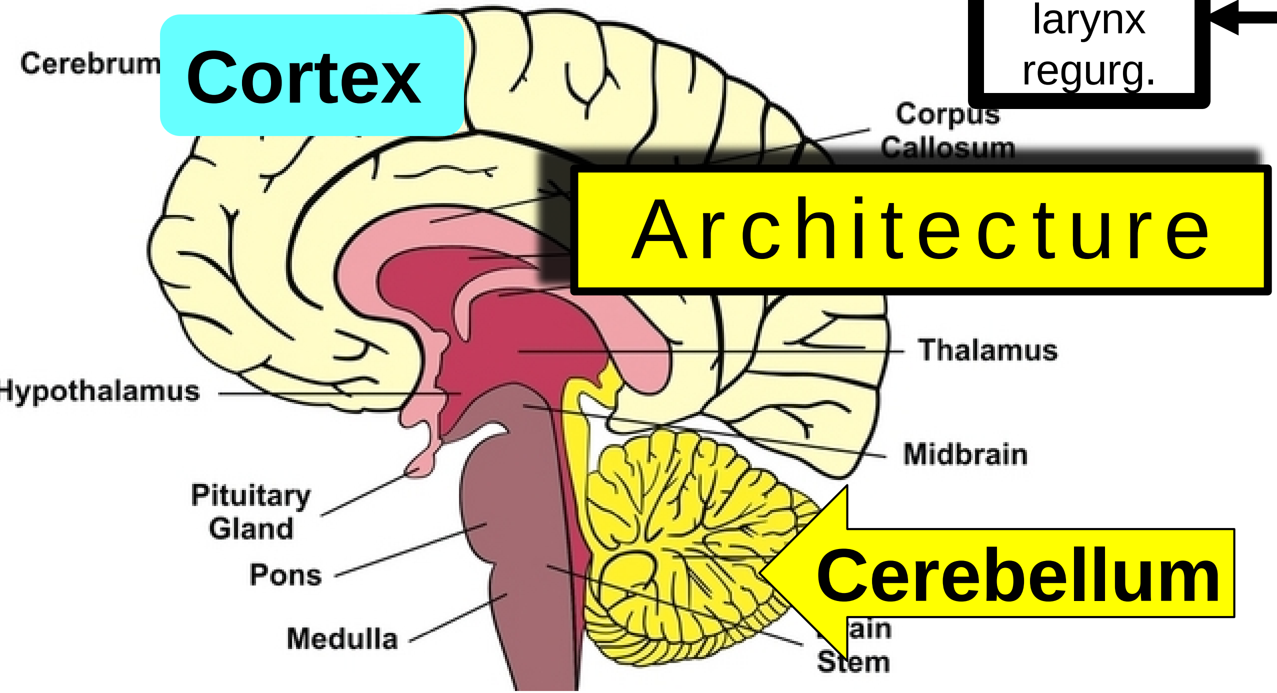


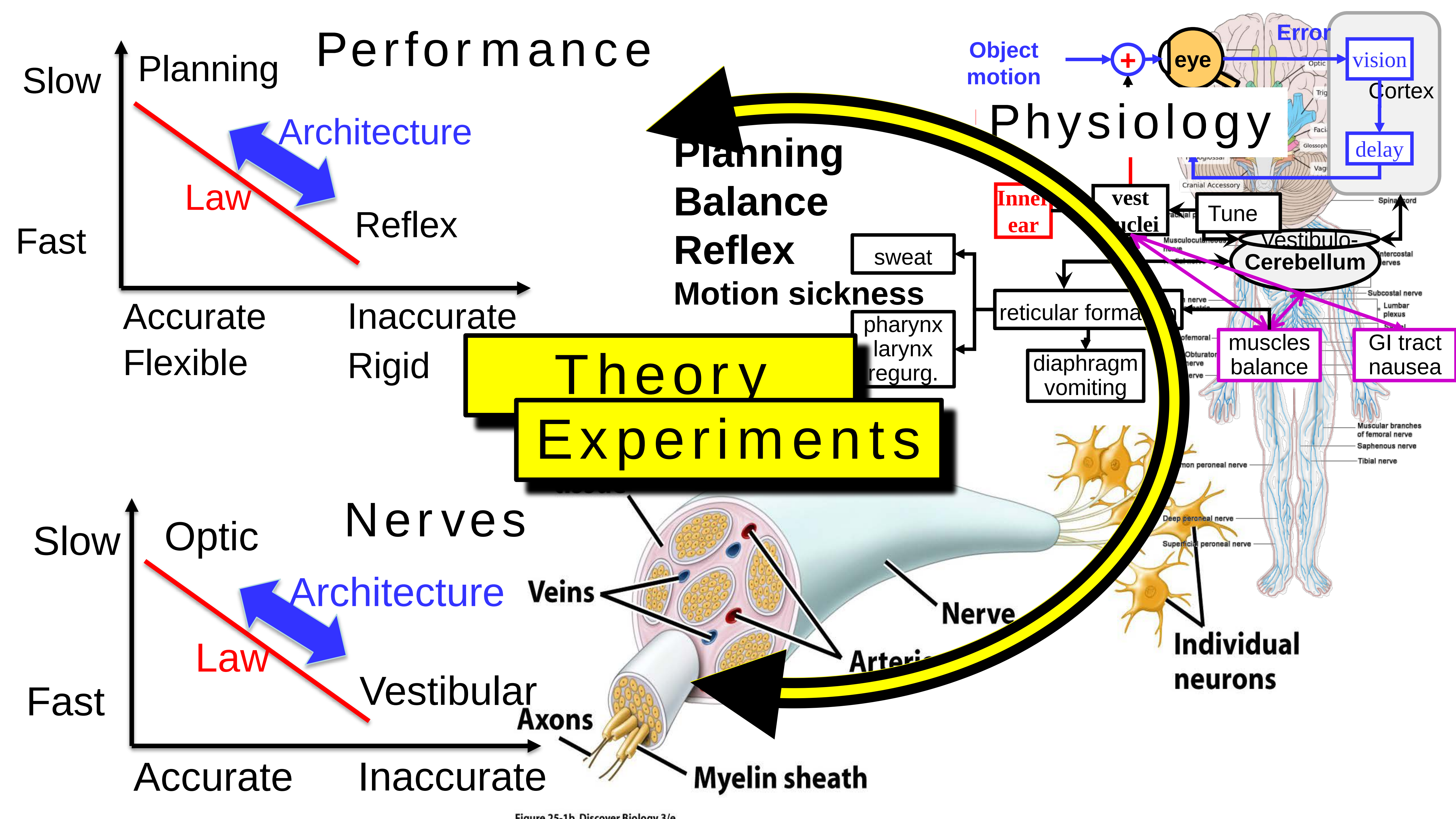
Planning
Balance
Reflex
Motion sickness

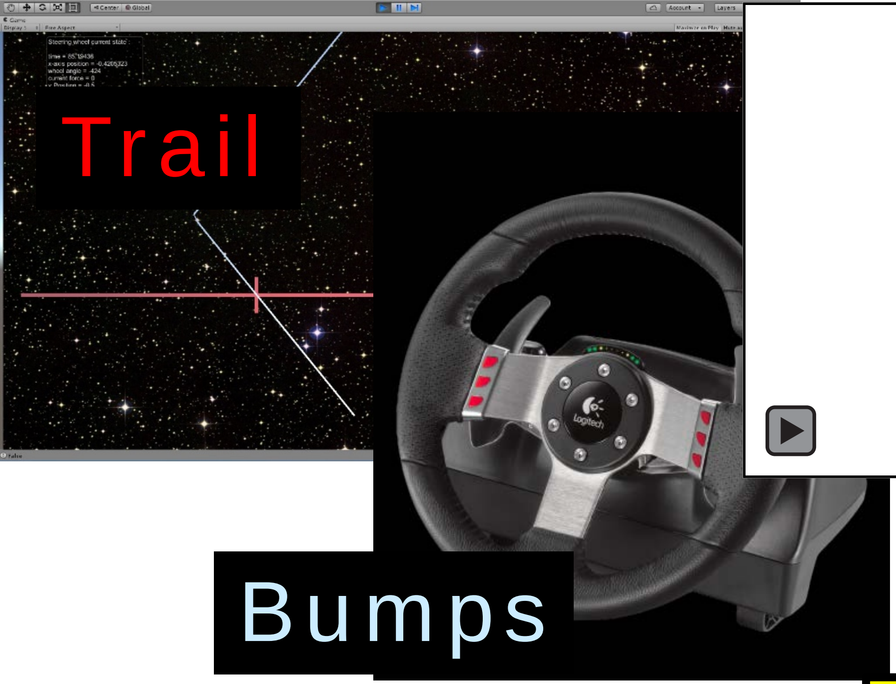
Performance

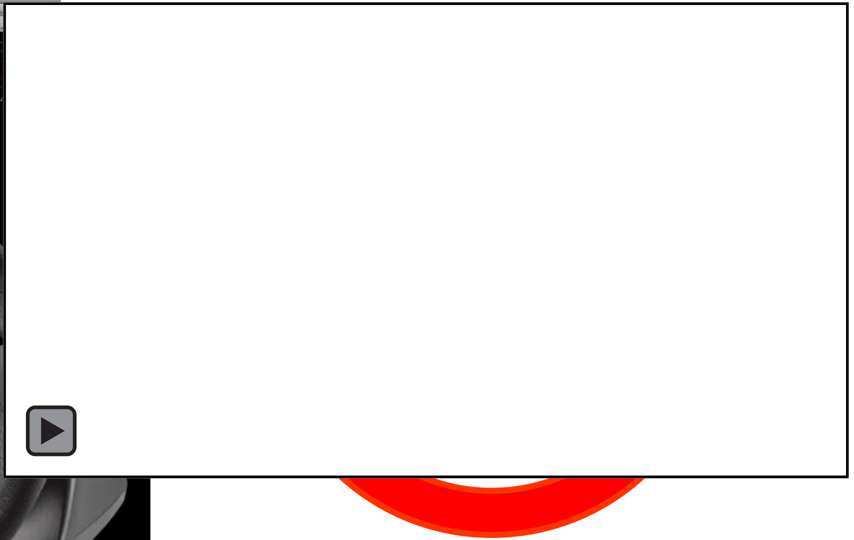
Vision, VOR **(reflex),** balance, motion sickness






Performance
Slow
Planning
Architecture
Law
Reflex
Fast
Accurate
Flexible
Inaccurate
Rigid
Object motion
eye
Error
vision
Cortex
delay
Physiology
Planning
Balance
Reflex
Motion sickness
Inner ear
vest nuclei
Tune
Vestibulo-
Cerebellum
sweat
pharynx
larynx
regurg.
reticular formation
diaphragm
vomiting
muscles
balance
GI tract
nausea
Theory
Experiments
Nerves
Slow
Optic
Architecture
Law
Vestibular
Fast
Accurate
Inaccurate
Veins
Nerve
Arteries
Axons
Myelin sheath
Individual neurons
Figure 25-1b Discover Biology 3/e



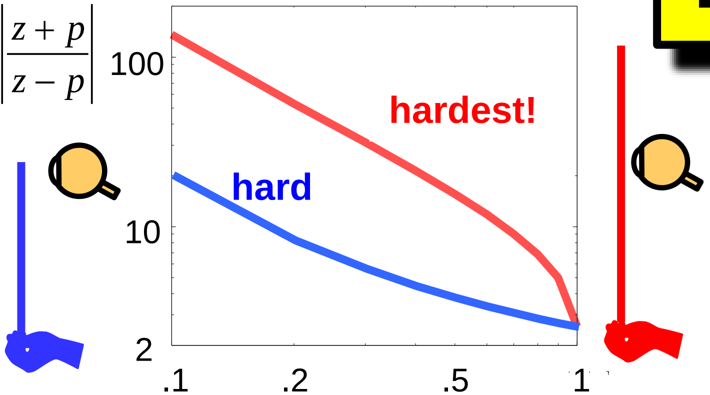


Object motion

Slow

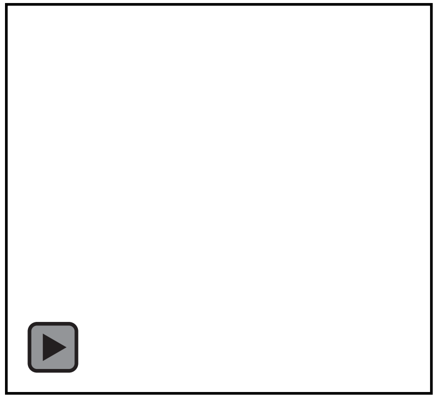
Experiments

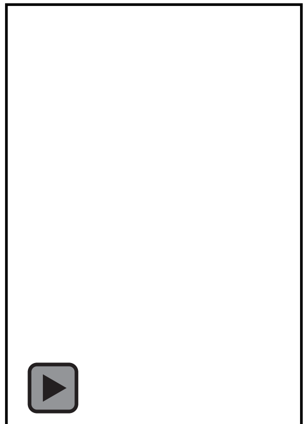
$$\exp(p\tau)\left|\frac{z+p}{z-p}\right|$$



Waterbed

$$\left.\begin{matrix}\exp\left(\int \ln|T|\right)\\ \|T\|_\infty\end{matrix}\right\} \geq \exp(p\tau)\left|\frac{z+p}{z-p}\right|$$





Head motion

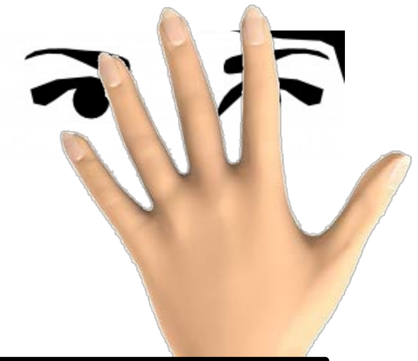
Fast

Theory

Experiments

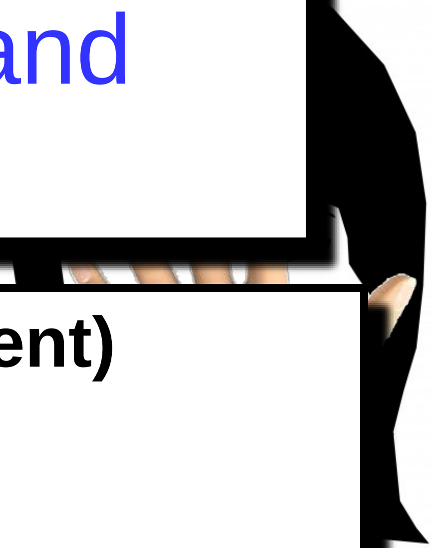
Object motion

Slow



- Video biking game with trails and bumps
- Balancing stick (inverted pendulum)
- Vision and VOR with object and head motion
- Balancing body with vision, vestibular, and proprioception

$\exp(p\tau$



2

.1

Waterbed

- **Quantitative match with theory (but equipment)**
- **Qualitative (but easy to do live demos)**
- **Both**

$\exp(\int$

$\|T\|_\infty$

Note: This doesn't work in video format, so this experiment to be done using .pptx format.

Easy to read slow text

.5 Hz

1 Hz

Easy to read slow text

Hard to read fast text

2 Hz

3 Hz

Hard to read fast text

Easy to read
slow text

.5 Hz

1 Hz

Easy to read
slow text

Hard to read
fast text

2 Hz

Shake your
head “no” as
fast as you can

3 Hz

Hard to read
fast text

Easy to read
slow text

.5 Hz

1 Hz

Easy to read
slow text

Shake your
head “no” as
fast as you can

Hard to read
fast text

2 Hz

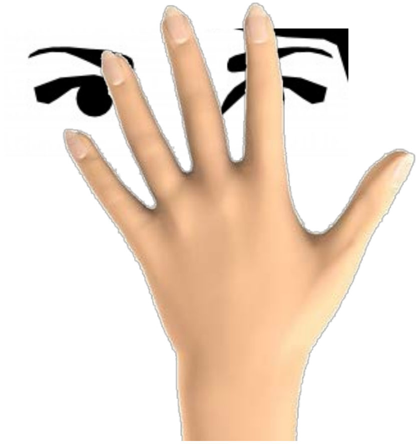
3 Hz

Hard to read
fast text

Why?

Object motion

Slow



Head motion

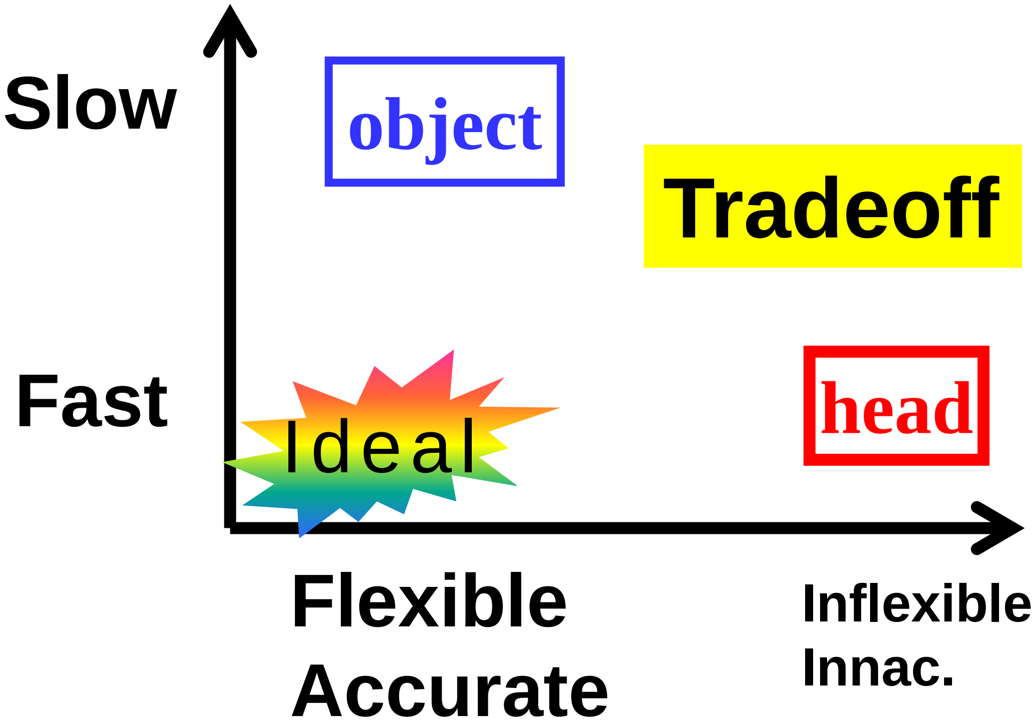
Fast

System/environ behavior
Extreme diversity

Object motion

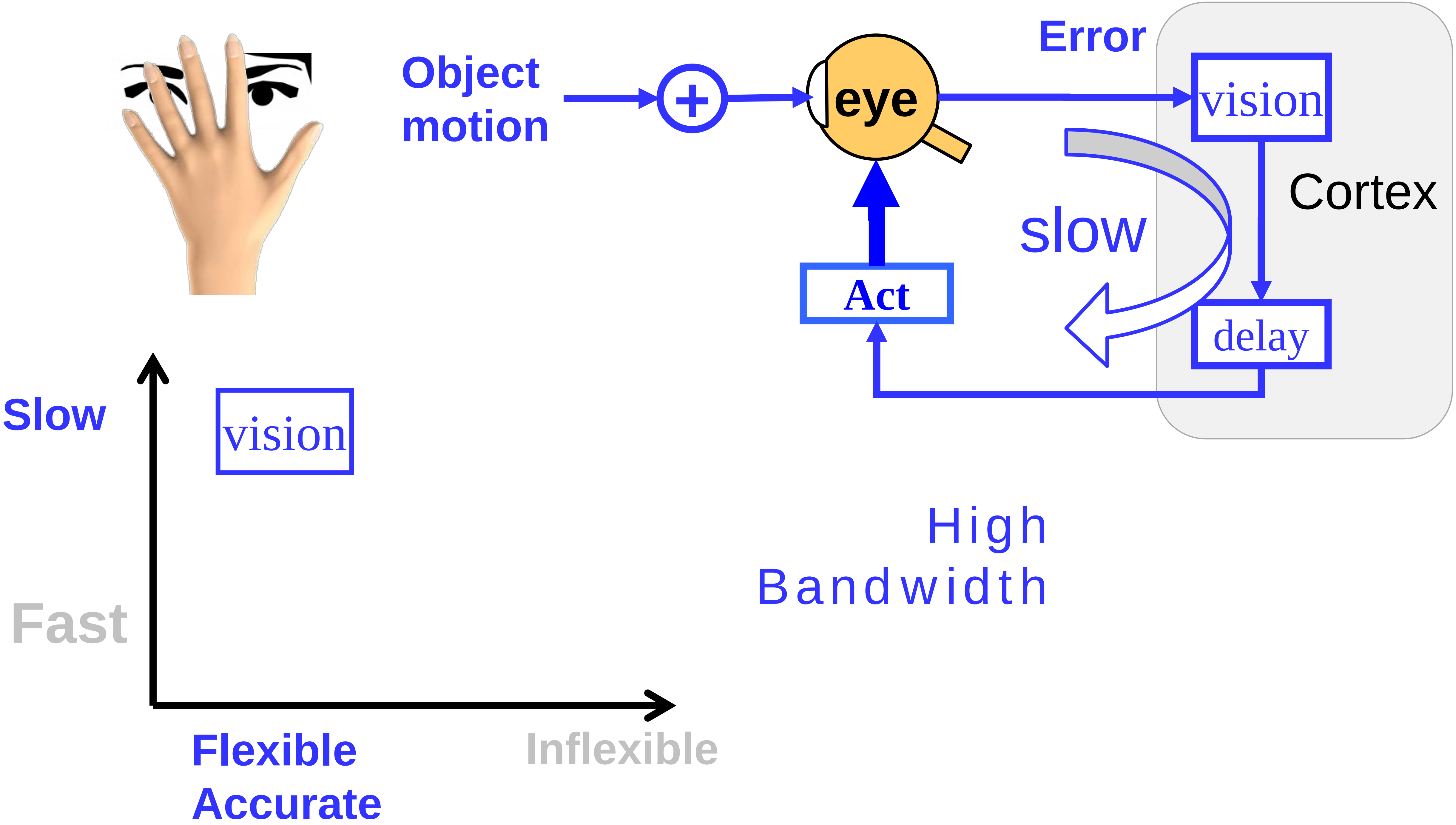
Slow

Why? How?



Head motion

Fast


Object
motion
eye
Error
vision
Cortex
slow
Act
delay
Slow
vision
Fast
High
Bandwidth
Flexible
Accurate
Inflexible

Object motion

Head motion

eye

Error

vision

delay

Act

VOR

fast

slow

Does not use "vision"?

Low delay

Slow

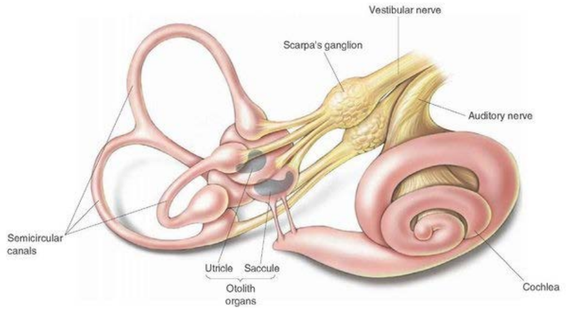
vision

Fast

Flexible

Inflexible

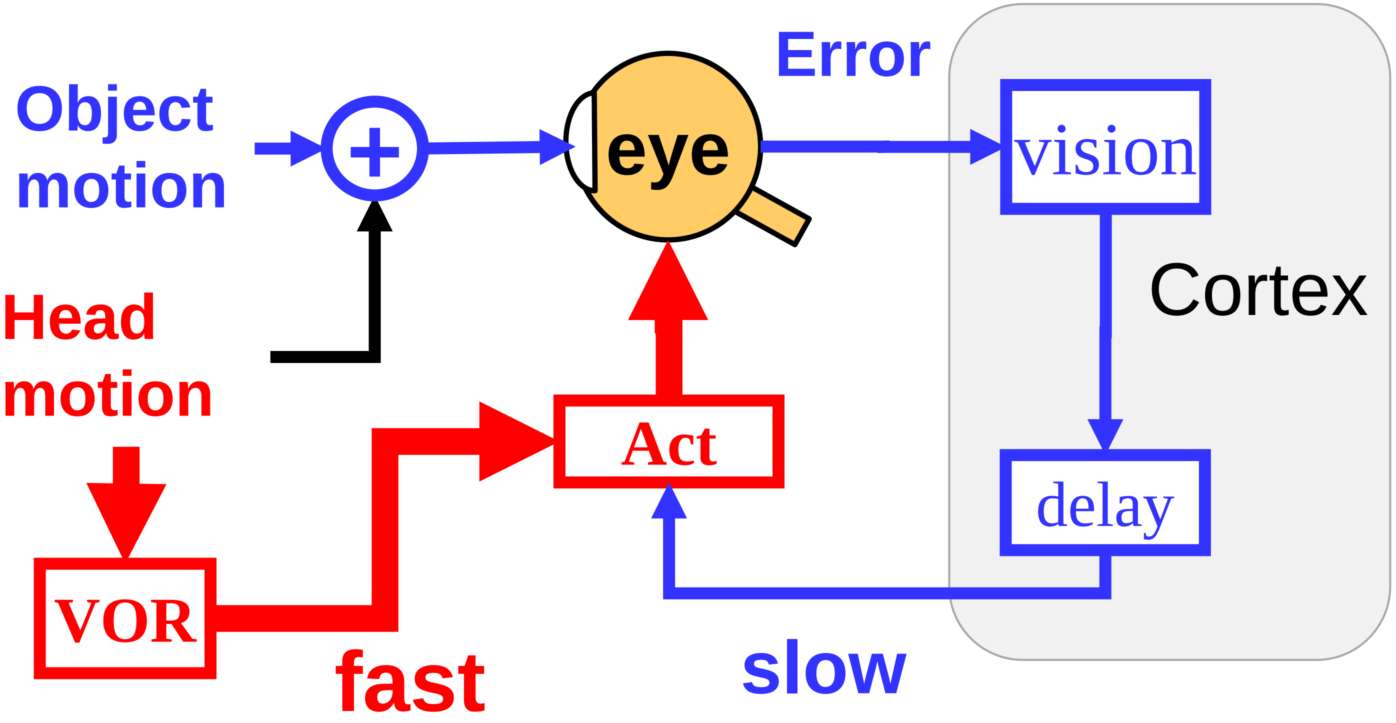
Inaccurrate



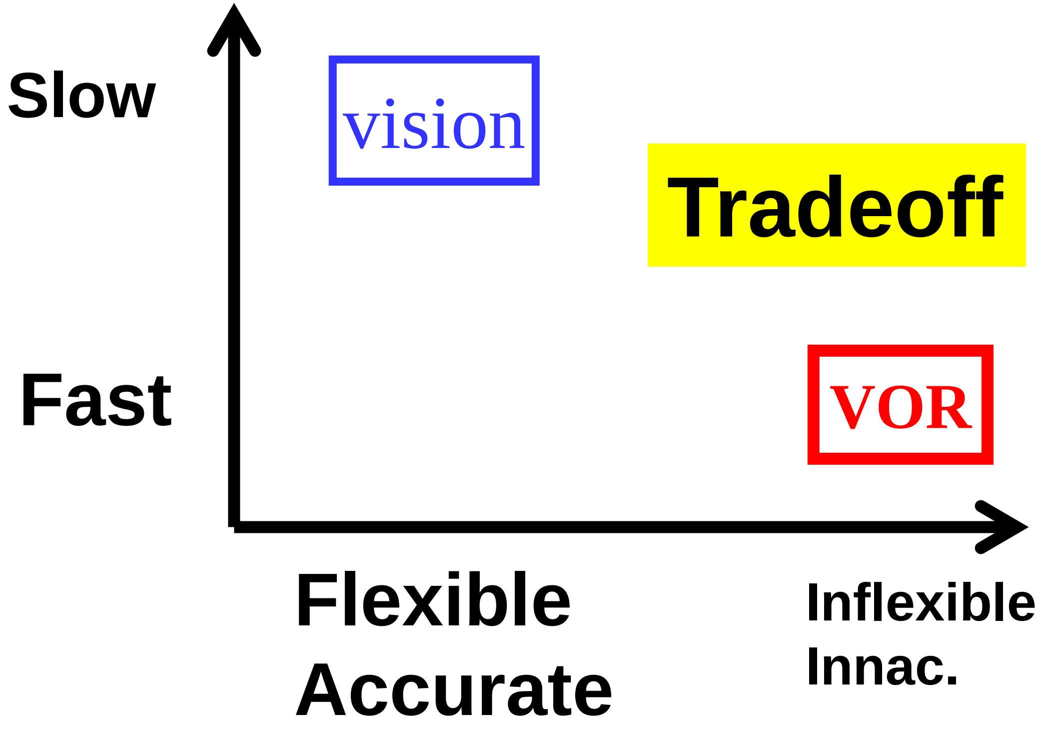
Vestibular
Ocular
Reflex
(VOR)

Mechanism

Minimal cartoon

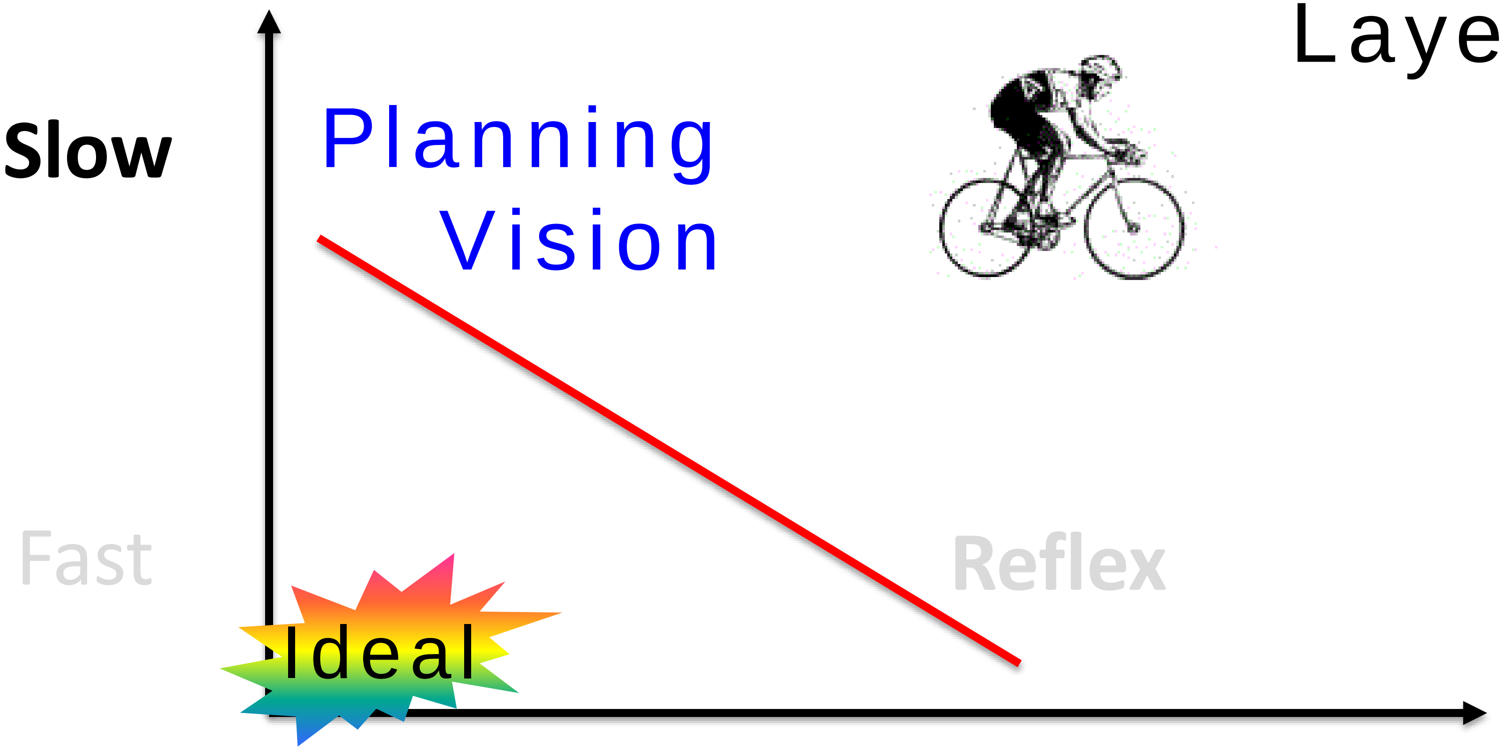


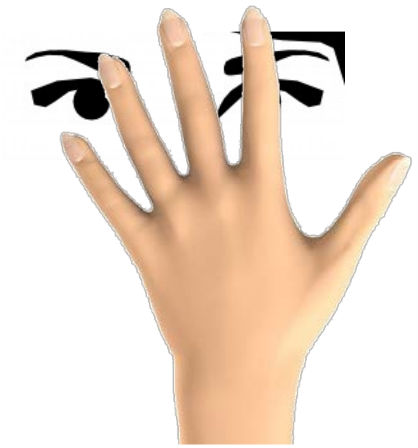
Tradeoff



Why?

Layers





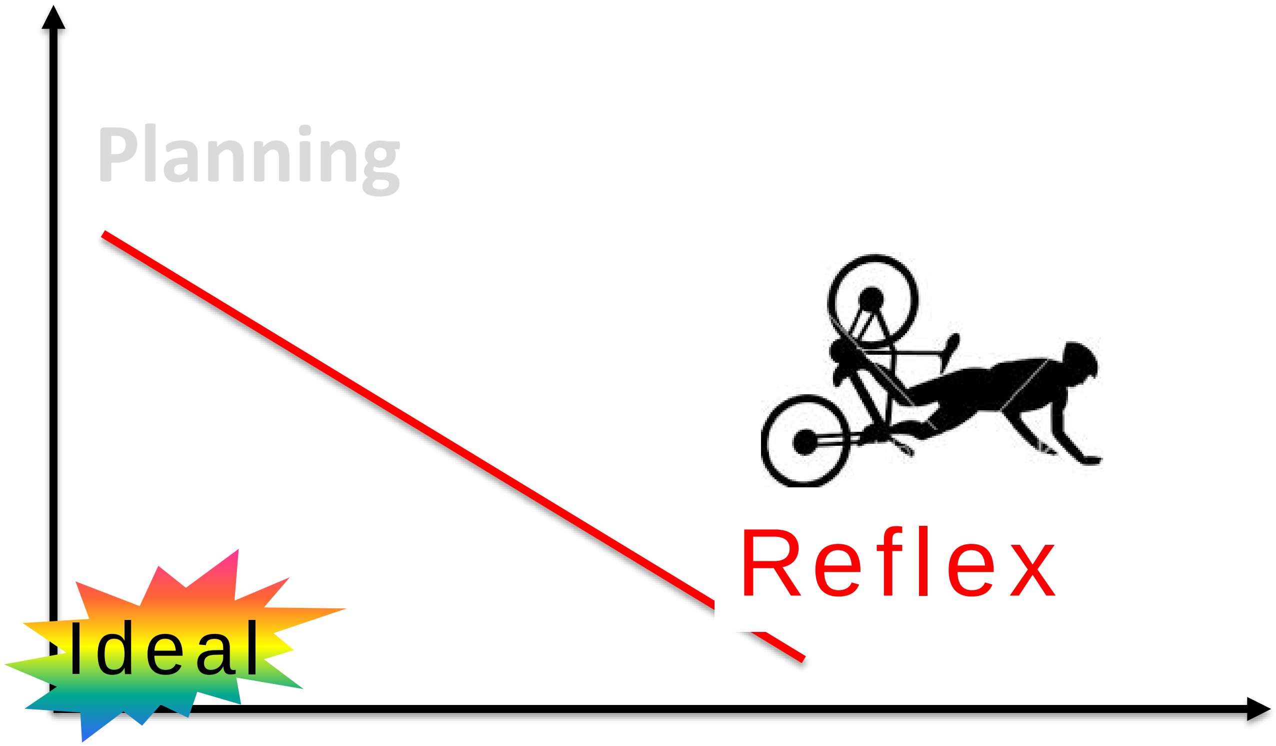
Object motion

Slow

Accurate	Inaccurate
Flexible	Rigid
Centralized	Localized, distributed
Conscious	Unconscious
Deliberate	Automatic
Stable virtual	Unstable real dynamics

Slow

Fast

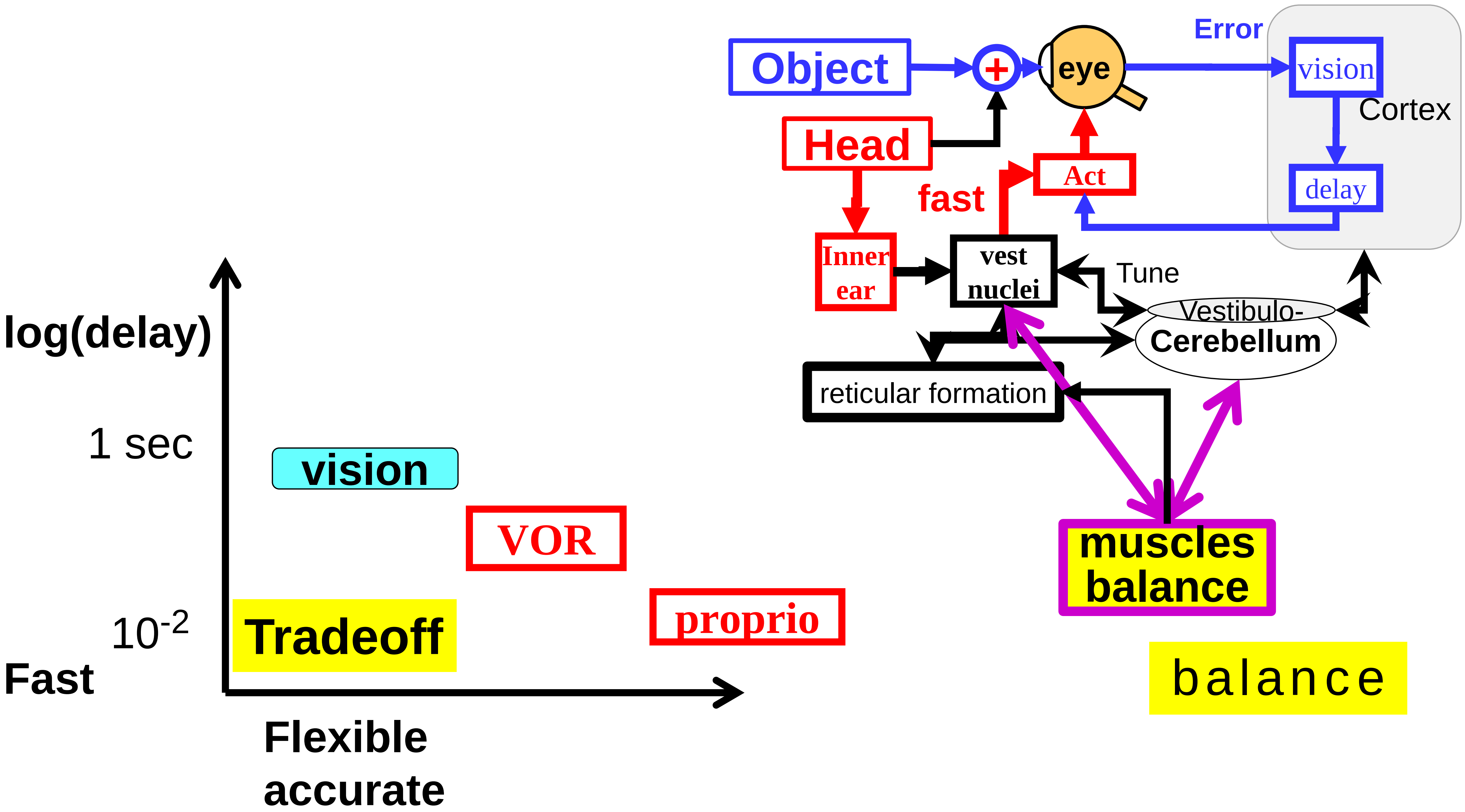


Head motion

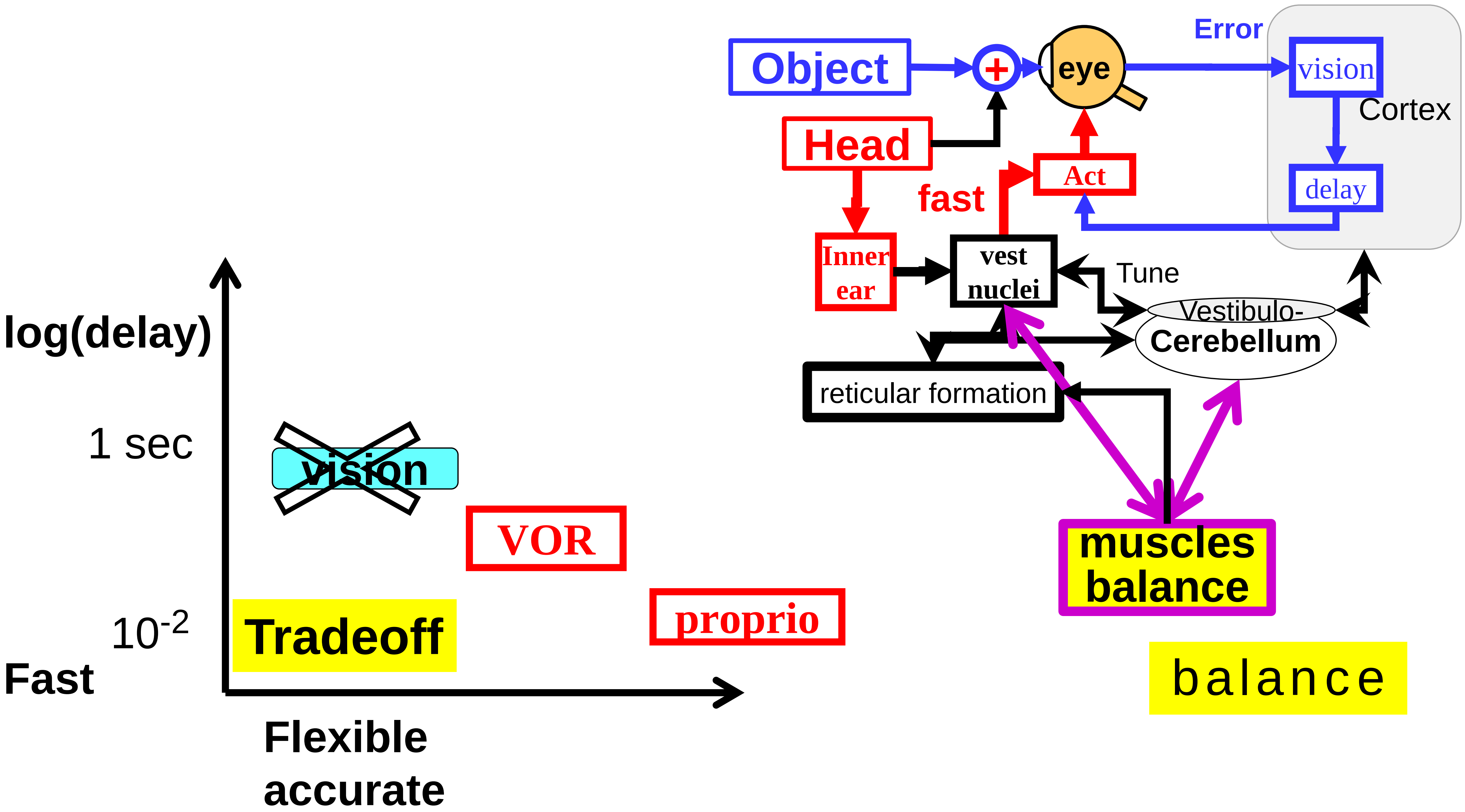
Fast

Accurate
Flexible
Centralized
Conscious
Deliberate
Stable virtual

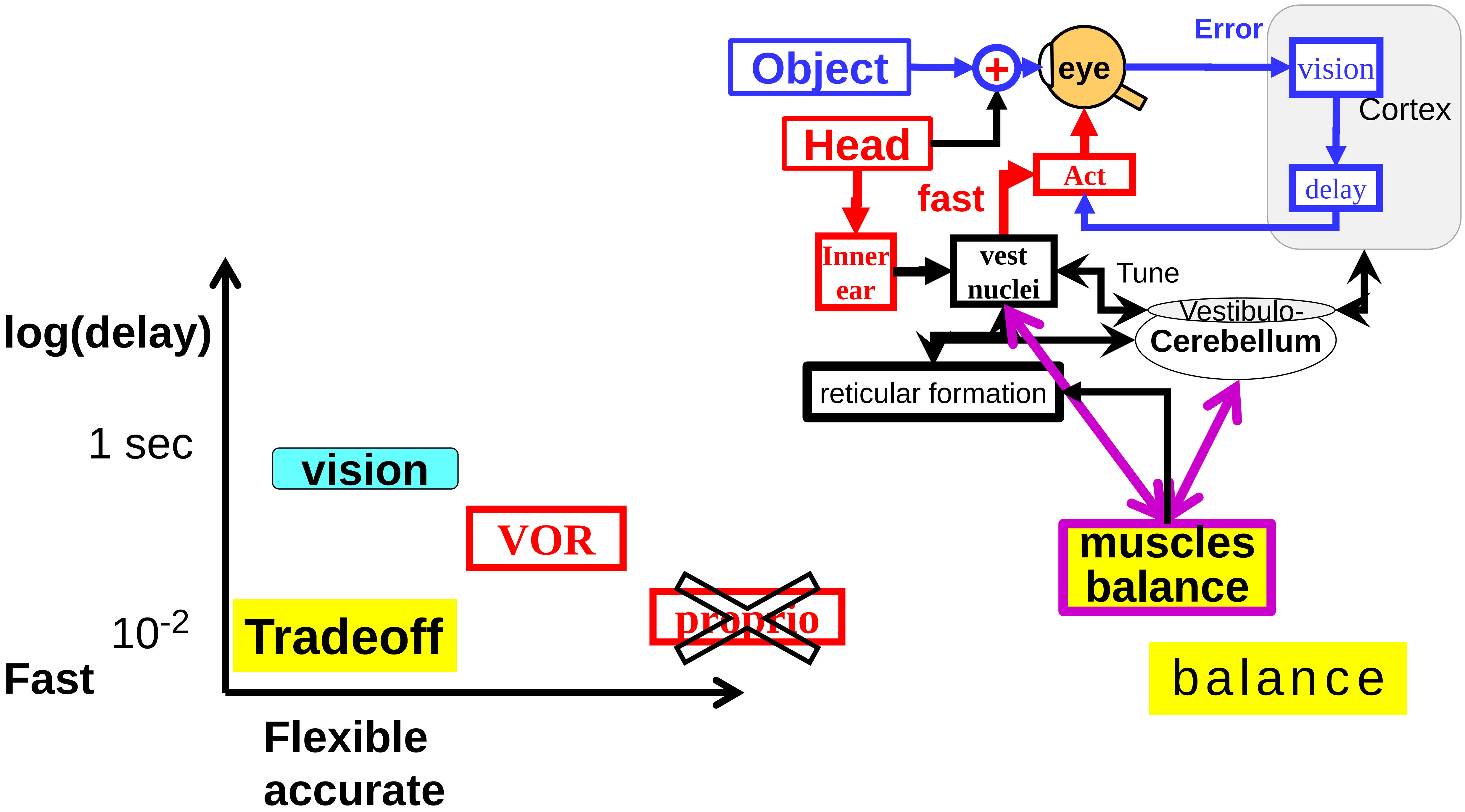
Inaccurate
Rigid
Localized, distributed
Unconscious
Automatic
Unstable real dynamics



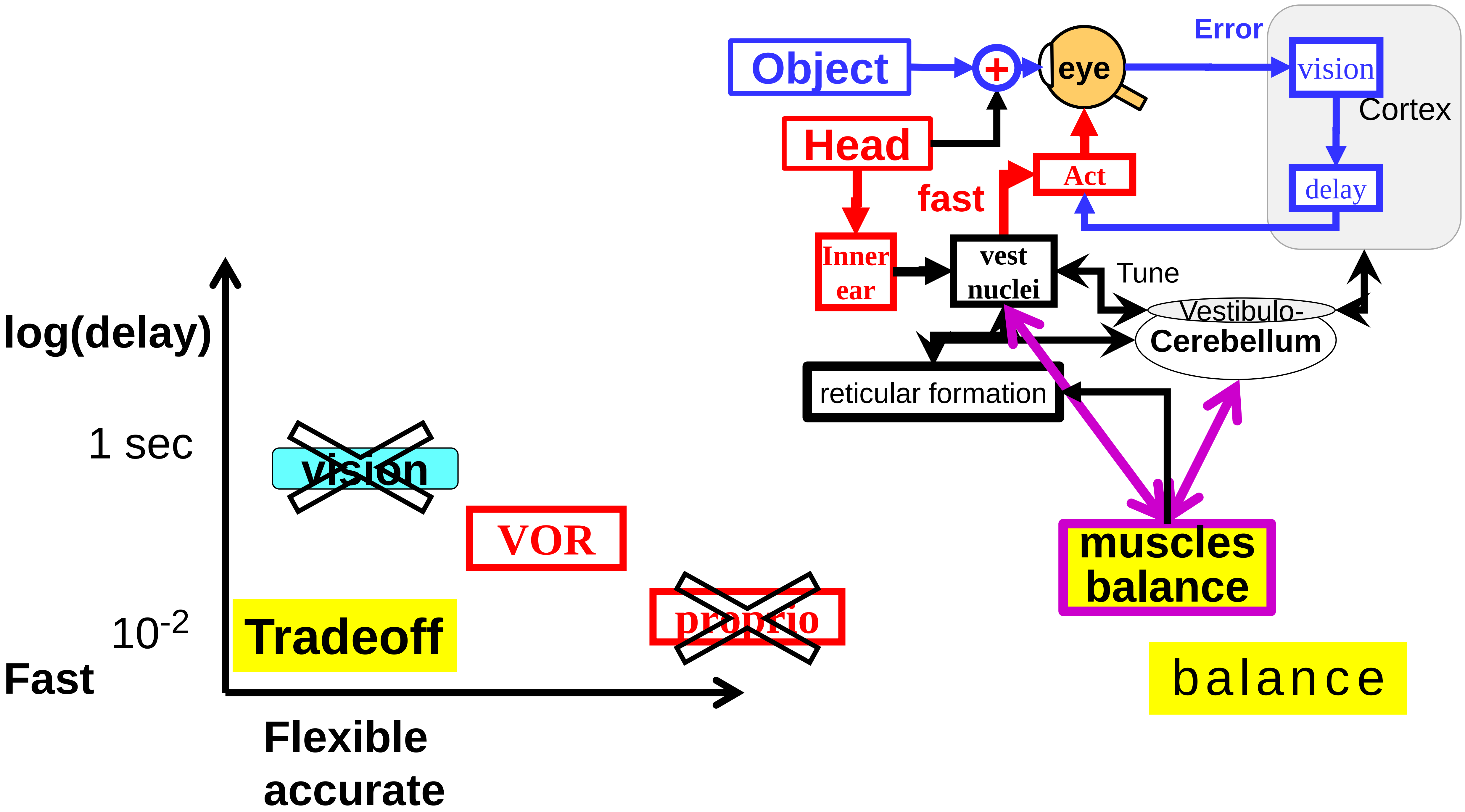
Object
eye
Error
vision
Cortex
delay
Head
Act
fast
Inner ear
vest nuclei
Tune
Vestibulo-
Cerebellum
reticular formation
muscles balance
balance
log(delay)
1 sec
10^{-2}
Fast
vision
VOR
proprio
Tradeoff
Flexible
accurate



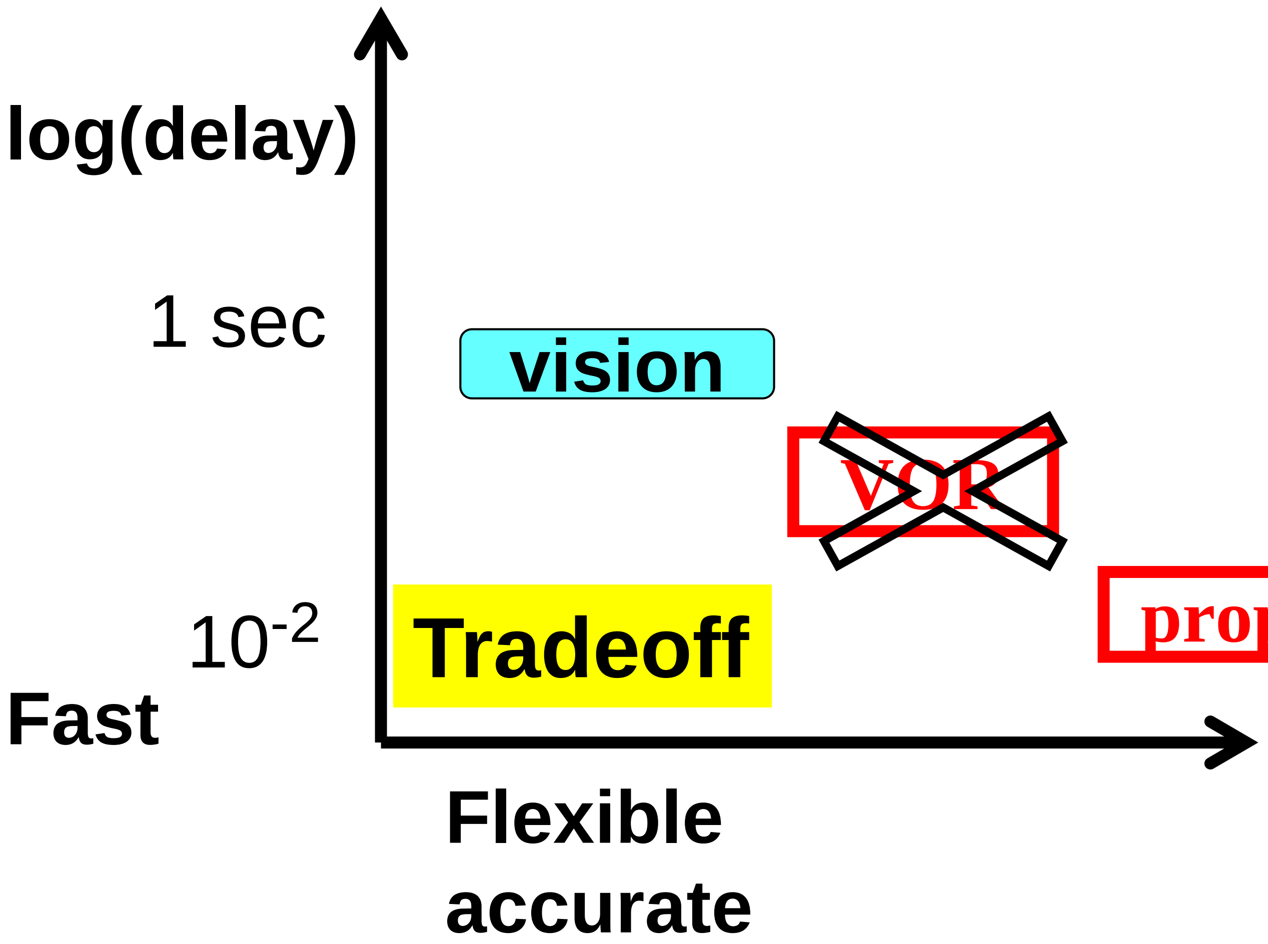
log(delay)
1 sec
10^{-2}
Fast
vision
VOR
proprio
Tradeoff
Flexible
accurate
Object
eye
Error
vision
Cortex
delay
Head
Act
fast
Inner ear
vest nuclei
Tune
Vestibulo-
Cerebellum
reticular formation
muscles balance
balance

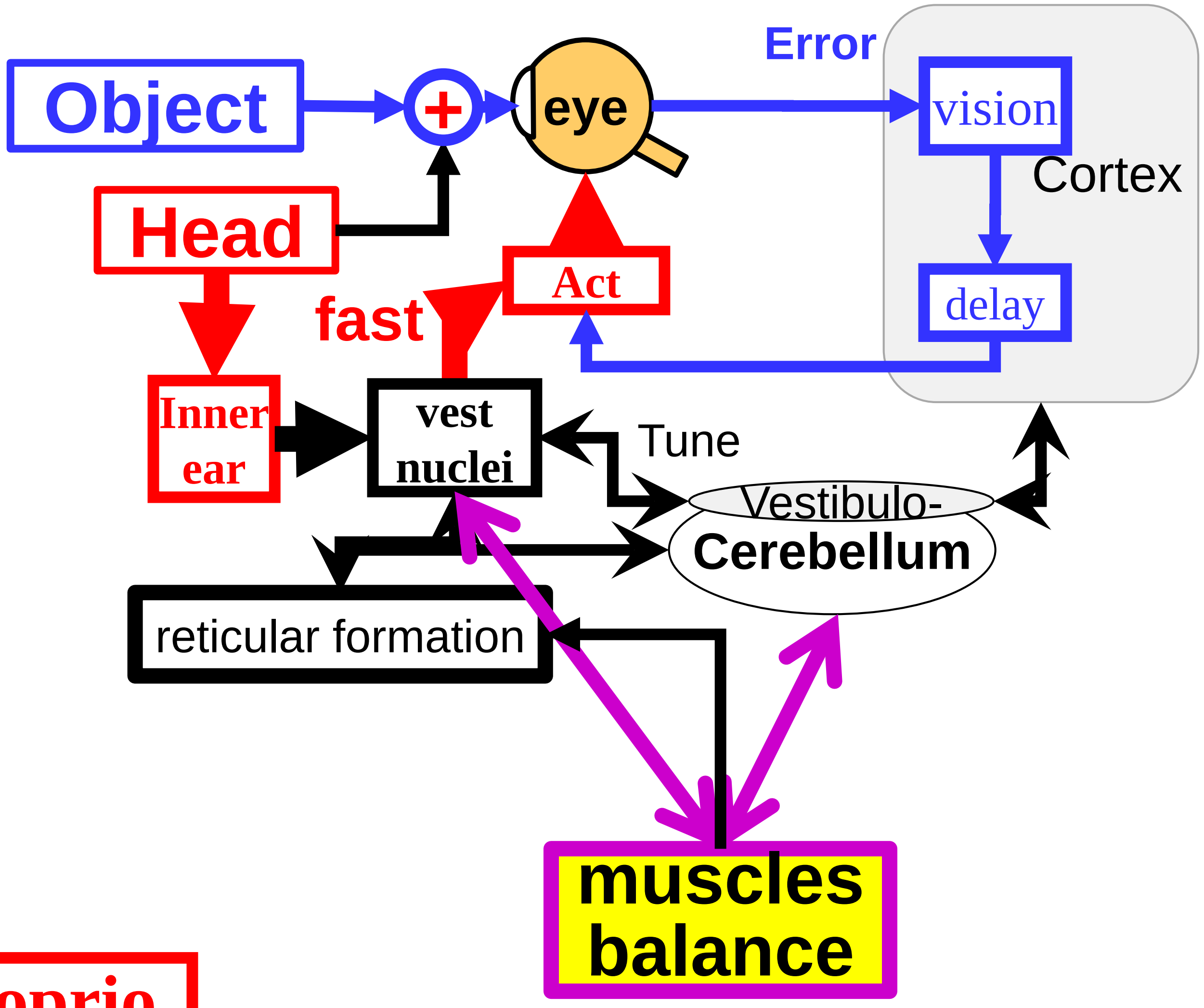


log(delay)
1 sec
10^-2
Fast
vision
VOR
proprio
Tradeoff
Flexible
accurate
Object
eye
Error
vision
Cortex
delay
Head
Act
fast
Inner ear
vest nuclei
Tune
Vestibulo-
Cerebellum
reticular formation
muscles balance
balance



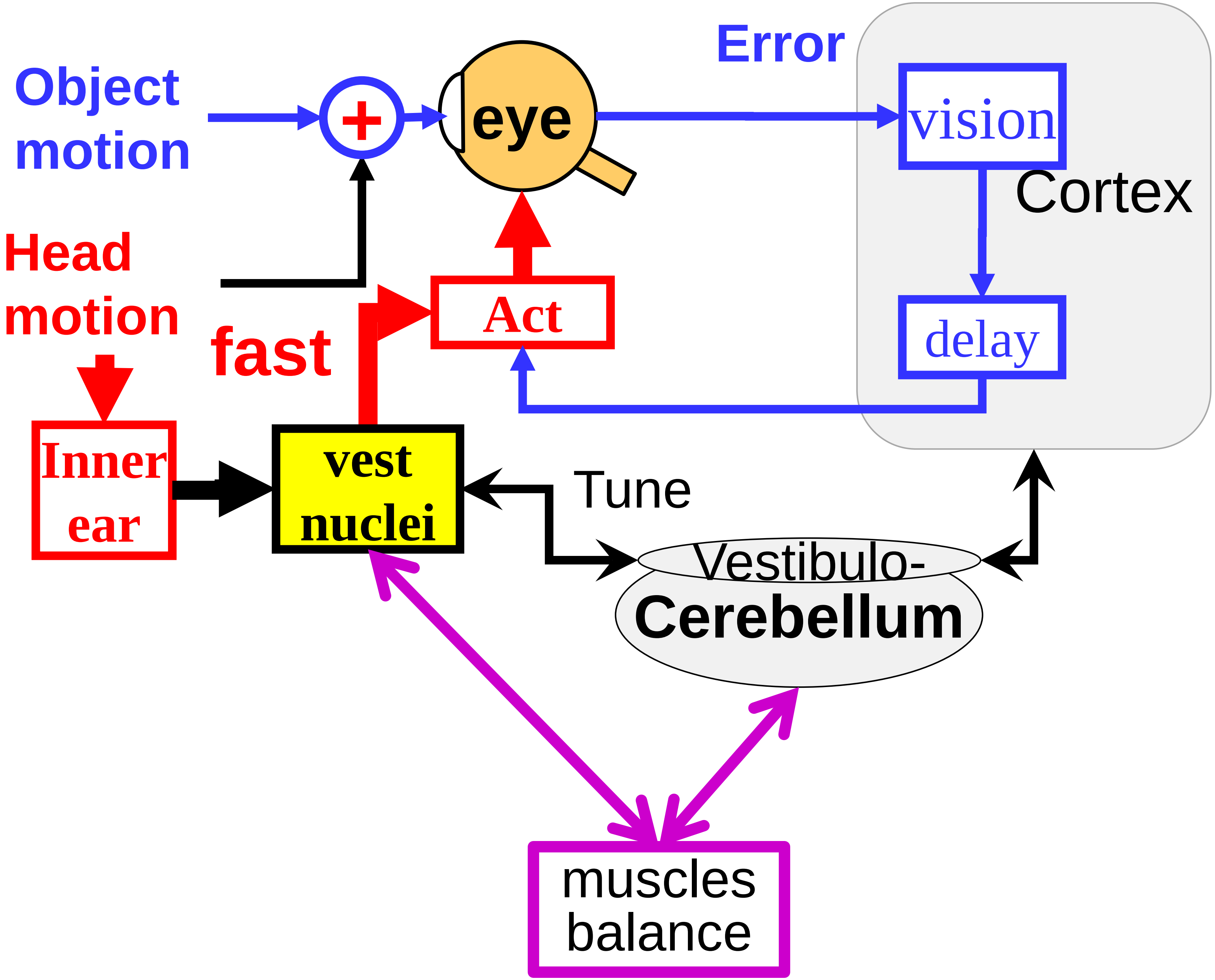
Object
eye
Error
vision
Cortex
Head
delay
Act
fast
Inner ear
vest nuclei
Tune
Vestibulo-
Cerebellum
reticular formation
muscles balance
balance
log(delay)
1 sec
vision
VOR
proprio
10^{-2}
Tradeoff
Fast
Flexible
accurate

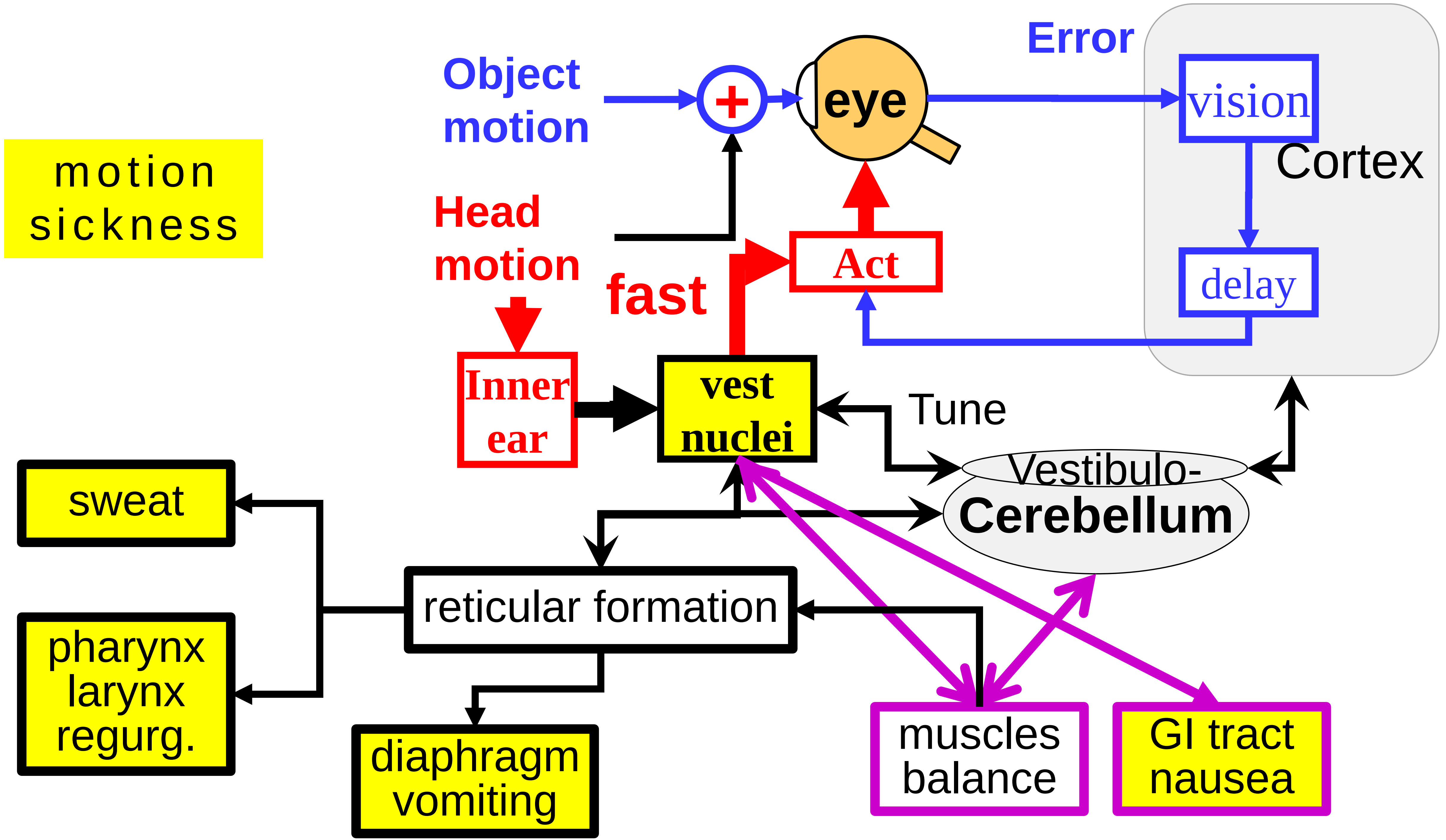

log(delay)
1 sec
10^-2
Fast
vision
VOR
Tradeoff
proprio
Flexible
accurate


Object
eye
Error
vision
Cortex
delay
Head
Act
fast
Inner ear
vest nuclei
Tune
Vestibulo-
Cerebellum
reticular formation
muscles
balance

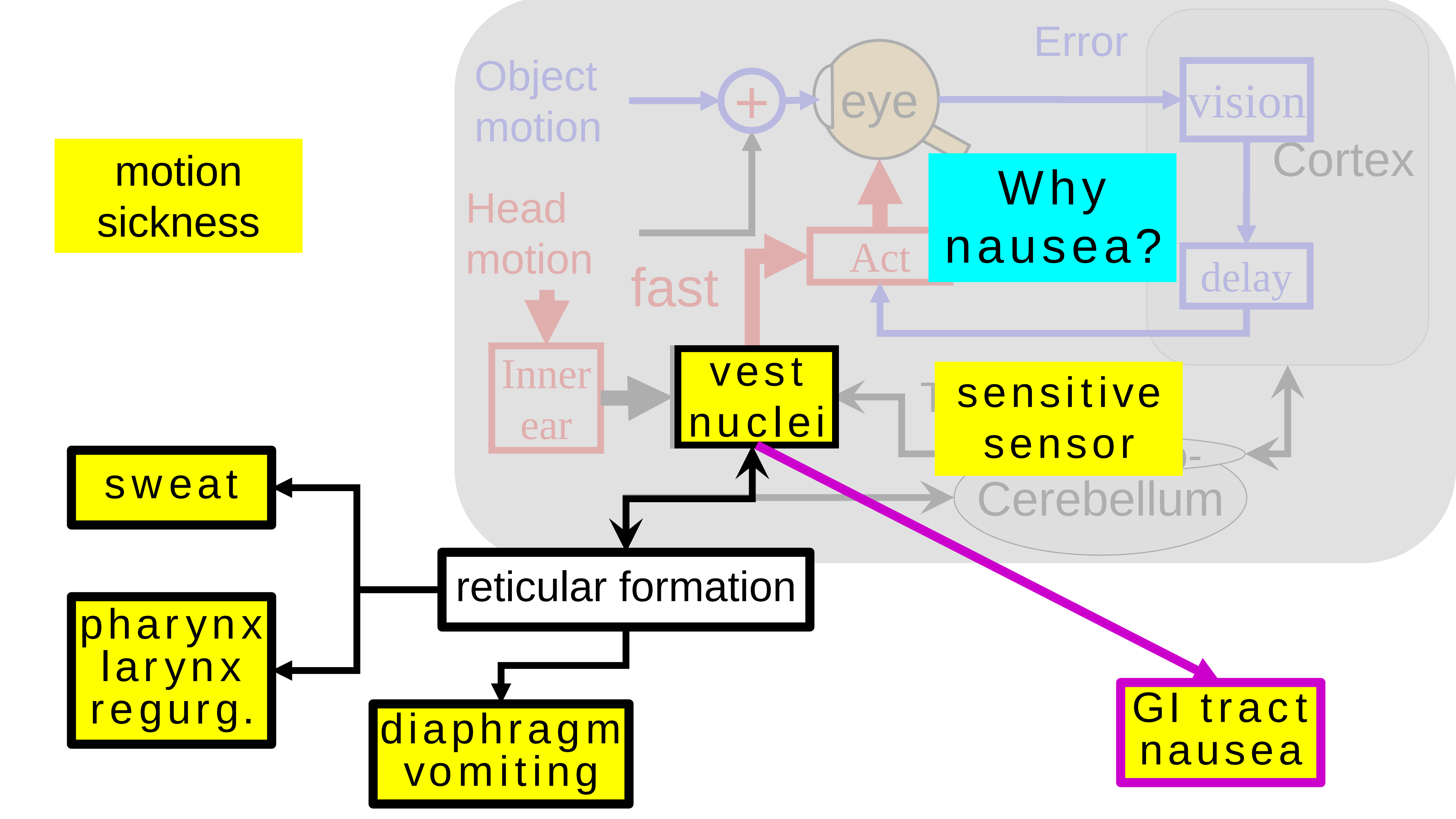
balance

motion sickness?



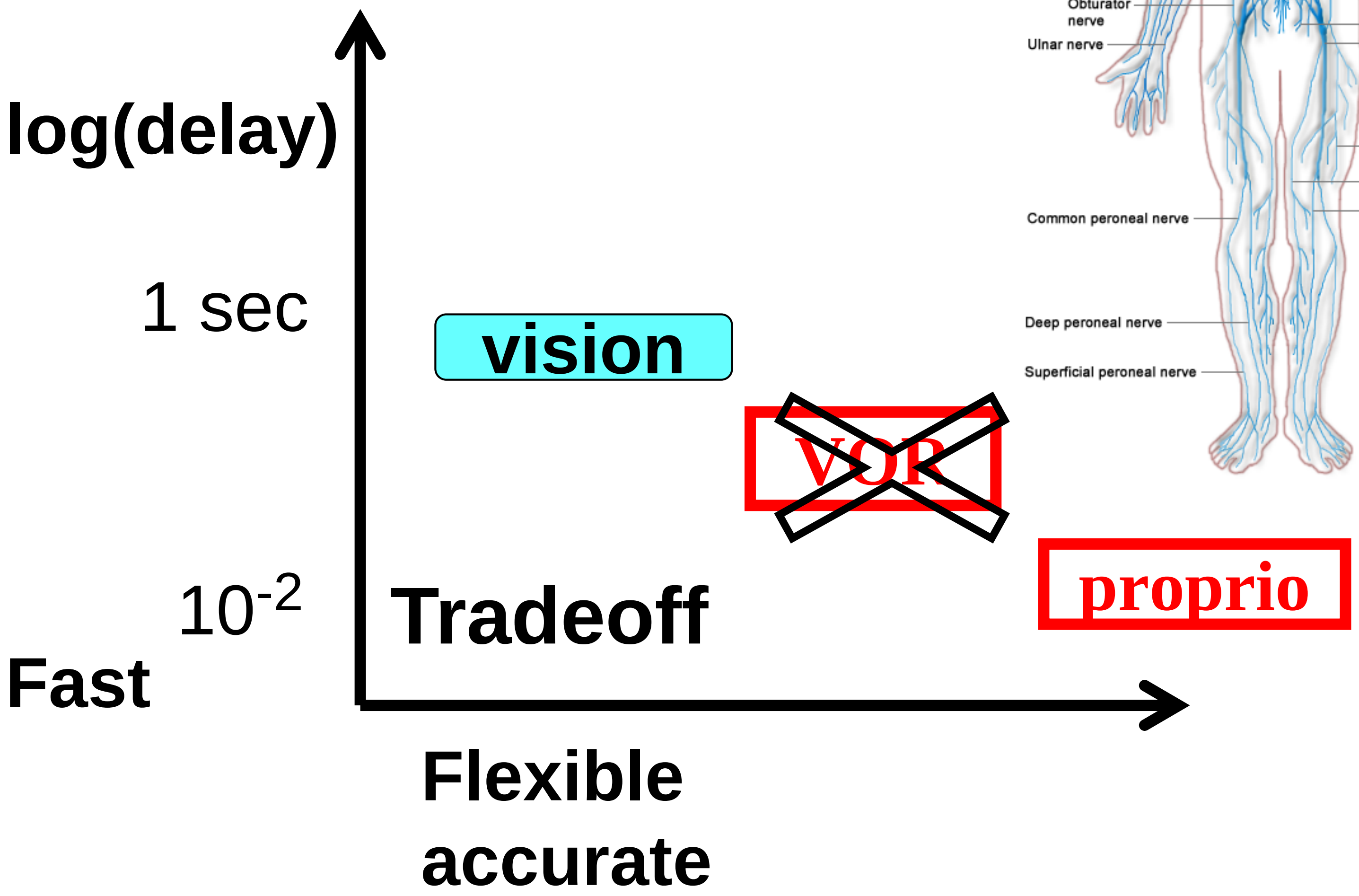


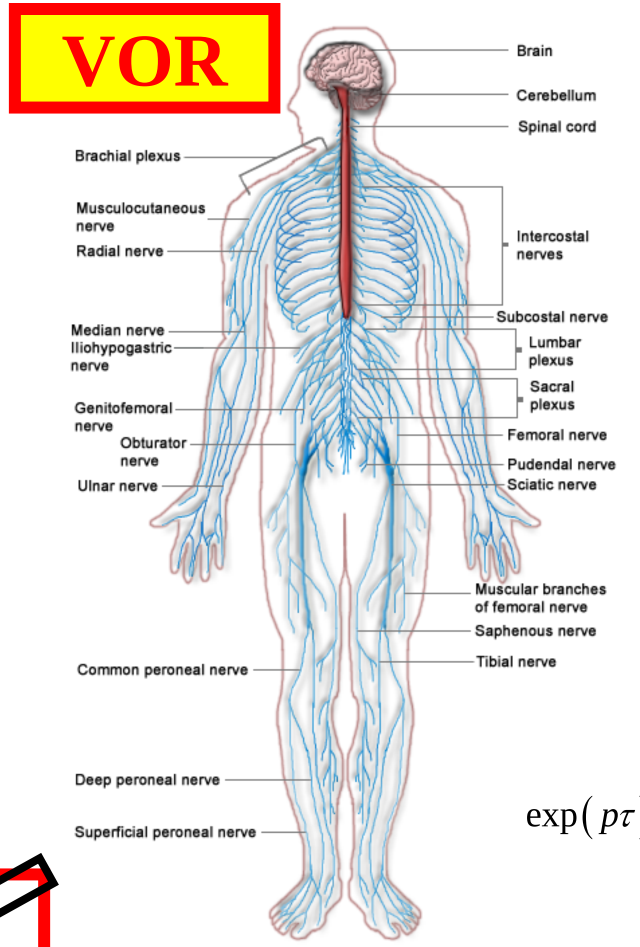
motion sickness
Object motion
Head motion
Error
eye
vision
Cortex
delay
Act
fast
Inner ear
vest nuclei
Tune
Vestibulo-
Cerebellum
sweat
pharynx larynx regurg.
reticular formation
diaphragm vomiting
muscles balance
GI tract nausea

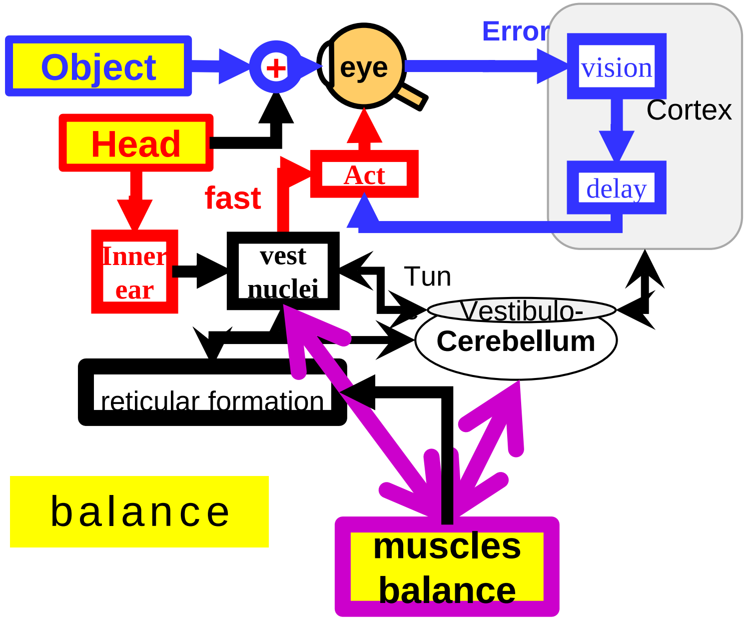


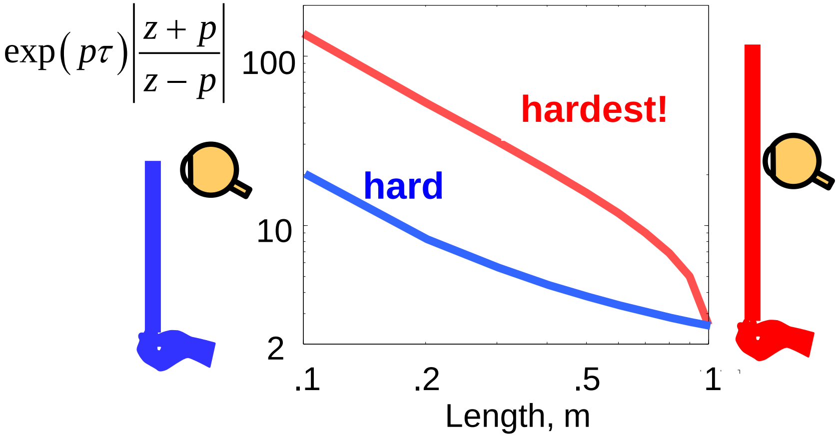
motion sickness
Object motion
eye
Error
vision
Cortex
Head motion
fast
Act
Why nausea?
delay
Inner ear
vest nuclei
sensitive sensor
Cerebellum
sweat
reticular formation
pharynx larynx regurg.
diaphragm vomiting
GI tract nausea

Need sensor that is fast and high. Why?



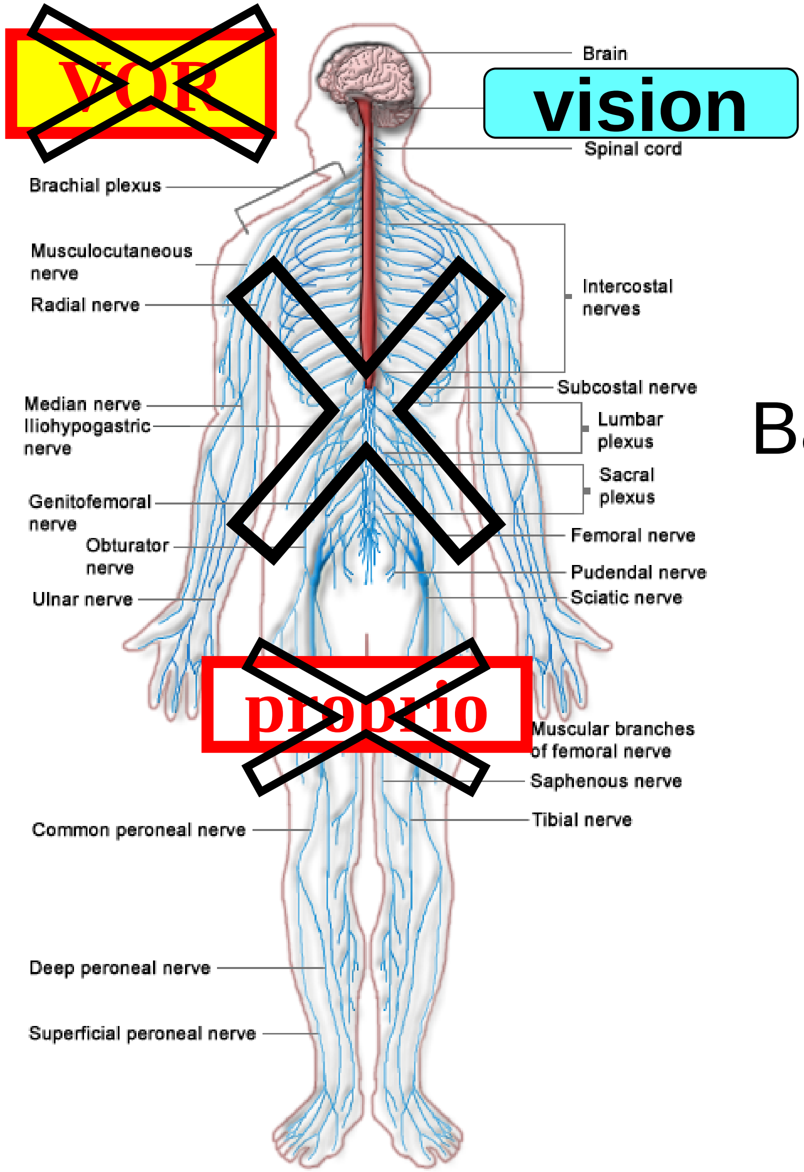






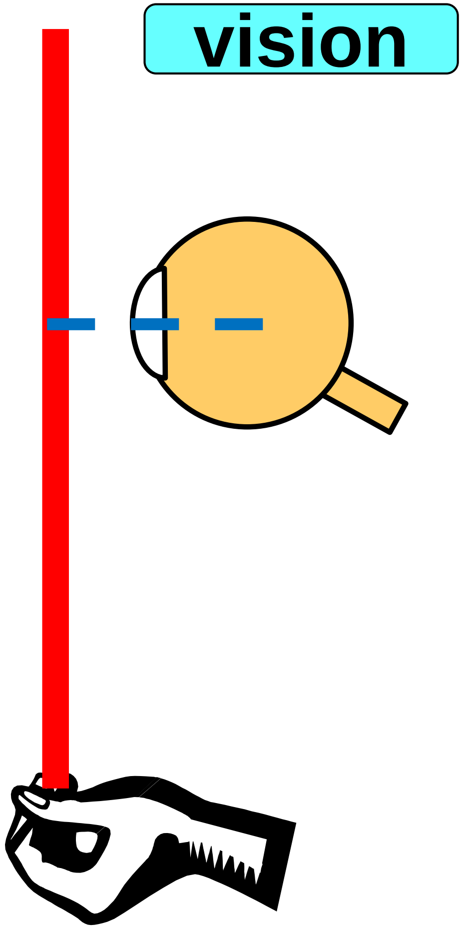
Waterbed

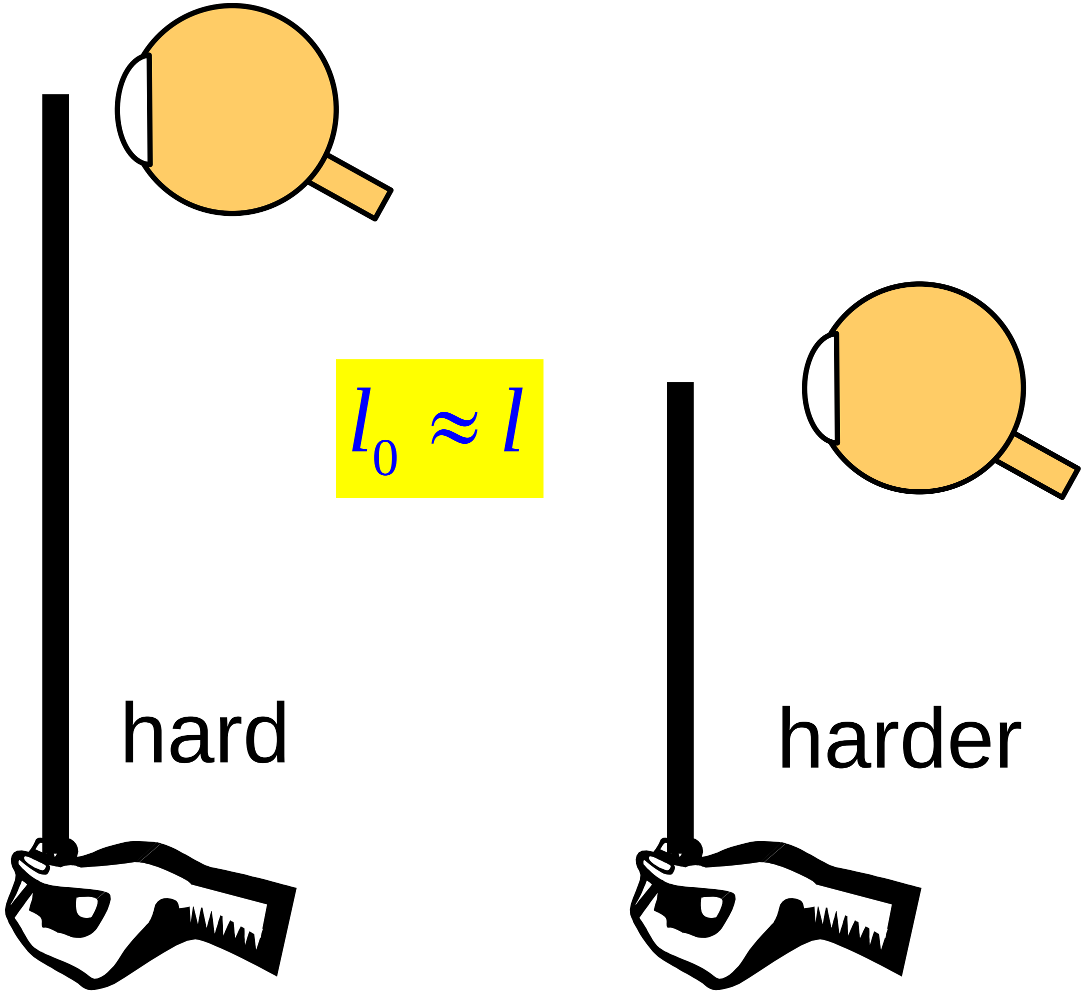
$$\frac{\exp\left(\int \ln|T|\right)}{\|T\|_\infty} \geq \exp(p\tau)\left|\frac{z+p}{z-p}\right|$$



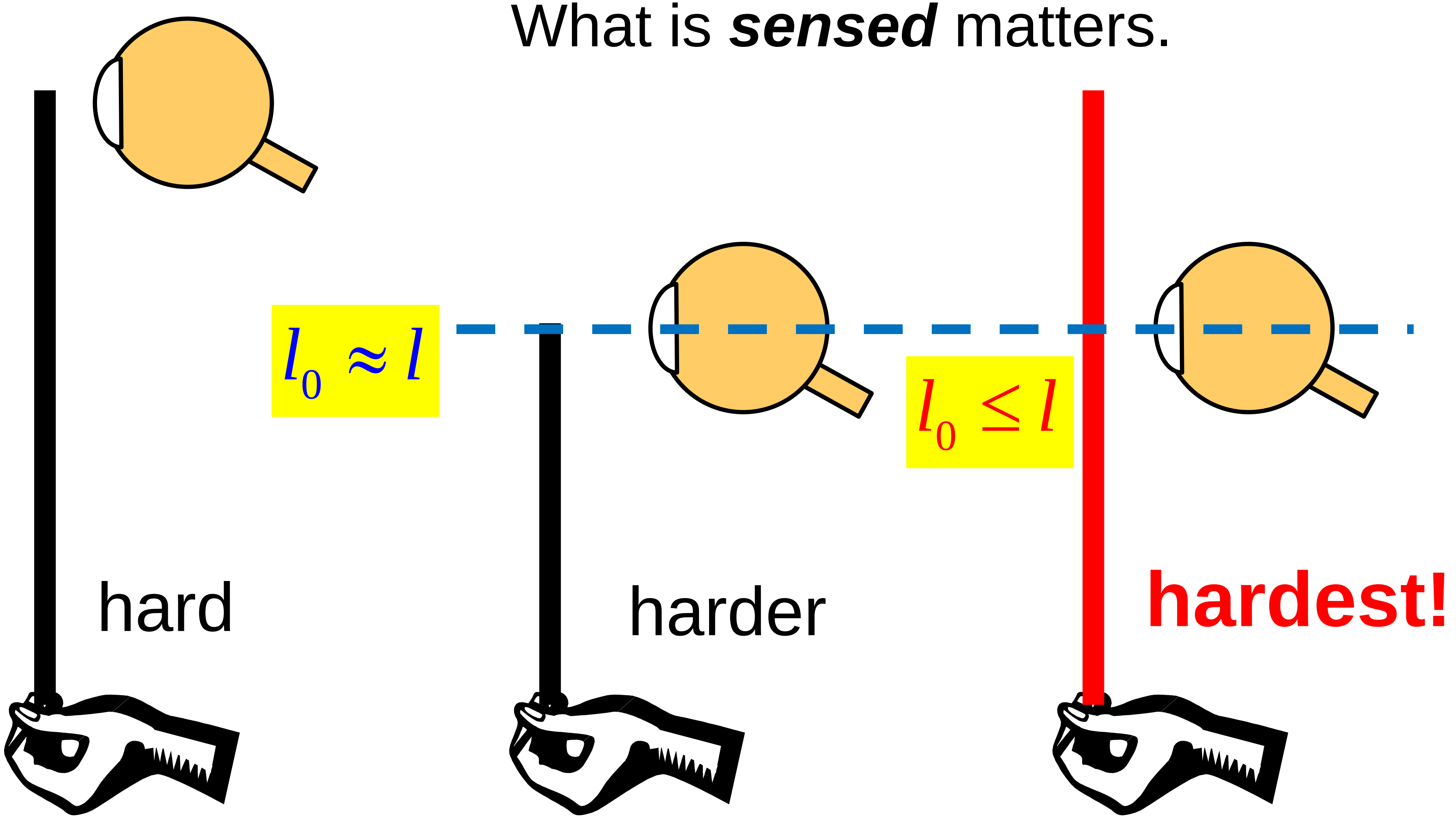
Balancing bodies

Balancing sticks

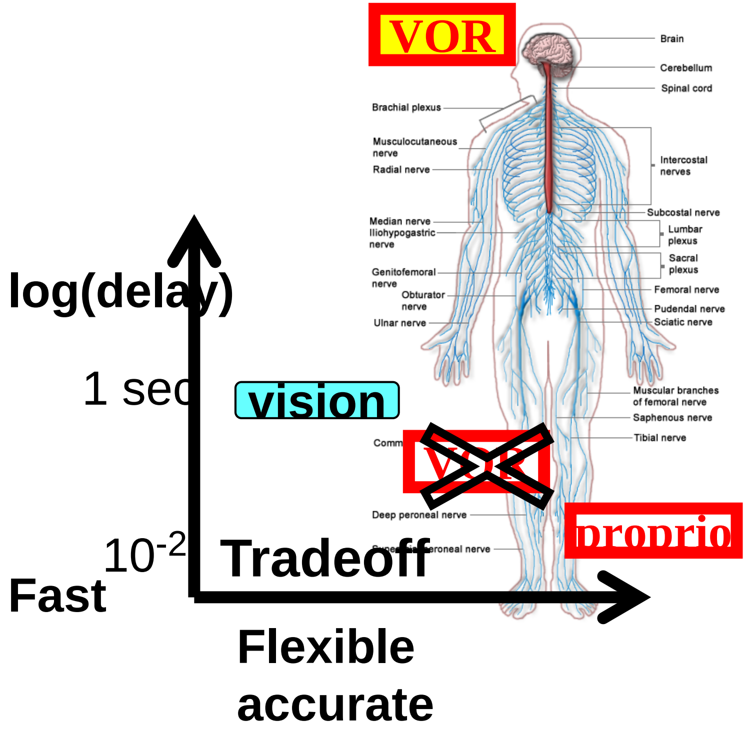


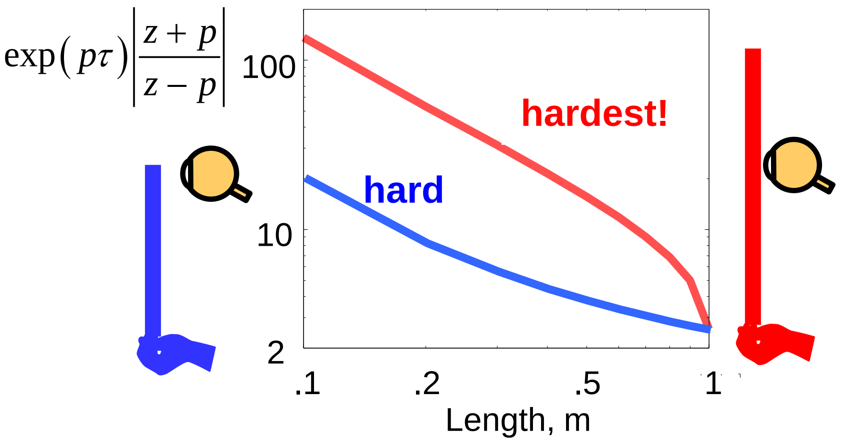

$l_0 \approx l$
hard
harder

What is ***sensed*** matters.



Need sensor that is fast and high. Why?





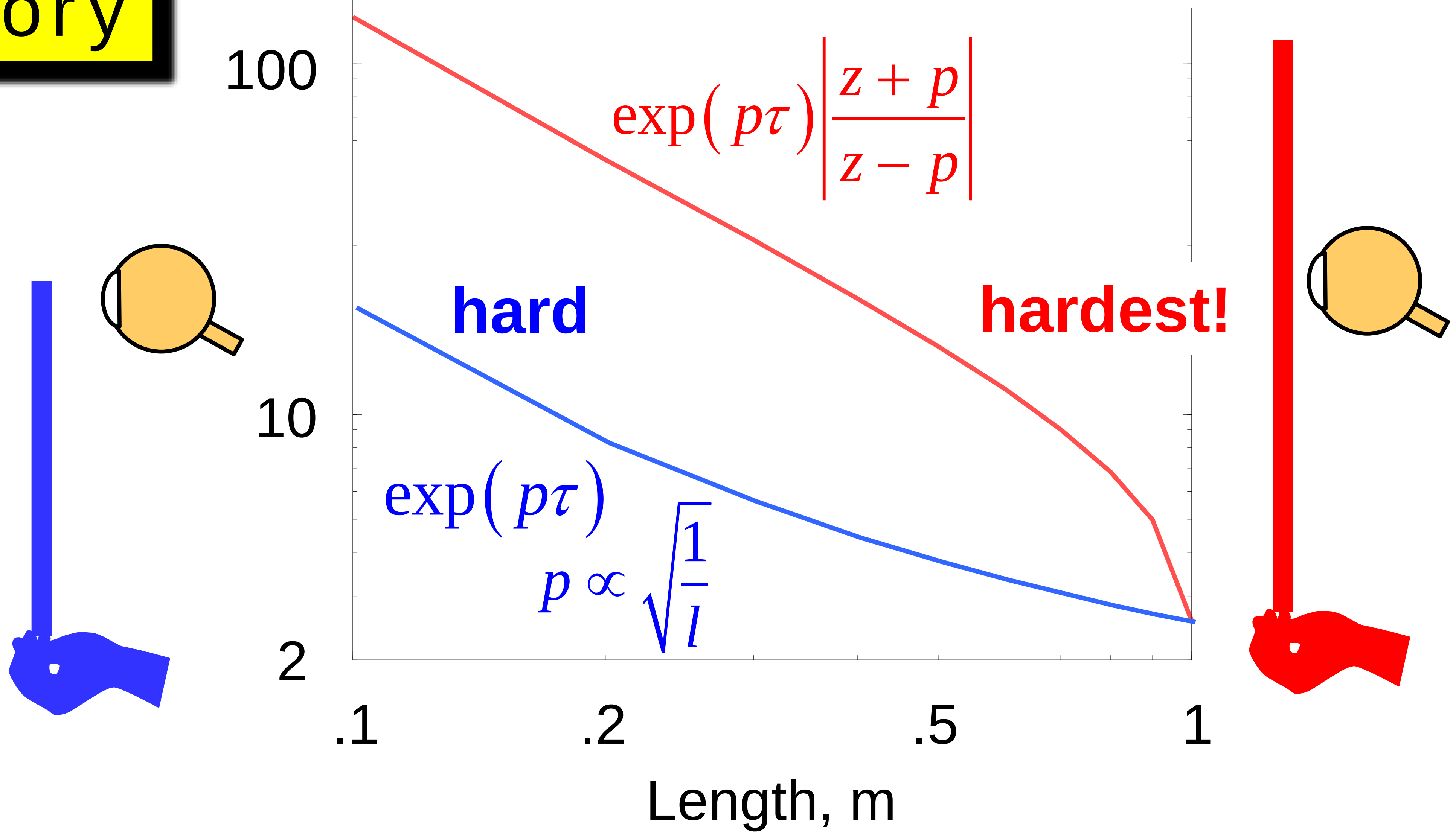
Waterbed

$$\left.\begin{array}{c}\exp\left(\int \ln|T|\right)\\ \|T\|_\infty\end{array}\right\} \geq \exp(p\tau)\left|\frac{z+p}{z-p}\right|$$

Theory

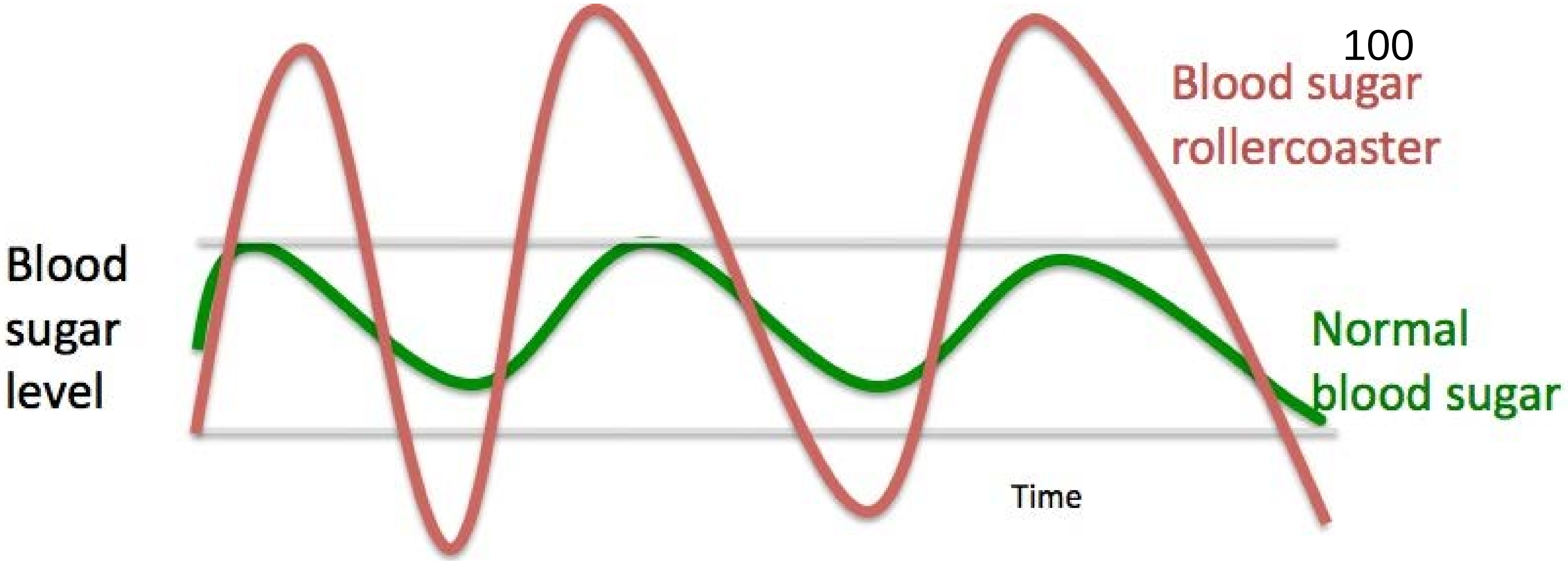
$$\tau = .3s$$

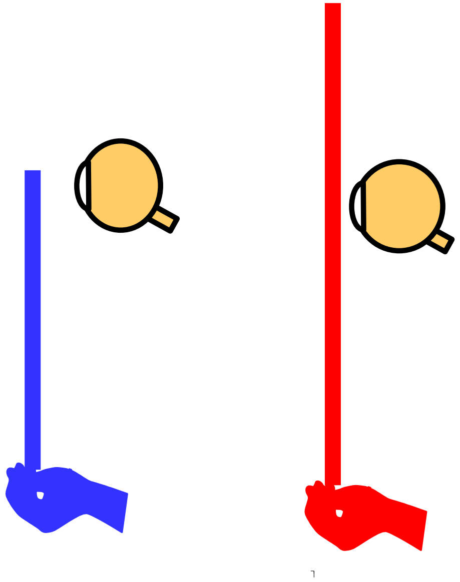
$$\left.\begin{matrix} \exp\left(\int \ln|T|\right) \\ \|T\|_\infty \end{matrix}\right\} \geq \exp(p\tau)\left|\frac{z+p}{z-p}\right| \geq \exp(p\tau)$$



$$\left.\begin{array}{c}\exp\left(\int \ln|T|\right)\\ \|T\|_\infty\end{array}\right\} \geq \exp(p\tau)\left|\frac{z+p}{z-p}\right|$$

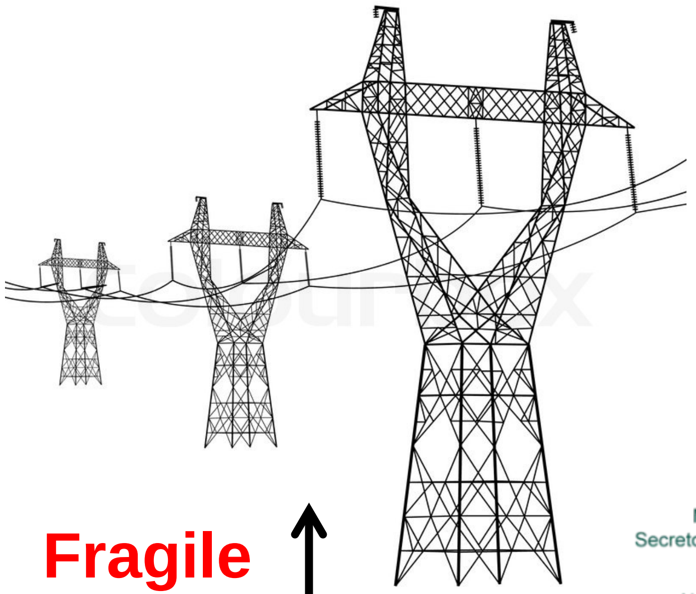
How ***controlled*** systems crash.

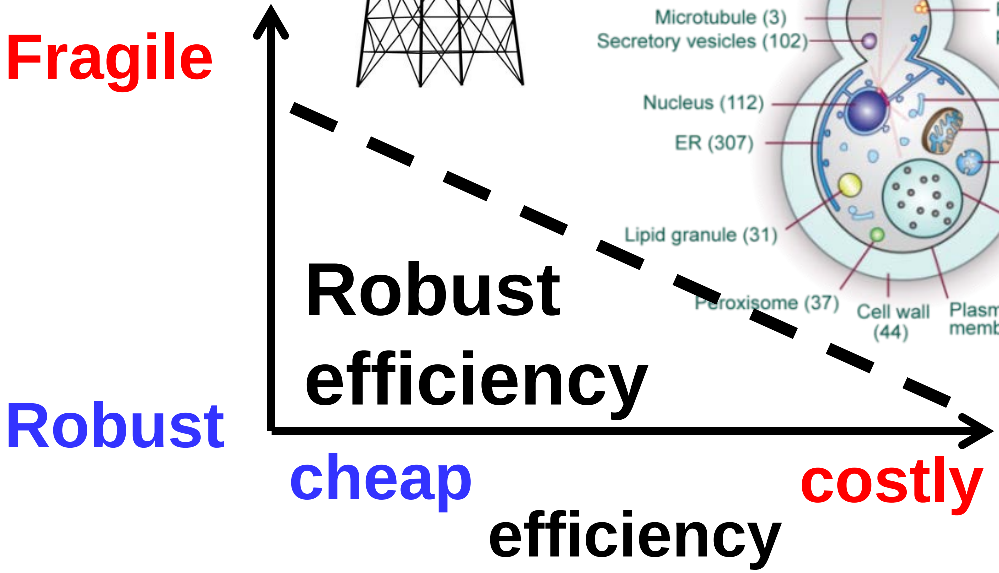


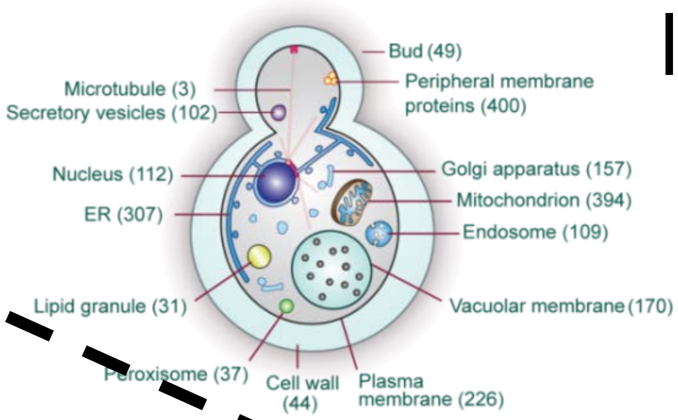


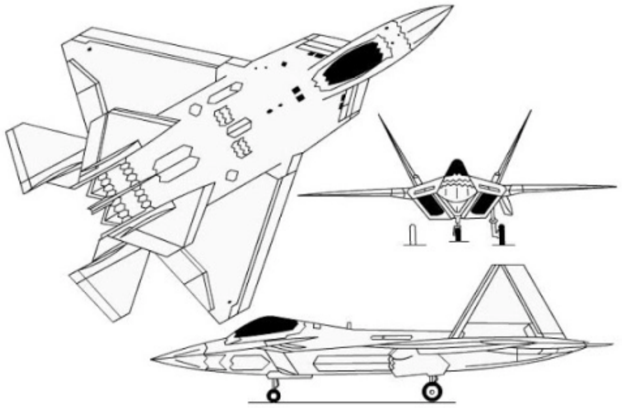
$$\left.\begin{array}{c}\exp\left(\int \ln|T|\right)\\ \|T\|_\infty\end{array}\right\} \geq \exp(p\tau)\left|\frac{z+p}{z-p}\right|$$

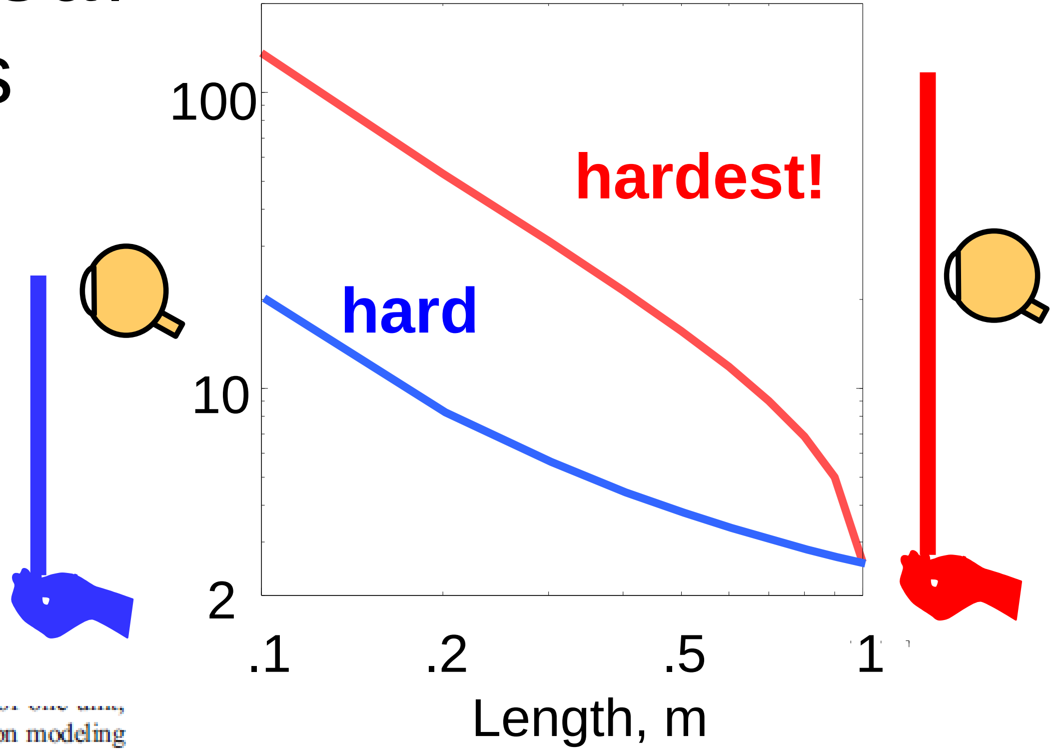
Universal laws







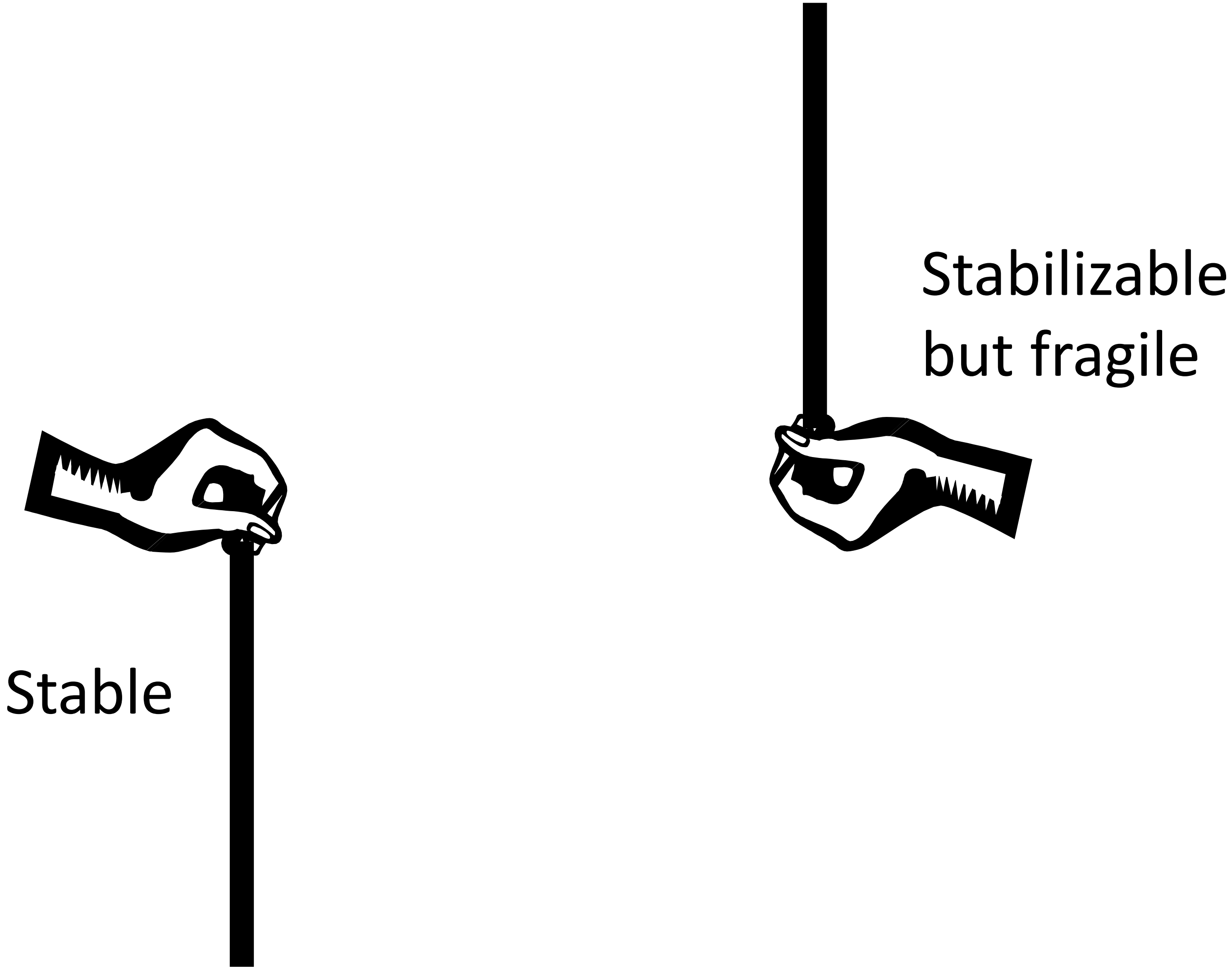




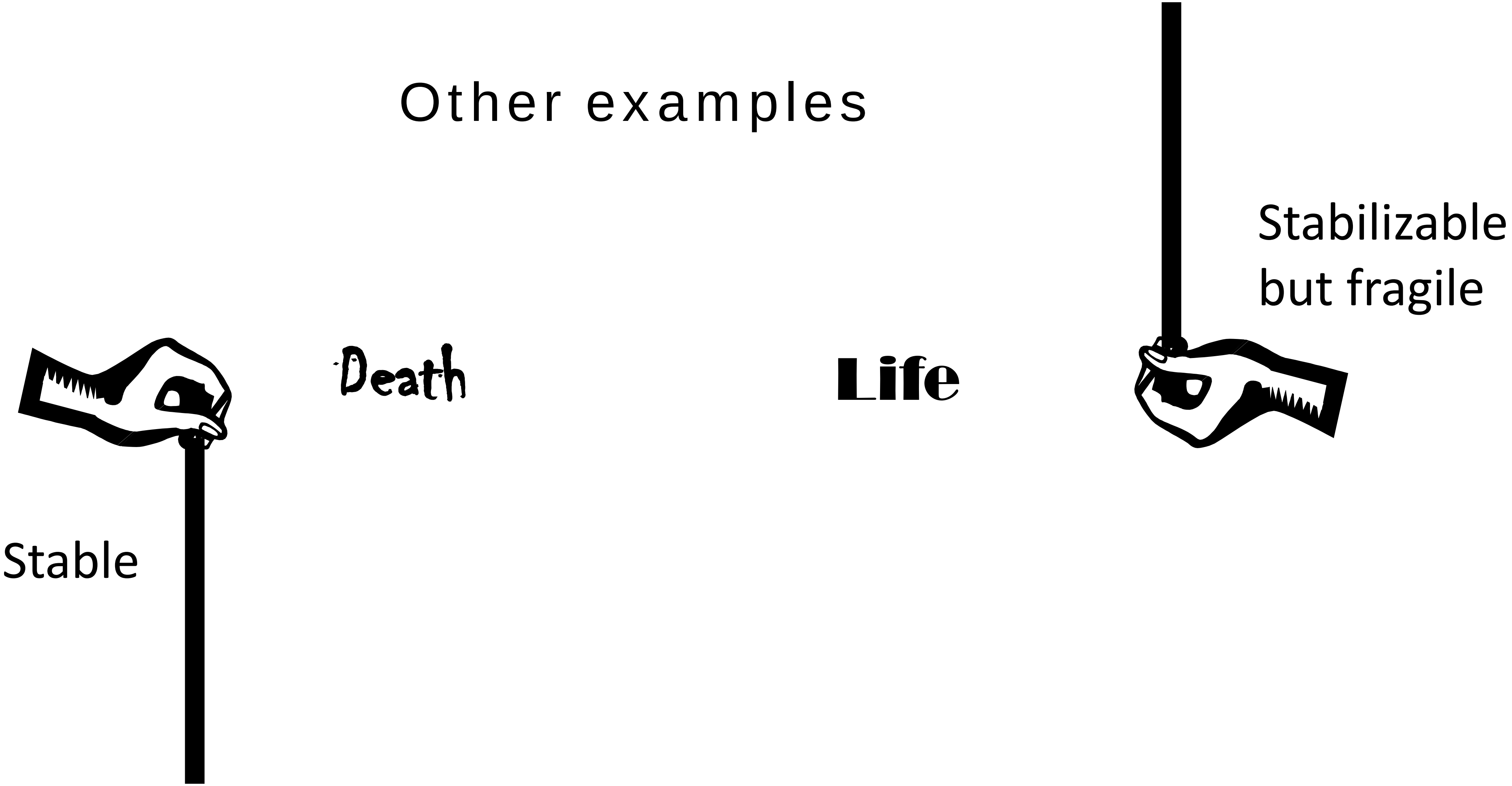
Glycolytic Oscillations and Limits on Robust Efficiency

Fiona A. Chandra,[1]* Gentian Buzi,[2] John C. Doyle[2]

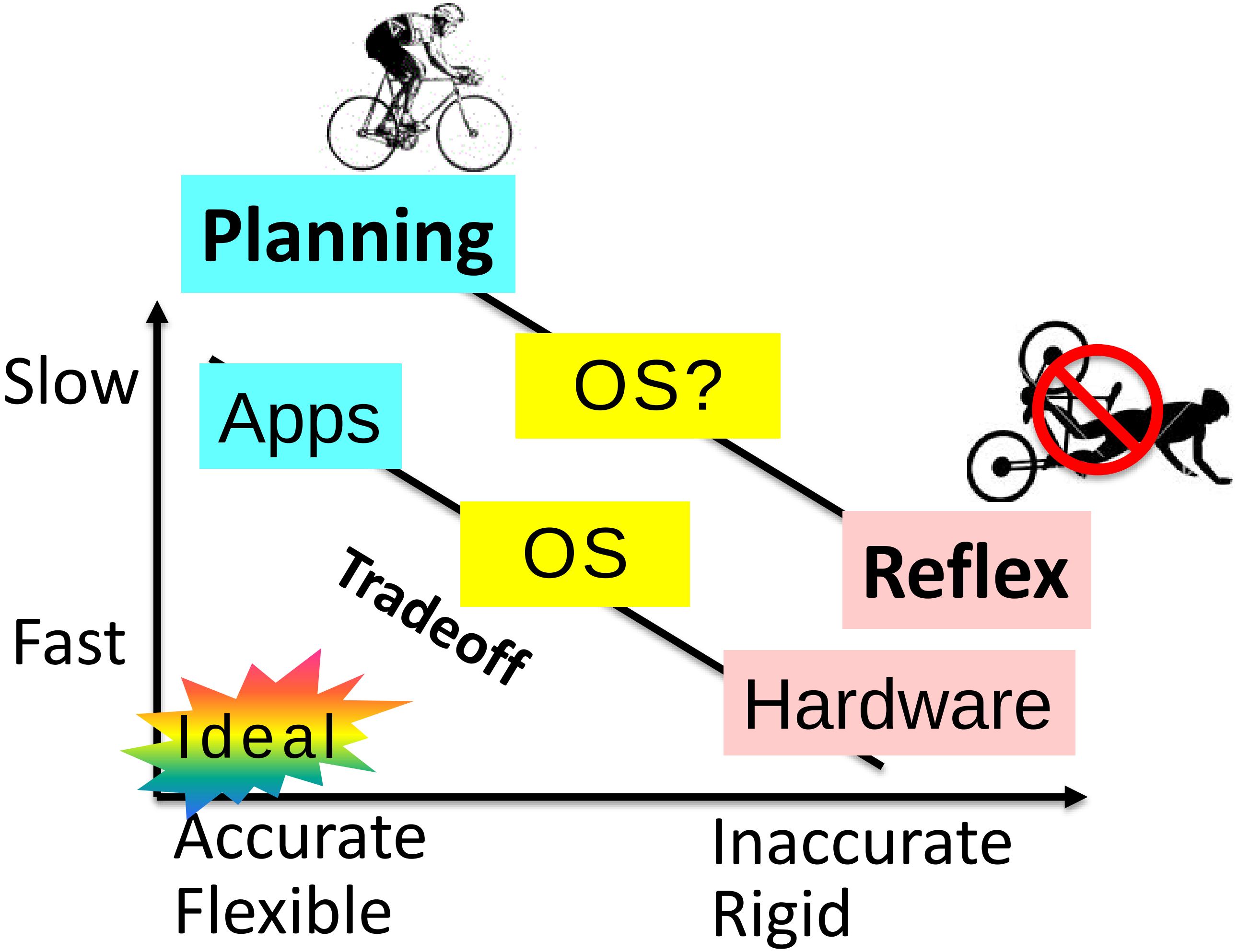
which is consumed in a final reaction modeling
In glycolysis, two ATP
d upstream and four are
hich normalizes to $q = 1$
s two downstream) with
To highlight essential
st possible analysis, we

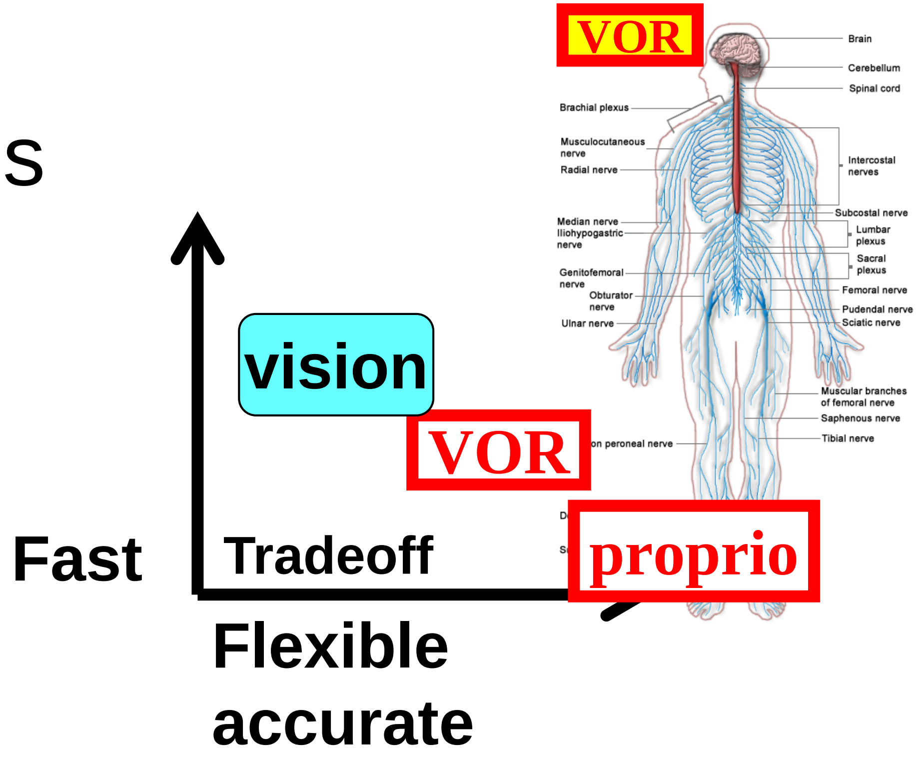

Stable
Stabilizable
but fragile

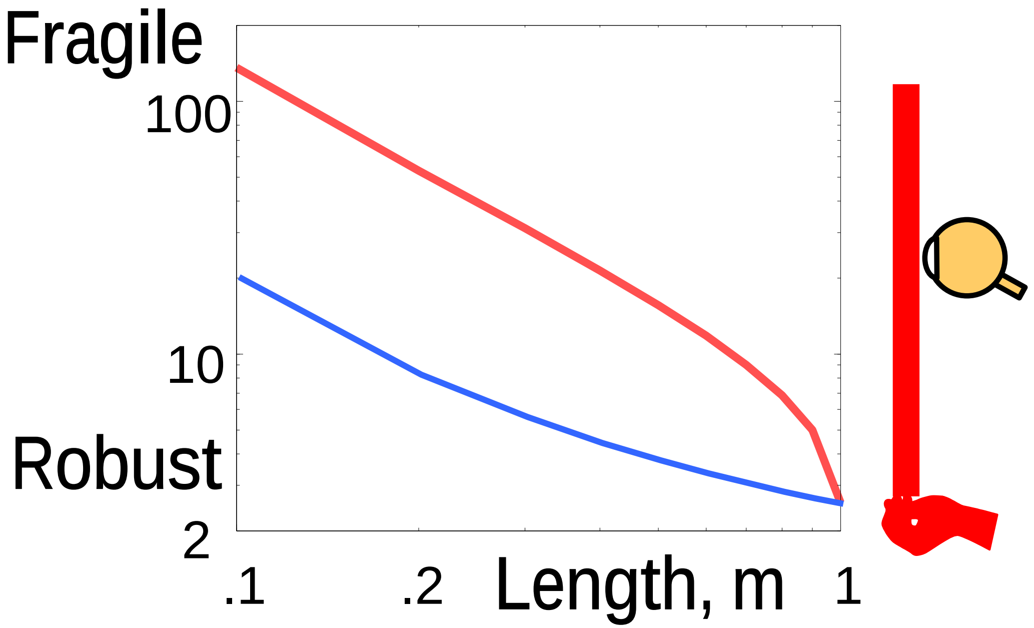
Other examples

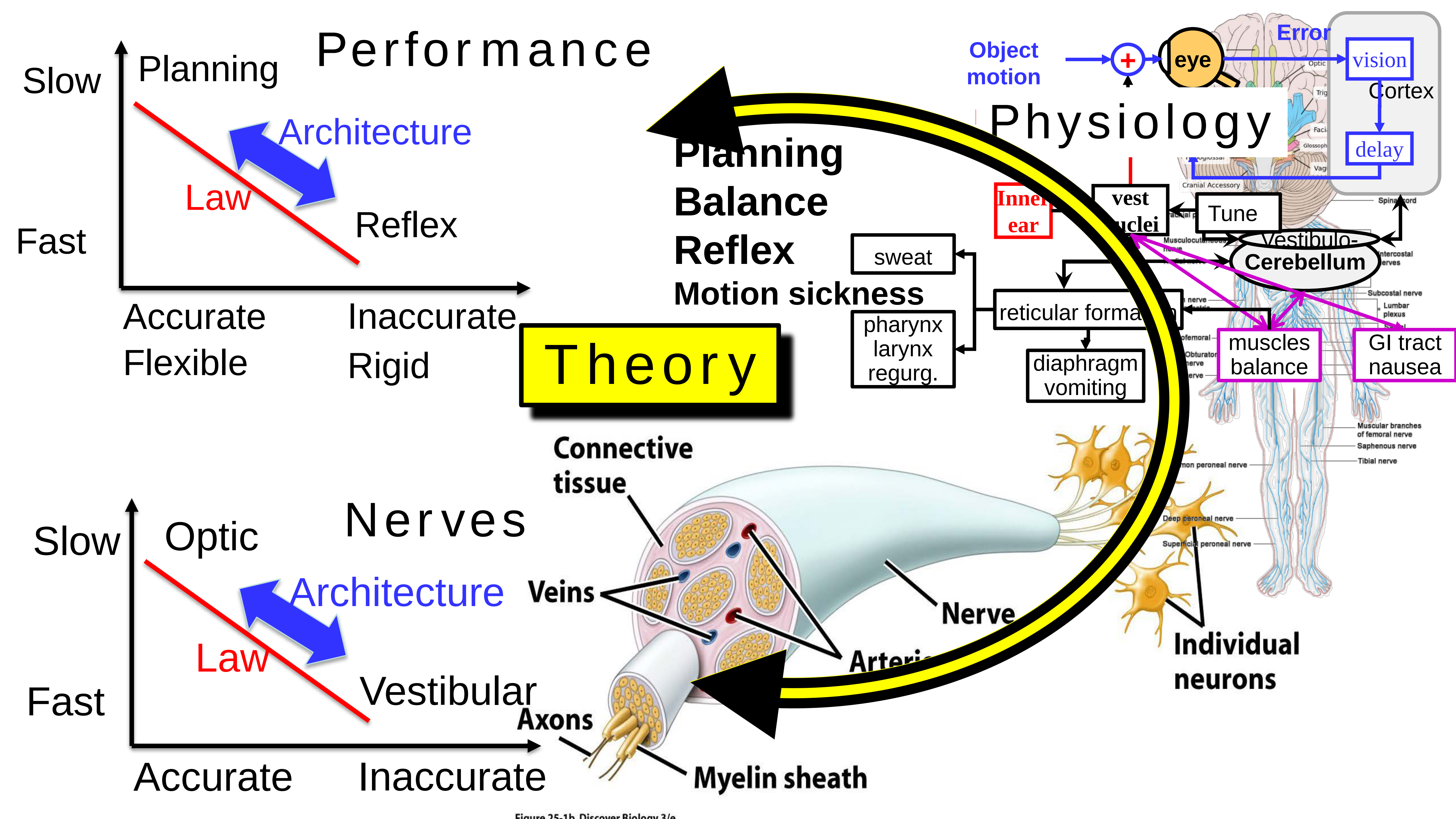


Universal laws and architectures

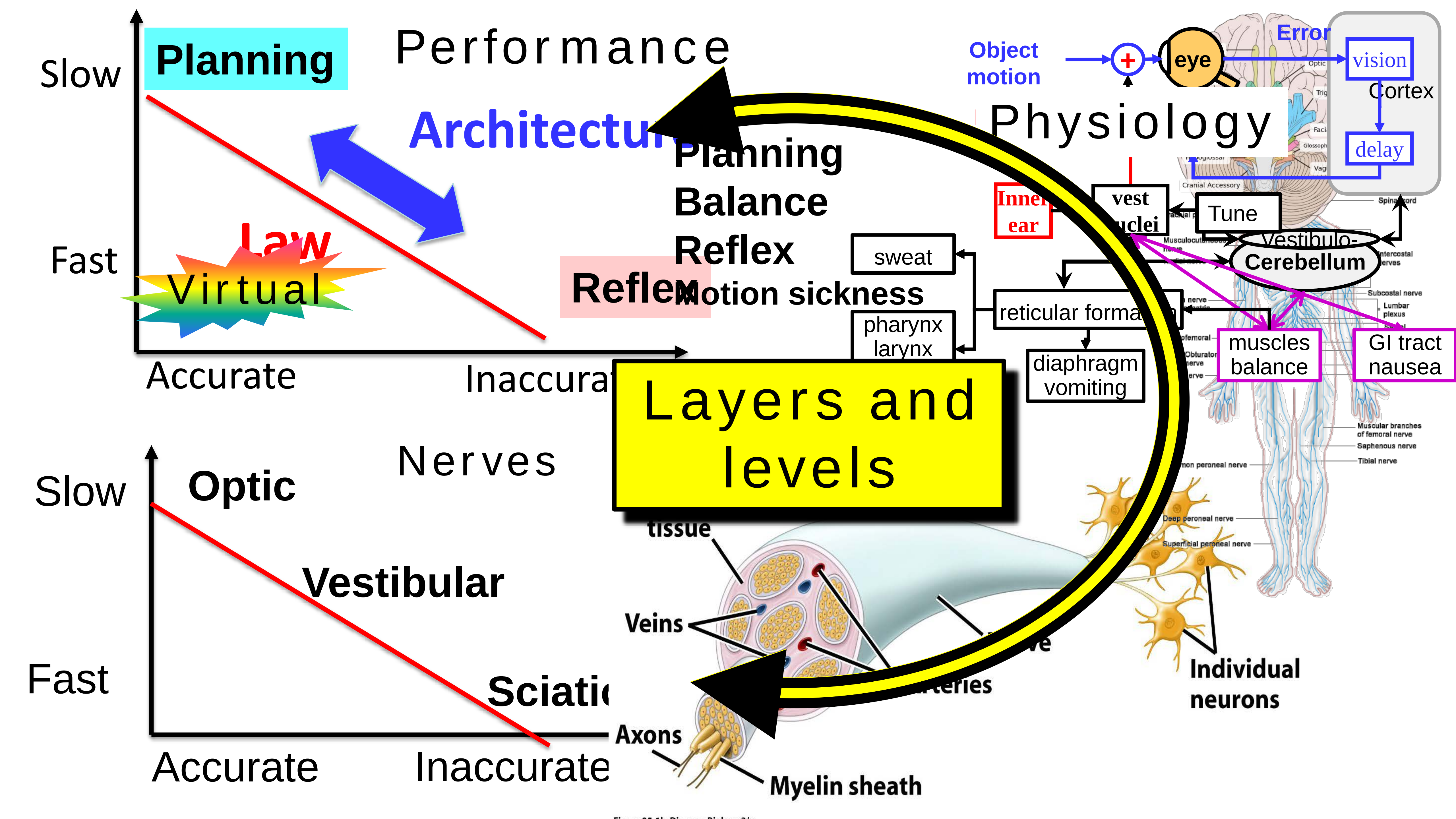








Performance
Slow
Fast
Planning
Architecture
Law
Reflex
Accurate
Flexible
Inaccurate
Rigid
Theory
Planning
Balance
Reflex
Motion sickness
Physiology
Object motion
eye
Error
vision
Cortex
delay
Inner ear
vest nuclei
Tune
Vestibulo-Cerebellum
sweat
pharynx larynx regurg.
reticular formation
diaphragm vomiting
muscles balance
GI tract nausea
Nerves
Slow
Fast
Optic
Architecture
Law
Vestibular
Accurate
Inaccurate
Connective tissue
Veins
Nerve
Arteries
Axons
Myelin sheath
Individual neurons
Figure 25-1b Discover Biology 3/e

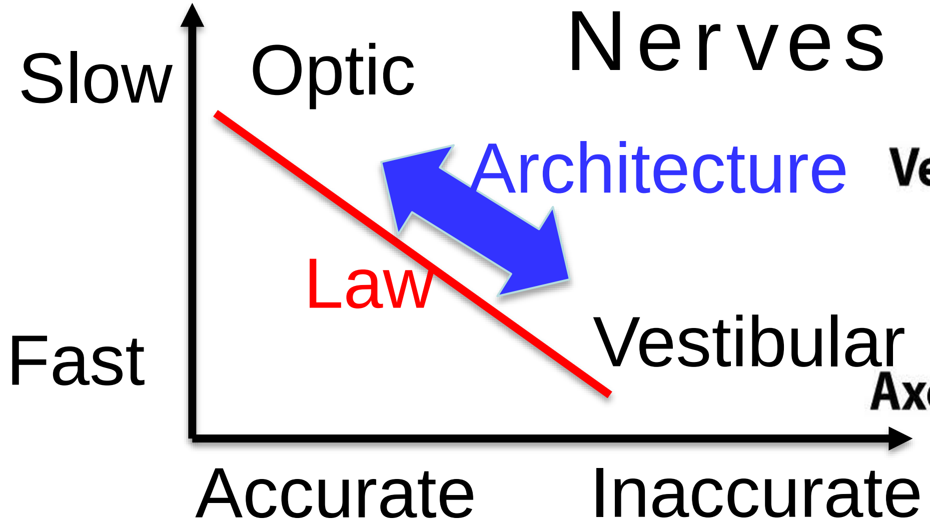


Performance
Slow
Planning
Architecture
Law
Virtual
Fast
Reflex
Accurate
Inaccurate
Planning
Balance
Reflex
Motion sickness
Object motion
Error
eye
vision
Cortex
delay
Physiology
Inner ear
vest nuclei
Tune
Vestibulo-
Cerebellum
sweat
reticular formation
pharynx larynx
diaphragm vomiting
muscles balance
GI tract nausea
Layers and levels
Nerves
Slow
Optic
Vestibular
Fast
Sciatic
Accurate
Inaccurate
Veins
Axons
Myelin sheath
Individual neurons

Physiology

levels

Nerves



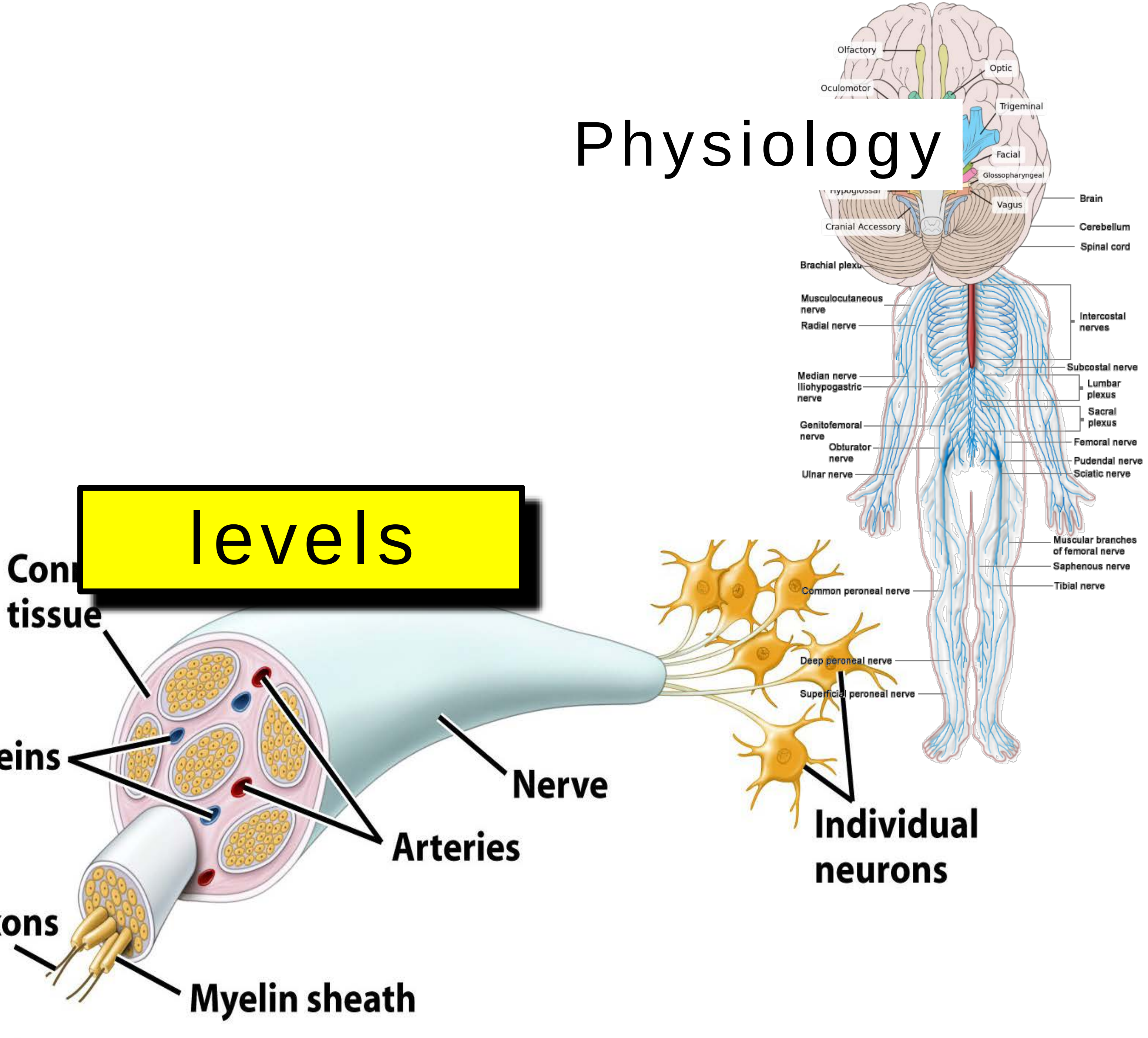


Figure 25-1b Discover Biology 3/e

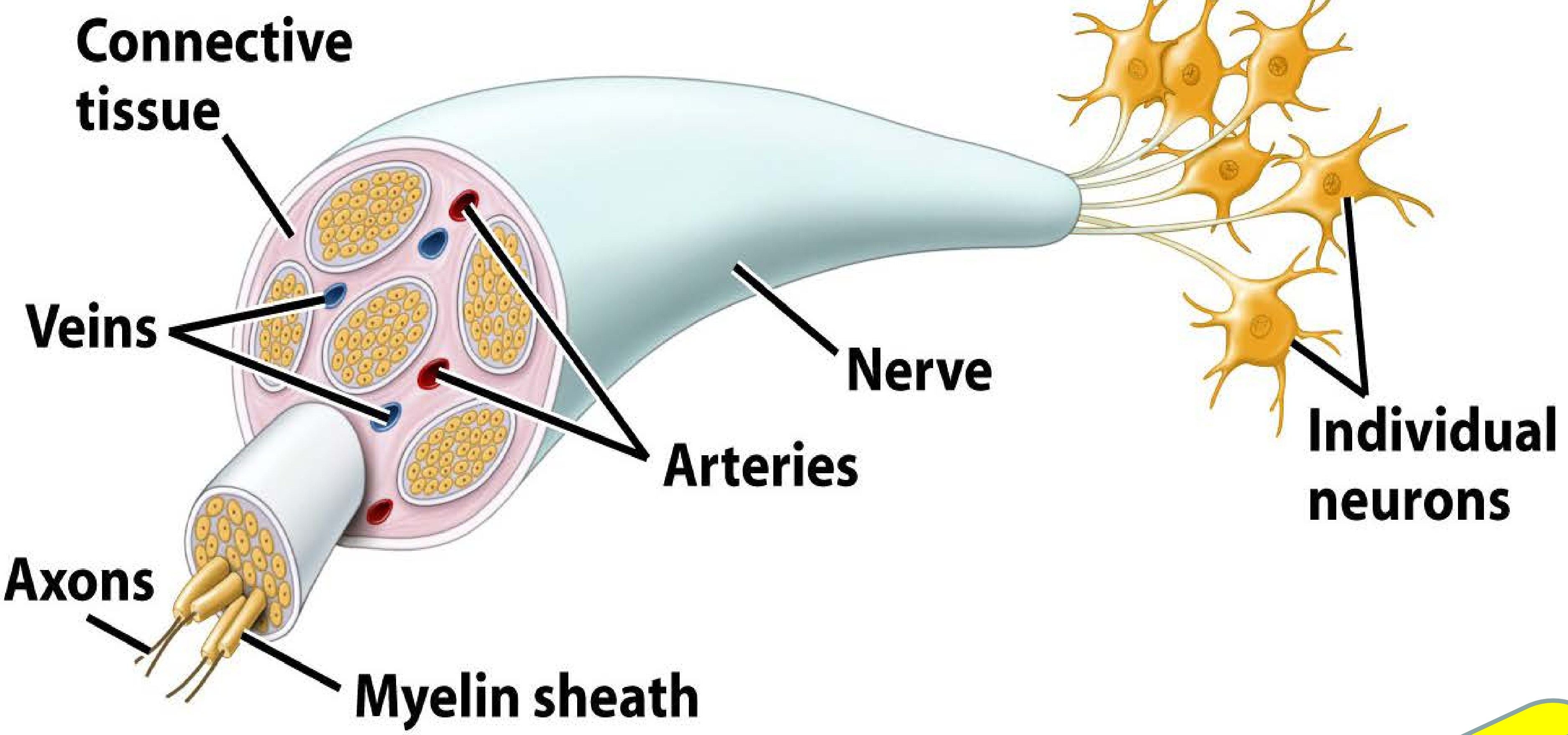
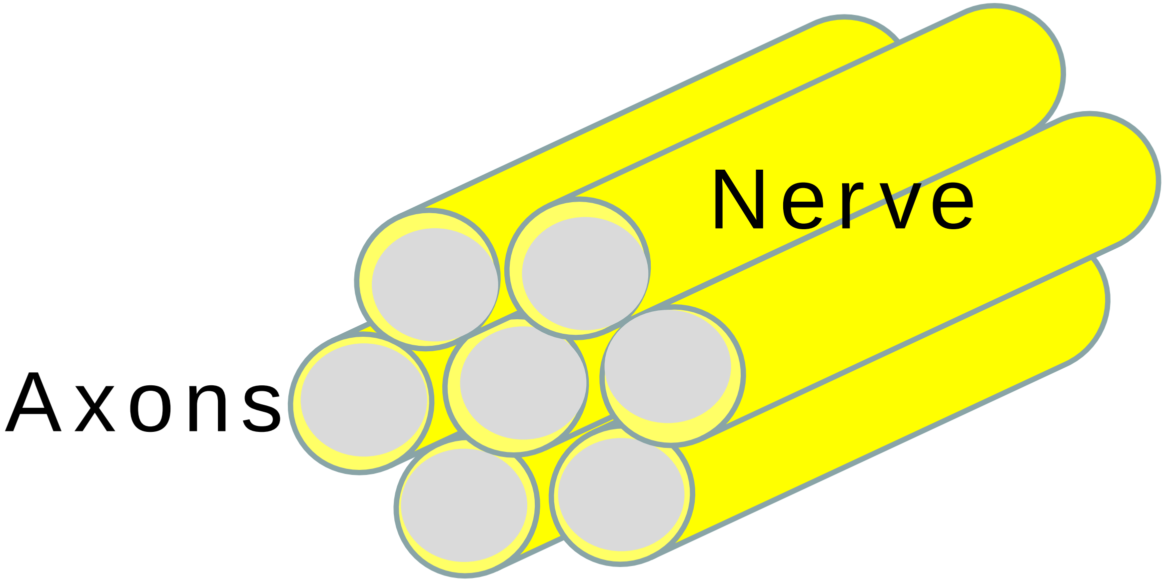


Figure 25-1b Discover Biology 3/e



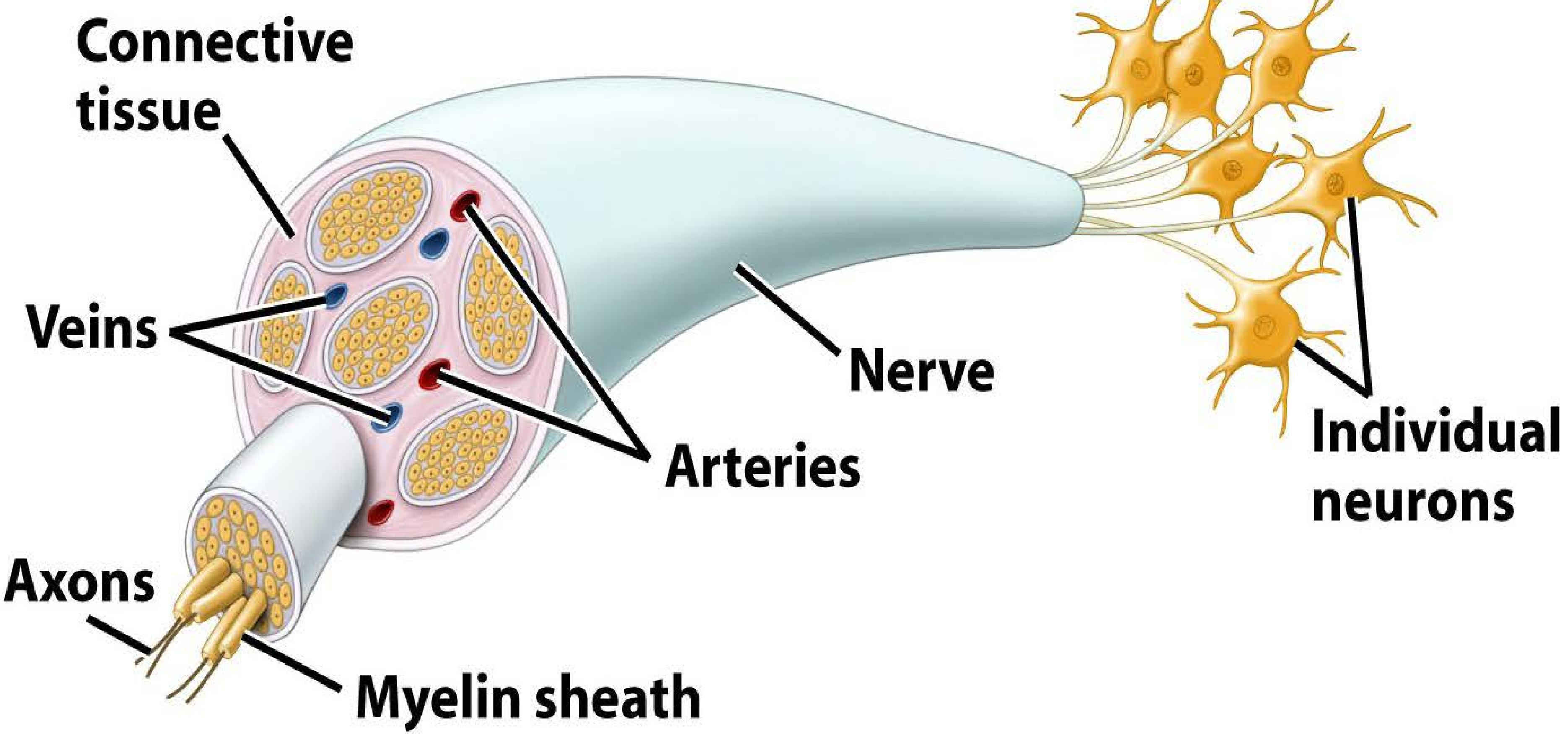
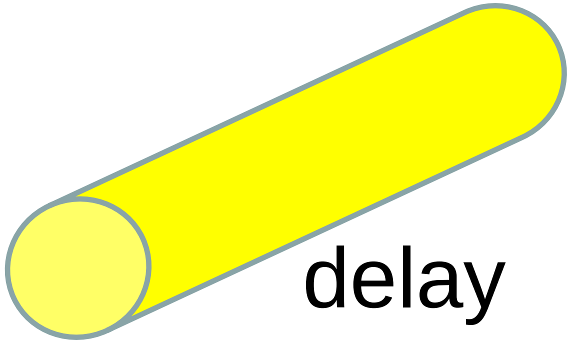


Figure 25-1b Discover Biology 3/e

quantization

Axons



delay

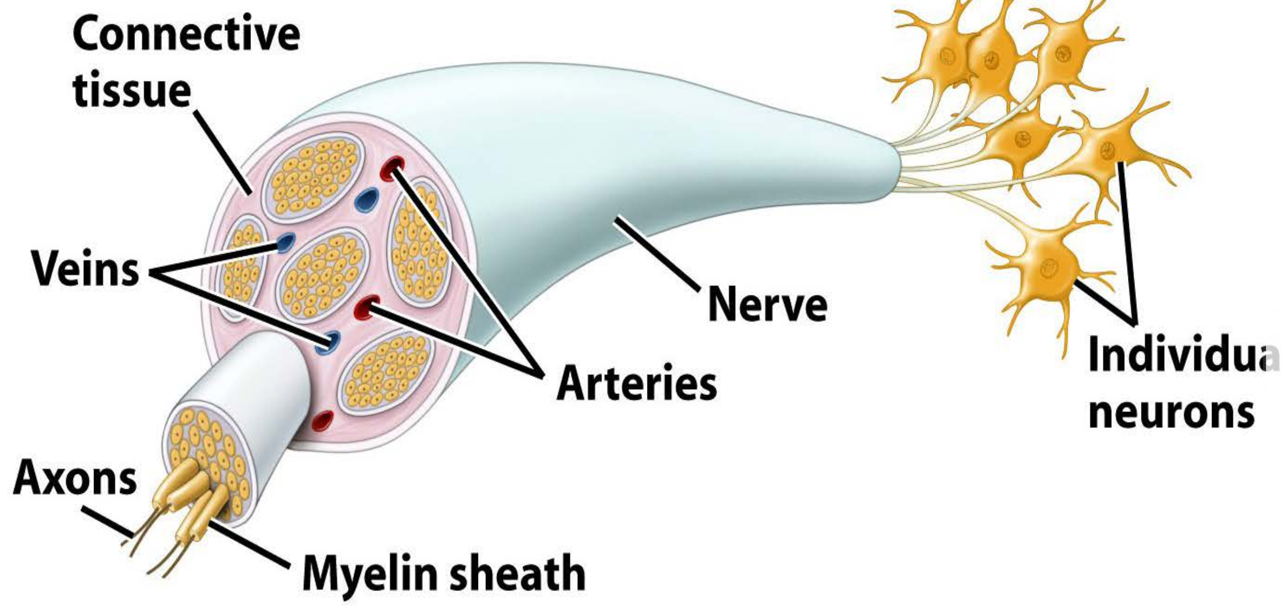
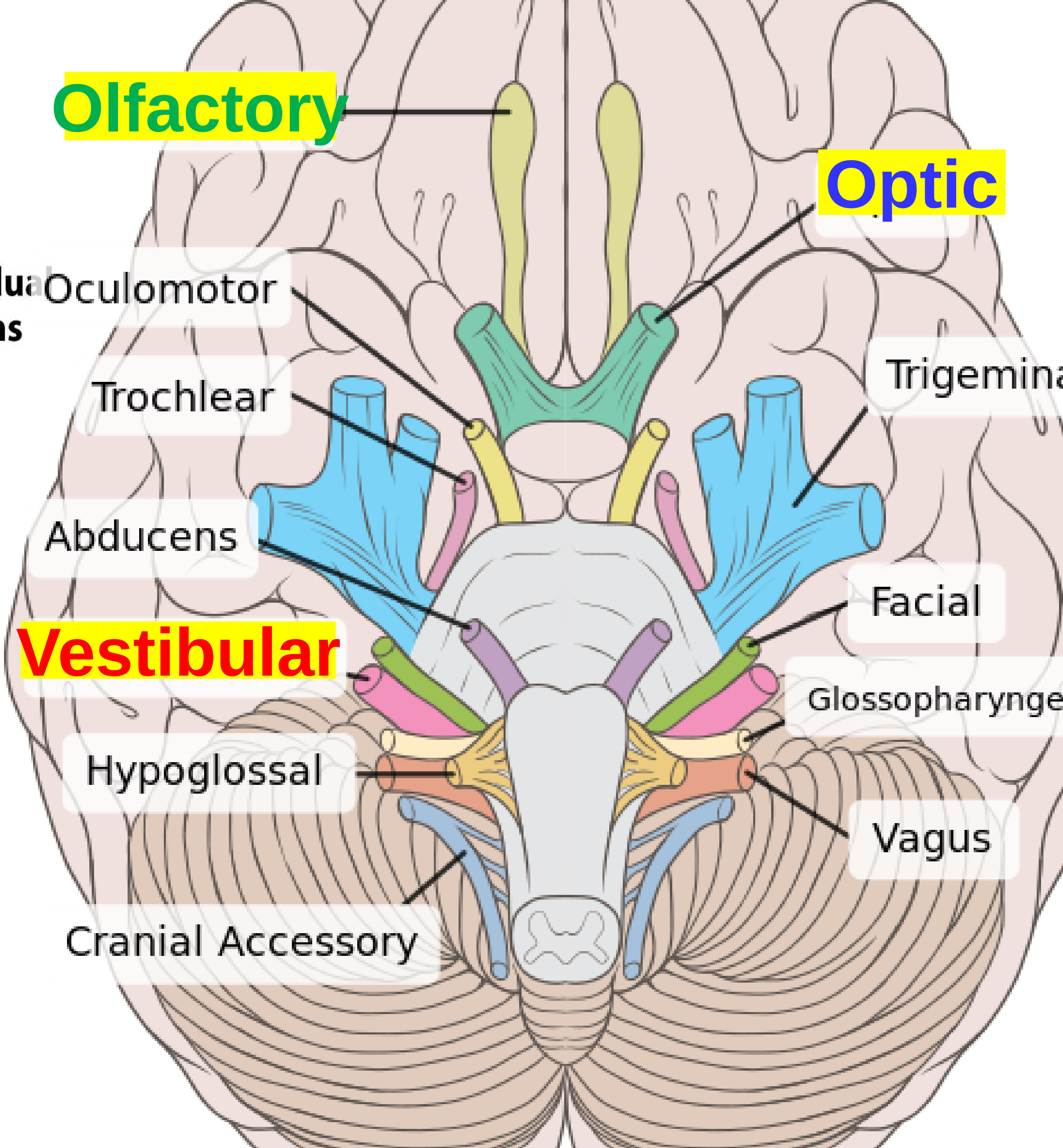
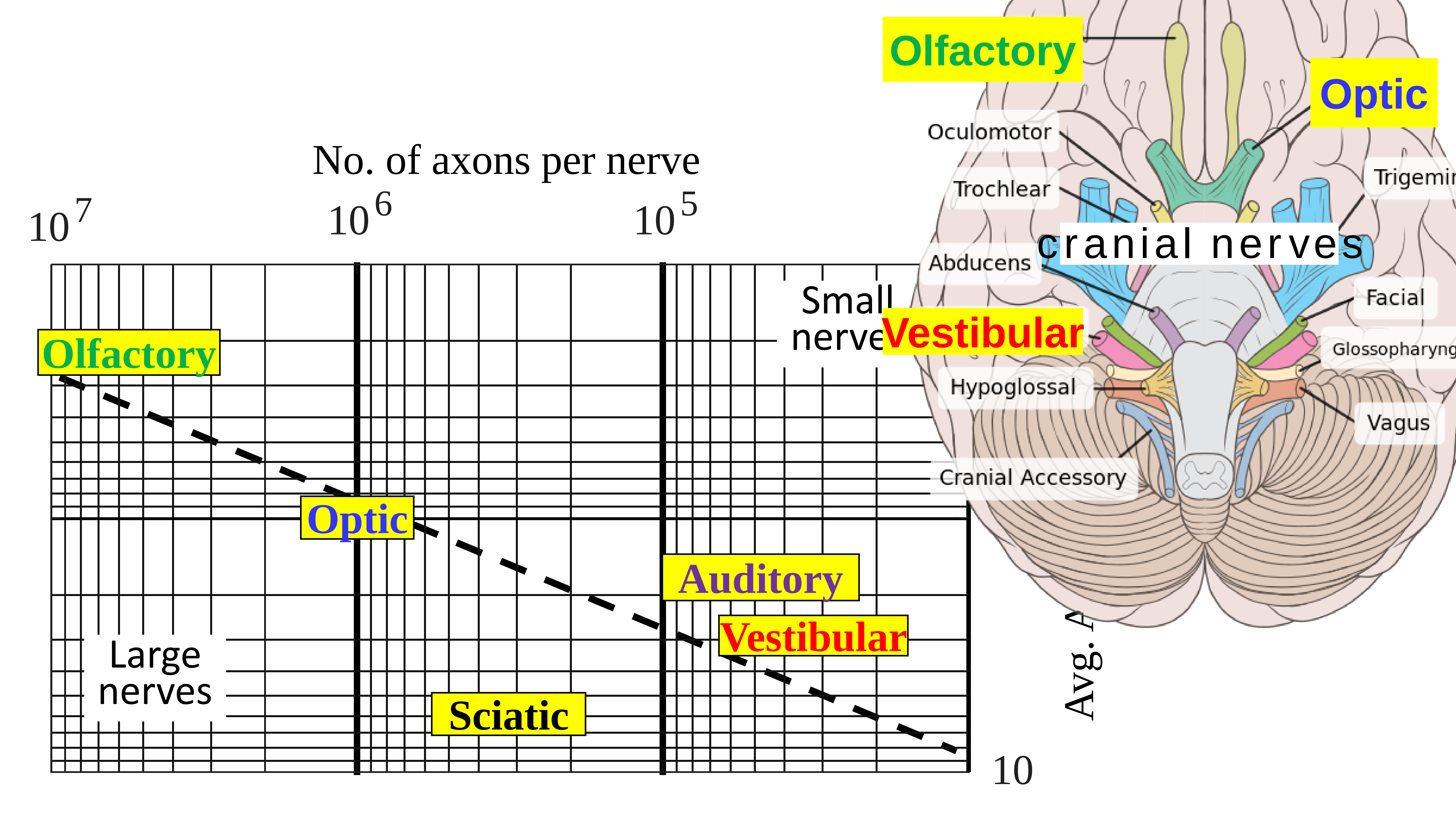


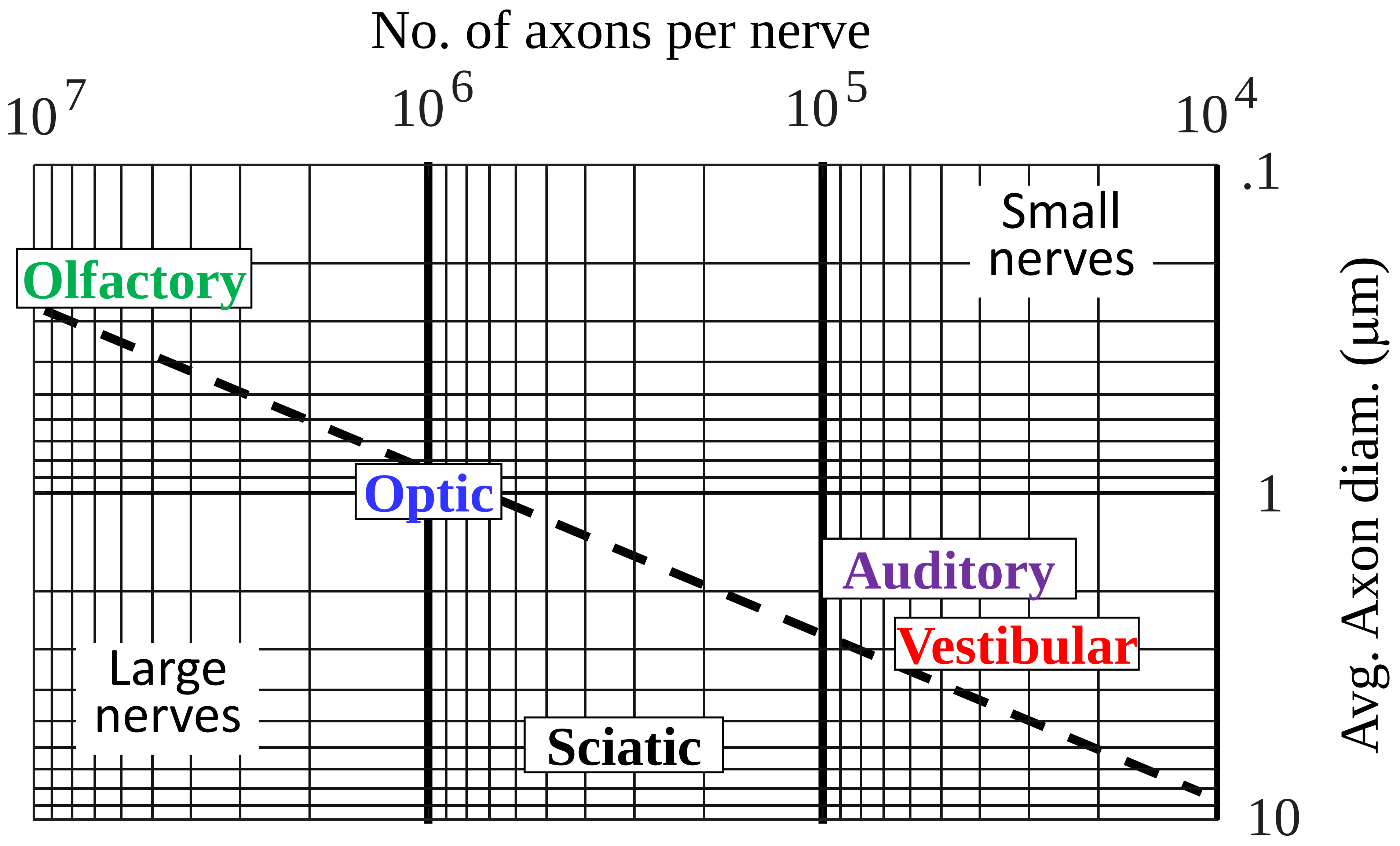
Figure 25-1b Discover Biology 3/e



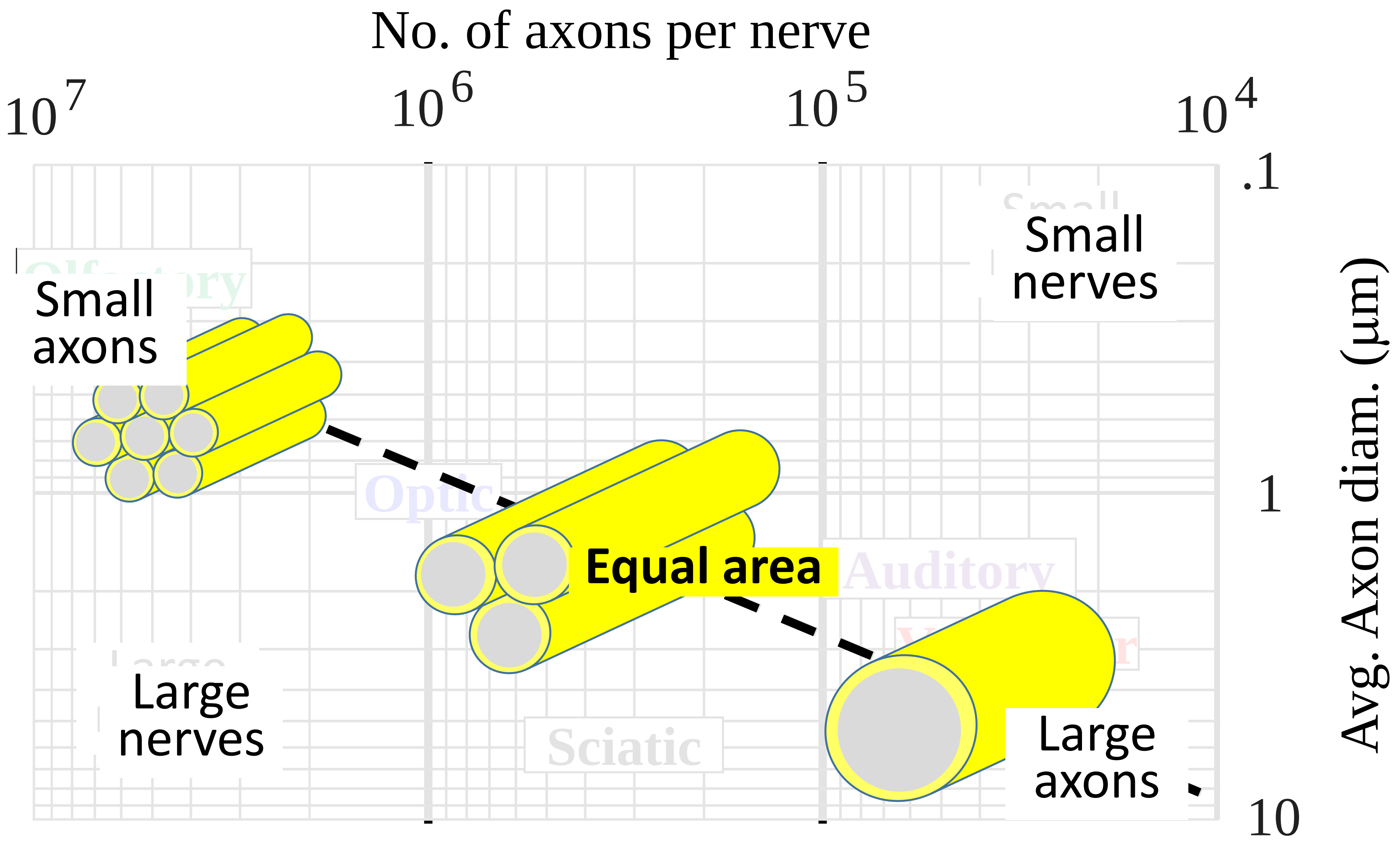
cranial nerves

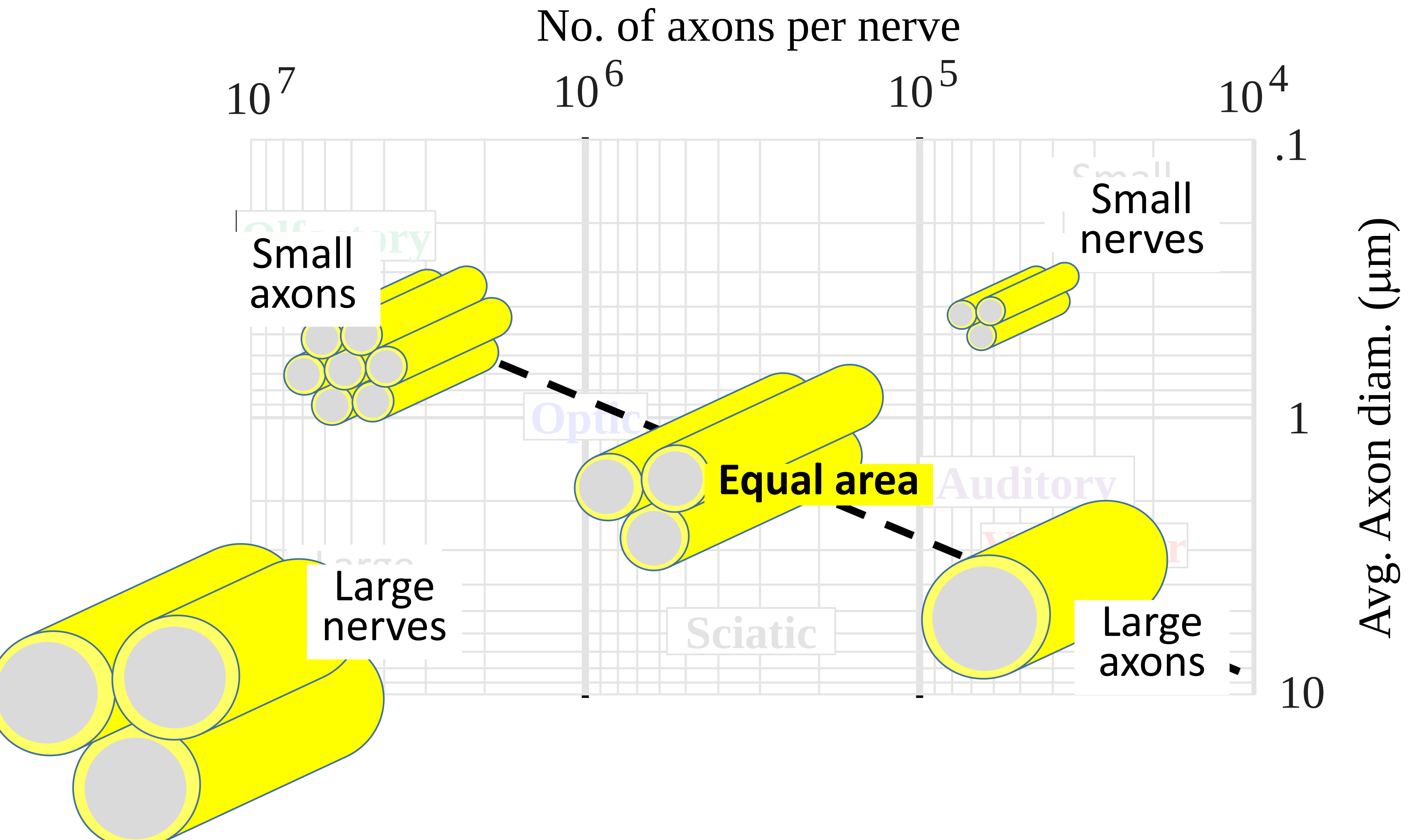
- similar diameters
- diverse lengths
- diverse composition
- bottlenecks?

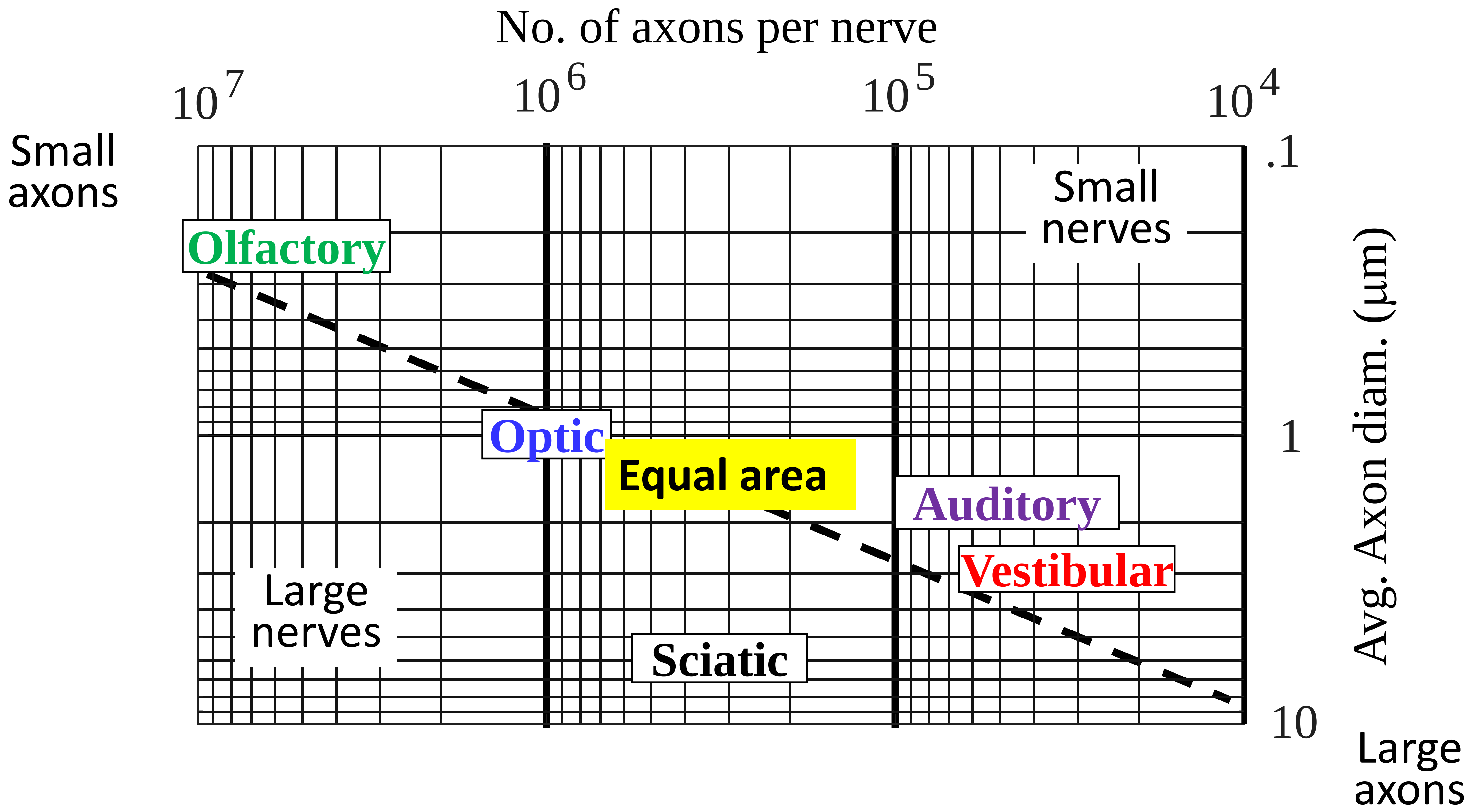

No. of axons per nerve
10 7
10 6
10 5
10
Avg.
Small nerve
Large nerves
Olfactory
Optic
Auditory
Vestibular
Sciatic
cranial nerves
Olfactory
Optic
Oculomotor
Trochlear
Abducens
Vestibular
Hypoglossal
Cranial Accessory
Facial
Vagus

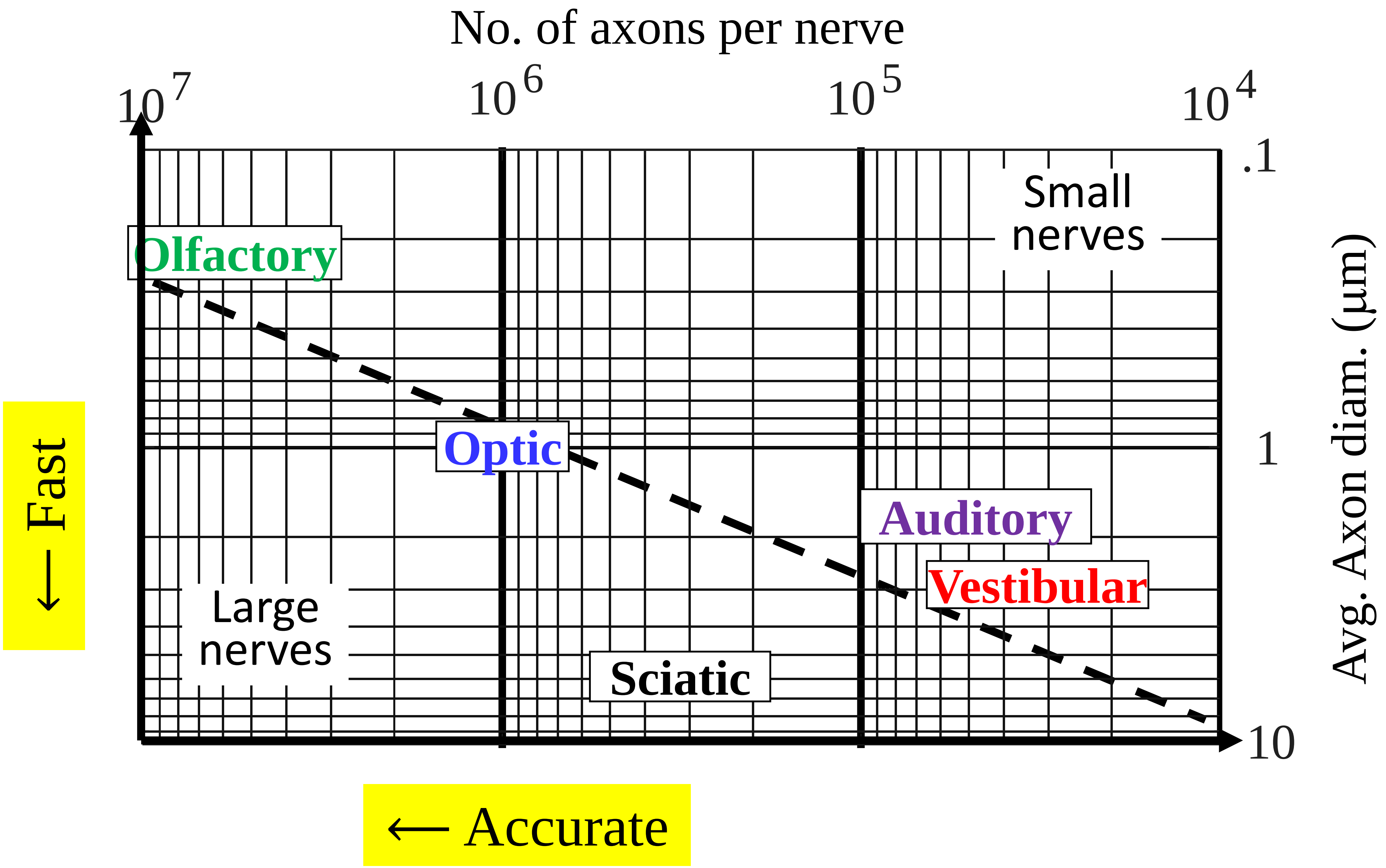


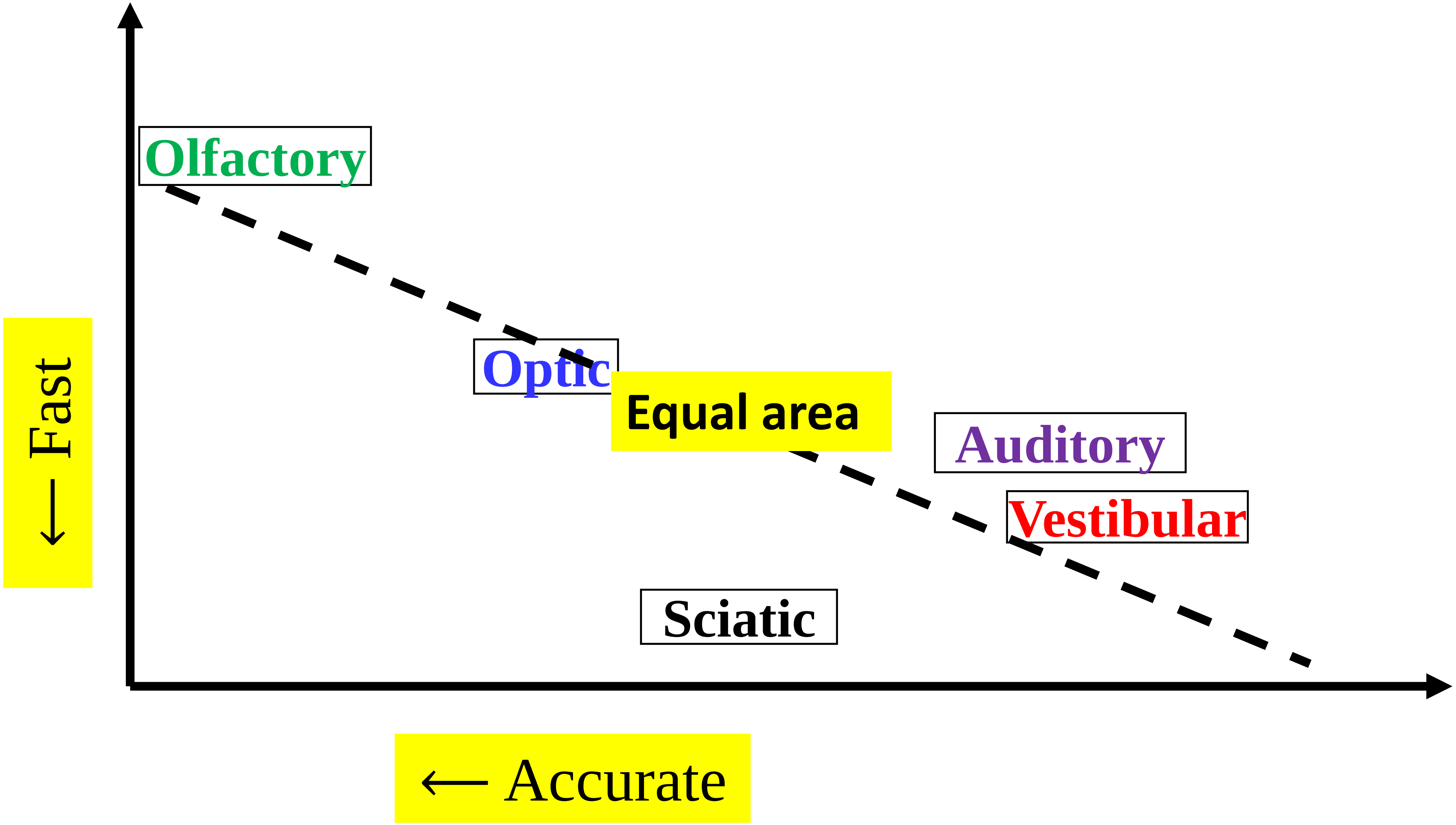
No. of axons per nerve
10 7
10 6
10 5
10 4
.1
1
10
Avg. Axon diam. (μm)
Small
nerves
Olfactory
Optic
Auditory
Vestibular
Large
nerves
Sciatic


No. of axons per nerve
10^7
10^6
10^5
10^4
.1
1
10
Avg. Axon diam. (μm)
Small axons
Small nerves
Optic
Equal area
Auditory
Large nerves
Sciatic
Large axons

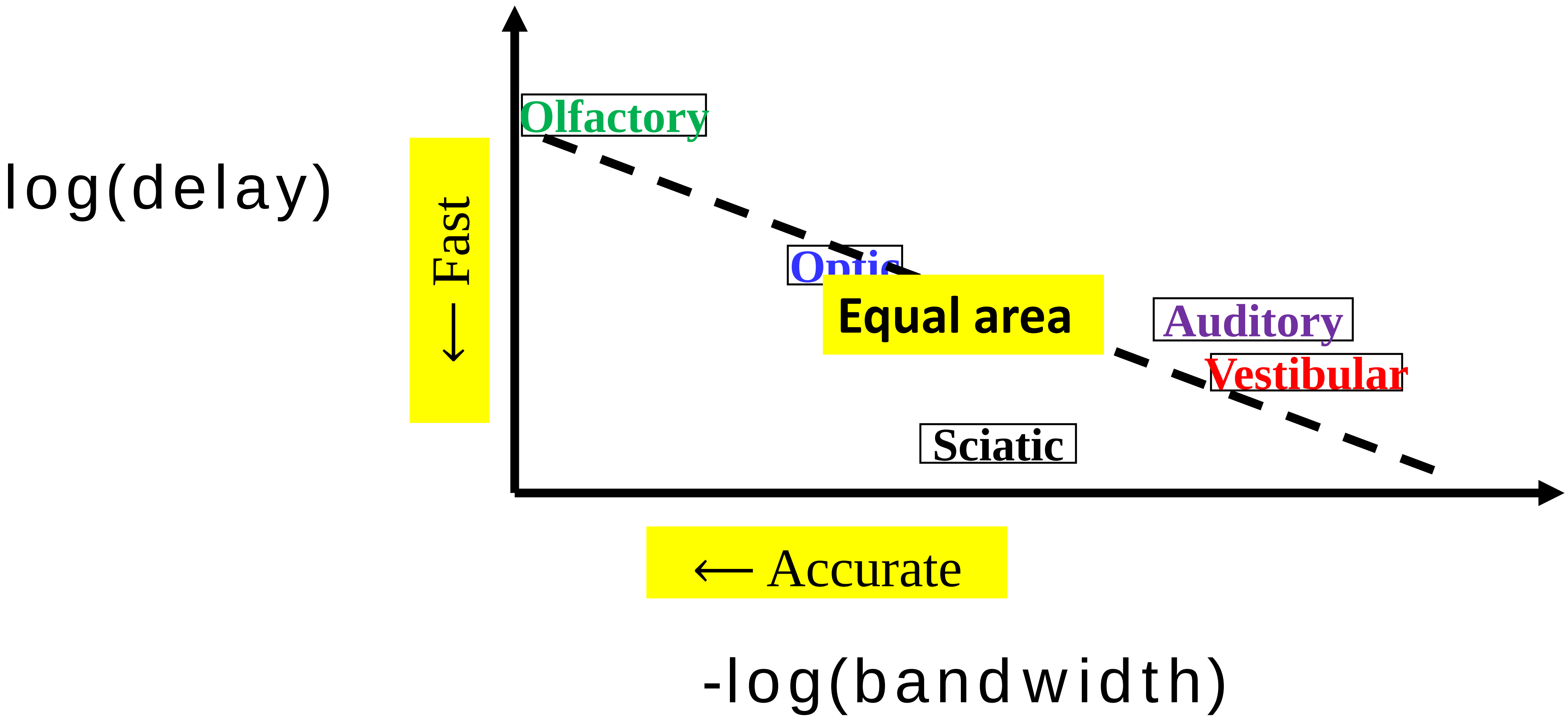

No. of axons per nerve
10^7
10^6
10^5
10^4
.1
1
10
Avg. Axon diam. (µm)
Small axons
Small nerves
Optic
Equal area
Auditory
Large nerves
Sciatic
Large axons


No. of axons per nerve
10^7
10^6
10^5
10^4
Small axons
Large axons
.1
1
10
Avg. Axon diam. (μm)
Small nerves
Large nerves
Olfactory
Optic
Equal area
Auditory
Vestibular
Sciatic


No. of axons per nerve
10^7
10^6
10^5
10^4
.1
1
10
Avg. Axon diam. (µm)
Small nerves
Olfactory
Optic
Auditory
Vestibular
Sciatic
Large nerves
← Fast
← Accurate

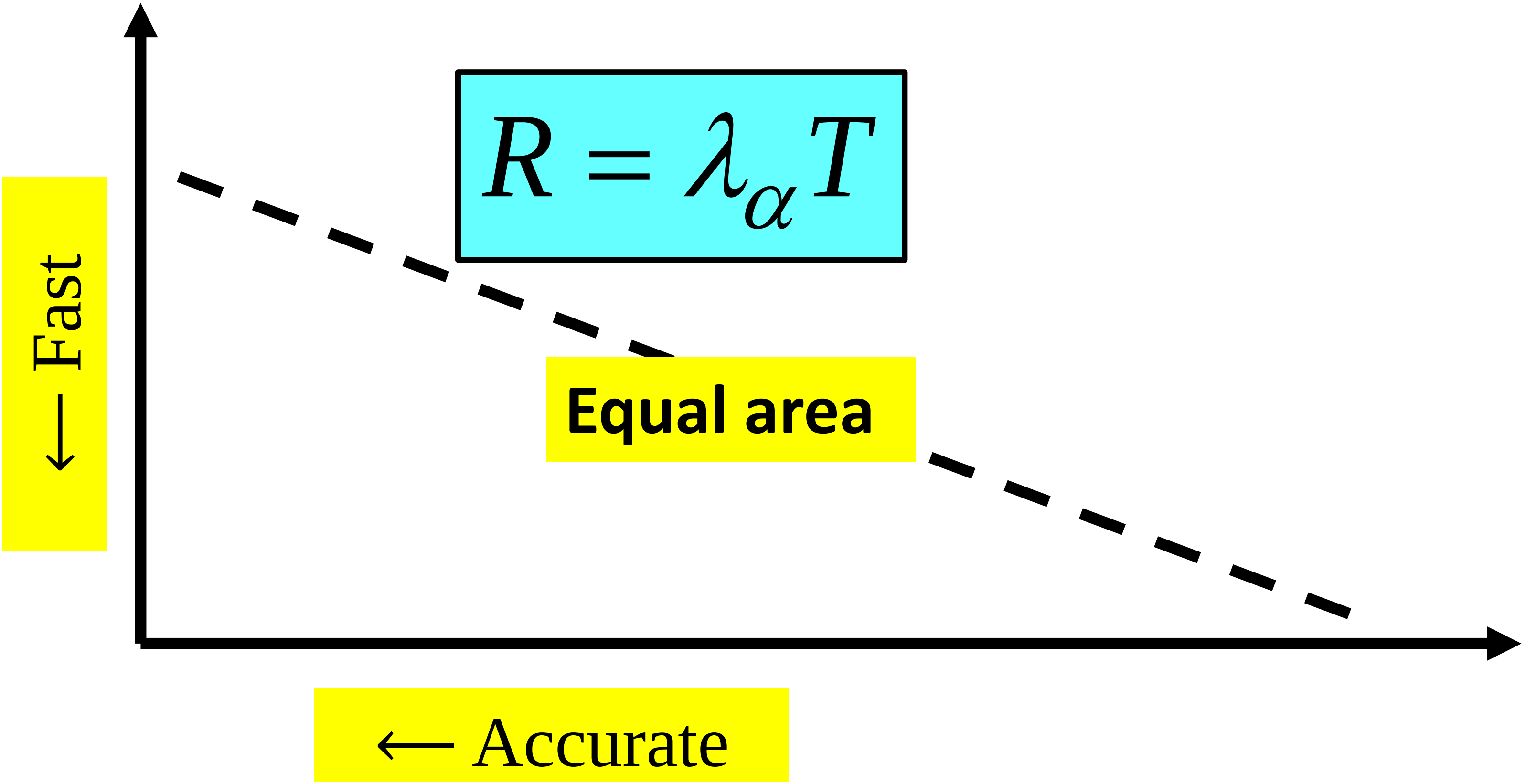


Olfactory
Optic
Equal area
Auditory
Vestibular
Sciatic
← Fast
← Accurate


log(delay)
← Fast
Olfactory
Optic
Equal area
Auditory
Vestibular
Sciatic
← Accurate
-log(bandwidth)

$\log(T)$

log(delay)



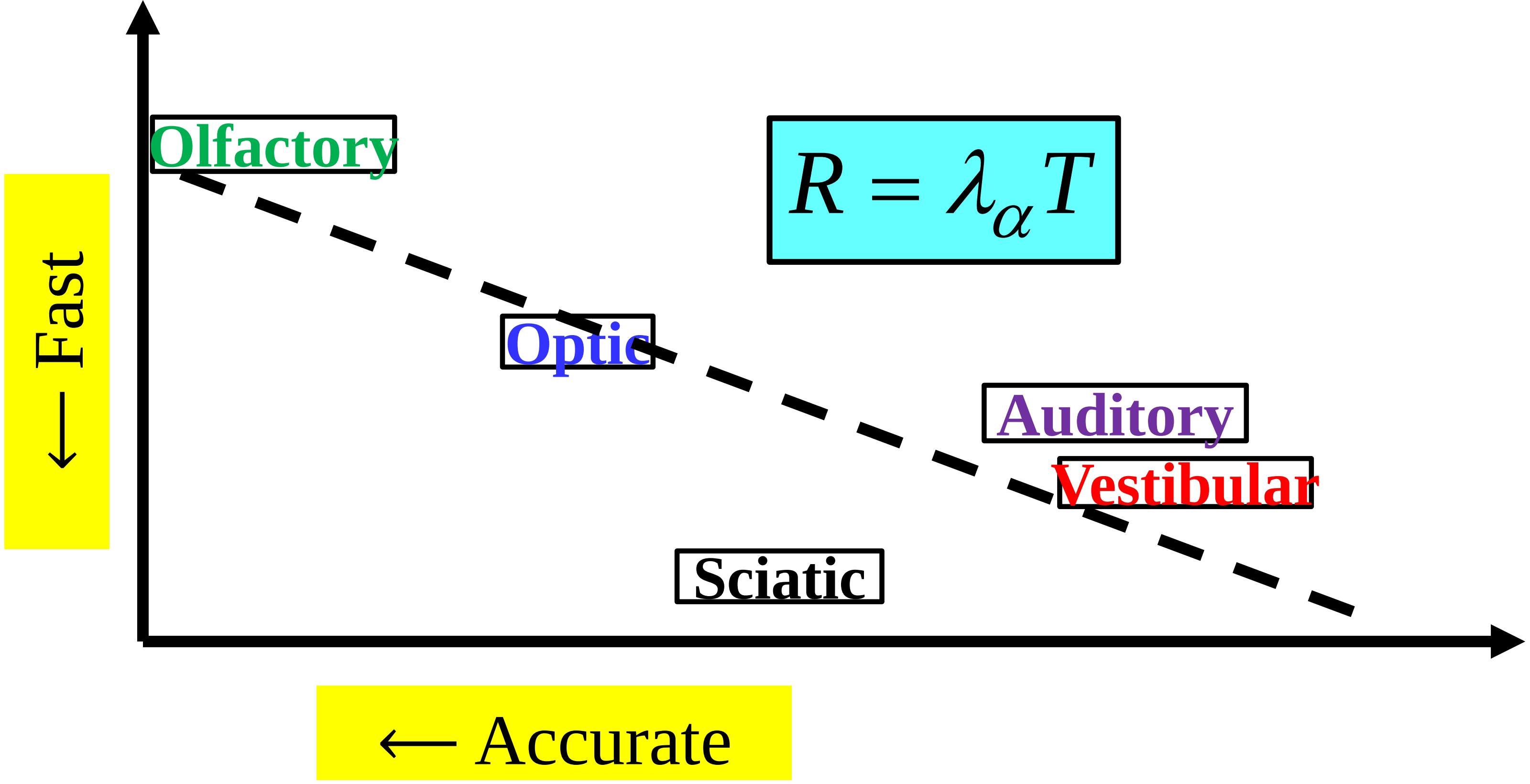
$-\log(R)$

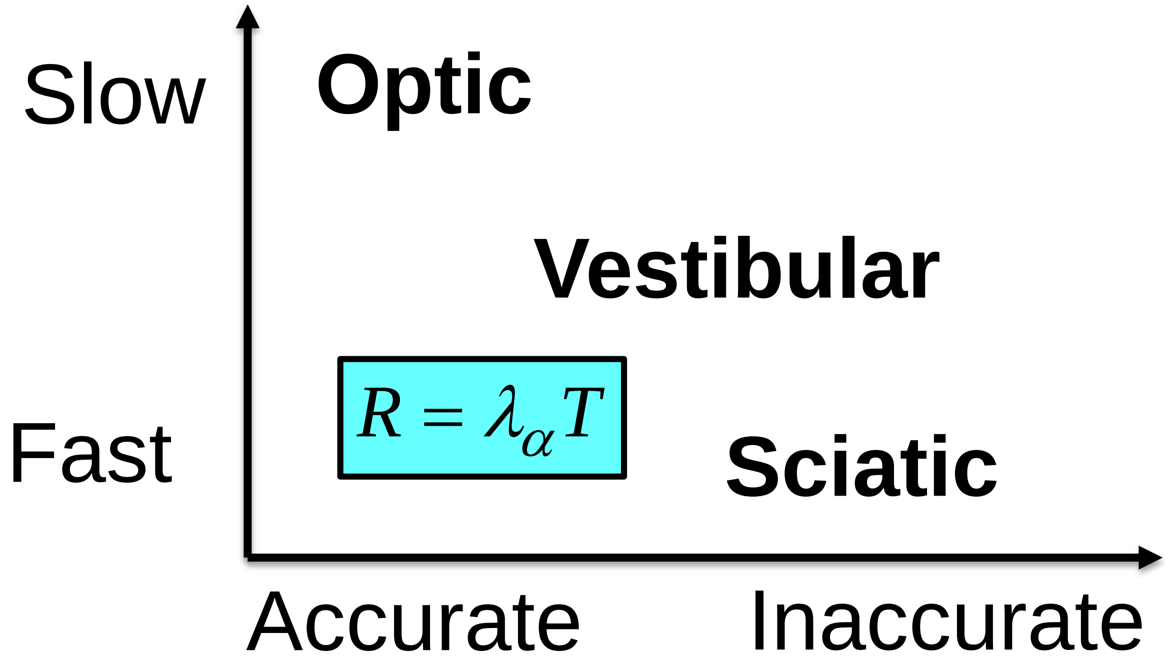
-log(bandwidth)

$$\lambda_\alpha \propto area$$

Simon Laughlin
Terry Sejnowski

Speed vs Accuracy





Nerves

Physiology

Why?

Extremely Diverse

Nerves

Slow

Fast

Optic

Vestibular

Sciatic

$$R = \lambda_{\alpha} T$$

Accurate Inaccurate

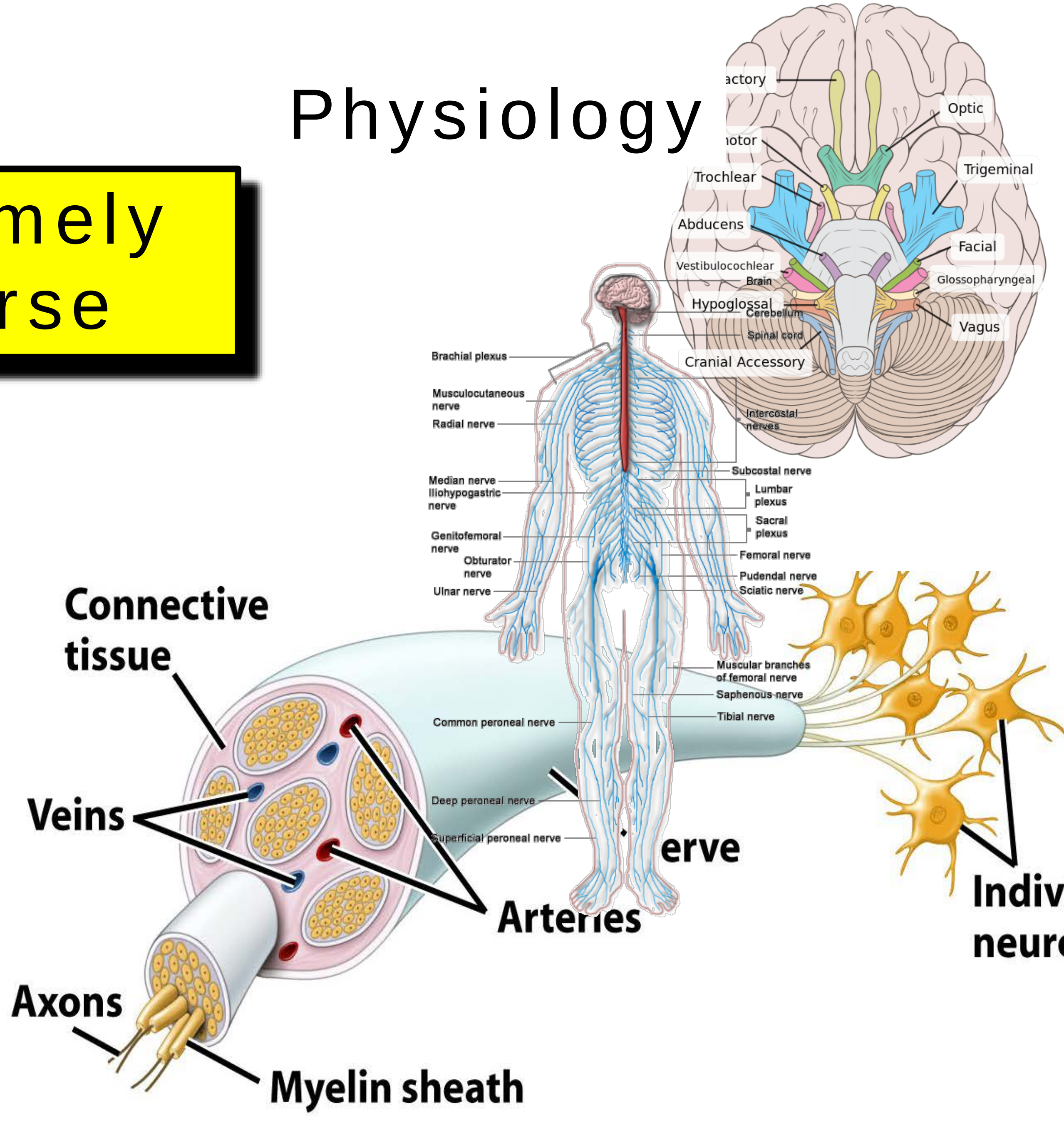
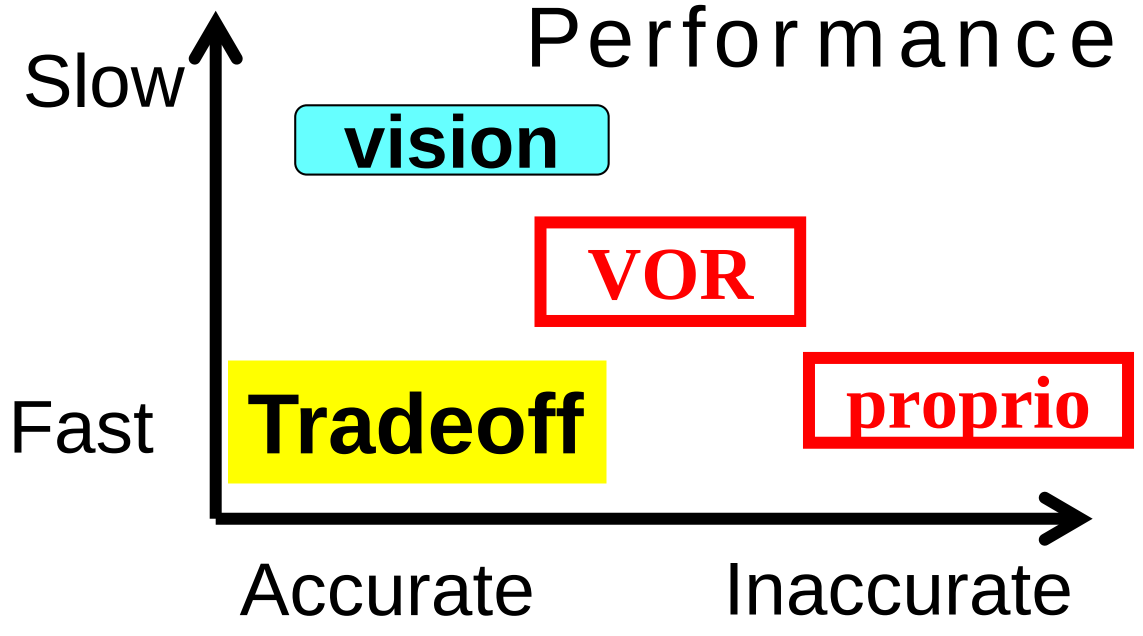
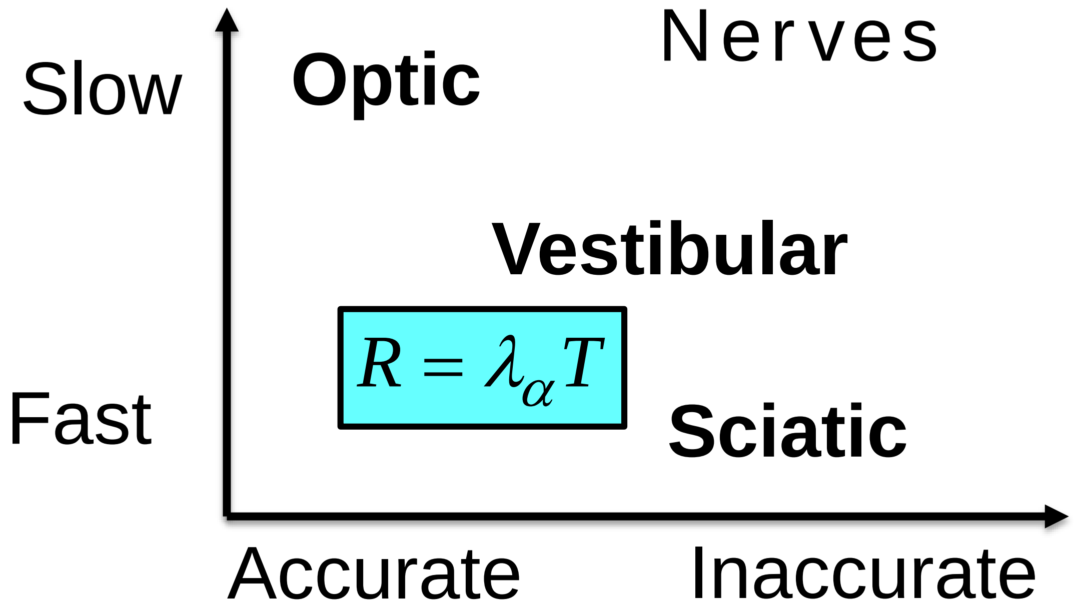


Figure 25-1b Discover Biology 3/e





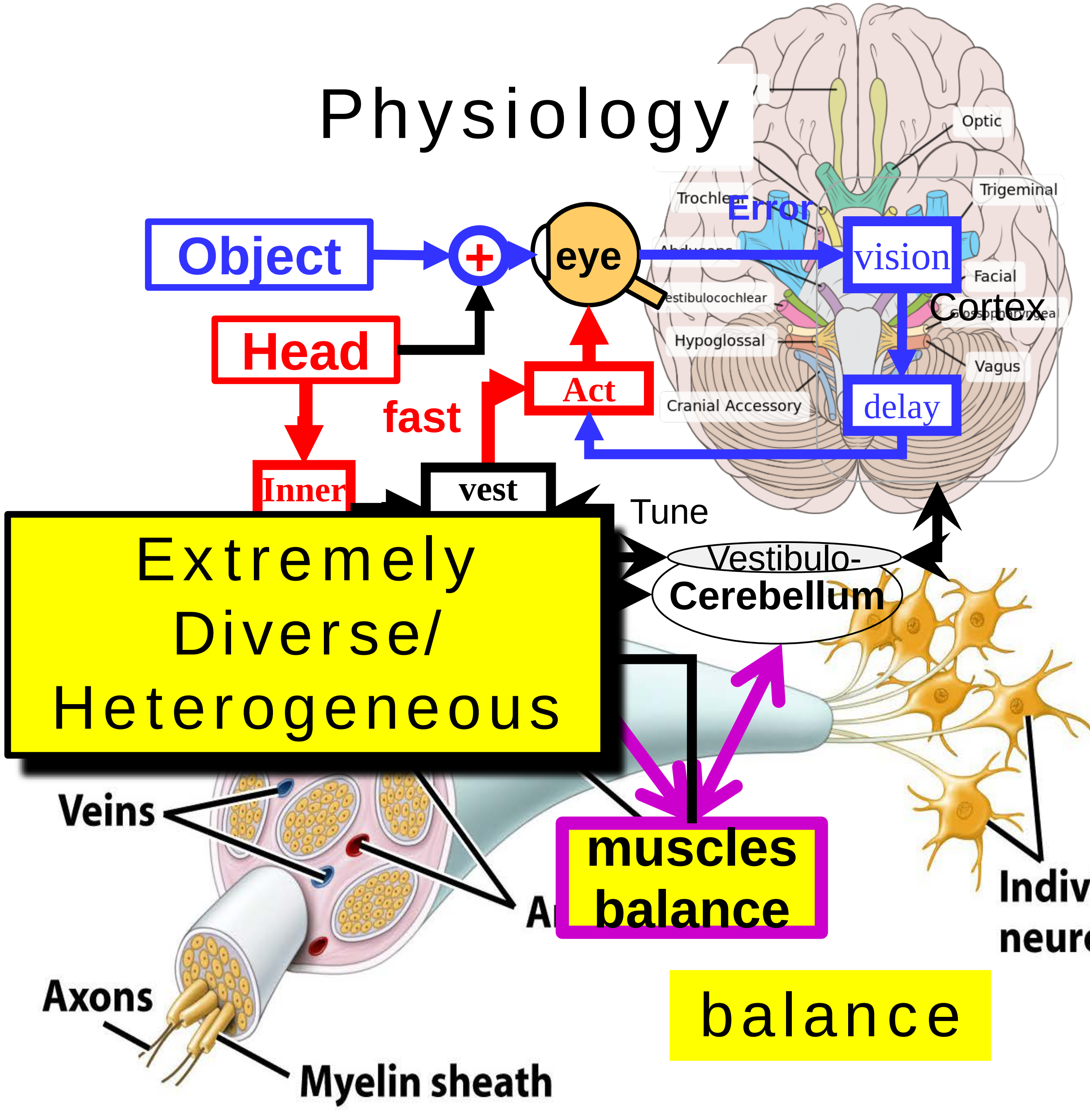
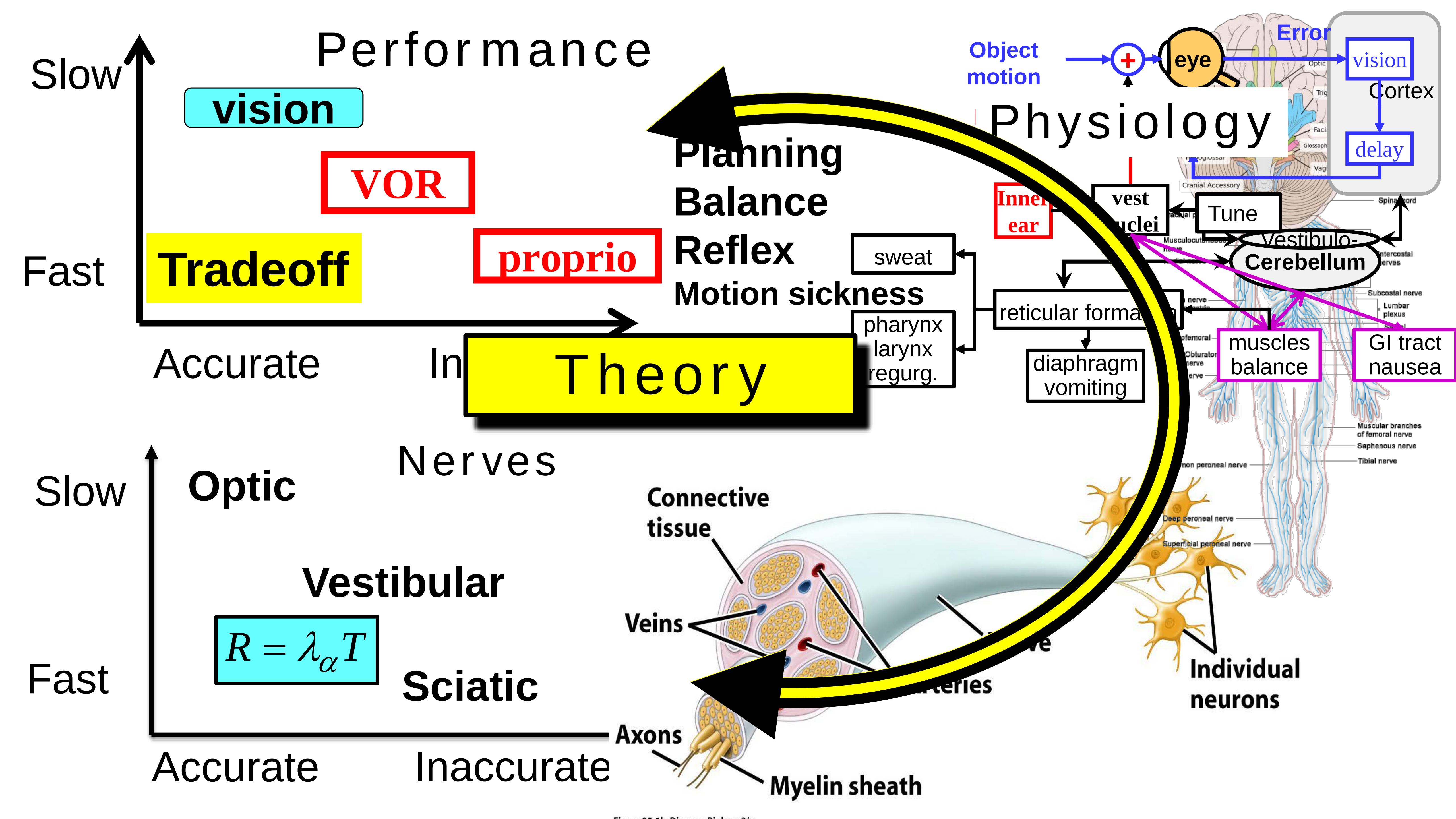
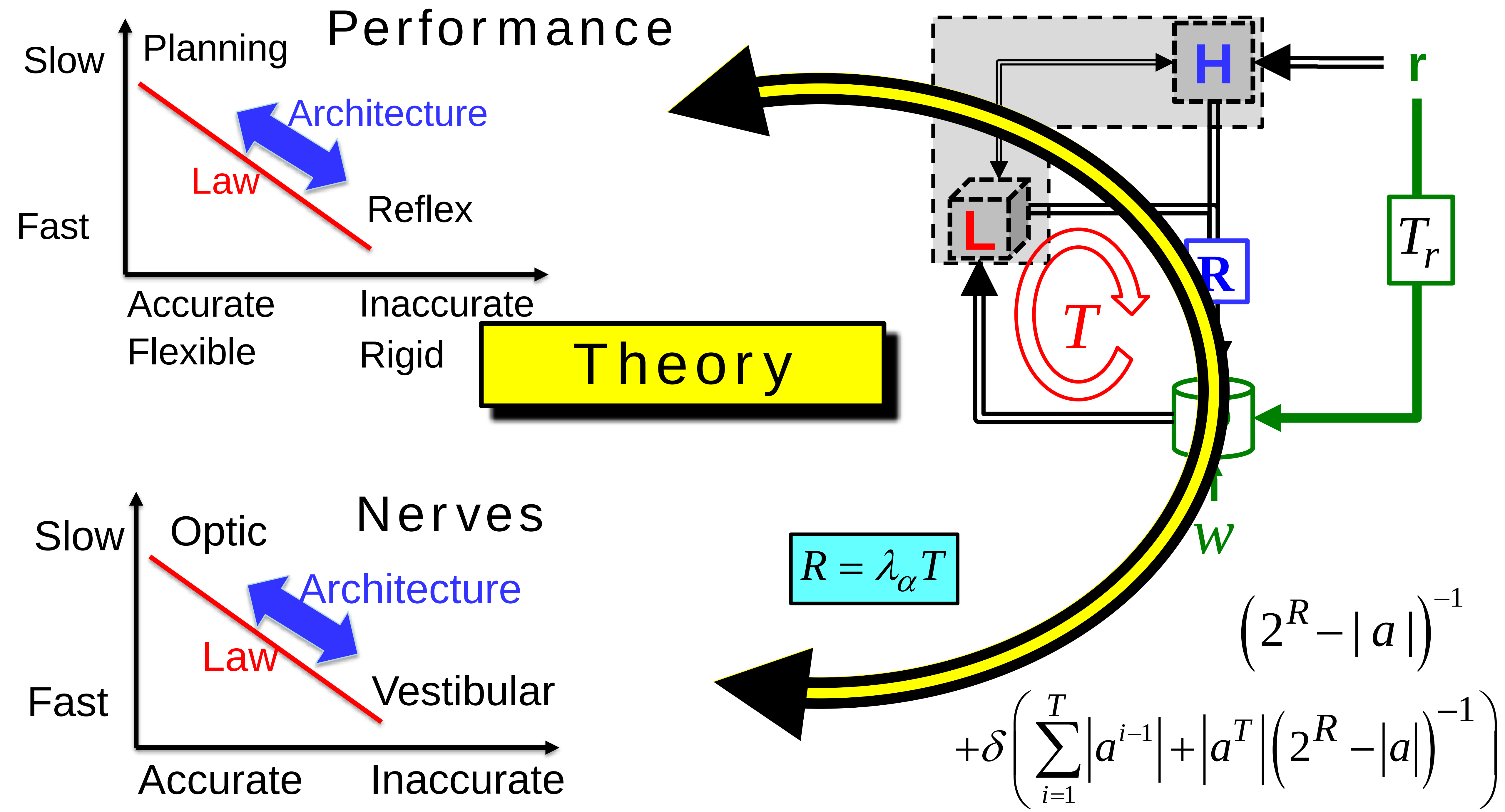
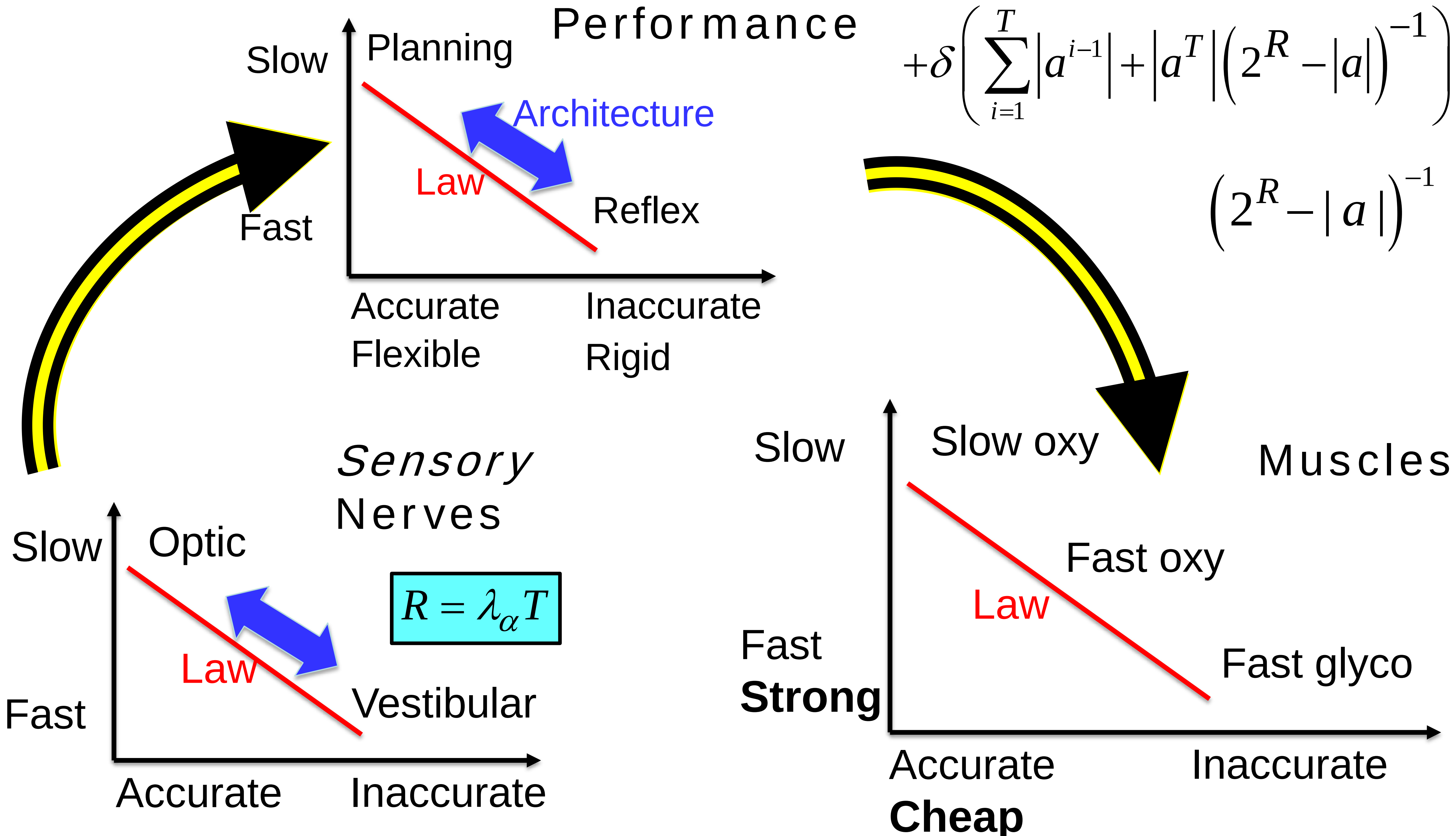


Figure 25-1b Discover Biology 3/e

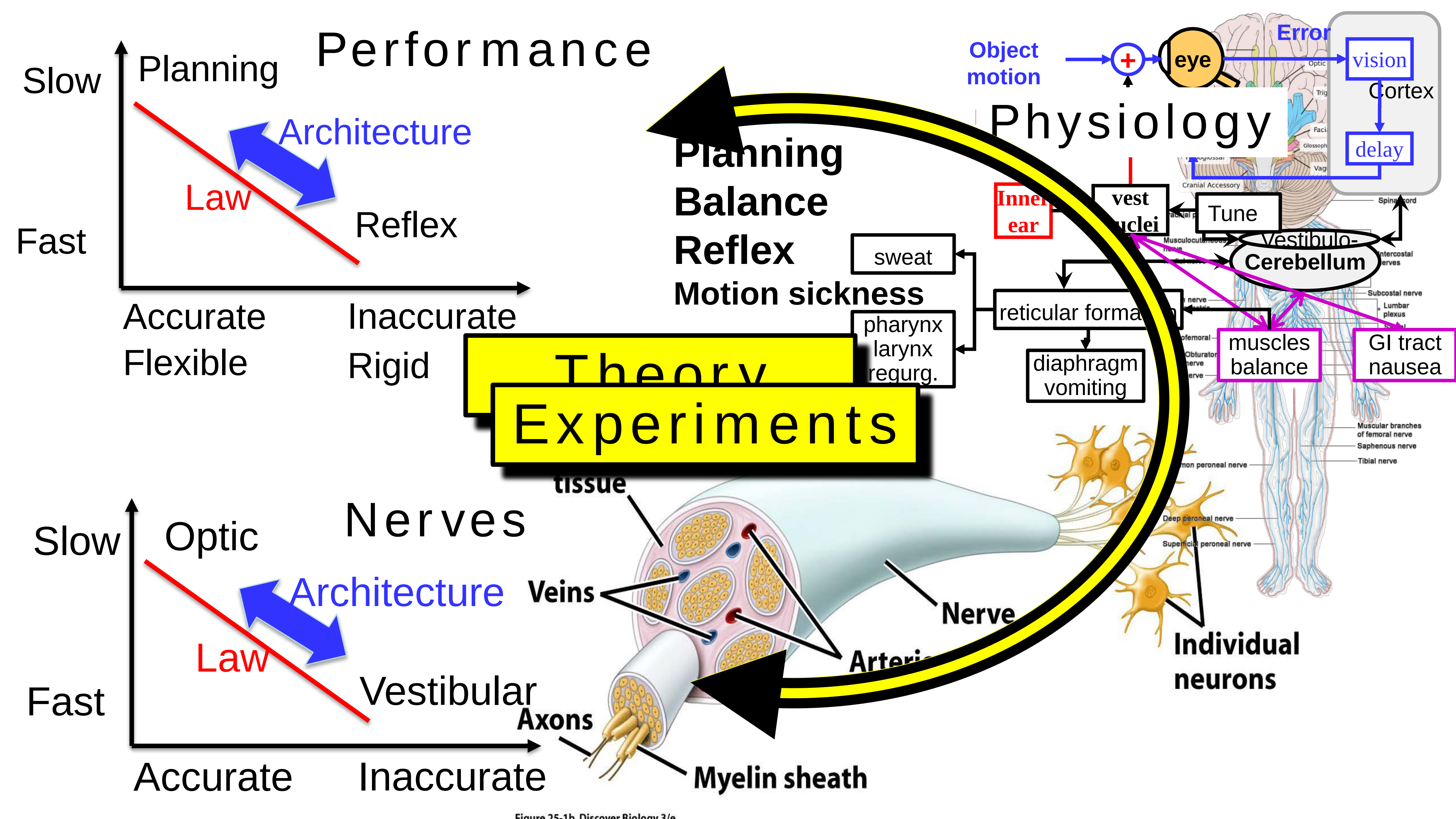


Performance
Slow
Fast
vision
VOR
Tradeoff
proprio
Accurate
Inaccurate
Planning
Balance
Reflex
Motion sickness
Theory
Physiology
Object motion
eye
Error
vision
Cortex
delay
Inner ear
vest nuclei
Tune
Vestibulo-Cerebellum
sweat
pharynx
larynx
regurg.
reticular formation
diaphragm
vomiting
muscles
balance
GI tract
nausea
Nerves
Slow
Optic
Vestibular
$R = \lambda_\alpha T$
Sciatic
Fast
Accurate
Inaccurate
Connective tissue
Veins
Axons
Myelin sheath
Individual neurons


Performance
Slow
Planning
Architecture
Law
Fast
Reflex
Accurate
Flexible
Inaccurate
Rigid
Theory
H
r
L
R
T
T_r
w
Nerves
Slow
Optic
Architecture
Law
Fast
Vestibular
Accurate
Inaccurate
$R = \lambda_\alpha T$
$\left(2^R - |a|\right)^{-1}$
$+\delta\left(\sum_{i=1}^{T}\left|a^{i-1}\right| + \left|a^T\right|\left(2^R - |a|\right)^{-1}\right)$

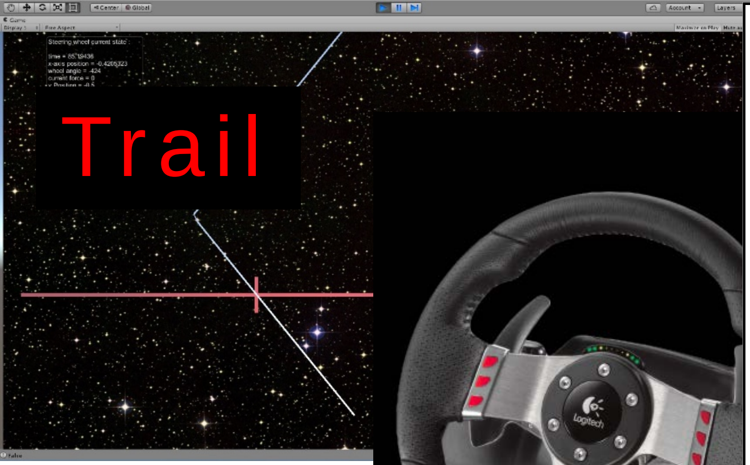


Performance
$+\delta\left(\sum_{i=1}^{T}\left|a^{i-1}\right|+\left|a^{T}\right|\left(2^{R}-|a|\right)^{-1}\right)$
$\left(2^{R}-|a|\right)^{-1}$
Slow
Planning
Architecture
Law
Reflex
Fast
Accurate
Flexible
Inaccurate
Rigid
Sensory
Nerves
Slow
Optic
$R=\lambda_{\alpha}T$
Law
Vestibular
Fast
Accurate
Inaccurate
Muscles
Slow
Slow oxy
Fast oxy
Law
Fast
Strong
Fast glyco
Accurate
Cheap
Inaccurate



Performance
Slow
Planning
Architecture
Law
Reflex
Fast
Accurate
Inaccurate
Flexible
Rigid
Physiology
Object motion
Error
eye
vision
Cortex
delay
Planning
Balance
Reflex
Motion sickness
sweat
pharynx
larynx
regurg.
Inner ear
vest nuclei
Tune
Vestibulo-
Cerebellum
reticular forma
diaphragm
vomiting
muscles
balance
GI tract
nausea
Theory
Experiments
Nerves
Slow
Optic
Architecture
Law
Vestibular
Fast
Accurate
Inaccurate
tissue
Veins
Nerve
Arteri
Axons
Myelin sheath
Individual neurons
Figure 25-1b Discover Biology 3/e

Experiments



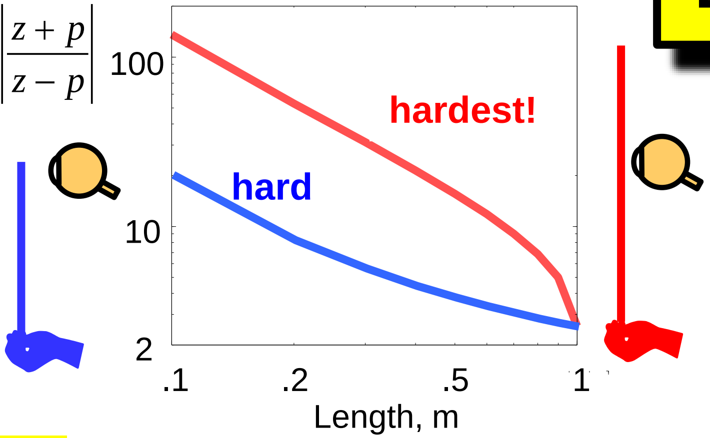
Object motion

Slow

Head motion

Fast

$\exp(p\tau)\left|\frac{z+p}{z-p}\right|$



Waterbed

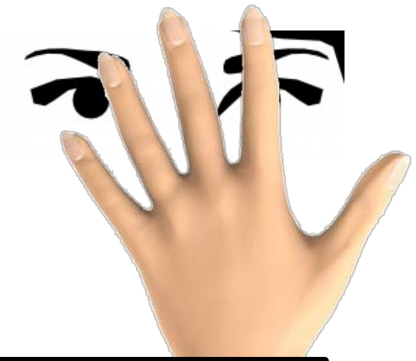
$$\left.\begin{matrix}\exp\left(\int \ln|T|\right) \\ \|T\|_\infty\end{matrix}\right\} \ge \exp(p\tau)\left|\frac{z+p}{z-p}\right|$$

Theory

Experiments

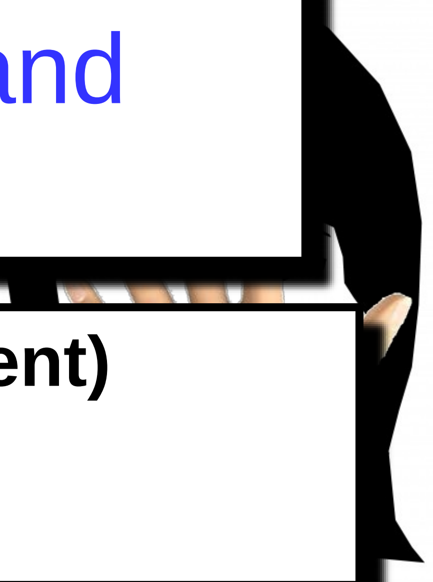
Object motion

Slow



- Video biking game with trails and bumps
- Balancing stick (inverted pendulum)
- Vision and VOR with object and head motion
- Balancing body with vision, vestibular, and proprioception

$\exp(p\tau$



2

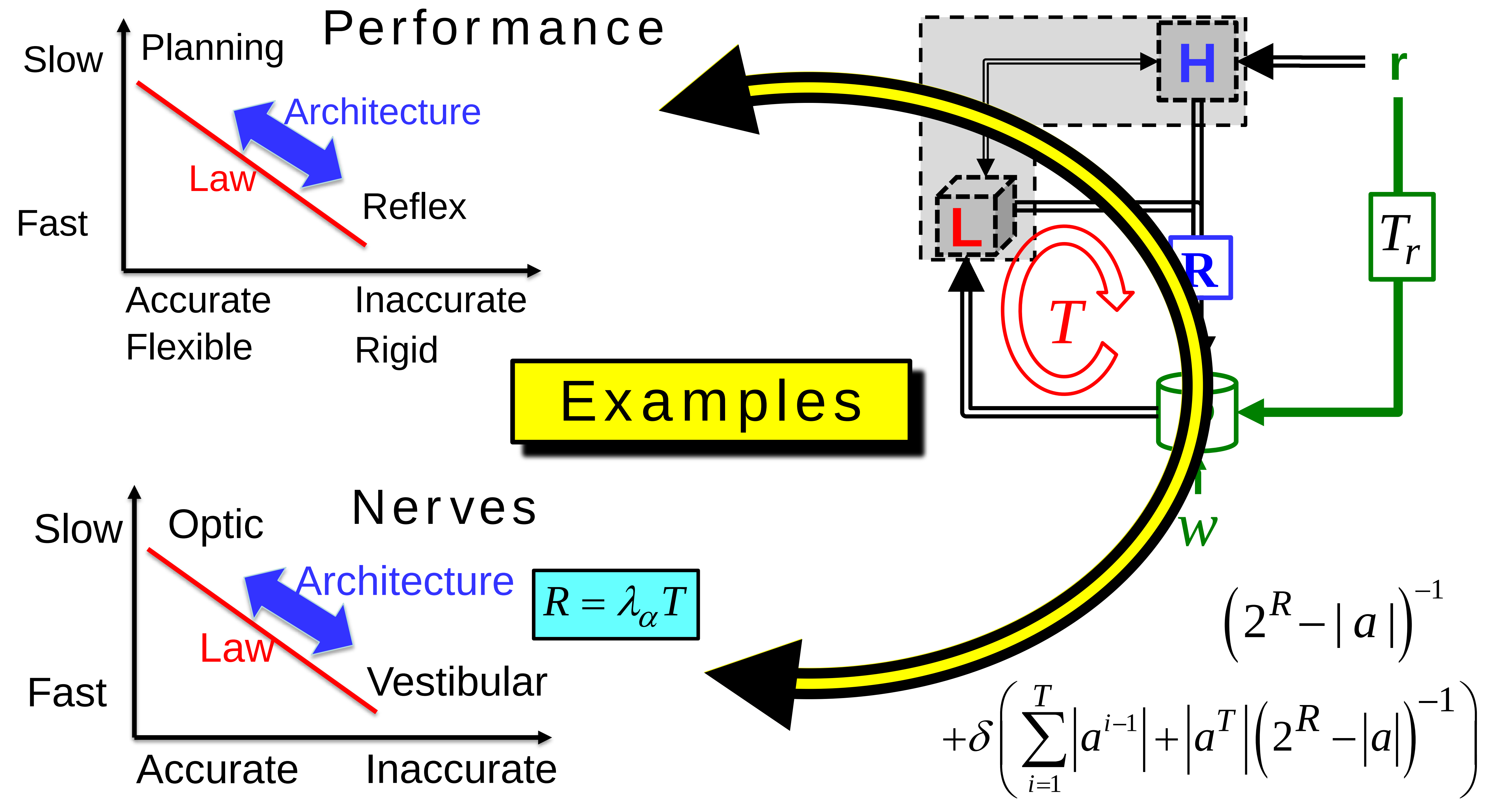
.1

Waterbed

$\exp(\int$

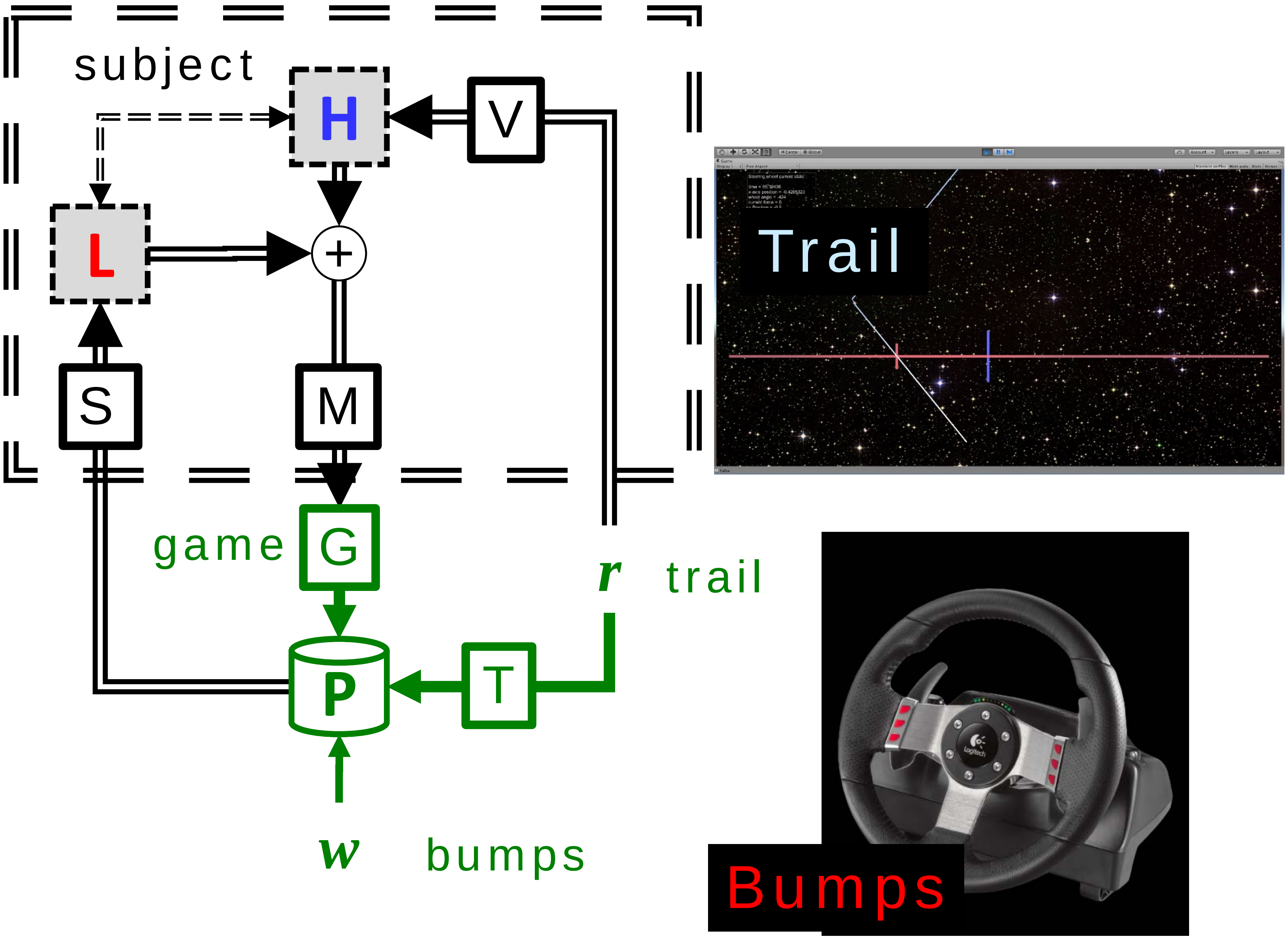
$\|T\|_\infty$

- **Quantitative match with theory (but equipment)**
- **Qualitative (but easy to do live demos)**
- **Both**


Performance
Slow
Planning
Architecture
Law
Fast
Reflex
Accurate
Flexible
Inaccurate
Rigid
Examples
Nerves
Slow
Optic
Architecture
Law
Fast
Vestibular
Accurate
Inaccurate
$R = \lambda_\alpha T$
H
r
L
R
T
T_r
w
$\left(2^R - |a|\right)^{-1}$
$+\delta\left(\sum_{i=1}^{T}\left|a^{i-1}\right| + \left|a^T\right|\left(2^R - |a|\right)^{-1}\right)$

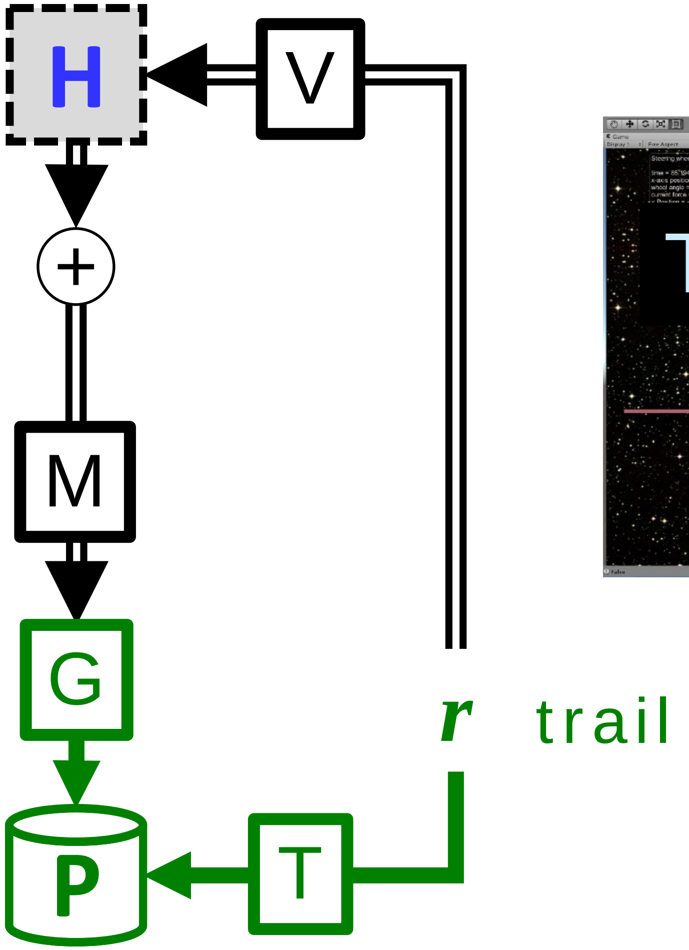
In subject
V=Vision
S=Spindle
M=Muscle
H=High layer
L=Low layer

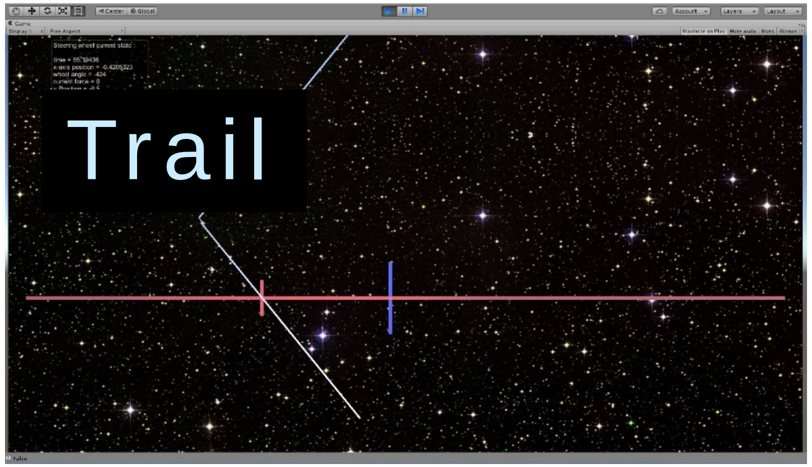
In game:
G=Game motor
T=Advance



In subject
V=Vision

M=Muscle
H=High layer





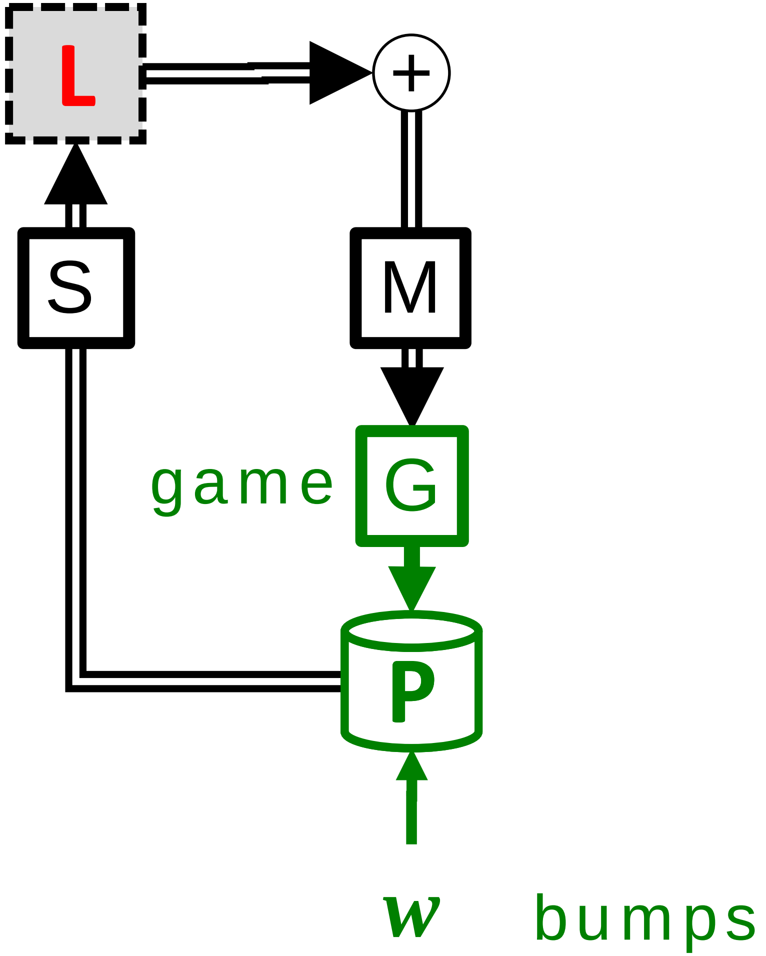
In game:
G=Game motor
T=Advance

In subject

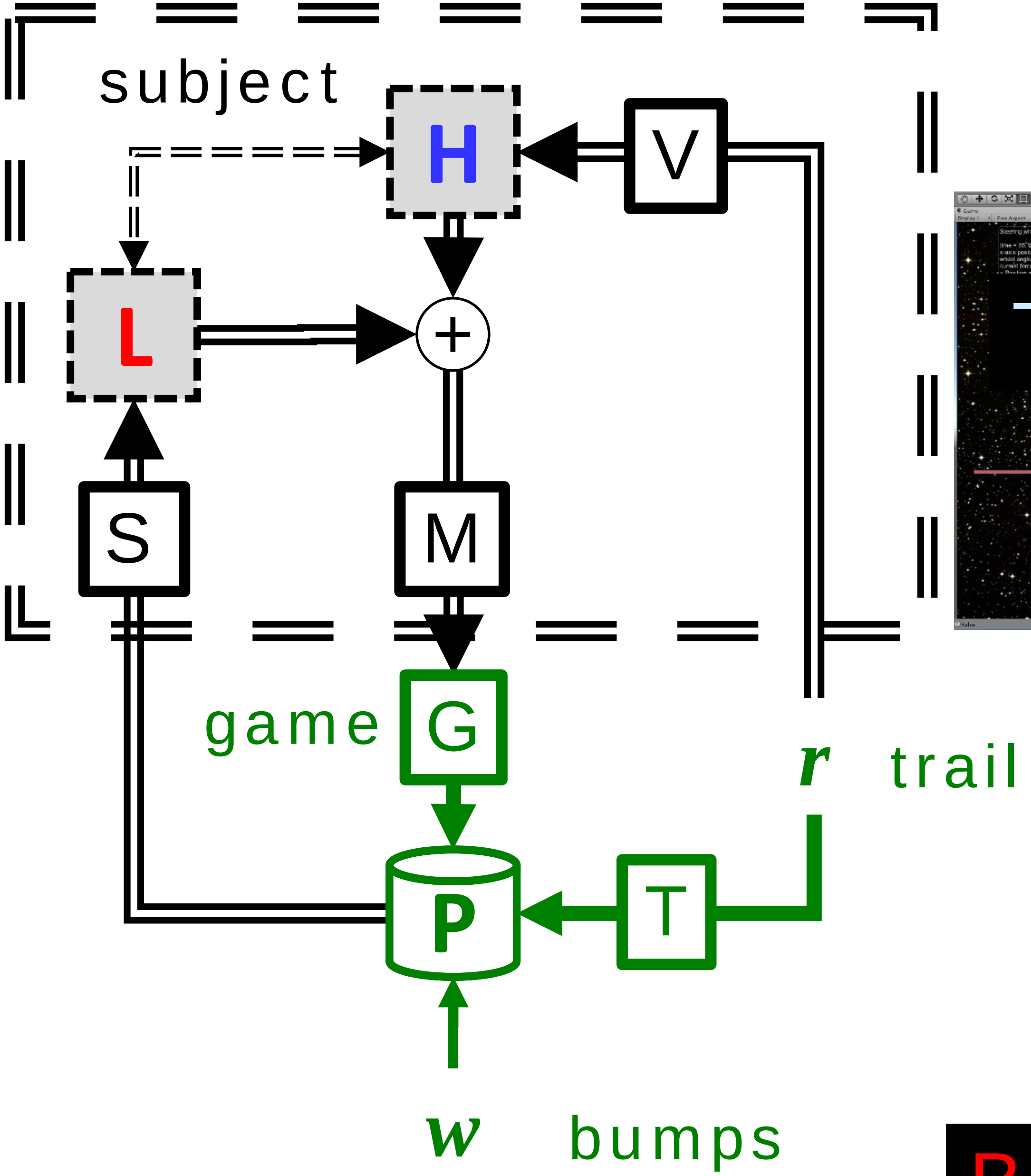
S=Spindle
M=Muscle

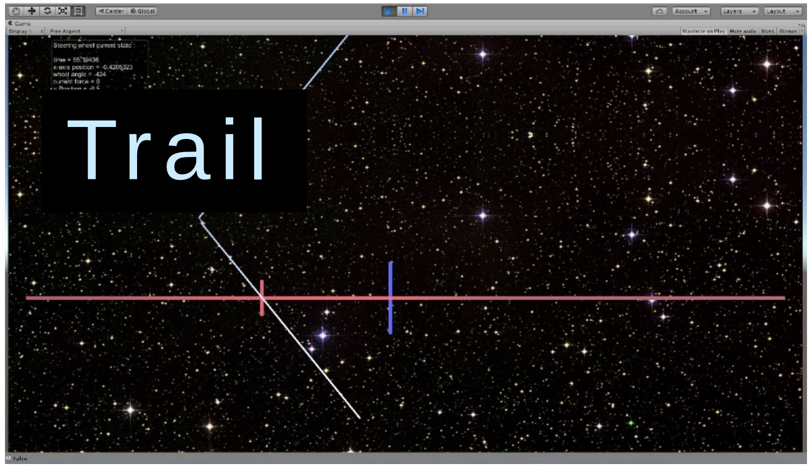
L=Low layer

In game:
G=Game motor



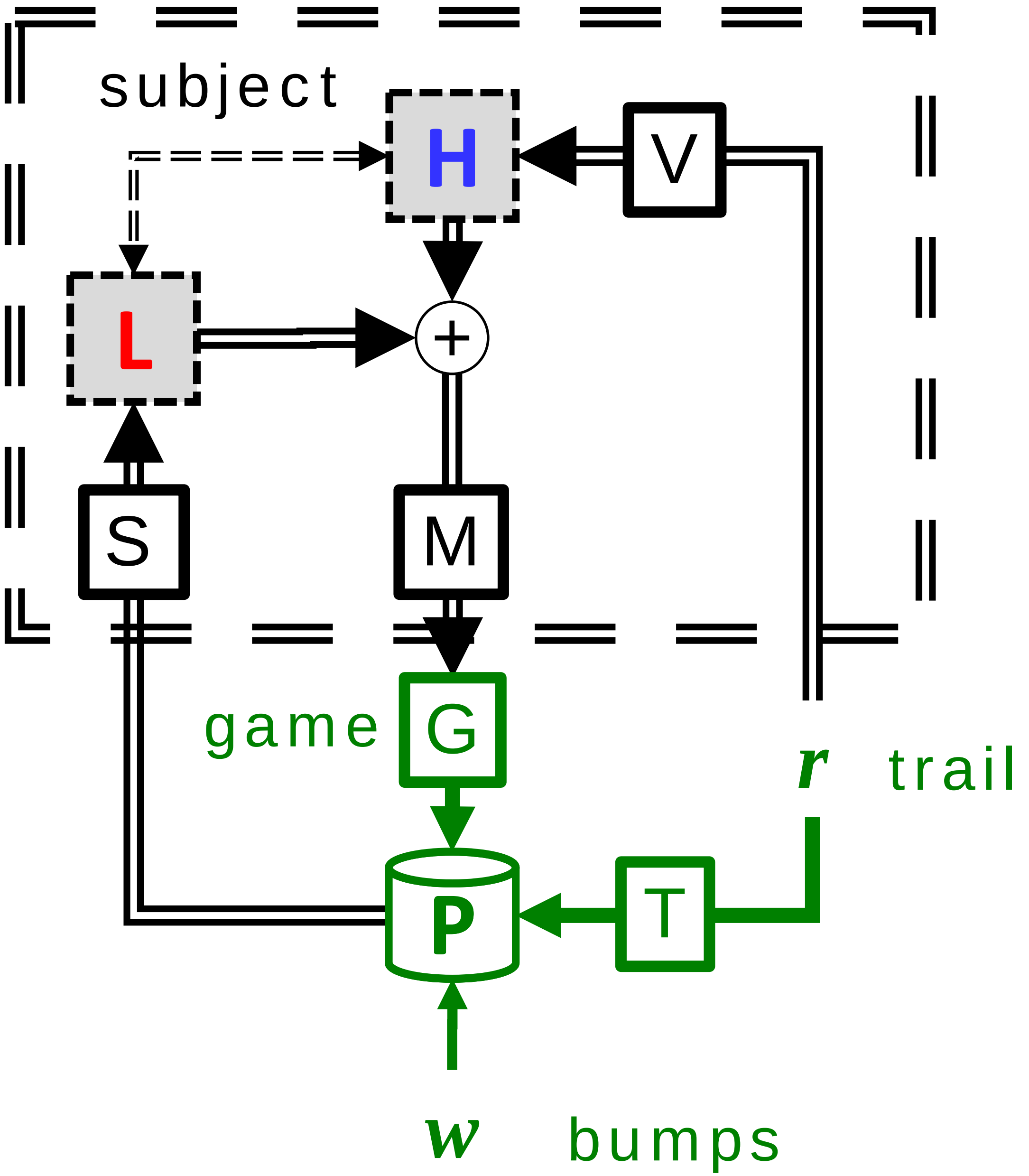
In subject
V=Vision
S=Spindle
M=Muscle
H=High layer
L=Low layer





In game:
G=Game motor
T=Advance

In subject
V=Vision
S=Spindle
M=Muscle
H=High layer
L=Low layer



Quantization and delay everywhere

In game:
G=Game motor
T=Advance

The Journal of Experimental Biology 216, 1003-1011

doi:10.1242/jeb.067231

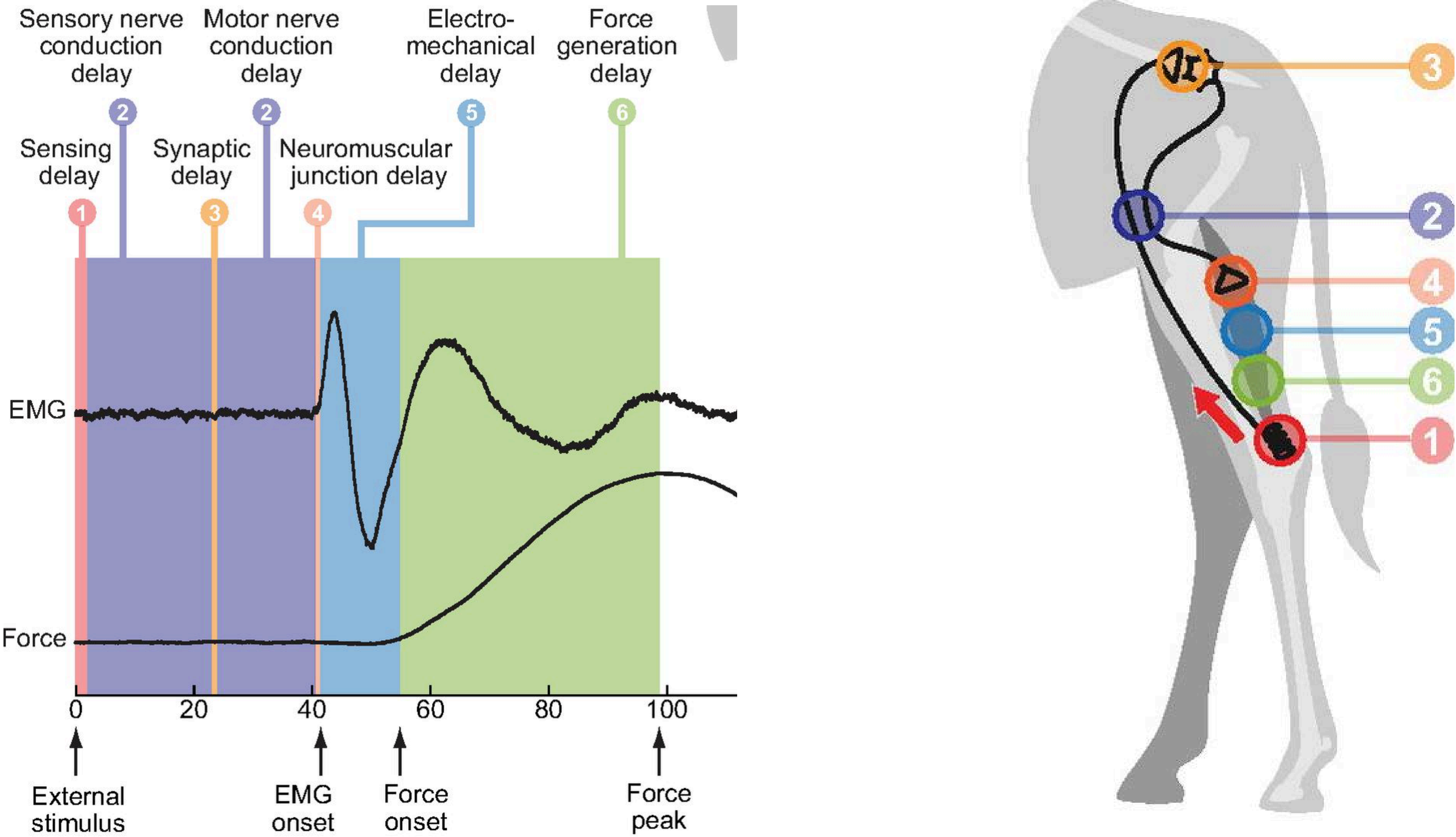
RESEARCH ARTICLE

Sensorimotor responsiveness and resolution in the giraffe

Heather L. More[1,*,†], Shawn M. O'Connor[1,*], Emil Brøndum[2], Tobias Wang[3], Mads F. Bertelsen[4], Carsten Grøndahl[4], Karin Kastberg[5], Arne Hørlyck[5], Jonas Funder[6] and J. Maxwell Donelan[1]

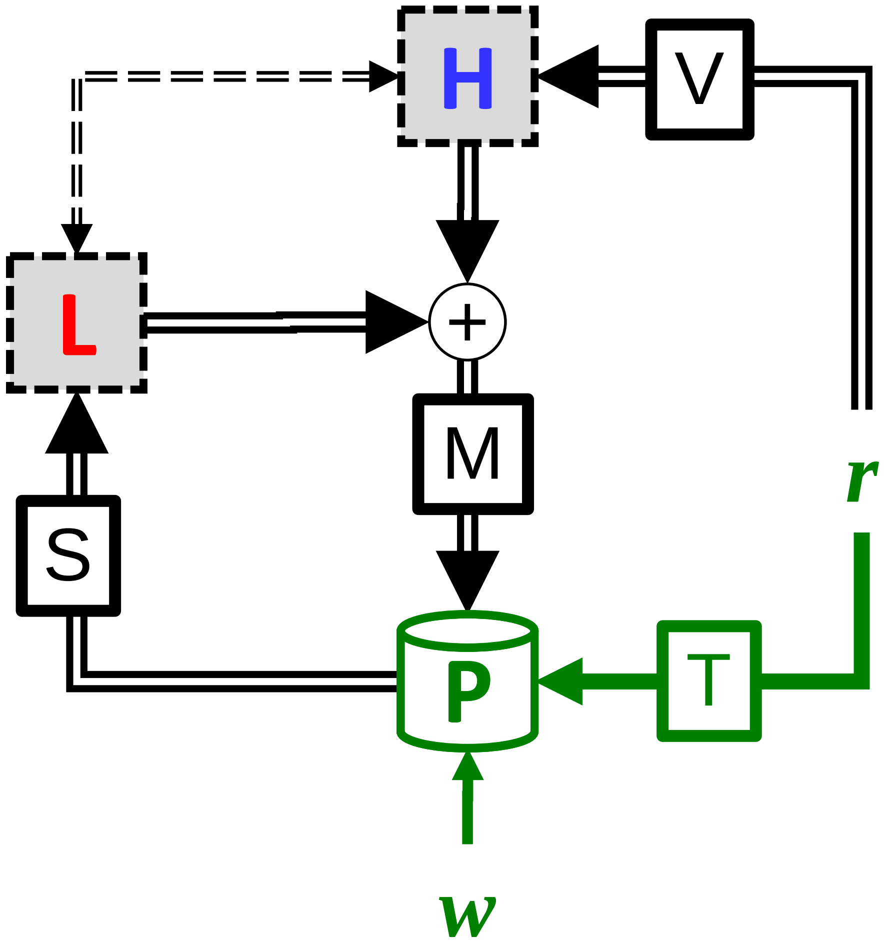
[1]Department of Biomedical Physiology and Kinesiology, Simon Fraser University, Canada, [2]Department of Biomedicine, Aarhus University, Denmark, [3]Zoophysiology, Department of Biosciences, Aarhus University, Denmark, [4]Center for Zoo and Wild Animal Health, Copenhagen Zoo, Frederiksberg, Denmark, [5]Department of Diagnostic Imaging, Aarhus University Hospital, Skejby, Denmark and [6]Department of CardioThoracic Surgery, Aarhus University Hospital, Skejby, Denmark

*These authors contributed equally to this work

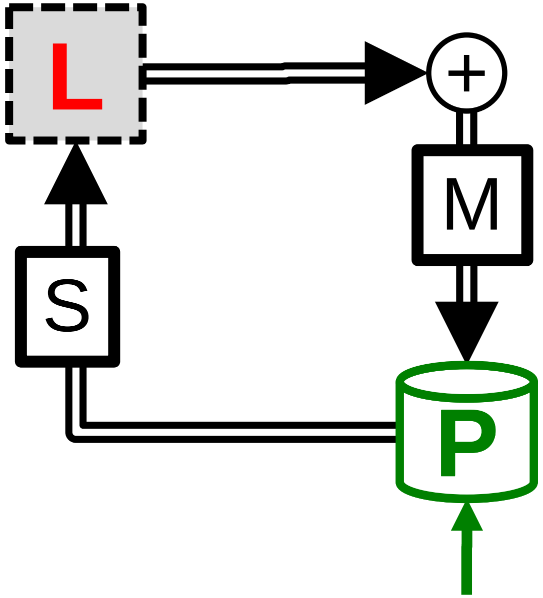


Sensory nerve conduction delay
Motor nerve conduction delay
Electro-mechanical delay
Force generation delay
2
2
5
6
Sensing delay
Synaptic delay
Neuromuscular junction delay
1
3
4
EMG
Force
0
20
40
60
80
100
External stimulus
EMG onset
Force onset
Force peak
3
2
4
5
6
1

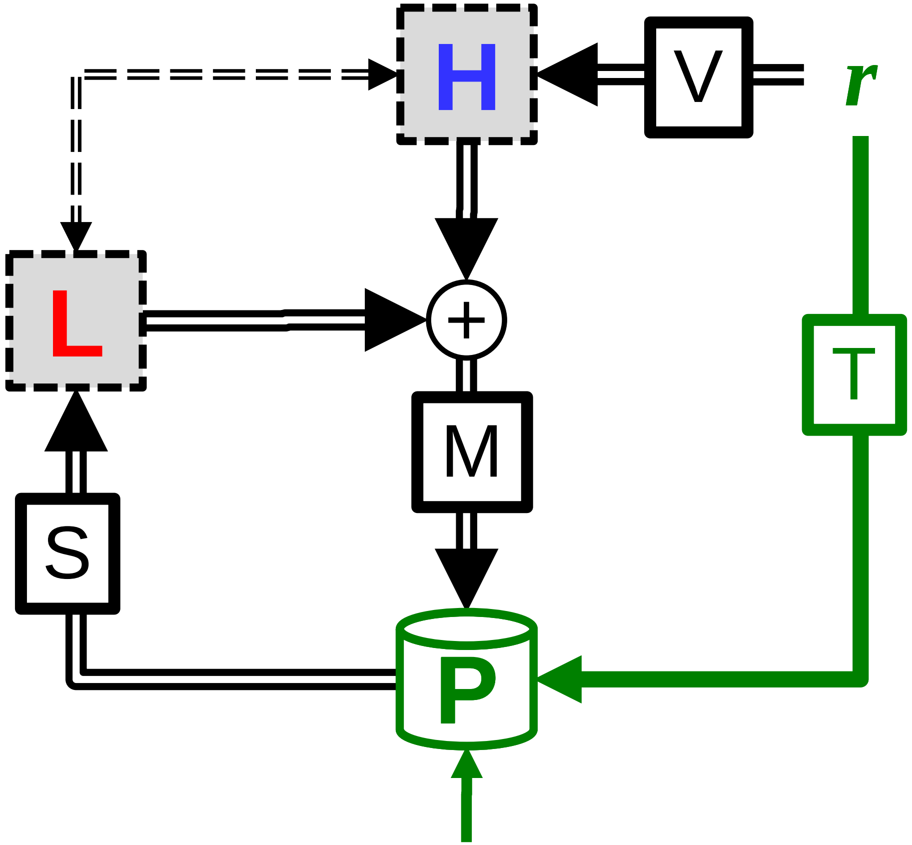
V=Vision
S=Spindle
M=Muscle
H=High layer
L=Low layer
T=Advance



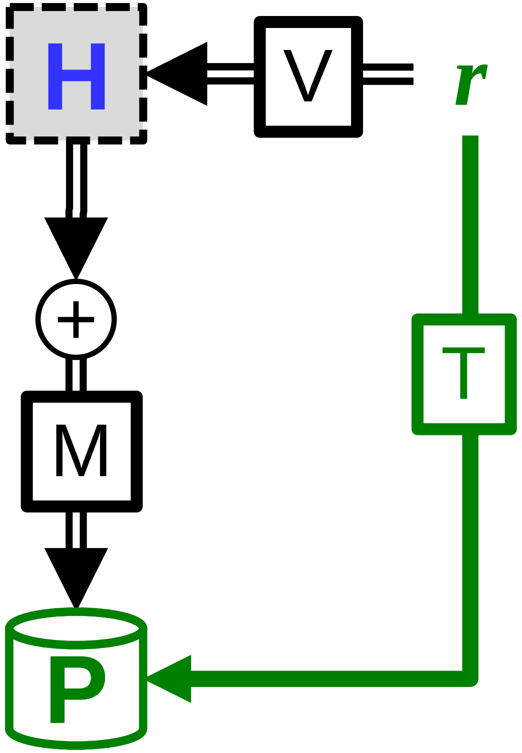
key idea



bumps



w



trail

$$\delta\left(\sum_{i=1}^{T}\left|a^{i-1}\right| + \left|a^{T}\right|\left(2^{R} - |a|\right)^{-1}\right)$$

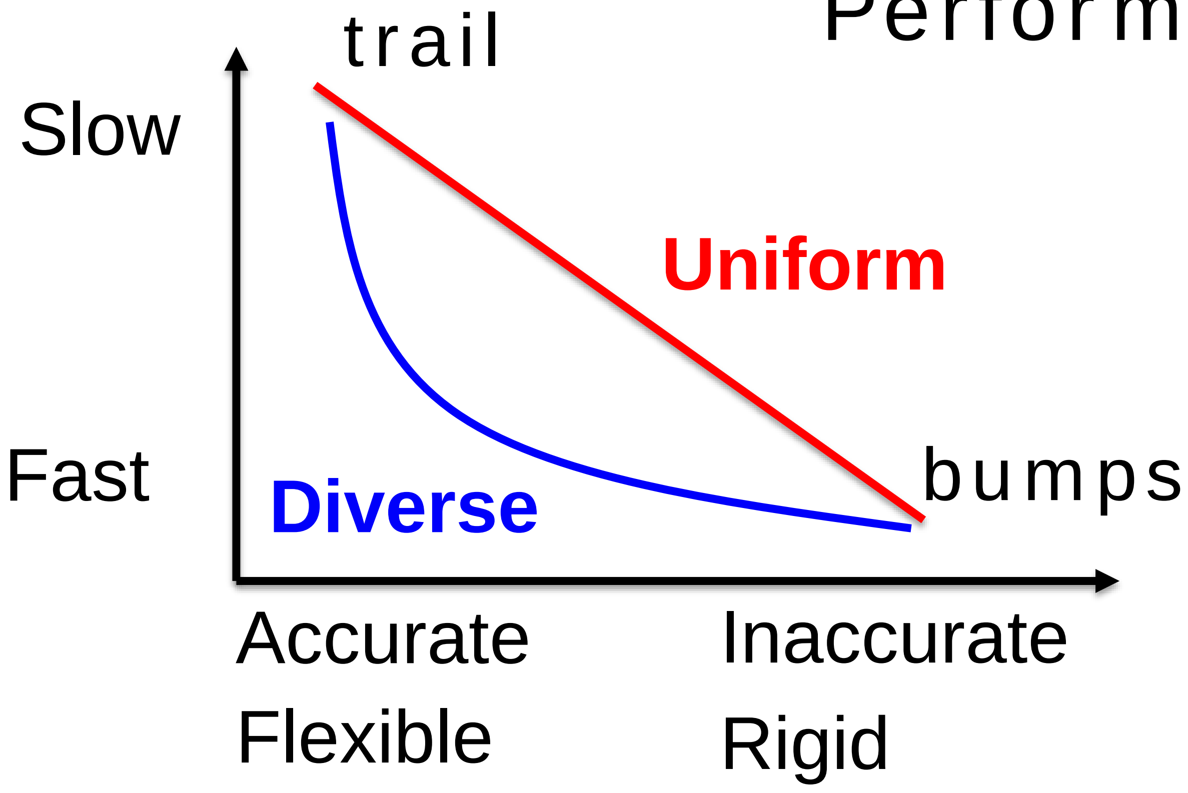
delay **delay+quant**

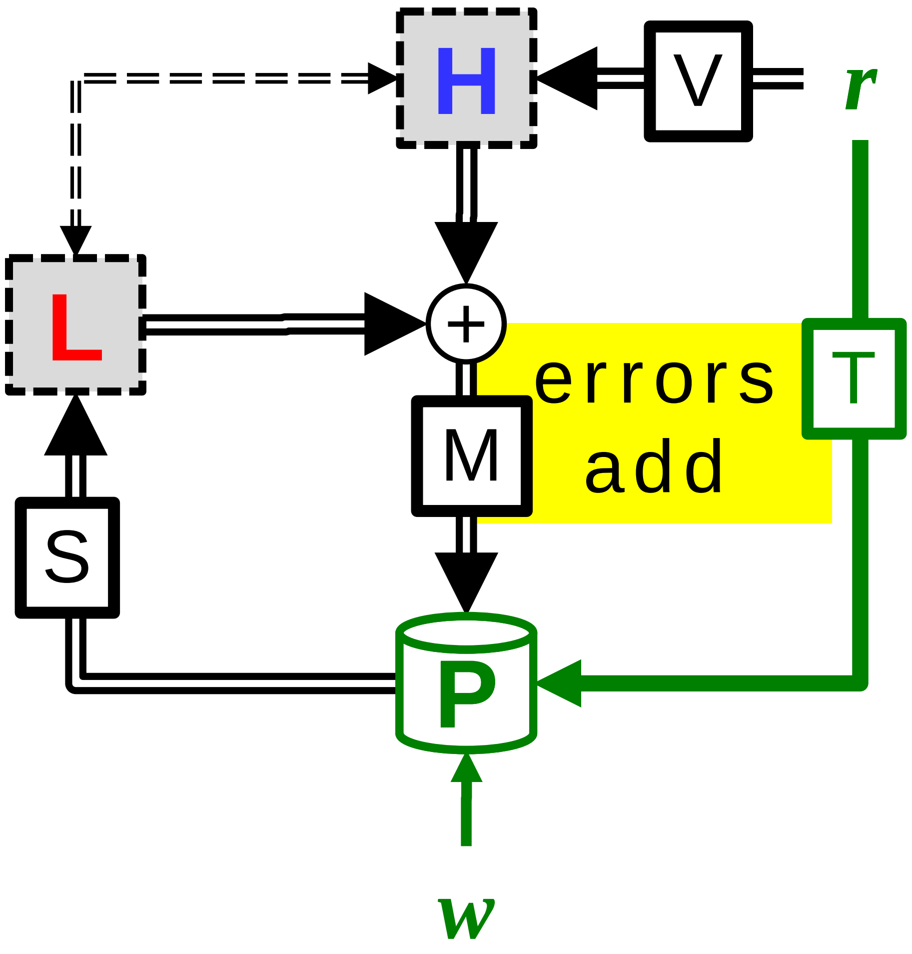
errors add

$$+\left(2^{R} - |a|\right)^{-1}$$

quant

Performance





Diversity sweet spot

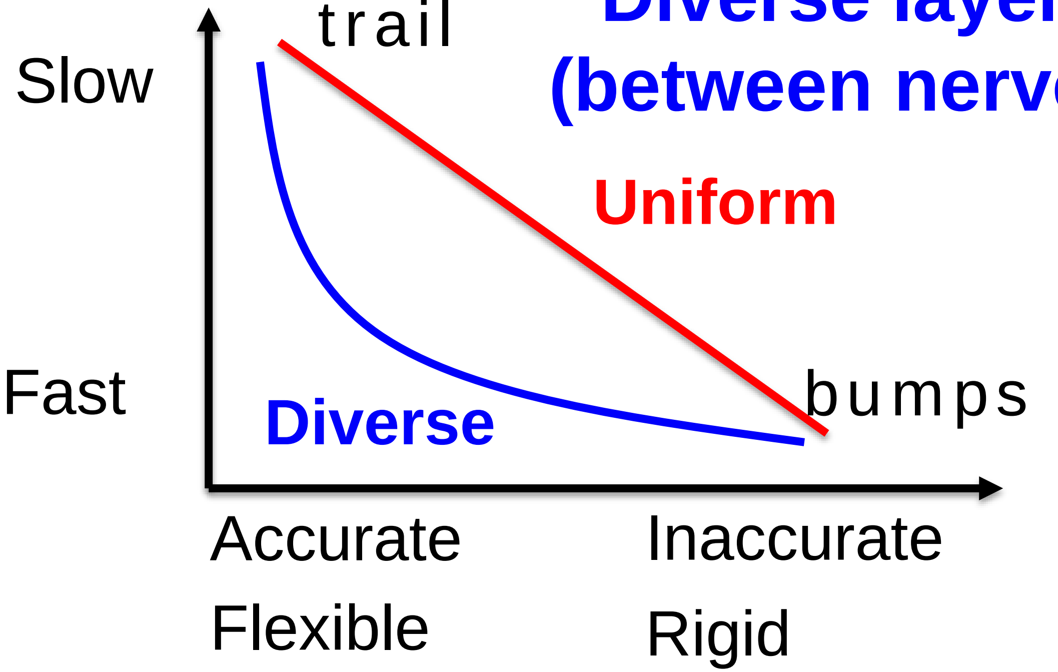
Diverse layers

(between nerves)

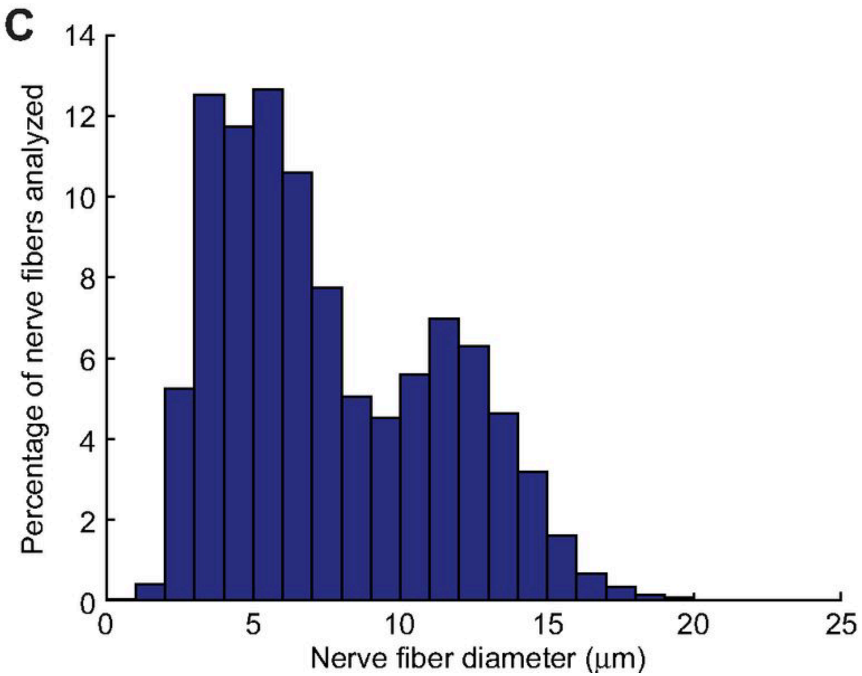
bumps trail

$$\delta\left(\sum_{i=1}^{T}\left|a^{i-1}\right|+\left|a^{T}\right|\left(2^{\lambda T}-|a|\right)^{-1}\right)+\left(2^{V}-|a|\right)^{-1}$$

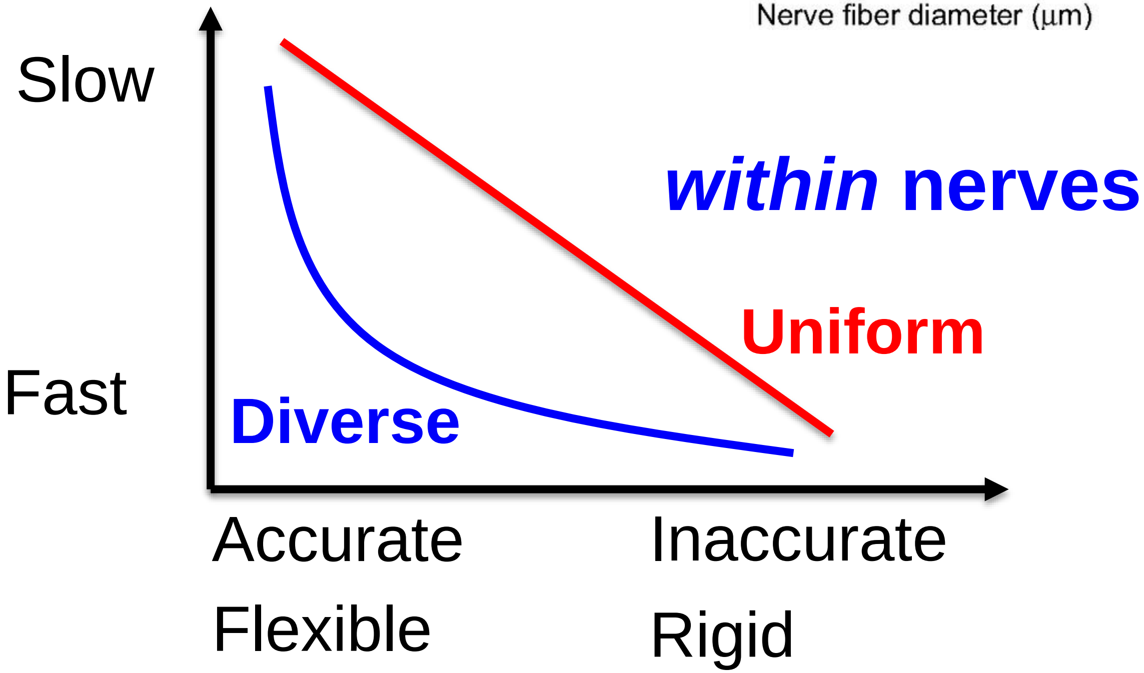
Diverse layers (between nerves)



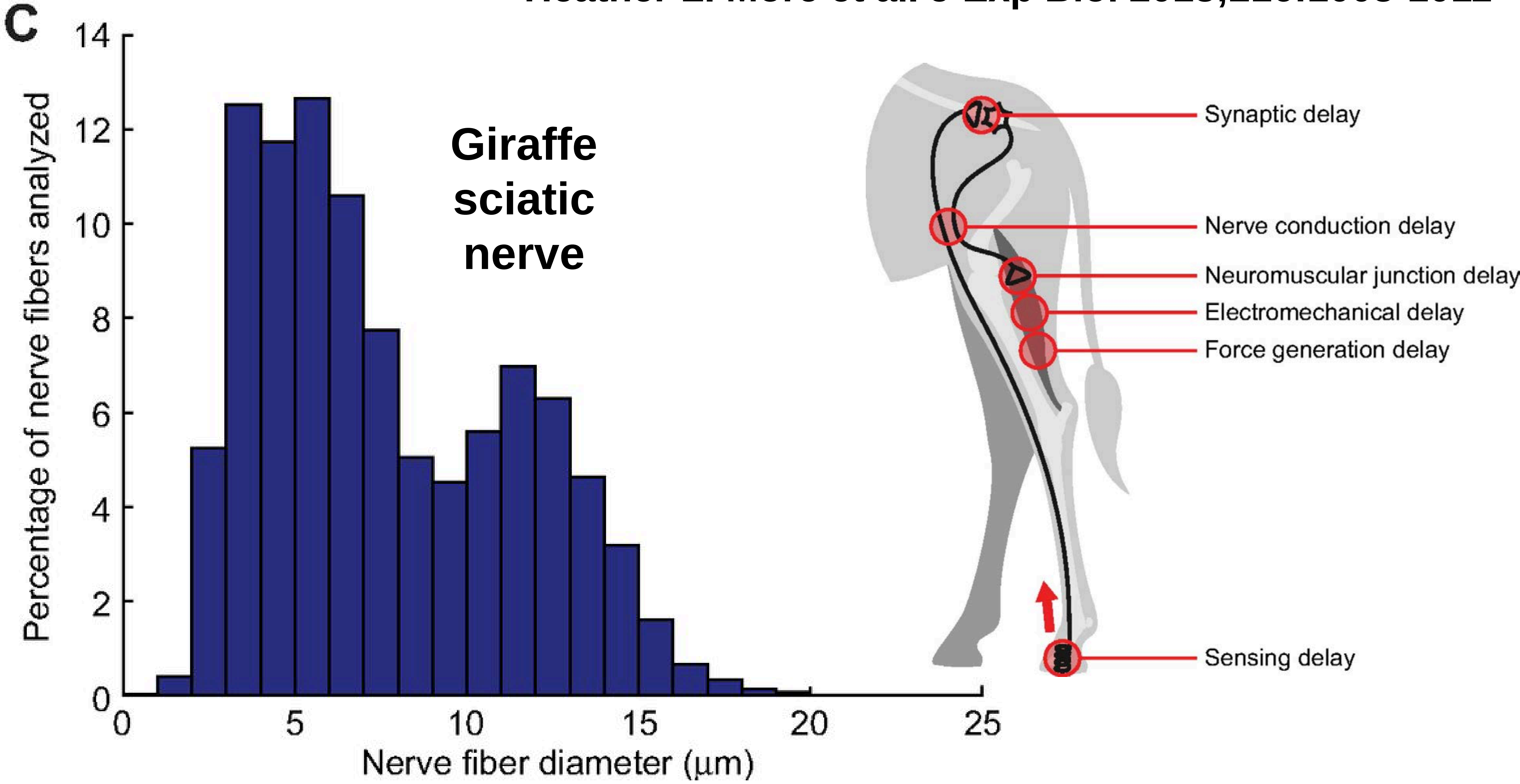
Heather L. More et al. J Exp Biol 2013;216:1003-1011



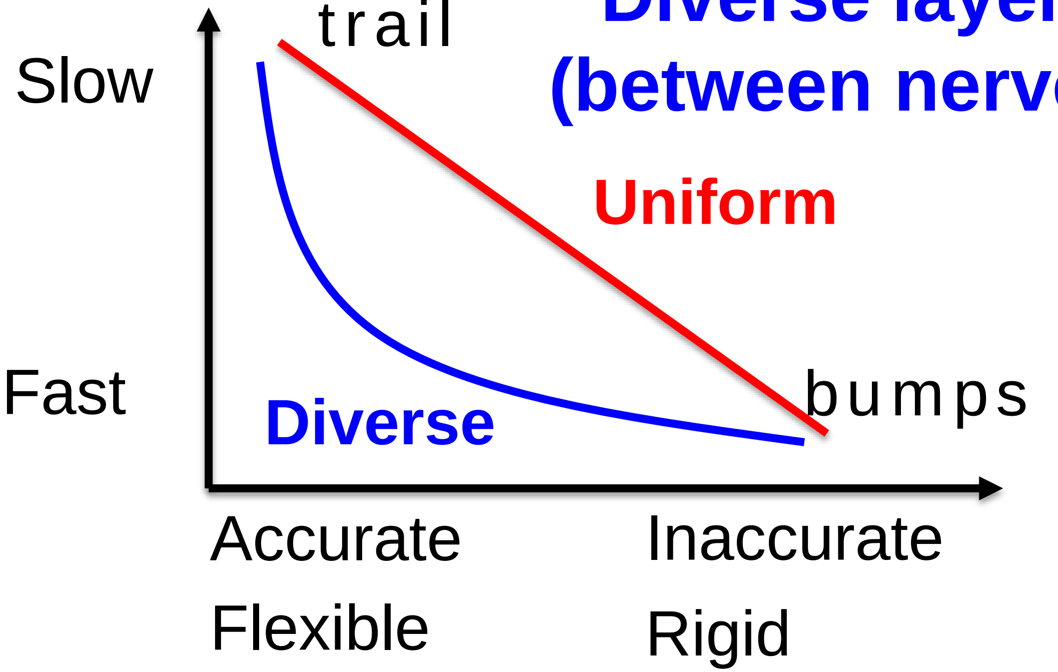
Diversity sweet spots



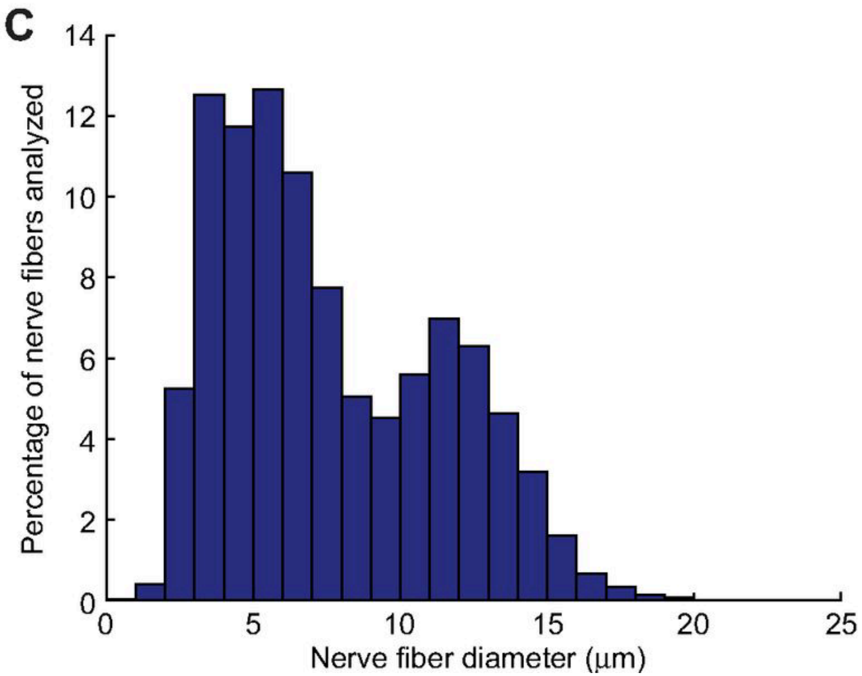
Heather L. More et al. J Exp Biol 2013;216:1003-1011



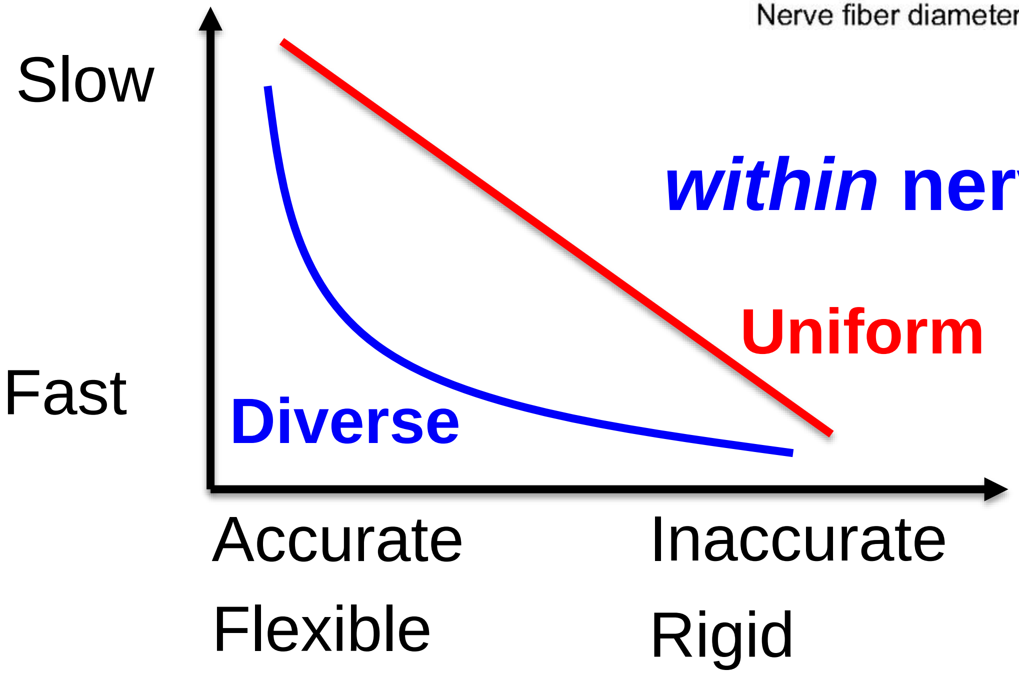
Diverse layers (between nerves)



Heather L. More et al. J Exp Biol 2013;216:1003-1011

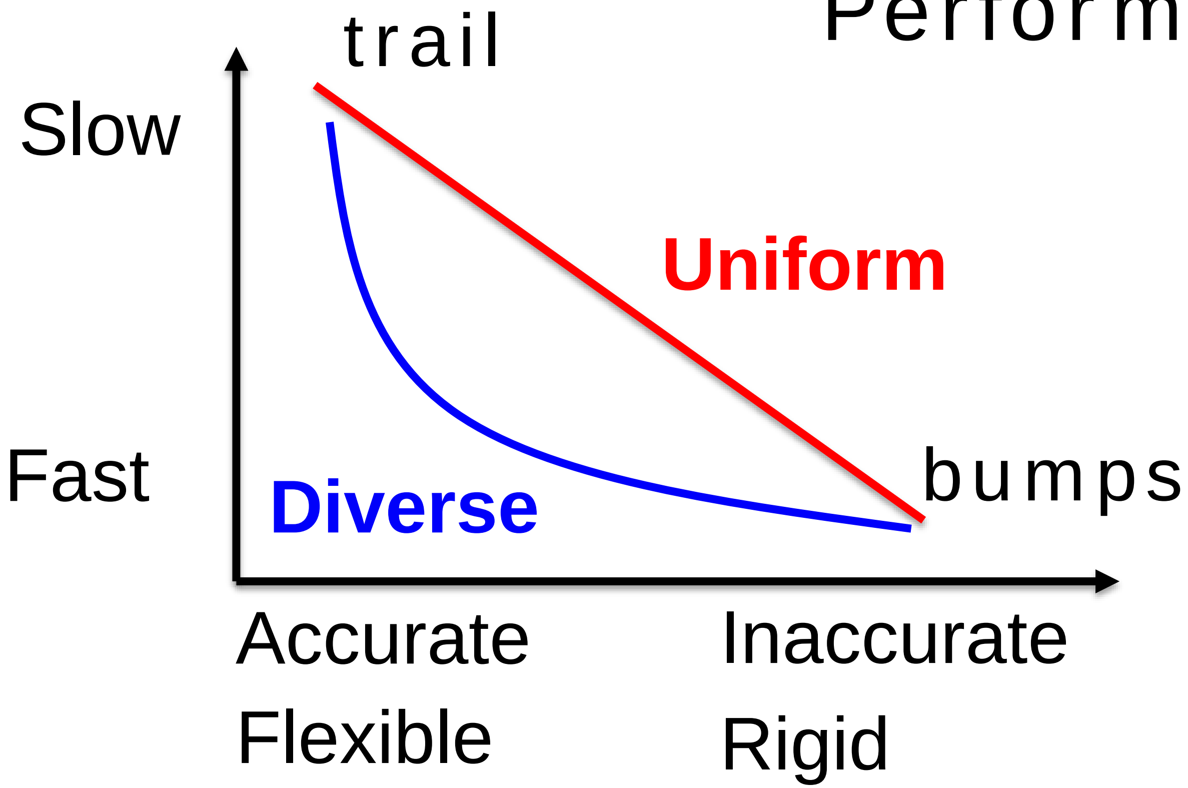


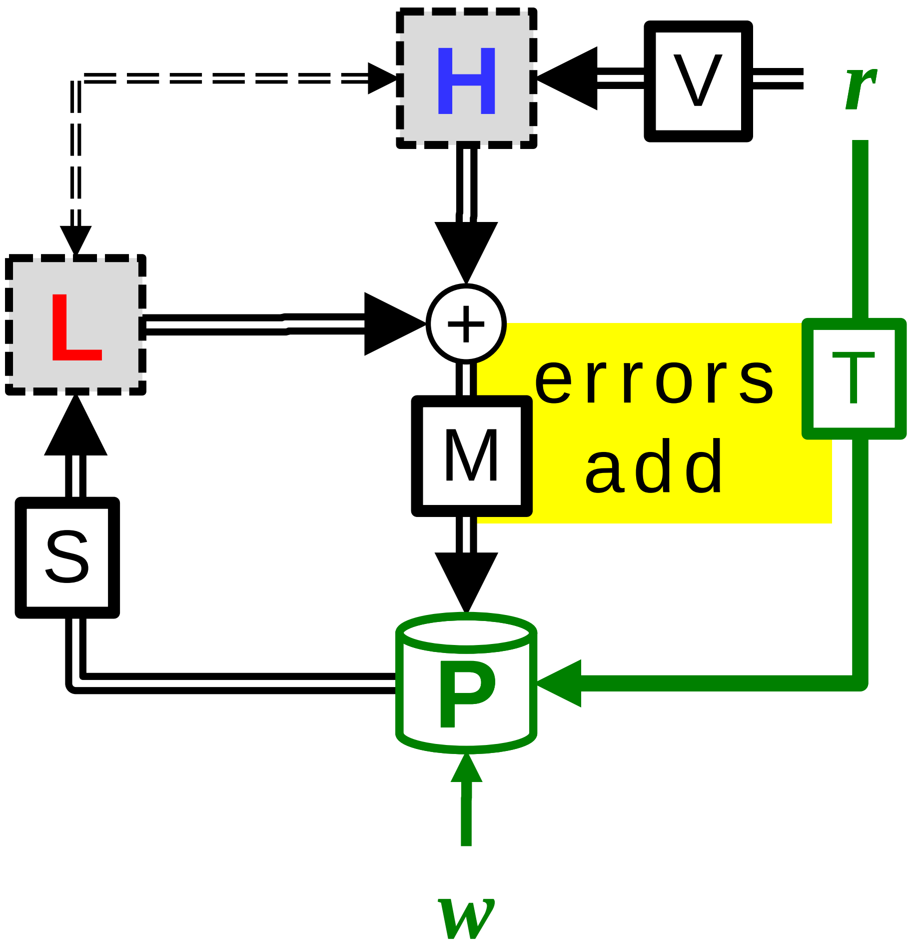
within nerves



Diversity sweet spots

Performance





Diversity sweet spot

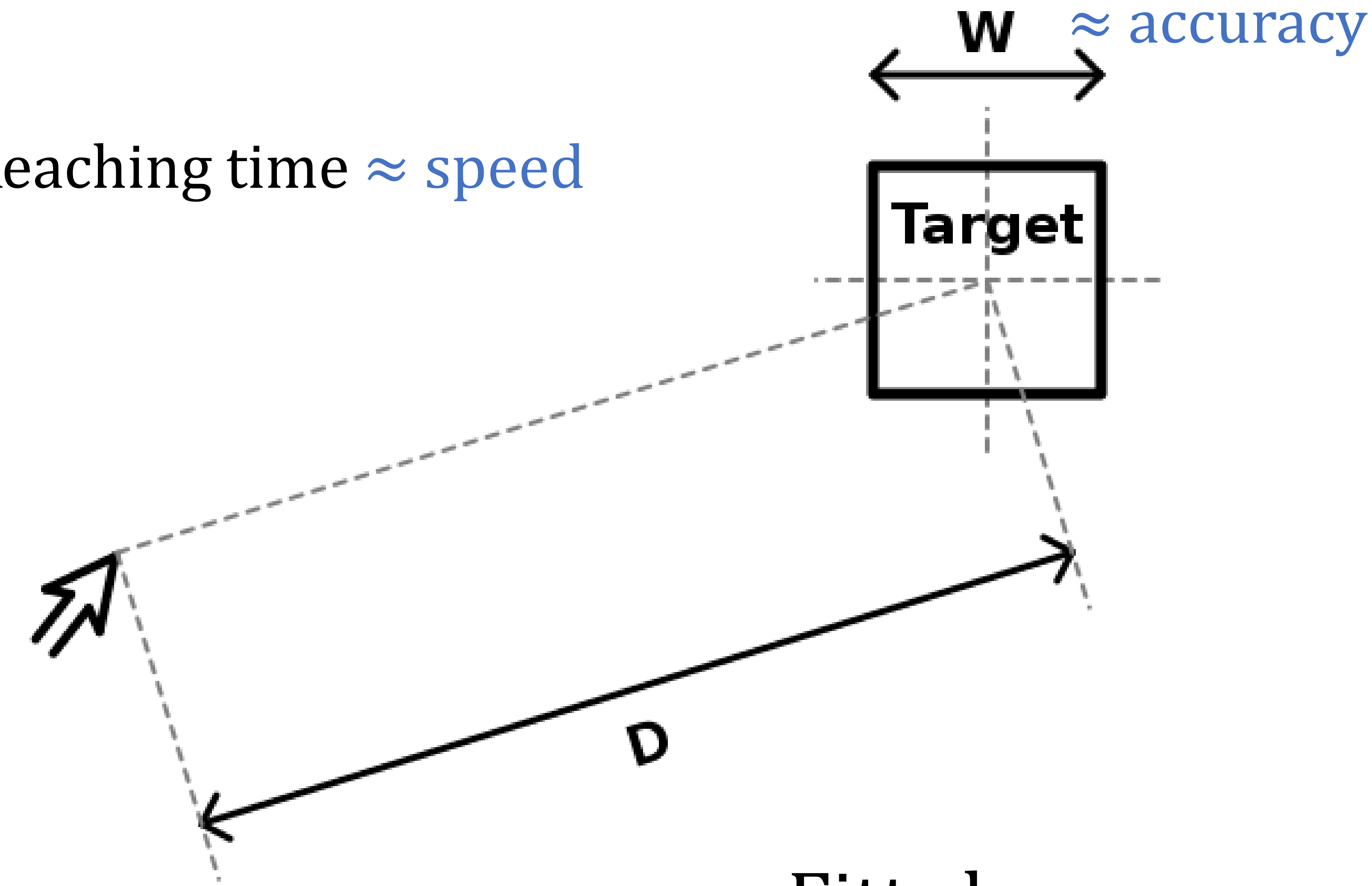
Diverse layers

(between nerves)

bumps trail

$$\delta\left(\sum_{i=1}^{T}\left|a^{i-1}\right|+\left|a^{T}\right|\left(2^{\lambda T}-|a|\right)^{-1}\right)+\left(2^{V}-|a|\right)^{-1}$$

Reaching time ≈ speed

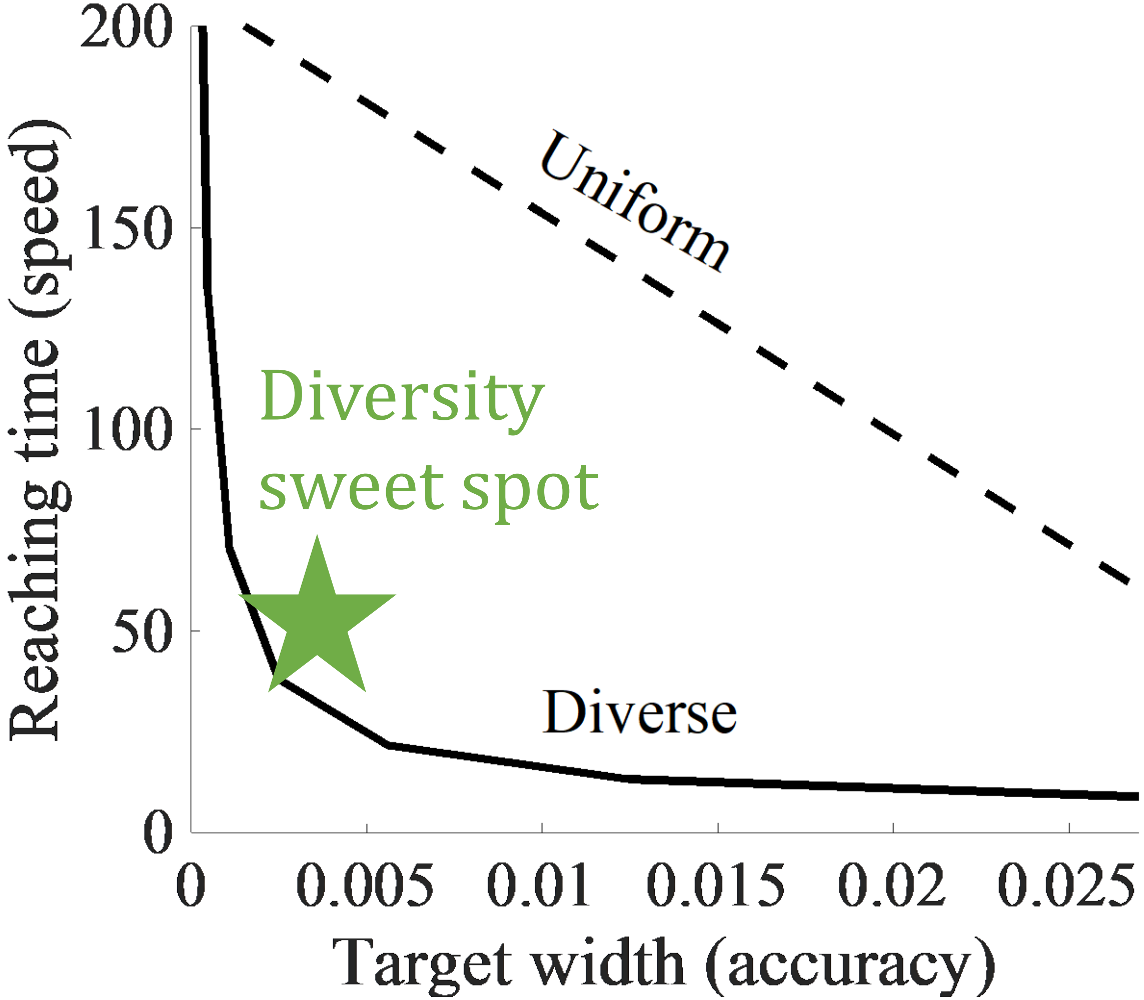


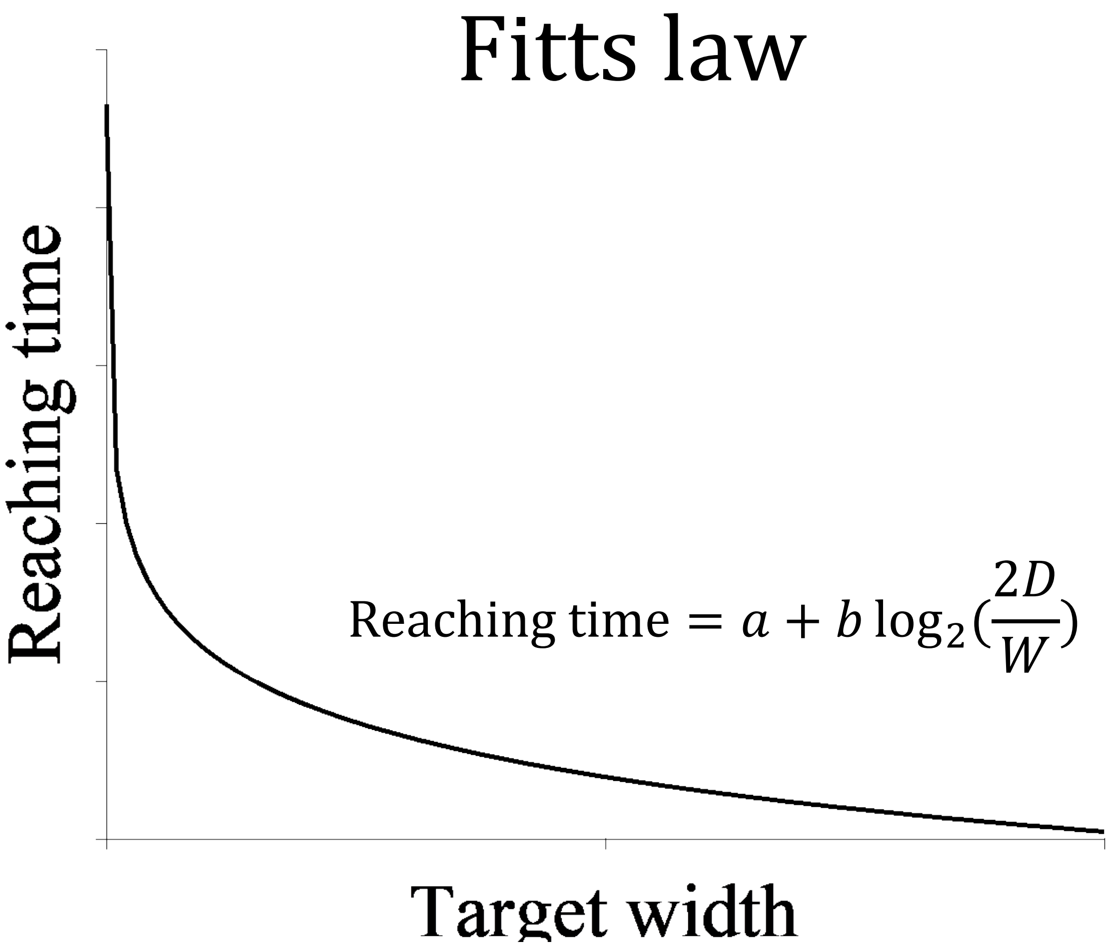
const

Fitts law

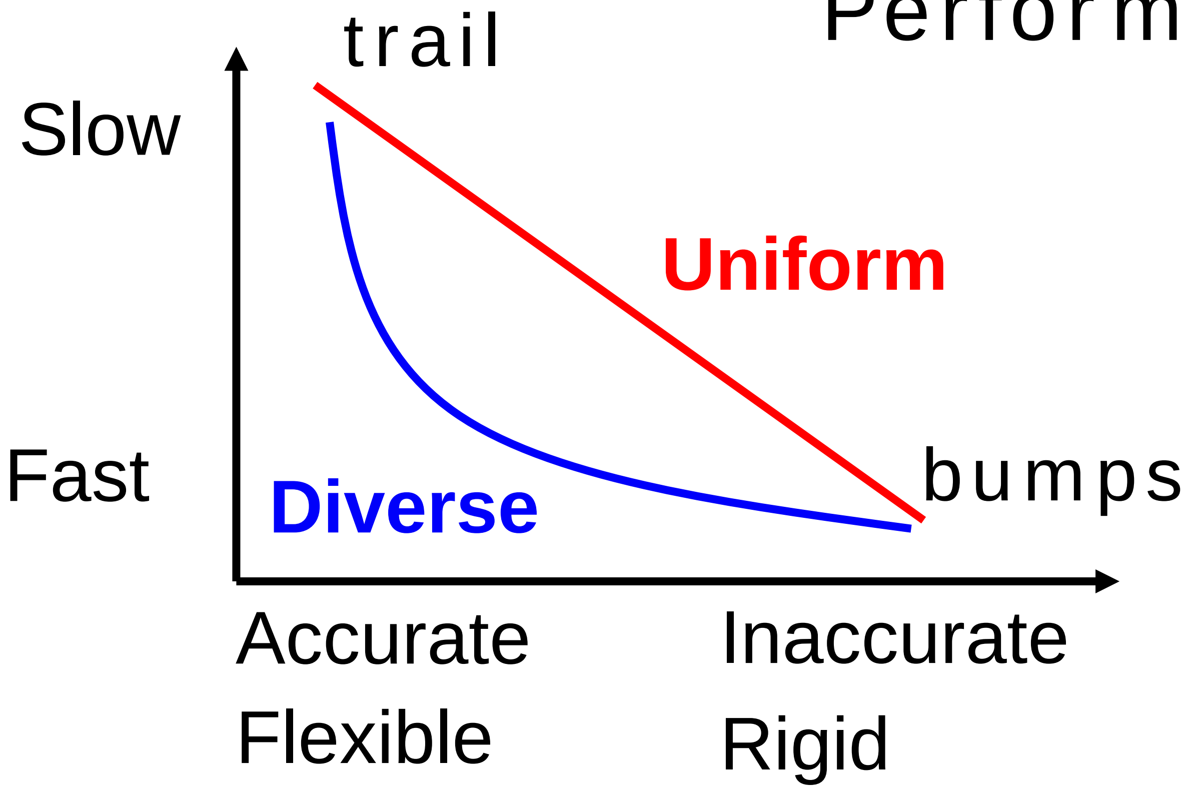
$$\text{Reaching time} = a + b\log_2\left(\frac{2D}{W}\right)$$

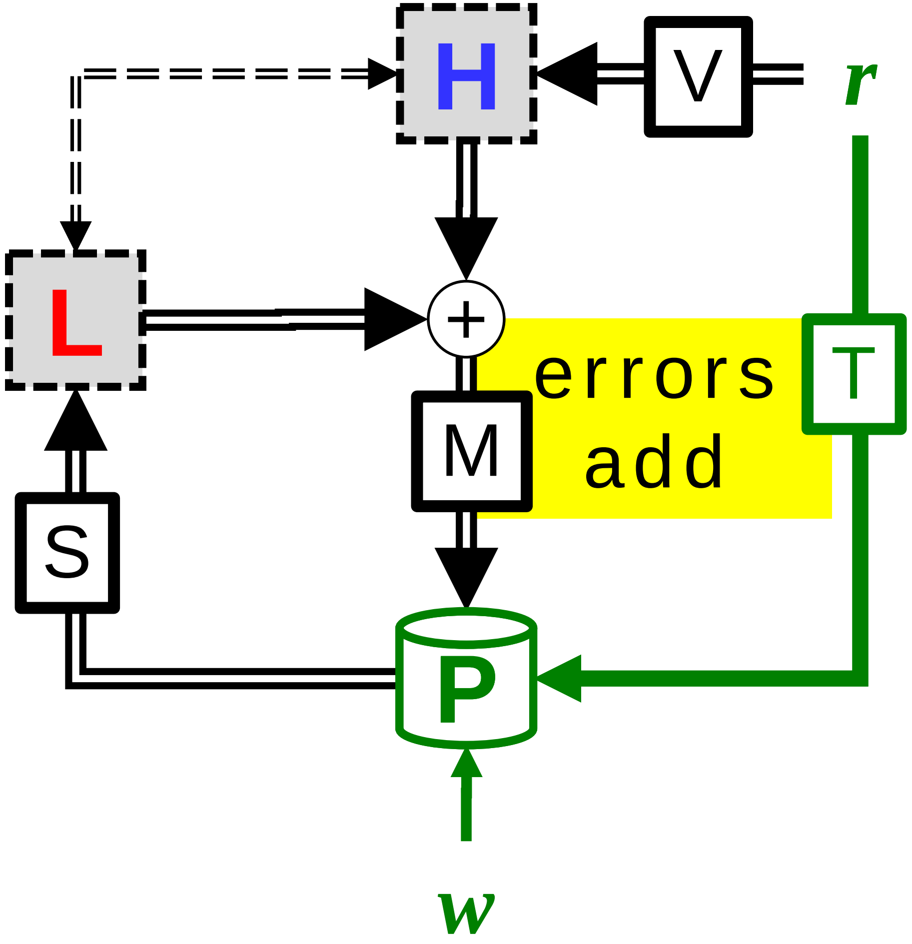
$$\text{Reaching time} = a + b\log_2\left(\frac{2D}{W}\right)$$





Performance



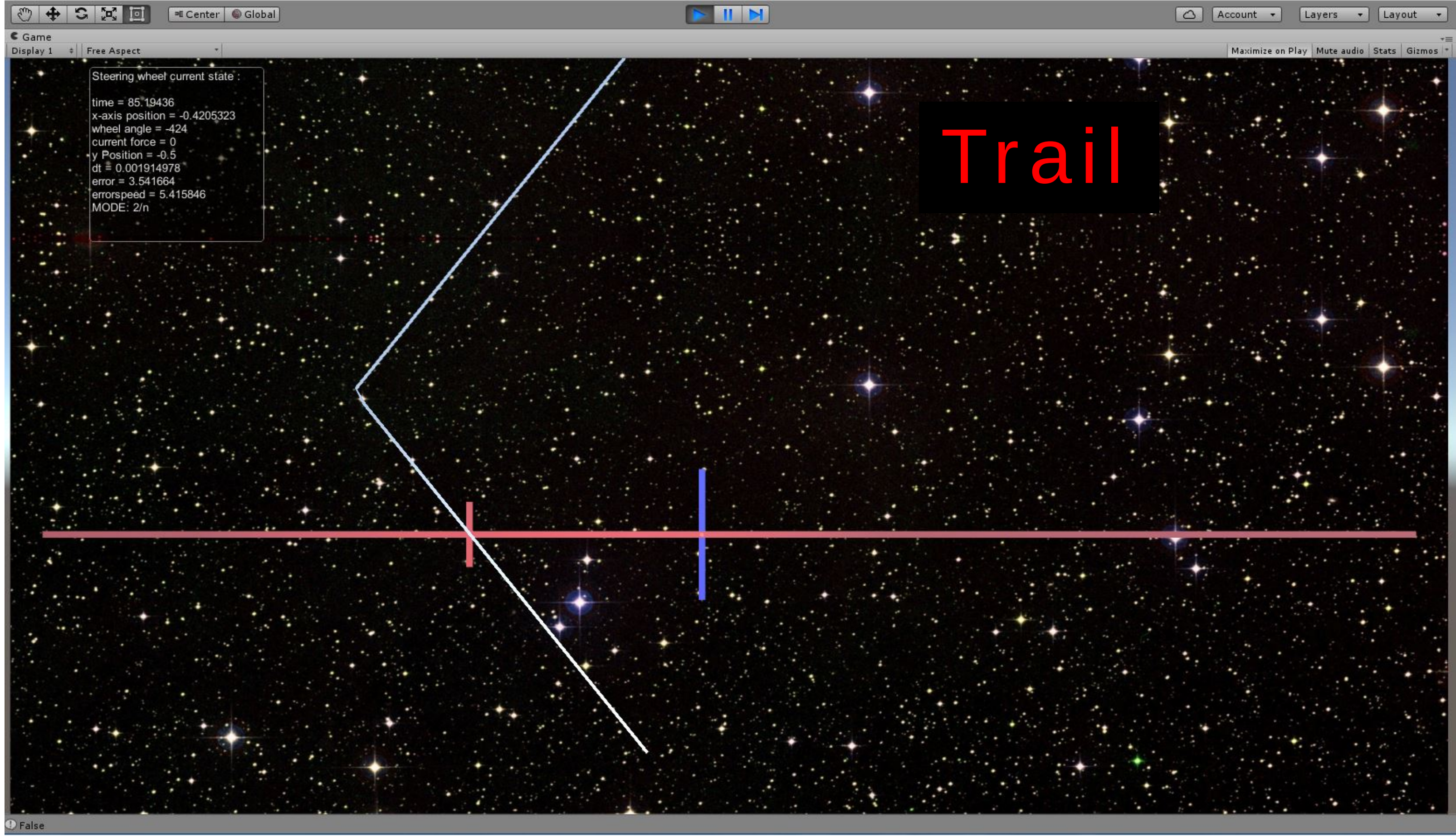


Diversity sweet spot

Diverse layers (between nerves)

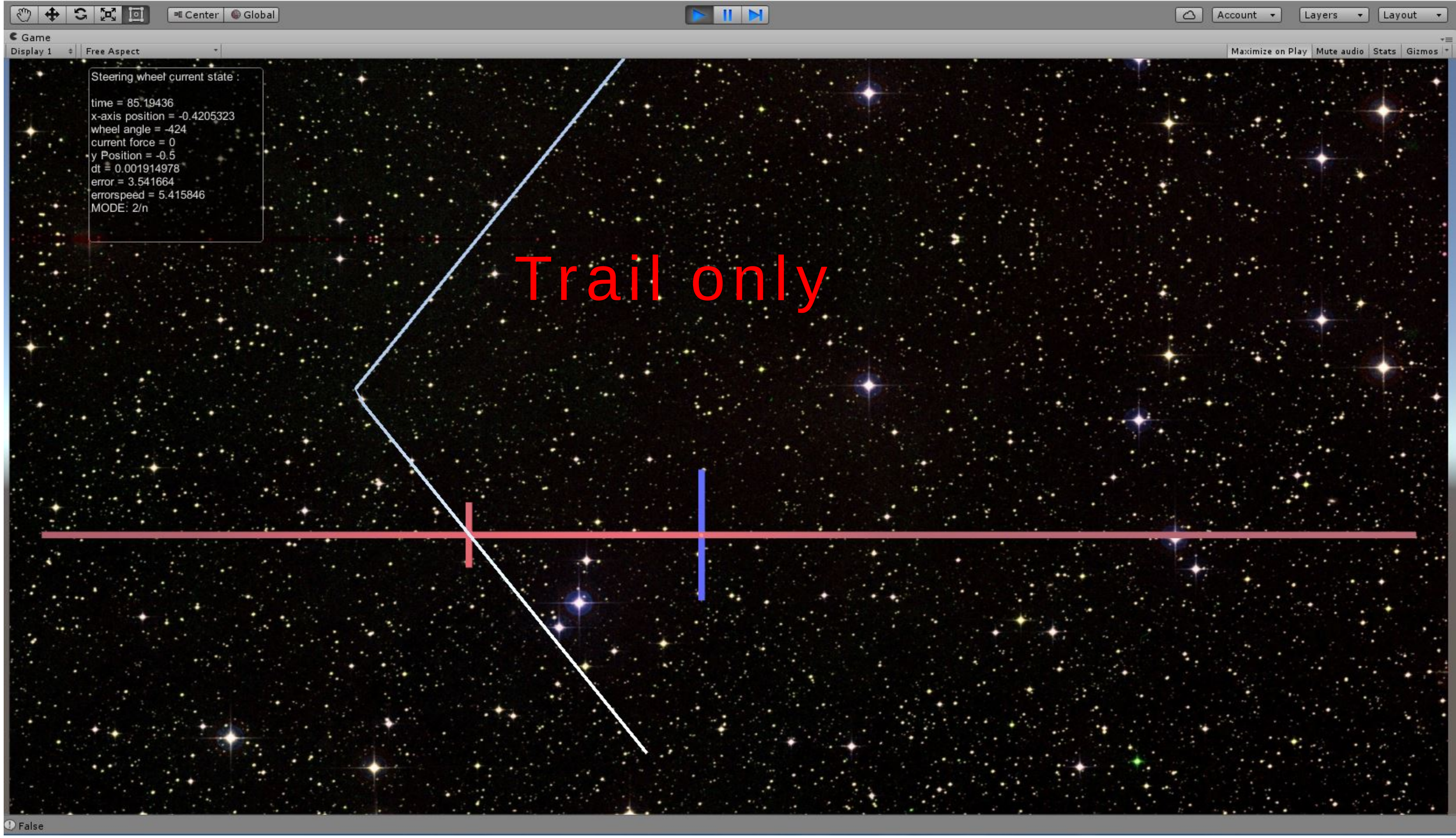
bumps trail

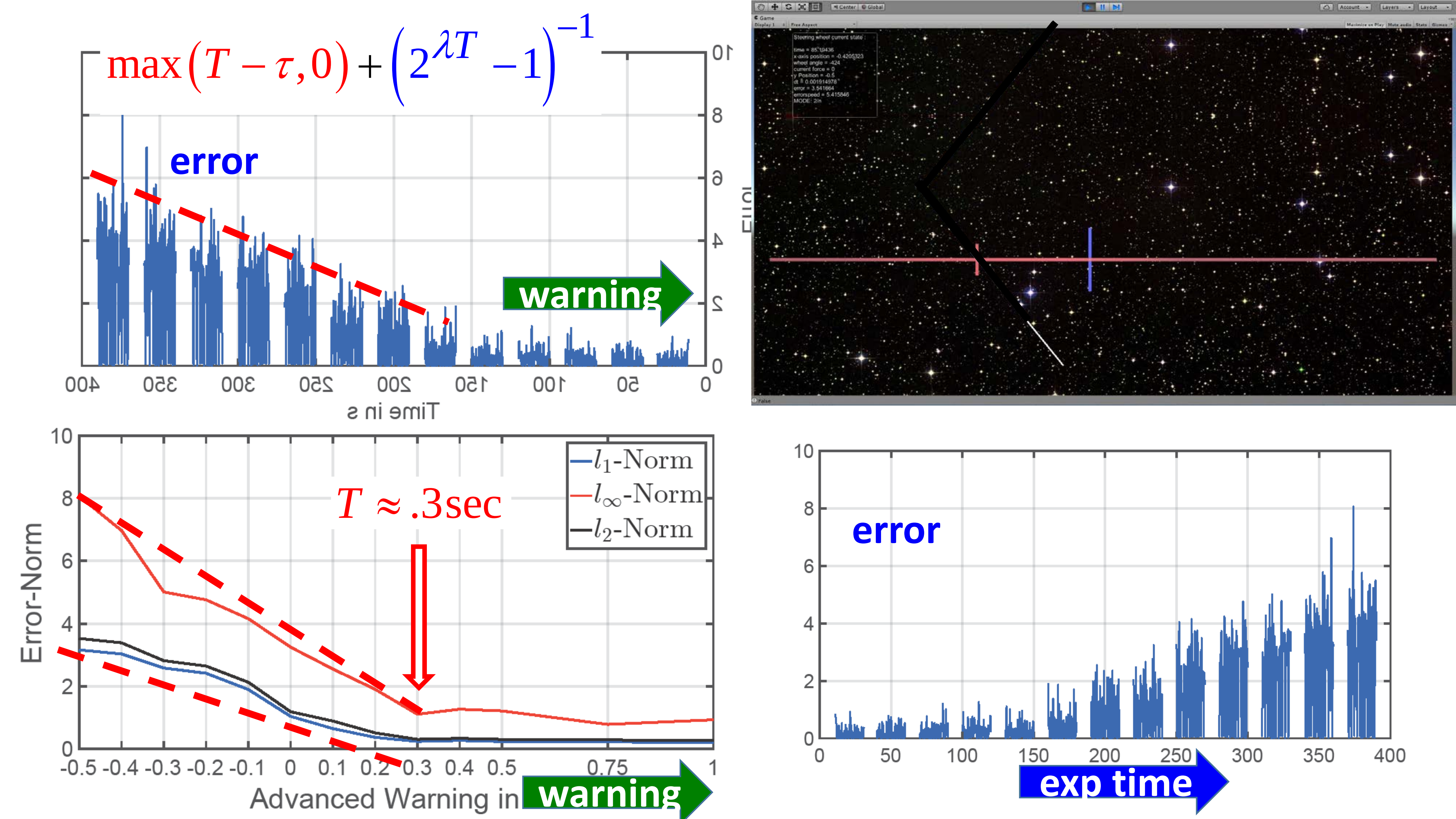
$$\delta\left(\sum_{i=1}^{T}\left|a^{i-1}\right|+\left|a^{T}\right|\left(2^{\lambda T}-|a|\right)^{-1}\right)+\left(2^{V}-|a|\right)^{-1}$$



bumps trail

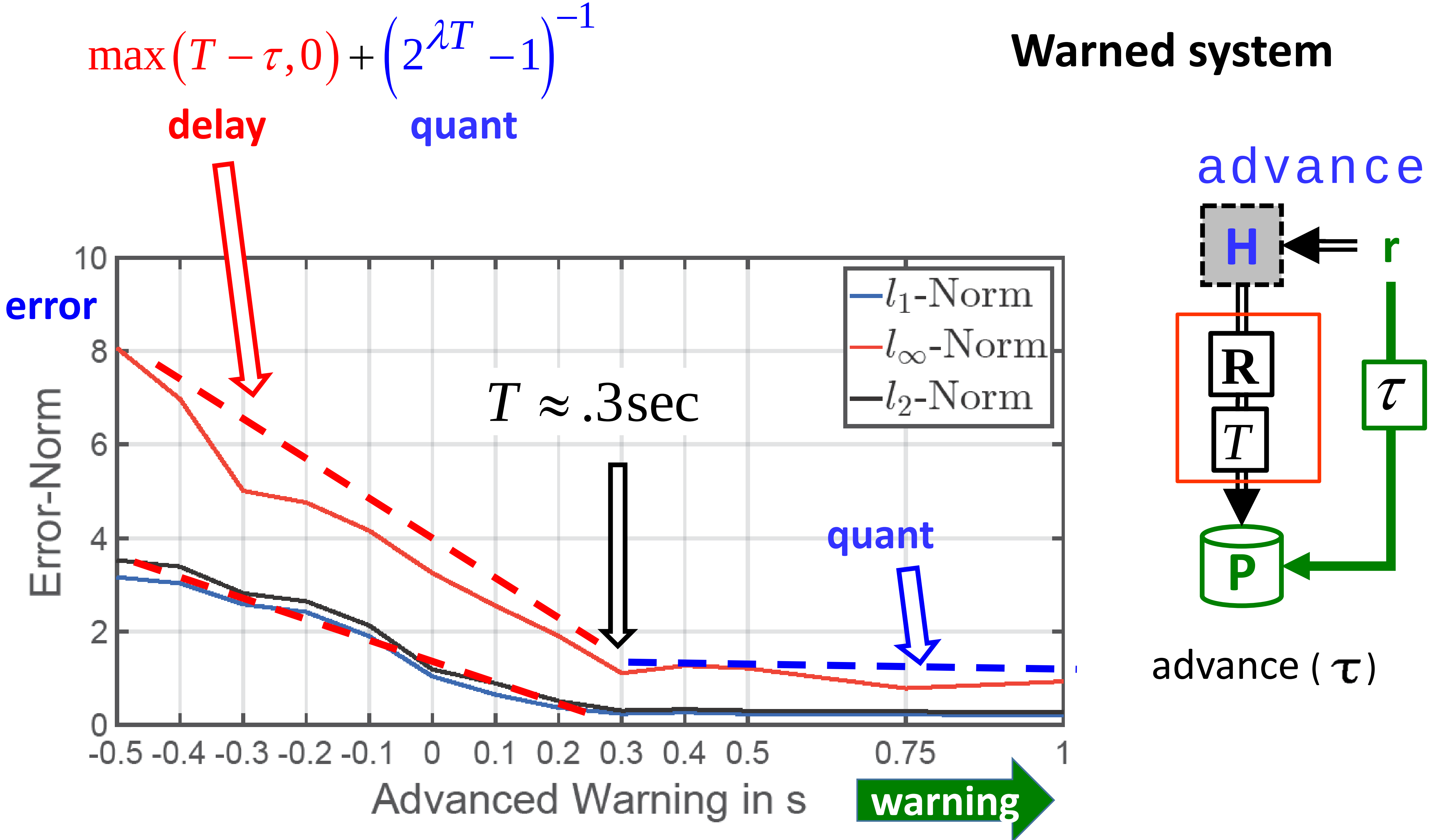
$$\delta\left(\sum_{i=1}^{T}\left|a^{i-1}\right|+\left|a^{T}\right|\left(2^{\lambda T}-|a|\right)^{-1}\right)+\left(2^{V}-|a|\right)^{-1}$$

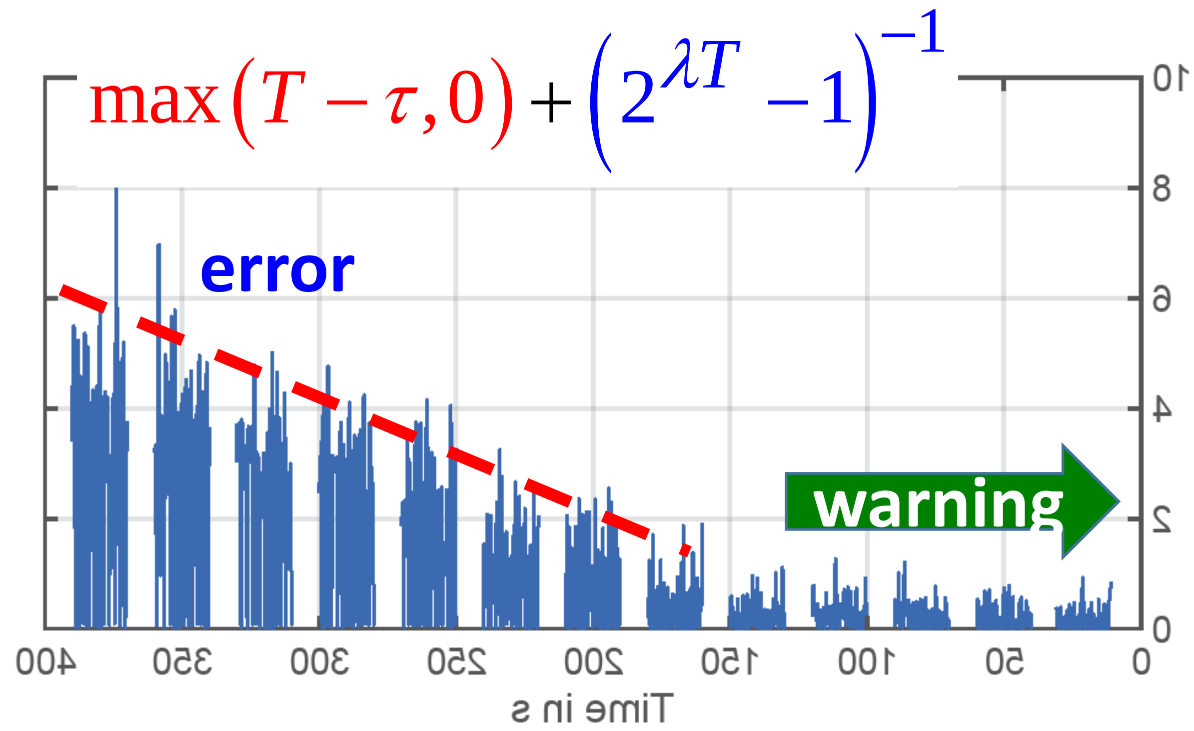

Center
Global
Account
Layers
Layout
Game
Display 1
Free Aspect
Maximize on Play
Mute audio
Stats
Gizmos
Steering wheel current state :
time = 85.19436
x-axis position = -0.4205323
wheel angle = -424
current force = 0
y Position = -0.5
dt = 0.001914978
error = 3.541664
errorspeed = 5.415846
MODE: 2/n
Trail only
False

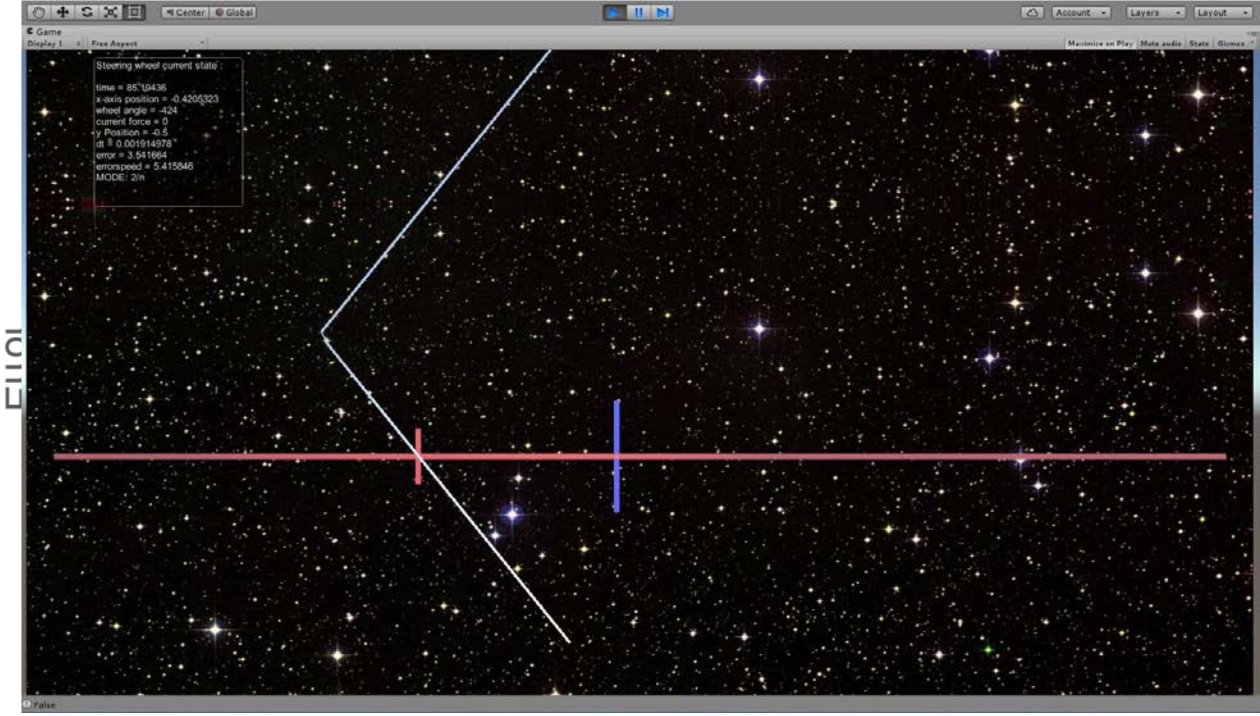


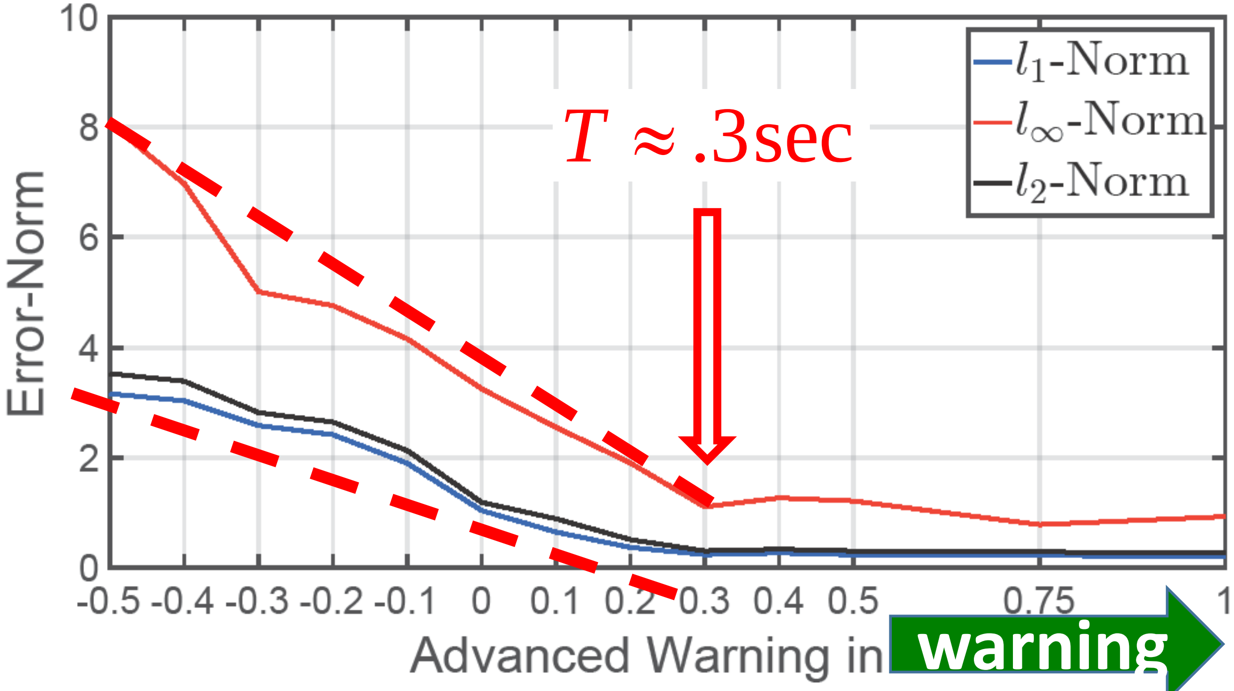
$\max(T-\tau,0)+\left(2^{\lambda T}-1\right)^{-1}$
error
warning
Time in s
$T \approx .3\mathrm{sec}$
l_1-Norm
l_∞-Norm
l_2-Norm
Error-Norm
Advanced Warning in
warning
error
exp time

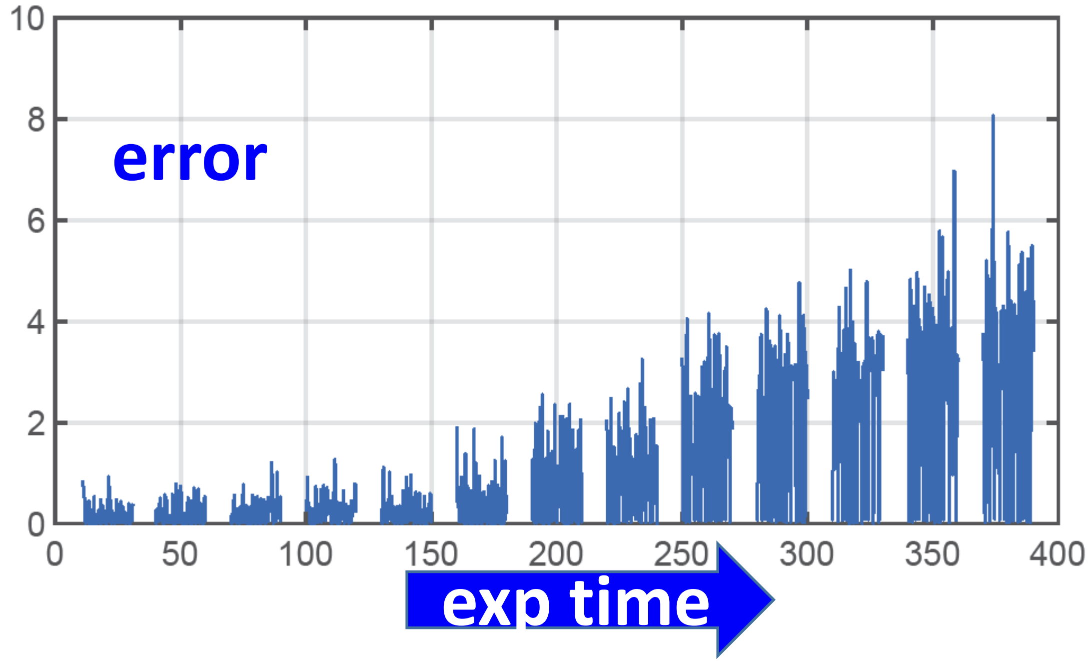
Warned system

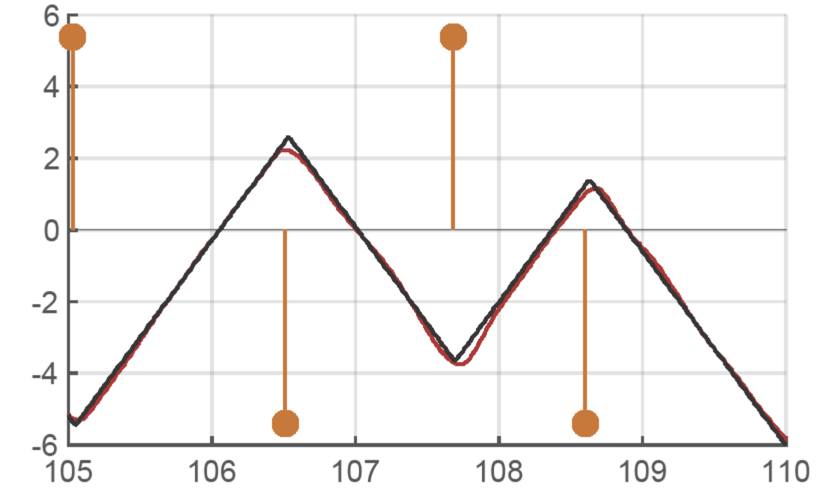


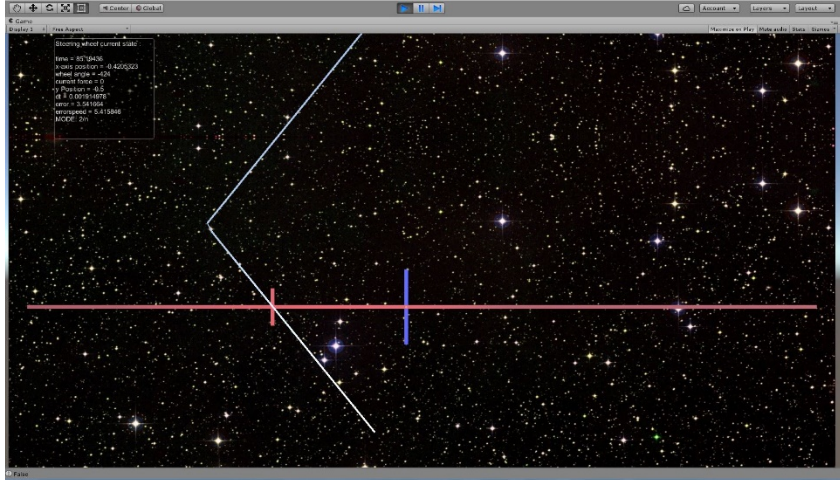

$\max(T-\tau,0)+\left(2^{\lambda T}-1\right)^{-1}$
error
warning



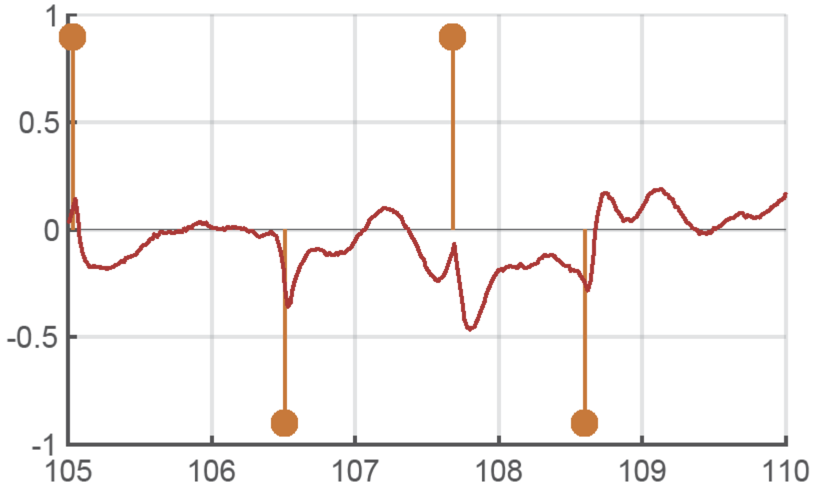

$T \approx .3\text{sec}$
l_1-Norm
l_∞-Norm
l_2-Norm
Error-Norm
Advanced Warning in
warning


error
exp time

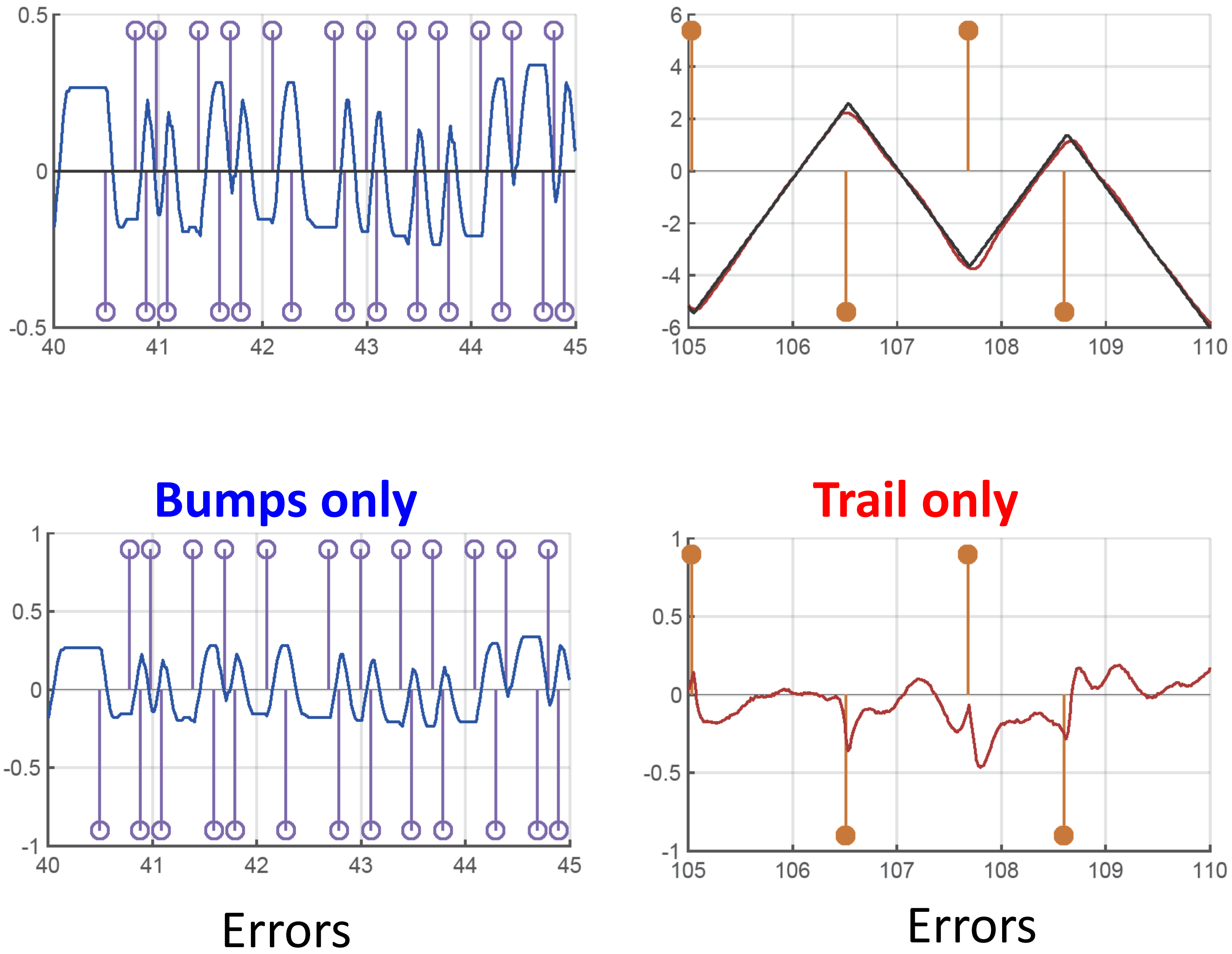


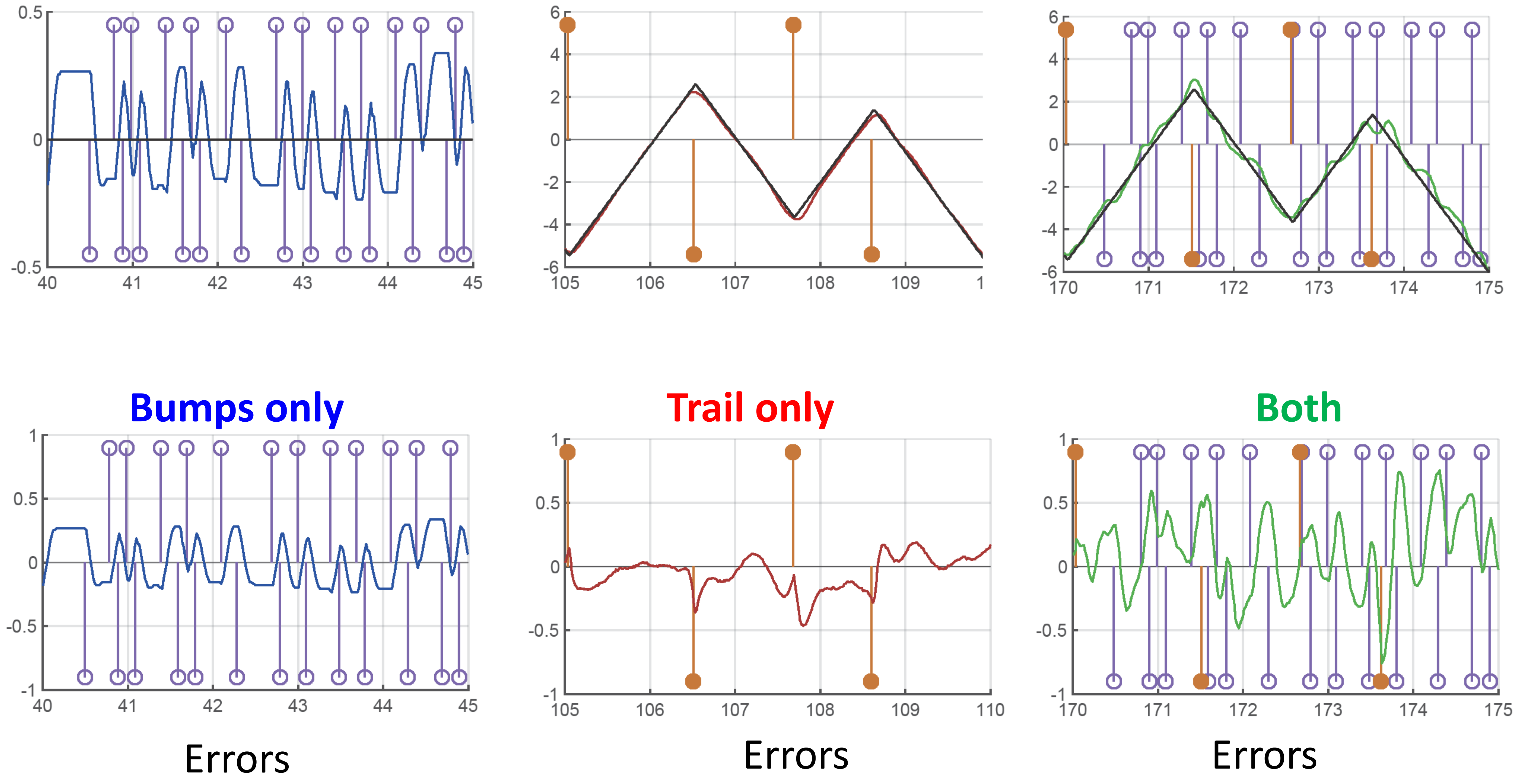


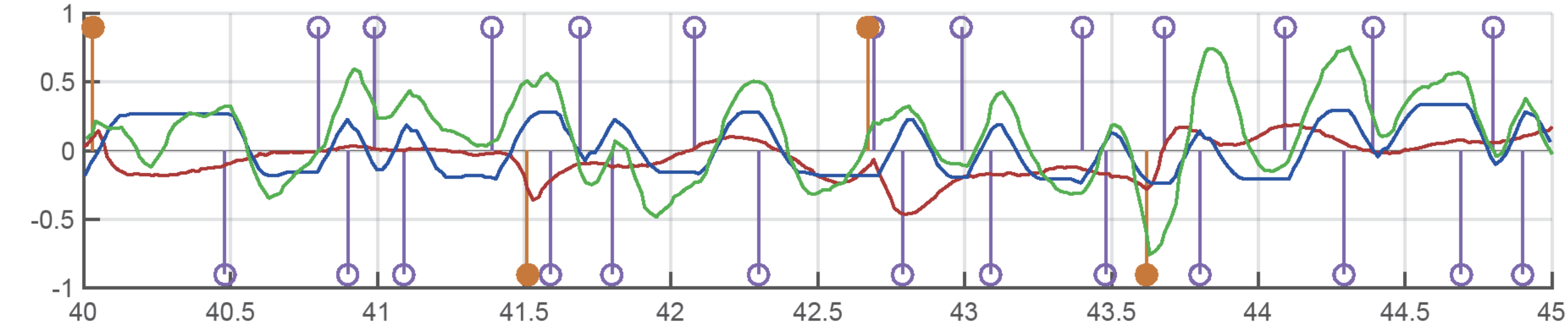
Trail only



Errors

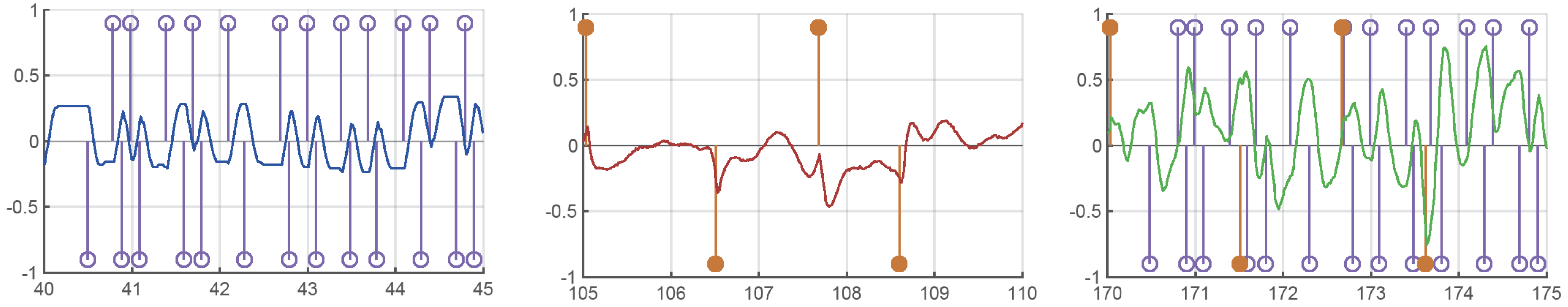

Bumps only
Trail only
Errors
Errors


Bumps only
Trail only
Both
Errors
Errors
Errors



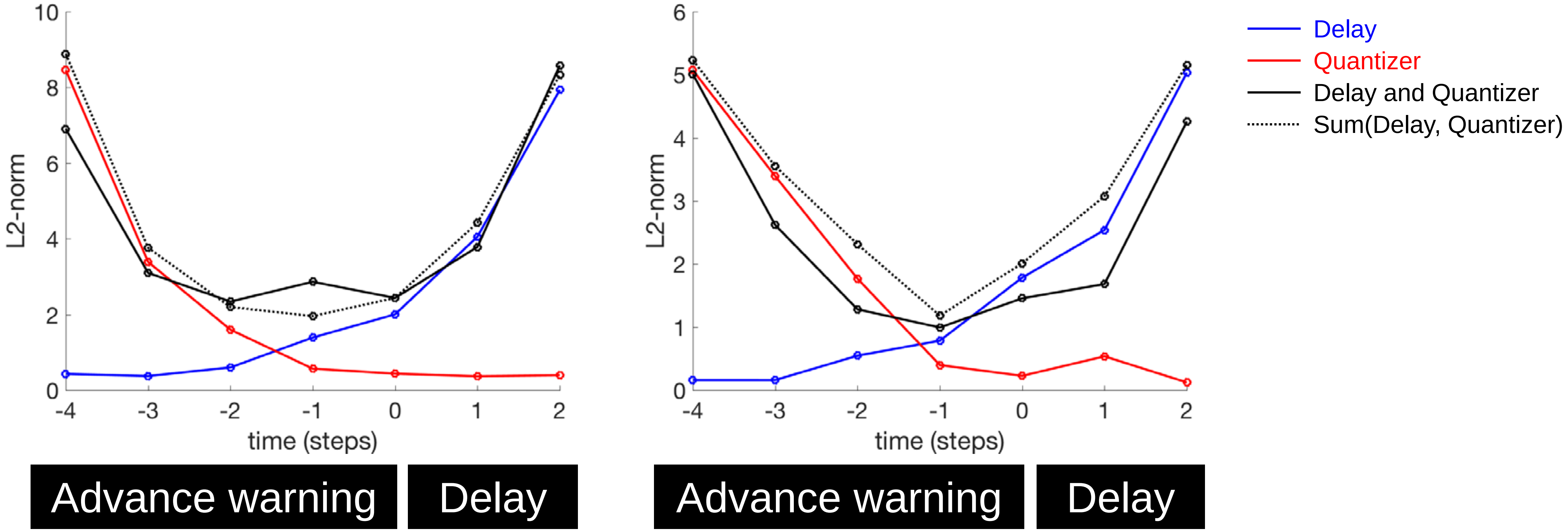
Errors

Bumps only + **Trail only** ≈ **Both**



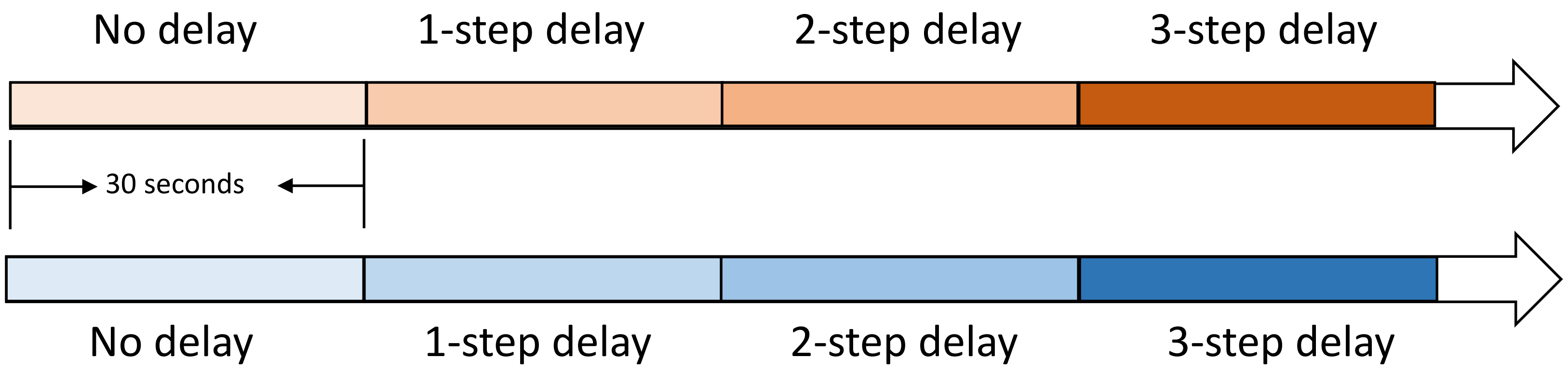
Virtualized (added) speed-accuracy tradeoff

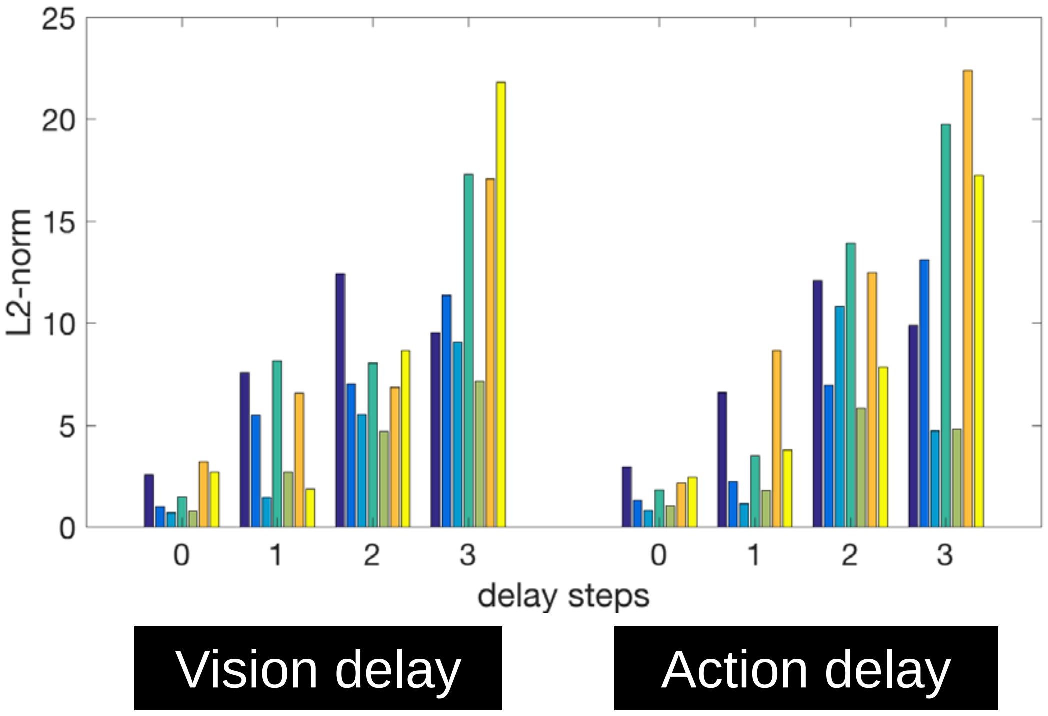
- Delay session: 30 second for each setting (T = -4, -3, -2, -1, 0, 1, 2)
- Quantizer session: 30 second (L = 1, 2, …, 7)
- Delay and Quantizer session: 30 second for each pair of settings

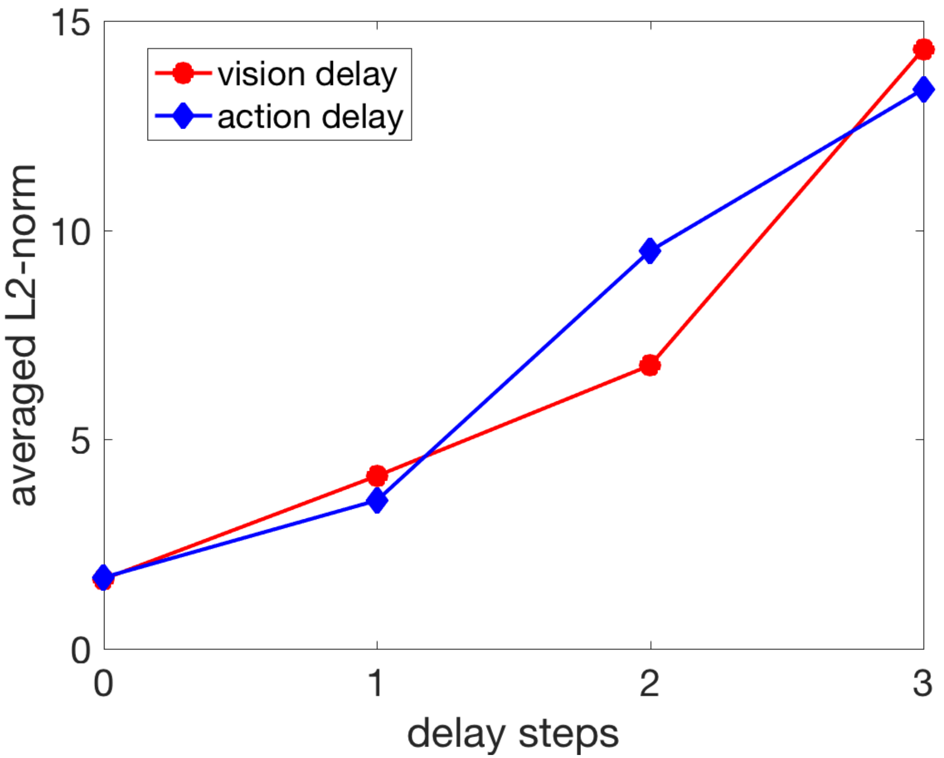


Delay in vision and in action

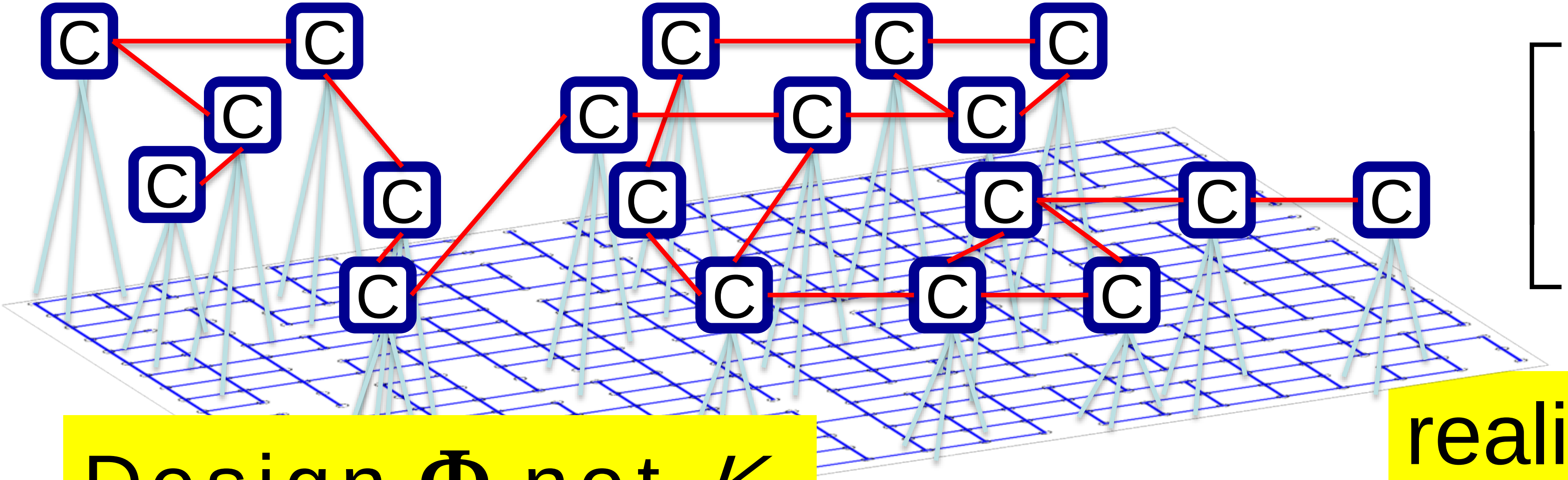
- Vision delay
- Action delay







Sparse sense, comms, comp, ctrl, act



$$\begin{bmatrix} x \\ u \end{bmatrix} = \begin{bmatrix} \Phi_{11} \\ \Phi_{21} \end{bmatrix} \delta x$$

Design $\mathbf{\Phi}$ not K.

realizable ($\exists$ K) iff

Affine constraint $$\begin{bmatrix} zI - A & -B \end{bmatrix} \begin{bmatrix} \Phi_{11} \\ \Phi_{21} \end{bmatrix} = I$$

State feedback $$K = \Phi_{21} \left(\Phi_{11} \right)^{-1}$$

Spacetime/sparsity constraints are convex in Φ but not in *K*.

$$\begin{bmatrix} x \\ u \end{bmatrix} = \begin{bmatrix} \Phi_{11} \\ \Phi_{21} \end{bmatrix} \delta x$$

local, strictly causal, sparse, structured

Design Φ not *K*.

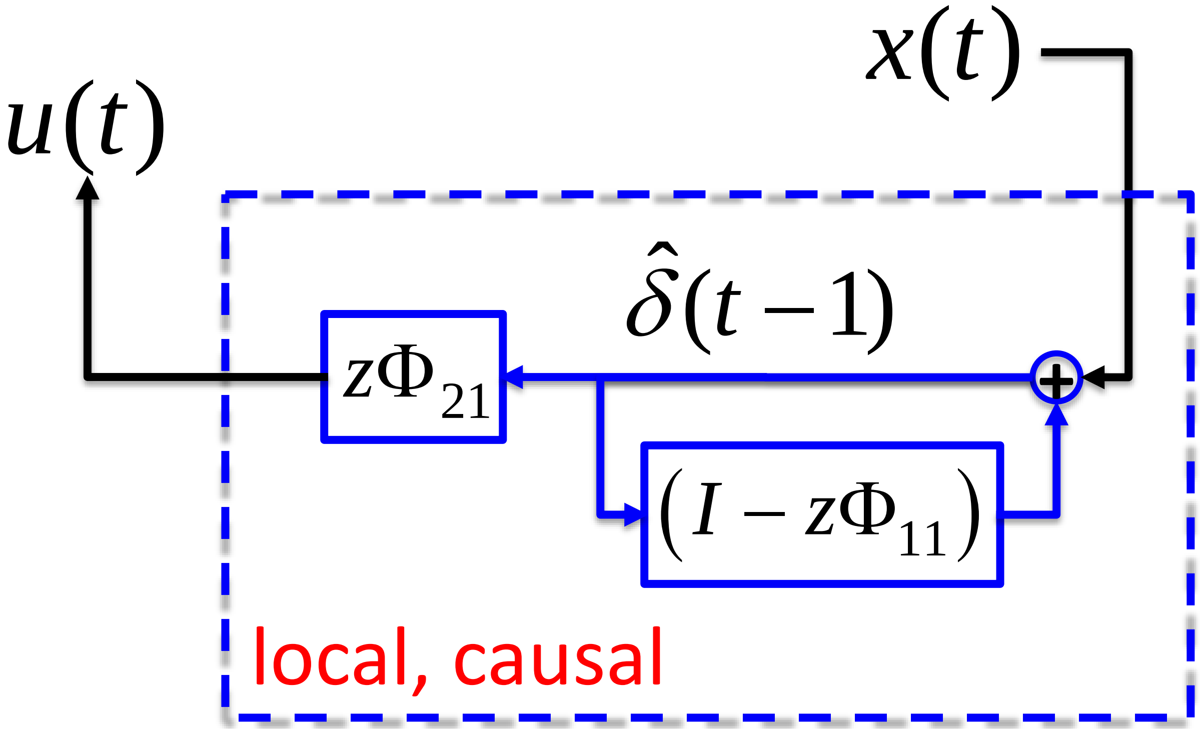
$$K = \Phi_{21}\left(\Phi_{11}\right)^{-1}$$

Spacetime/sparsity constraints are convex in Φ but not in *K*.

This is a very complicated but interesting way to implement K.

$$\begin{bmatrix} x \\ u \end{bmatrix} = \begin{bmatrix} \Phi_{11} \\ \Phi_{21} \end{bmatrix} \delta x$$

local, strictly causal



$$K = \Phi_{21}(\Phi_{11})^{-1}$$
$$= z\Phi_{21}(z\Phi_{11})^{-1}$$
$$= z\Phi_{21}\left[I - (I - z\Phi_{11})\right]^{-1}$$

local, causal

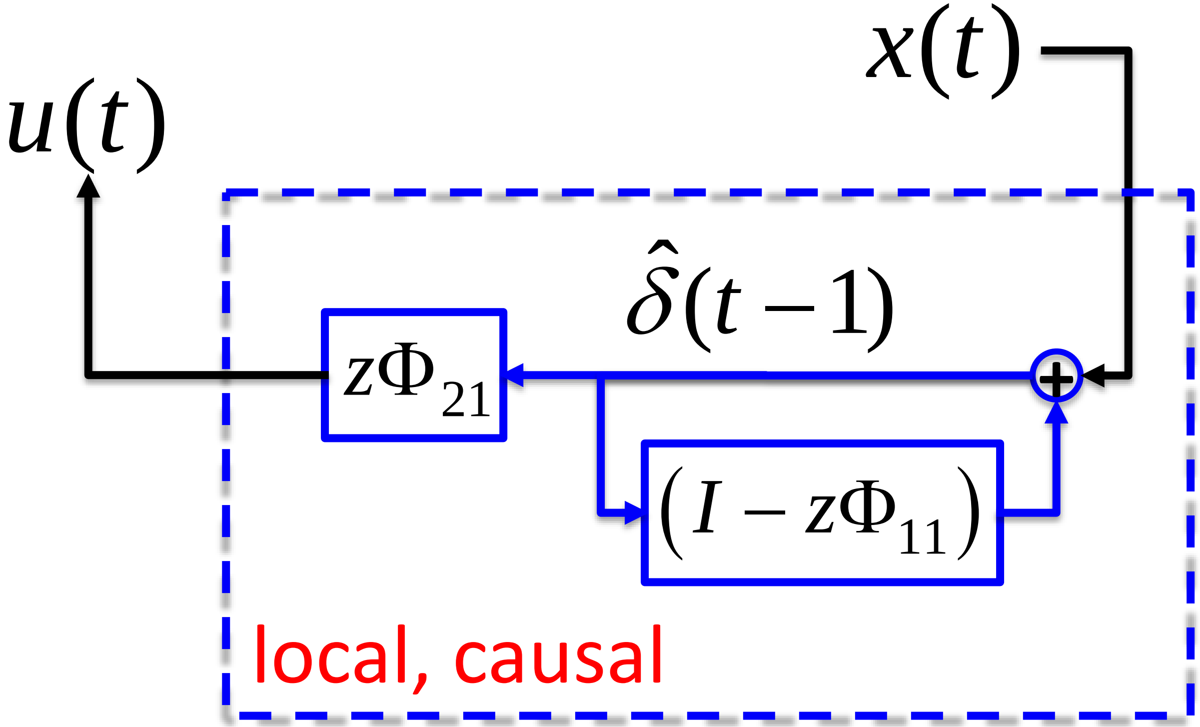
Spacetime/sparsity constraints are convex in Φ but not in *K*.

This is a very complicated but interesting way to implement K.

The interpretation of the controller components is clear however

$$\begin{bmatrix} x \\ u \end{bmatrix} = \begin{bmatrix} \Phi_{11} \\ \Phi_{21} \end{bmatrix} \delta x$$

local, strictly causal

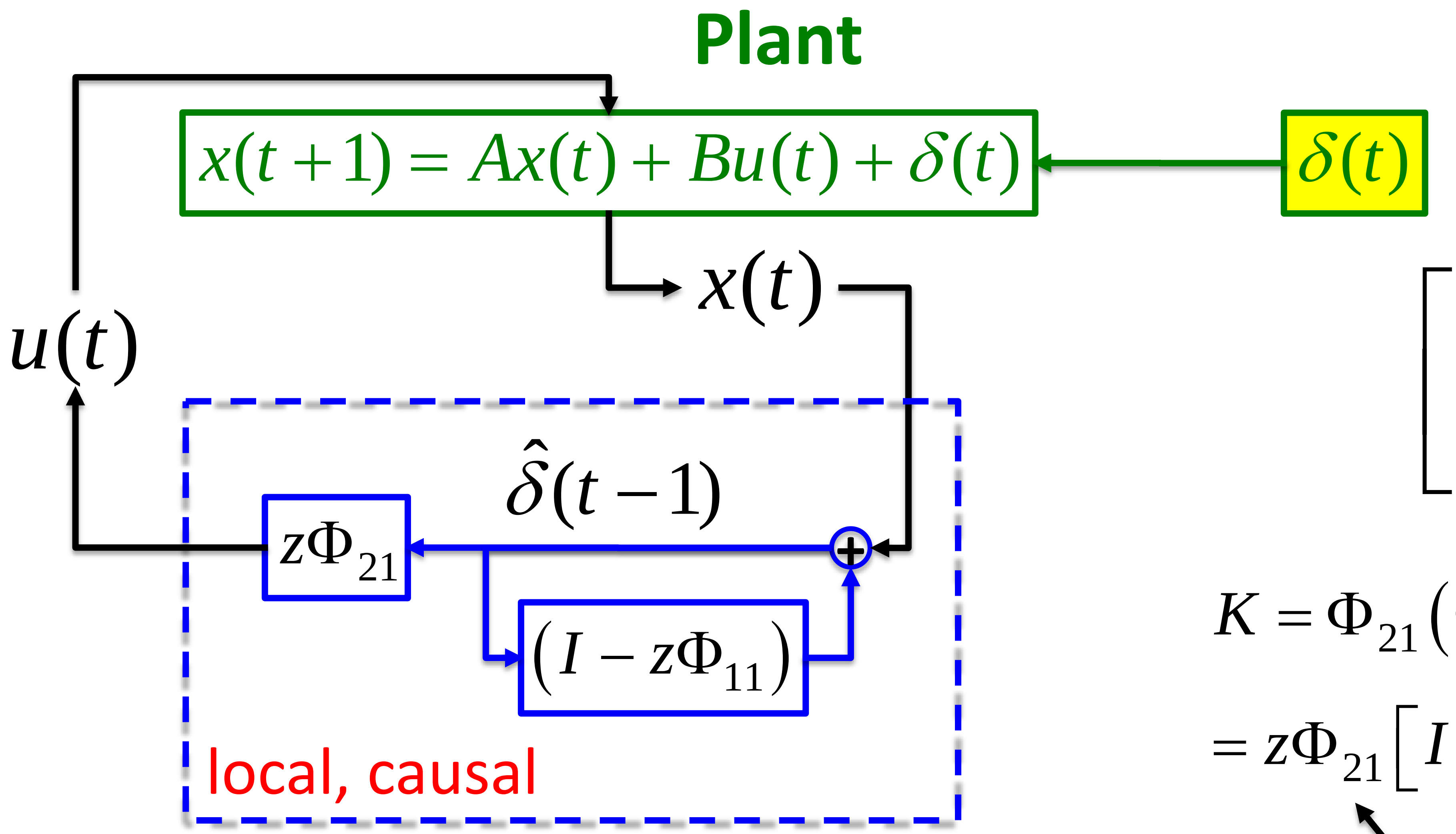


$$K = \Phi_{21}(\Phi_{11})^{-1}$$

$$= z\Phi_{21}(z\Phi_{11})^{-1}$$

$$= z\Phi_{21}\left[I - (I - z\Phi_{11})\right]^{-1}$$

local, causal



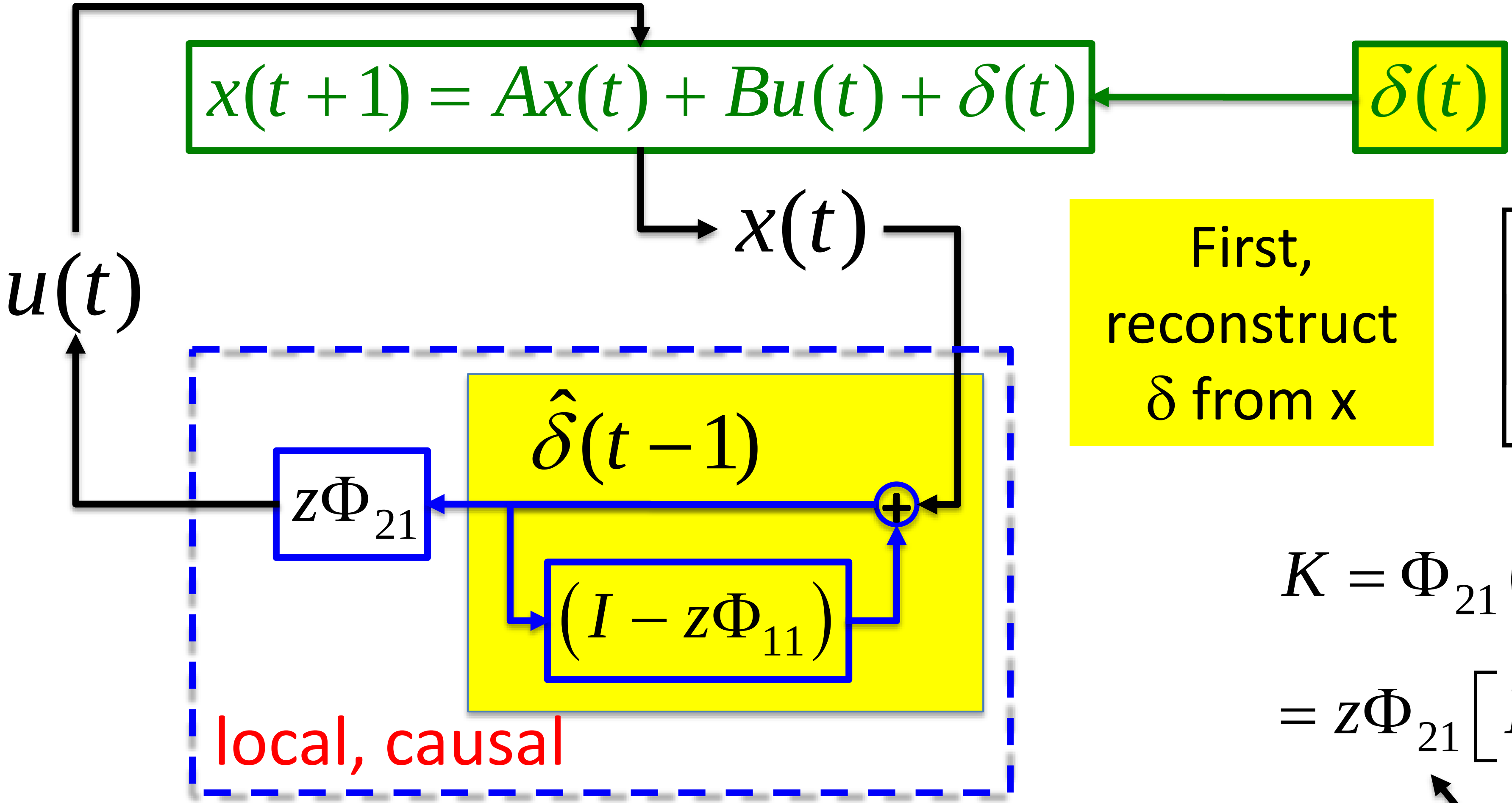
$$K = \Phi_{21}\left(\Phi_{11}\right)^{-1}$$

$$\begin{bmatrix} x \\ u \end{bmatrix} = \begin{bmatrix} \Phi_{11} \\ \Phi_{21} \end{bmatrix} \delta x$$

$$K = \Phi_{21}\left(\Phi_{11}\right)^{-1}$$

$$= z\Phi_{21}\left[I - \left(I - z\Phi_{11}\right)\right]^{-1}$$

local, causal



$$K = \Phi_{21}(\Phi_{11})^{-1}$$

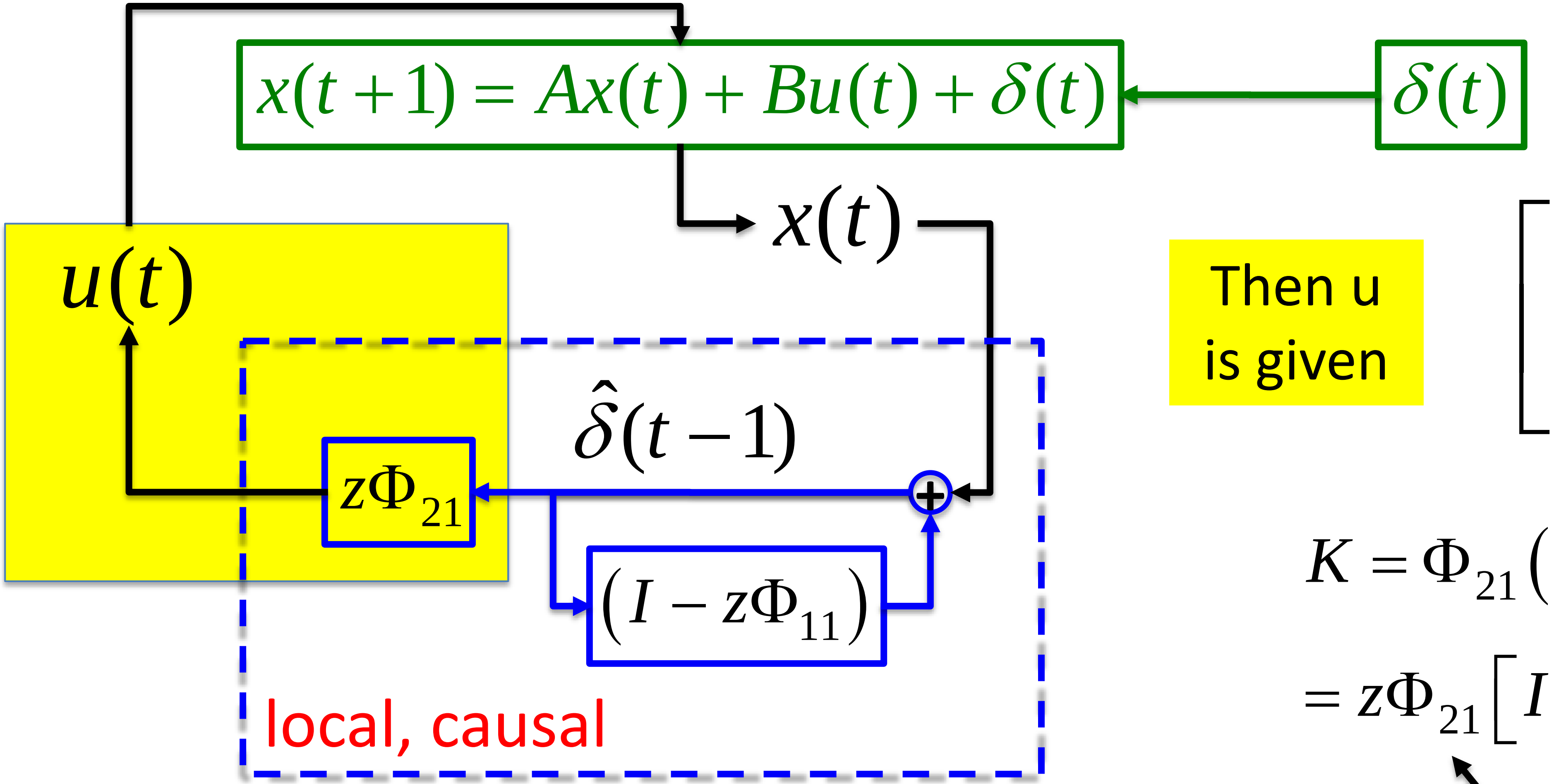
First, reconstruct δ from x

$$\begin{bmatrix} x \\ u \end{bmatrix} = \begin{bmatrix} \Phi_{11} \\ \Phi_{21} \end{bmatrix} \delta x$$

$$K = \Phi_{21}(\Phi_{11})^{-1}$$

$$= z\Phi_{21}\left[I - (I - z\Phi_{11})\right]^{-1}$$

local, causal



$$K = \Phi_{21}(\Phi_{11})^{-1}$$

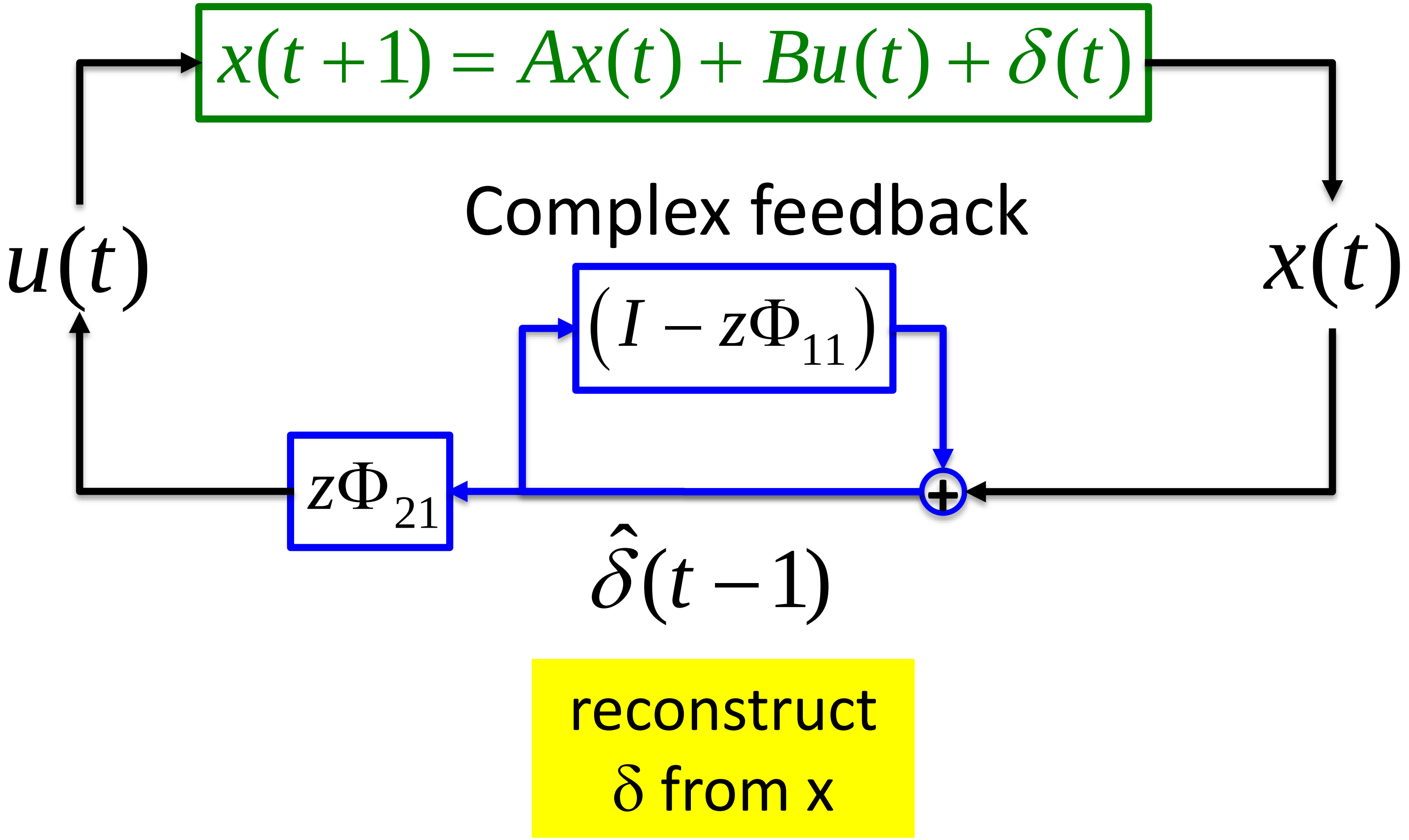
Then u is given

$$\begin{bmatrix} x \\ u \end{bmatrix} = \begin{bmatrix} \Phi_{11} \\ \Phi_{21} \end{bmatrix} \delta x$$

$$K = \Phi_{21}(\Phi_{11})^{-1}$$

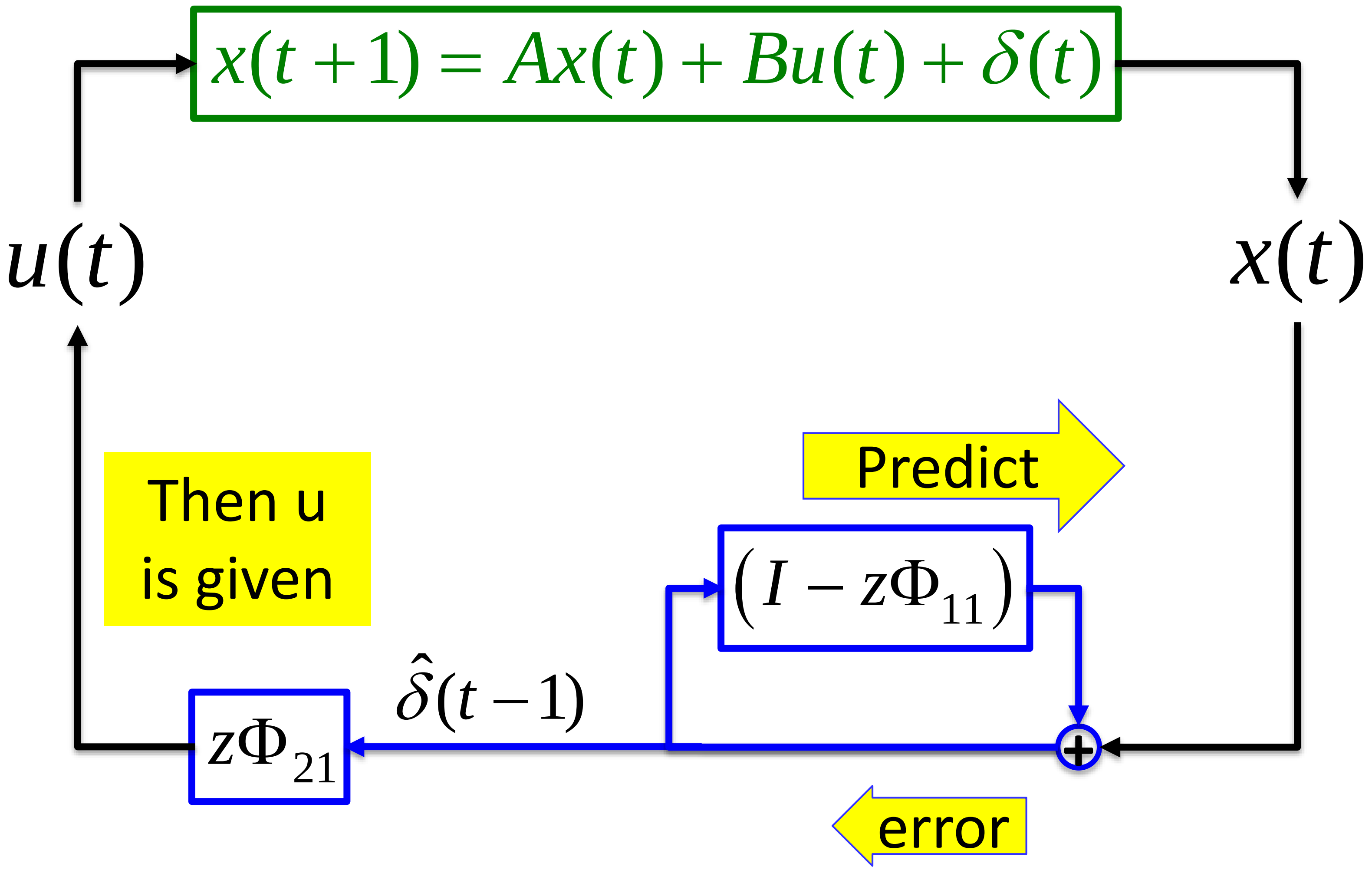
$$= z\Phi_{21}\left[I - (I - z\Phi_{11})\right]^{-1}$$

local, causal



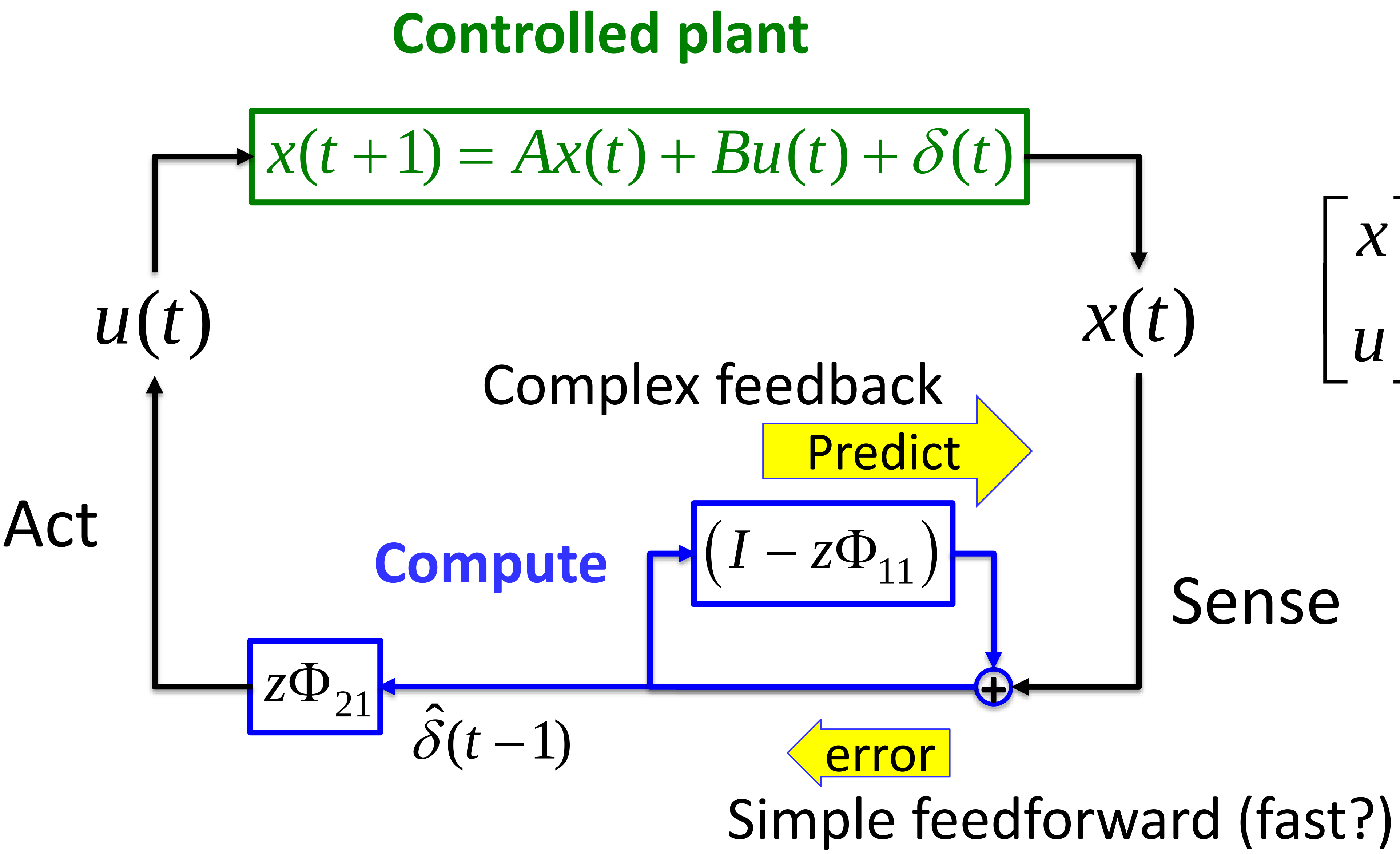
$$\begin{bmatrix} x \\ u \end{bmatrix} = \begin{bmatrix} \Phi_{11} \\ \Phi_{21} \end{bmatrix} \delta x$$

Why the feedback?



$$\begin{bmatrix} x \\ u \end{bmatrix} = \begin{bmatrix} \Phi_{11} \\ \Phi_{21} \end{bmatrix} \delta x$$

Why the feedback?



$$\begin{bmatrix} x \\ u \end{bmatrix} = \begin{bmatrix} \Phi_{11} \\ \Phi_{21} \end{bmatrix} \delta x$$

SUBMITTED TO IEEE TRANSACTIONS ON AUTOMATIC CONTROL, VOL. XX, NO. XX, OCTOBER 2016

A System Level Approach to Controller Synthesis

Yuh-Shyang Wang, *Member, IEEE,* Nikolai Matni, *Member, IEEE,* and John C. Doyle

Output feedback

$$\begin{bmatrix} zI - A & -B_2 \end{bmatrix} \begin{bmatrix} \mathbf{R} & \mathbf{N} \\ \mathbf{M} & \mathbf{L} \end{bmatrix} = \begin{bmatrix} I & 0 \end{bmatrix} \tag{20a}$$

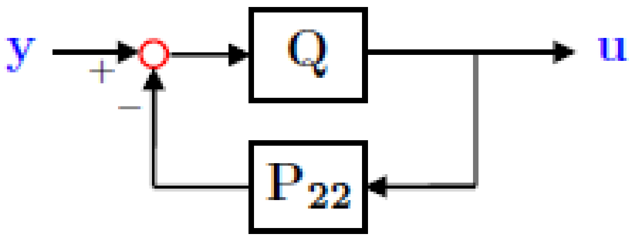
$$\begin{bmatrix} \mathbf{R} & \mathbf{N} \\ \mathbf{M} & \mathbf{L} \end{bmatrix} \begin{bmatrix} zI - A \\ -C_2 \end{bmatrix} = \begin{bmatrix} I \\ 0 \end{bmatrix} \tag{20b}$$

$$\mathbf{R}, \mathbf{M}, \mathbf{N} \in \frac{1}{z}\mathcal{RH}_\infty, \quad \mathbf{L} \in \mathcal{RH}_\infty \tag{20c}$$

Affine constraint

Special case: stable plant

$$\mathbf{Q} = \mathbf{L}$$

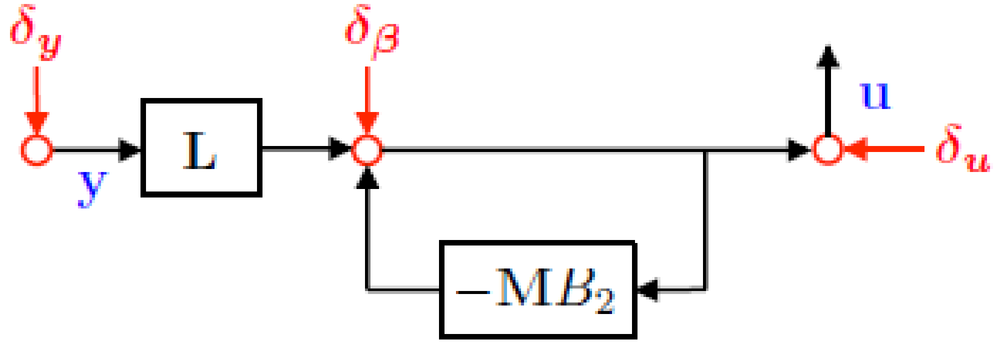


(a) Internal Model Control

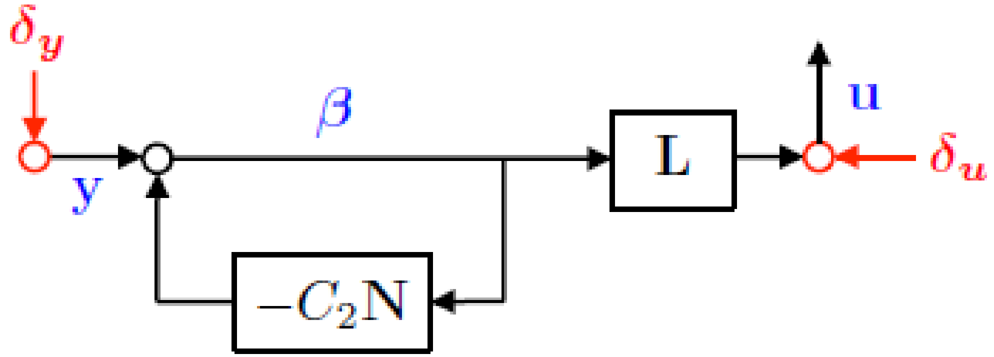
$$\begin{bmatrix} zI - A & -B_2 \end{bmatrix} \begin{bmatrix} \mathbf{R} & \mathbf{N} \\ \mathbf{M} & \mathbf{L} \end{bmatrix} = \begin{bmatrix} I & 0 \end{bmatrix} \quad \text{(20a)}$$

$$\begin{bmatrix} \mathbf{R} & \mathbf{N} \\ \mathbf{M} & \mathbf{L} \end{bmatrix} \begin{bmatrix} zI - A \\ -C_2 \end{bmatrix} = \begin{bmatrix} I \\ 0 \end{bmatrix} \quad \text{(20b)}$$

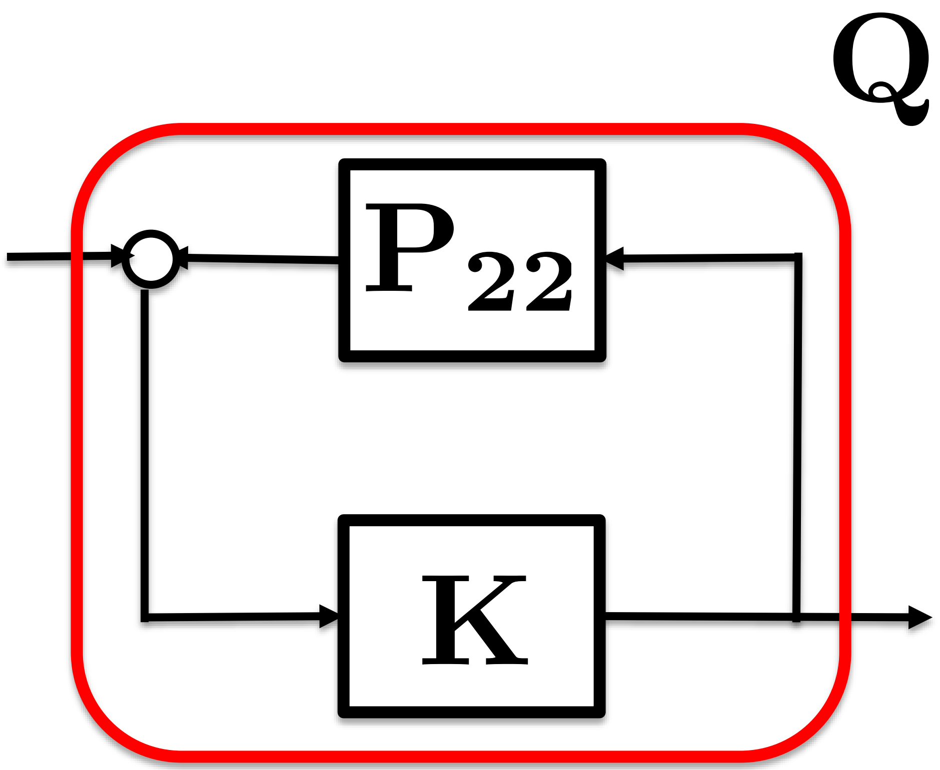
$$\mathbf{R}, \mathbf{M}, \mathbf{N} \in \frac{1}{z}\mathcal{RH}_\infty, \quad \mathbf{L} \in \mathcal{RH}_\infty \quad \text{(20c)}$$

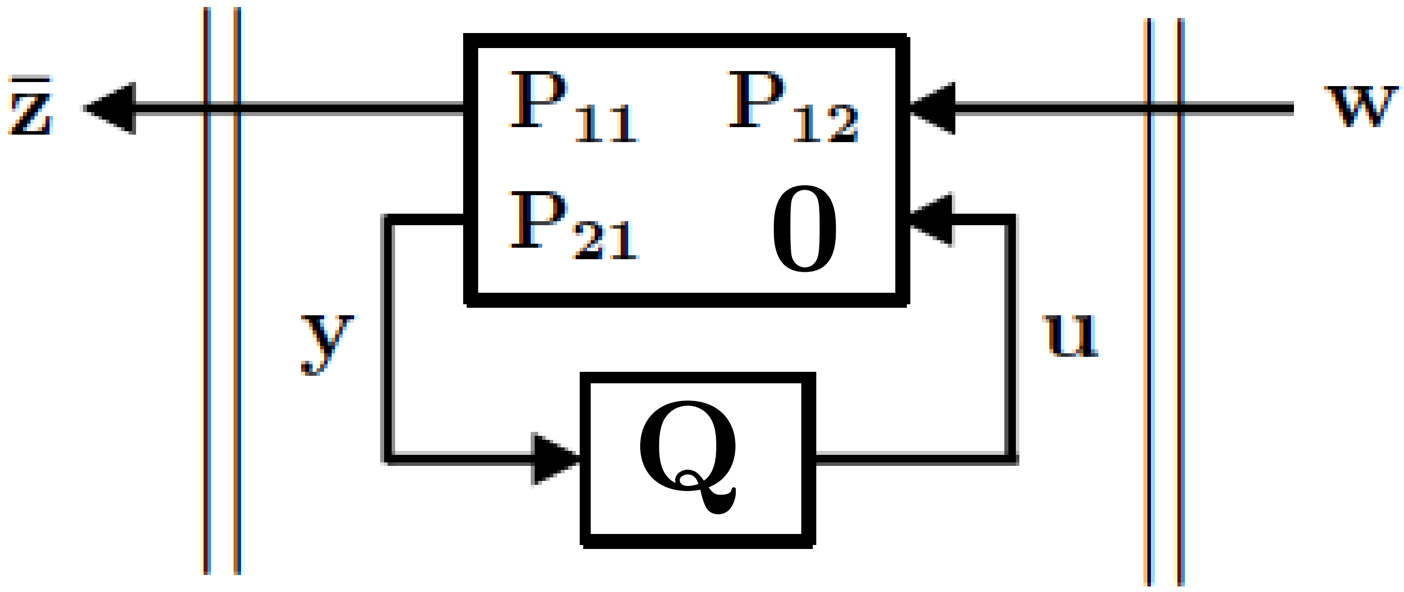


(b) Structure 1



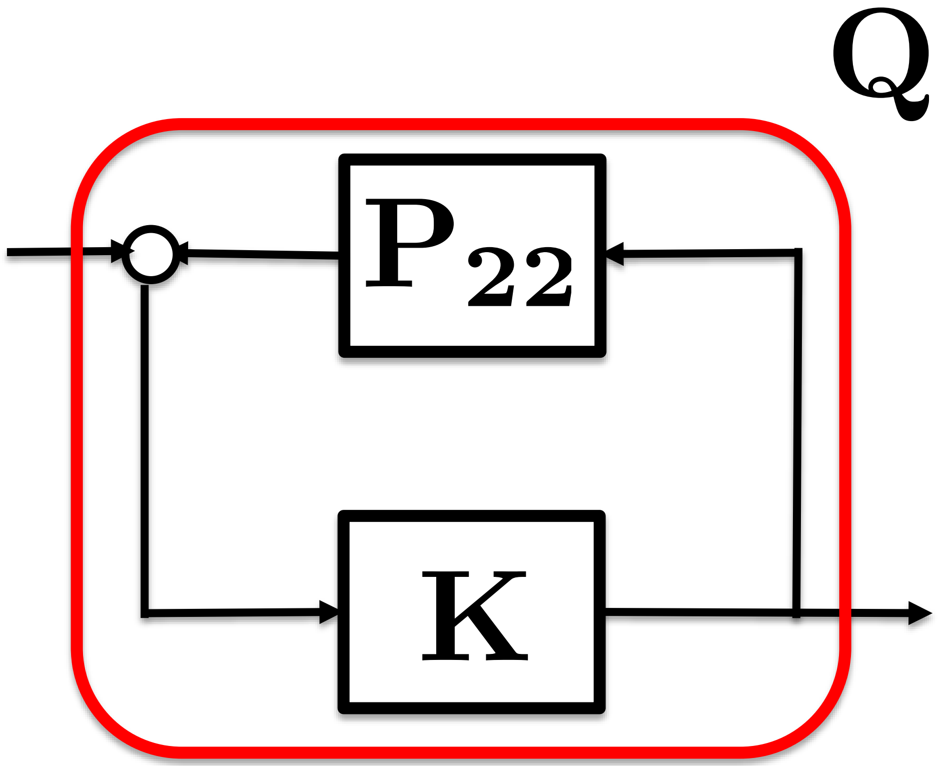
(c) Structure 2

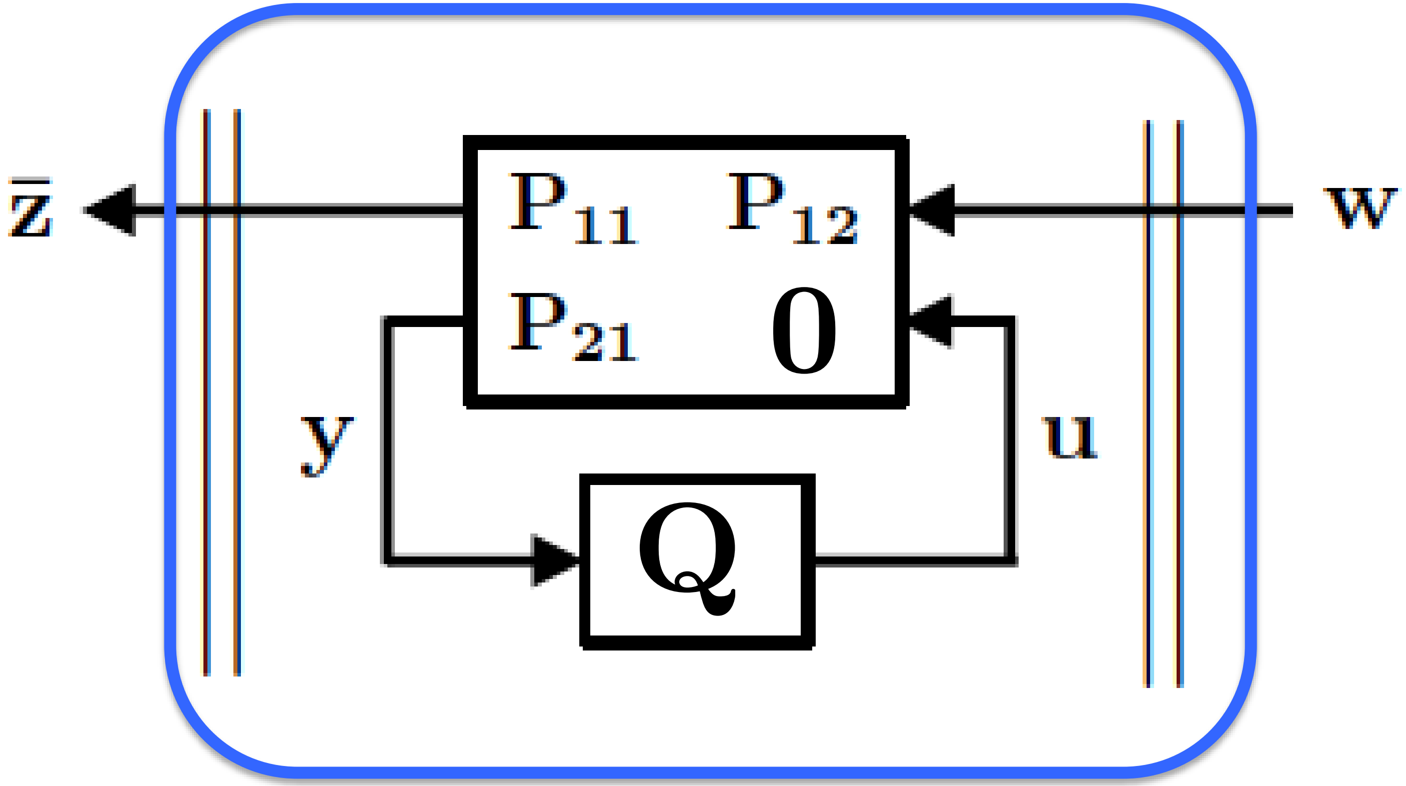




convex!

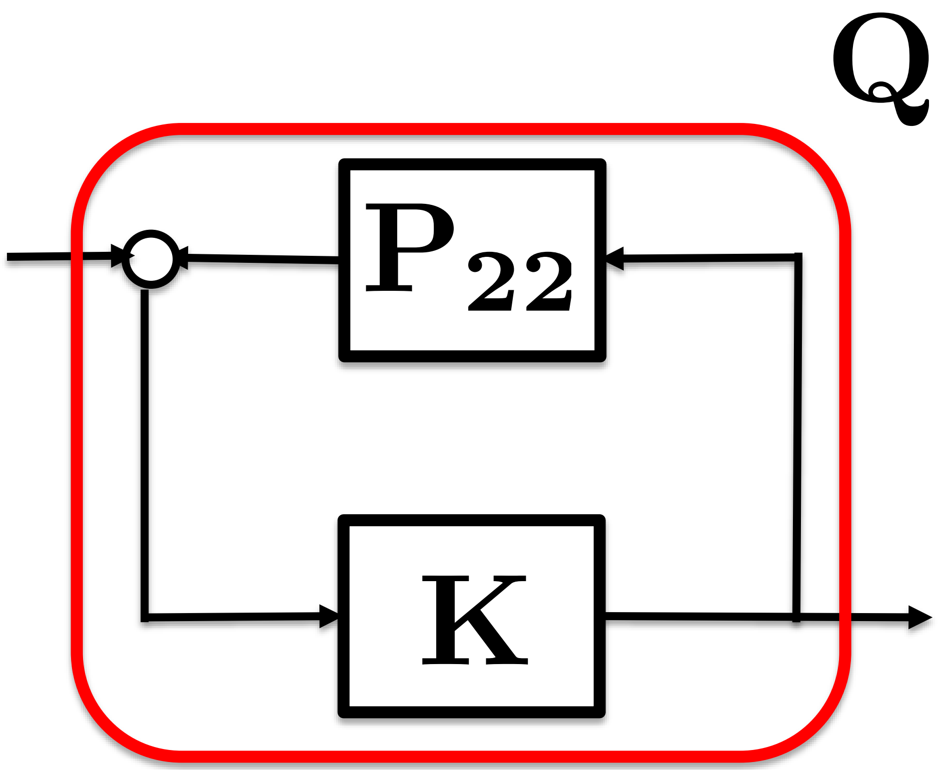
$$\begin{aligned} &\text{minimize } \|\mathbf{P_{11}} - \mathbf{P_{12}QP_{21}}\| \\ &\text{subject to } \mathbf{Q} \text{ stable} \\ &\mathbf{K} \in \mathcal{C} \end{aligned}$$

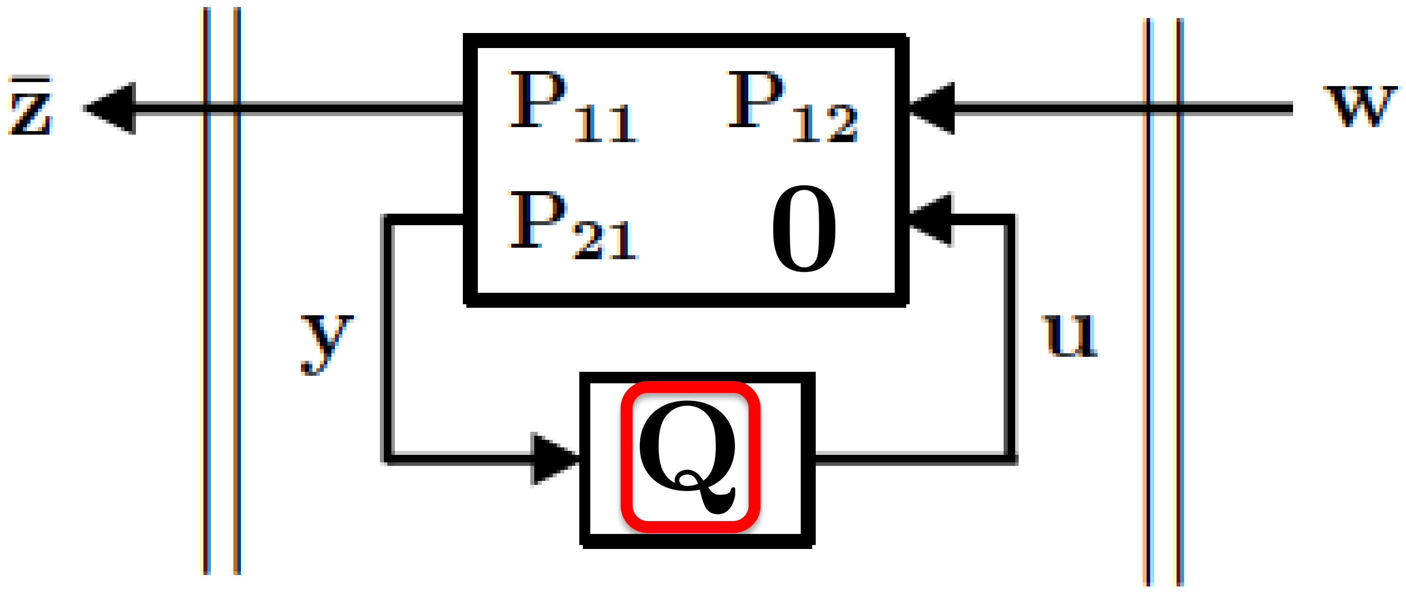




$$\begin{array}{ll} \text{minimize} & \|\mathbf{P}_{11} - \mathbf{P}_{12}\mathbf{Q}\mathbf{P}_{21}\| \\ \text{subject to} & \mathbf{Q} \text{ stable} \\ & \mathbf{K} \in \mathcal{C} \end{array}$$

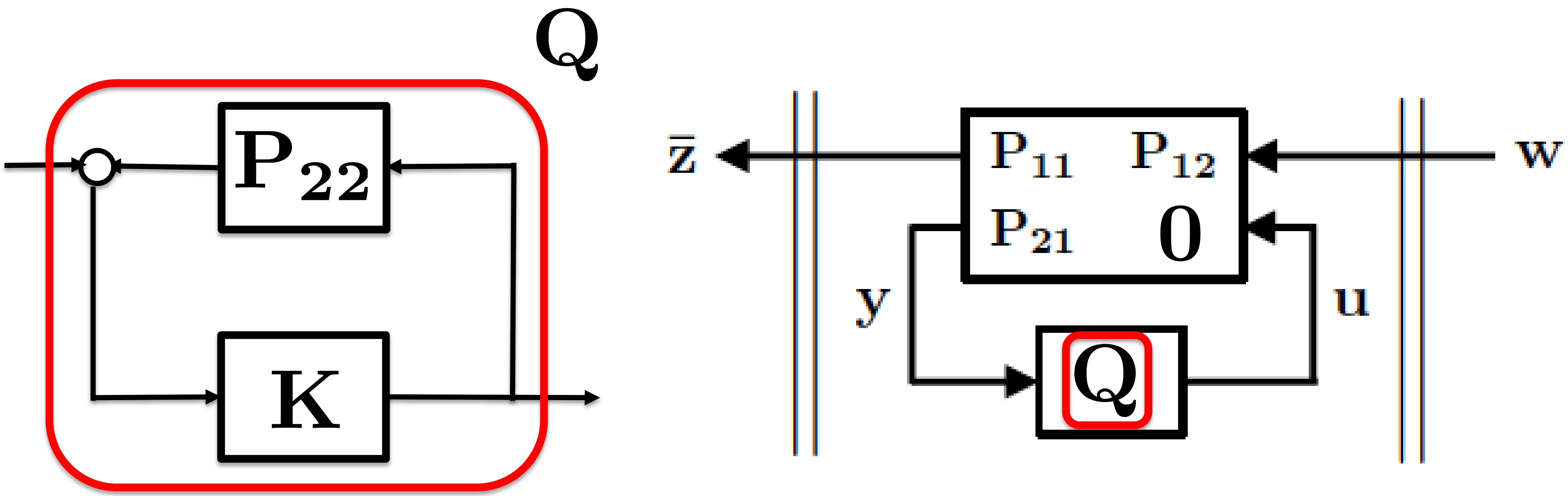
What we care about





$$\text{minimize } \|\mathbf{P}_{11} - \mathbf{P}_{12}\mathbf{Q}\mathbf{P}_{21}\|$$
$$\text{subject to } \mathbf{Q} \text{ stable}$$
$$\mathbf{K} \in \mathcal{C}$$

model matching

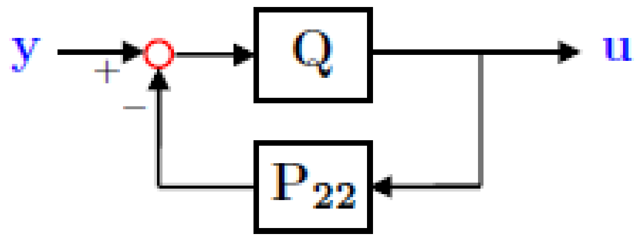


$$\text{minimize } \|\mathbf{P_{11}} - \mathbf{P_{12}}\mathbf{Q}\mathbf{P_{21}}\|$$
$$\text{subject to } \mathbf{Q} \text{ stable}$$

$\mathbf{K} \in \mathcal{C}$ **structure in *K*?**

Special case: stable plant

$$\mathbf{Q} = \mathbf{L}$$

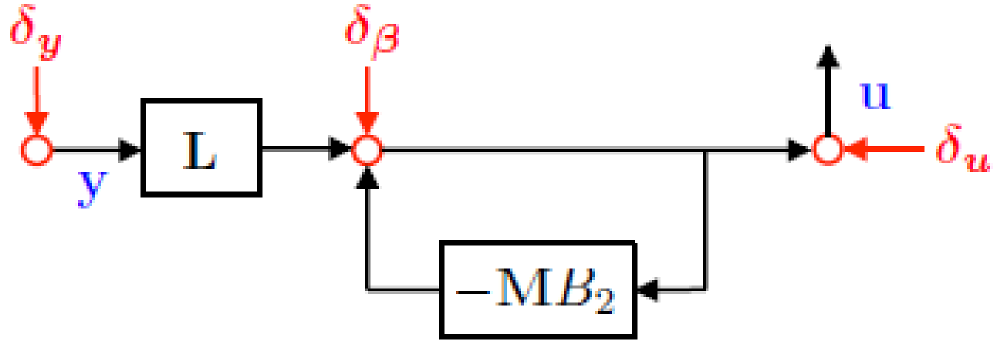


(a) Internal Model Control

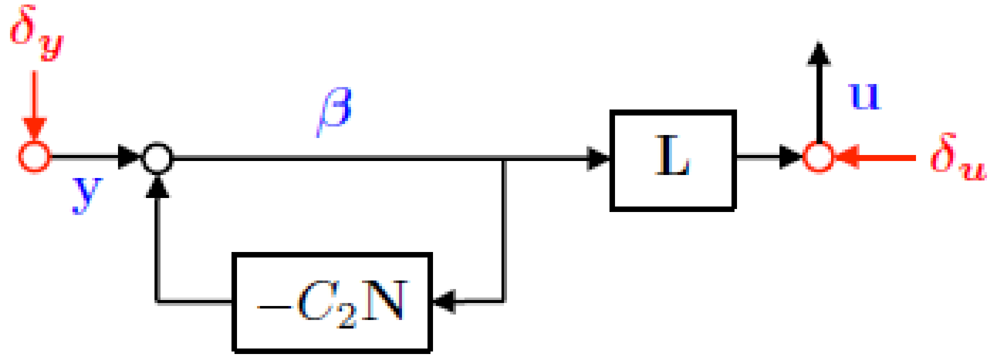
$$\begin{bmatrix} zI - A & -B_2 \end{bmatrix} \begin{bmatrix} \mathbf{R} & \mathbf{N} \\ \mathbf{M} & \mathbf{L} \end{bmatrix} = \begin{bmatrix} I & 0 \end{bmatrix} \tag{20a}$$

$$\begin{bmatrix} \mathbf{R} & \mathbf{N} \\ \mathbf{M} & \mathbf{L} \end{bmatrix} \begin{bmatrix} zI - A \\ -C_2 \end{bmatrix} = \begin{bmatrix} I \\ 0 \end{bmatrix} \tag{20b}$$

$$\mathbf{R}, \mathbf{M}, \mathbf{N} \in \frac{1}{z}\mathcal{RH}_\infty, \quad \mathbf{L} \in \mathcal{RH}_\infty \tag{20c}$$



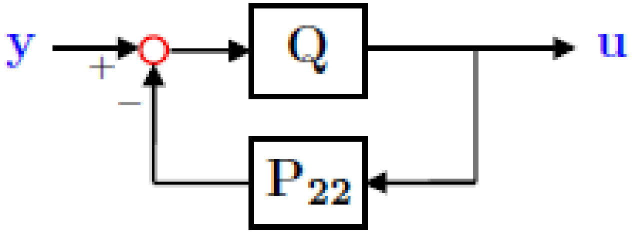
(b) Structure 1



(c) Structure 2

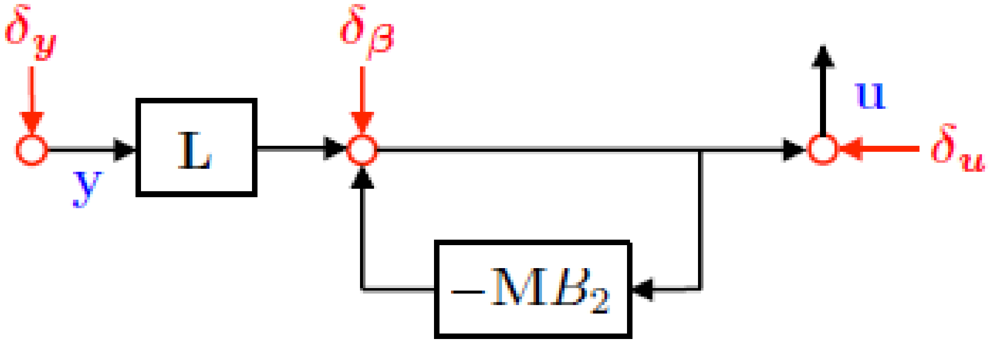
$$\begin{bmatrix} \mathbf{x} \\ \mathbf{u} \end{bmatrix} = \begin{bmatrix} \mathbf{R} & \mathbf{N} \\ \mathbf{M} & \mathbf{L} \end{bmatrix} \begin{bmatrix} \delta_x \\ \delta_y \end{bmatrix}$$

$$\mathbf{Q} = \mathbf{L}$$



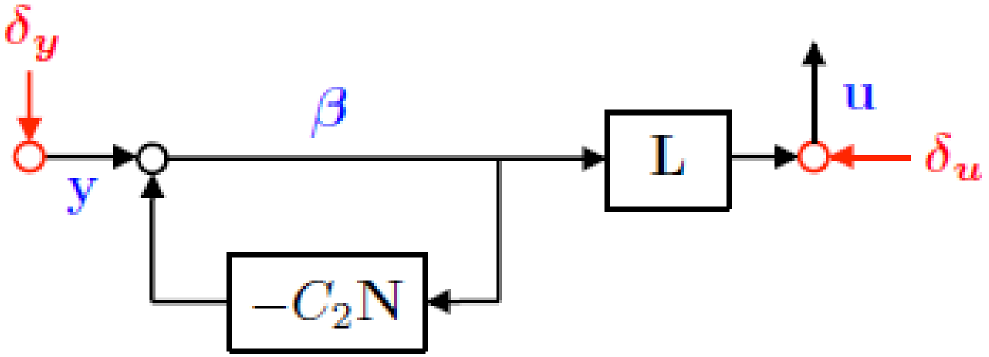
(a) Internal Model Control

$$\begin{bmatrix} \mathbf{x} \\ \mathbf{u} \end{bmatrix} = \begin{bmatrix} \mathbf{R} & \mathbf{N} & \mathbf{R}B_2 & (zI - A)^{-1}B_2 \\ \mathbf{M} & \mathbf{L} & I + \mathbf{M}B_2 & I \end{bmatrix} \begin{bmatrix} \delta_x \\ \delta_y \\ \delta_u \\ \delta_\beta \end{bmatrix}$$



(b) Structure 1

$$\begin{bmatrix} \mathbf{x} \\ \mathbf{u} \\ \beta \end{bmatrix} = \begin{bmatrix} \mathbf{R} & \mathbf{N} & \mathbf{R}B_2 \\ \mathbf{M} & \mathbf{L} & I + \mathbf{M}B_2 \\ C_2(zI - A)^{-1} & I & C_2(zI - A)^{-1}B_2 \end{bmatrix} \begin{bmatrix} \delta_x \\ \delta_y \\ \delta_u \end{bmatrix}$$



(c) Structure 2

$$\begin{bmatrix} zI - A & -B_2 \end{bmatrix} \begin{bmatrix} \mathbf{R} & \mathbf{N} \\ \mathbf{M} & \mathbf{L} \end{bmatrix} = \begin{bmatrix} I & 0 \end{bmatrix} \tag{20a}$$

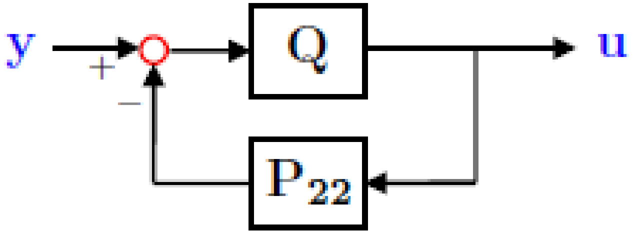
$$\begin{bmatrix} \mathbf{R} & \mathbf{N} \\ \mathbf{M} & \mathbf{L} \end{bmatrix} \begin{bmatrix} zI - A \\ -C_2 \end{bmatrix} = \begin{bmatrix} I \\ 0 \end{bmatrix} \tag{20b}$$

$$\mathbf{R}, \mathbf{M}, \mathbf{N} \in \frac{1}{z}\mathcal{RH}_\infty, \quad \mathbf{L} \in \mathcal{RH}_\infty \tag{20c}$$

Affine constraint

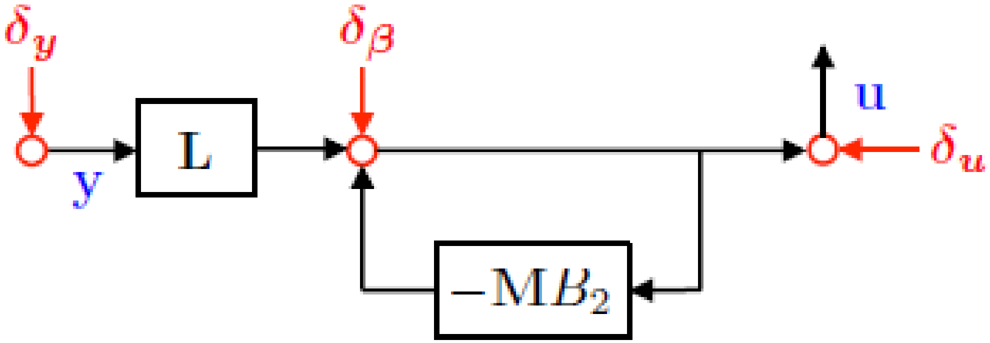
$$\begin{bmatrix} \mathrm{x} \\ \mathrm{u} \end{bmatrix} = \begin{bmatrix} \mathrm{R} & \mathrm{N} \\ \mathrm{M} & \mathrm{L} \end{bmatrix} \begin{bmatrix} \delta_x \\ \delta_y \end{bmatrix}$$

Q = L



(a) Internal Model Control

$$\begin{bmatrix} \mathrm{x} \\ \mathrm{u} \end{bmatrix} = \begin{bmatrix} \mathrm{R} & \mathrm{N} & \mathrm{R}B_2 & (zI - A)^{-1}B_2 \\ \mathrm{M} & \mathrm{L} & I + \mathrm{M}B_2 & I \end{bmatrix} \begin{bmatrix} \delta_x \\ \delta_y \\ \delta_u \\ \delta_\beta \end{bmatrix}$$



(b) Structure 1

$$\begin{bmatrix} \mathrm{R} & \mathrm{N} \\ \mathrm{M} & \mathrm{L} \end{bmatrix} \begin{bmatrix} zI - A \\ -C_2 \end{bmatrix} = \begin{bmatrix} I \\ 0 \end{bmatrix}$$

$$M = LC(zI - A)^{-1} \qquad \Rightarrow MB = LC(zI - A)^{-1}B = LP_{22}$$

$$\begin{bmatrix} zI - A & -B_2 \end{bmatrix} \begin{bmatrix} \mathbf{R} & \mathbf{N} \\ \mathbf{M} & \mathbf{L} \end{bmatrix} = \begin{bmatrix} I & 0 \end{bmatrix} \tag{20a}$$

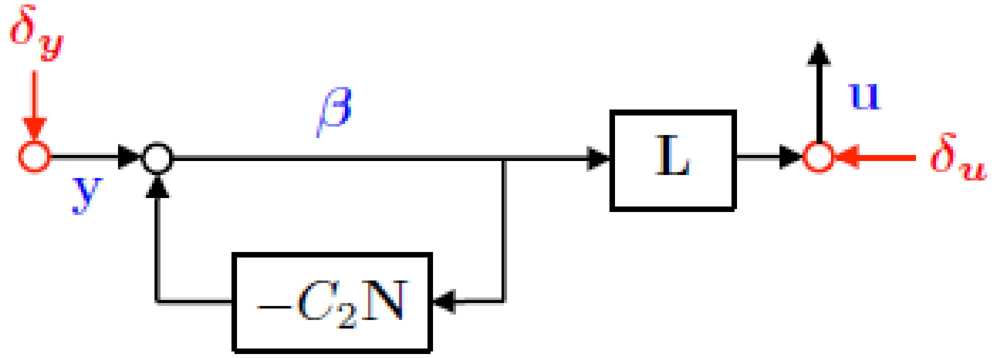
$$\begin{bmatrix} \mathbf{R} & \mathbf{N} \\ \mathbf{M} & \mathbf{L} \end{bmatrix} \begin{bmatrix} zI - A \\ -C_2 \end{bmatrix} = \begin{bmatrix} I \\ 0 \end{bmatrix} \tag{20b}$$

$$\mathbf{R}, \mathbf{M}, \mathbf{N} \in \frac{1}{z}\mathcal{RH}_\infty, \quad \mathbf{L} \in \mathcal{RH}_\infty \tag{20c}$$

$$N = (zI - A)^{-1} BL \quad \Rightarrow CN = C(zI - A)^{-1} BL = P_{22} L$$

$$\begin{bmatrix} zI - A & -B_2 \end{bmatrix} \begin{bmatrix} \mathbf{R} & \mathbf{N} \\ \mathbf{M} & \mathbf{L} \end{bmatrix} = \begin{bmatrix} I & 0 \end{bmatrix}$$

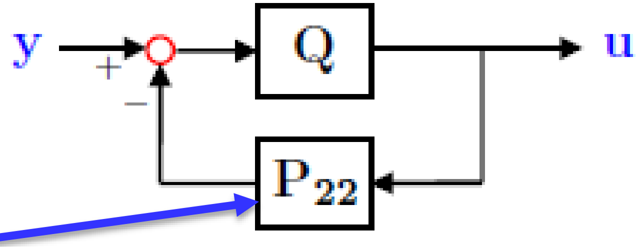
$$\begin{bmatrix} \mathbf{x} \\ \mathbf{u} \\ \beta \end{bmatrix} = \begin{bmatrix} \mathbf{R} & \mathbf{N} & \mathbf{R}B_2 \\ \mathbf{M} & \mathbf{L} & I + \mathbf{M}B_2 \\ C_2(zI - A)^{-1} & I & C_2(zI - A)^{-1}B_2 \end{bmatrix} \begin{bmatrix} \delta_x \\ \delta_y \\ \delta_u \end{bmatrix}$$



(c) Structure 2

$$\begin{bmatrix} x \\ u \end{bmatrix} = \begin{bmatrix} R & N \\ M & L \end{bmatrix} \begin{bmatrix} \delta_x \\ \delta_y \end{bmatrix}$$

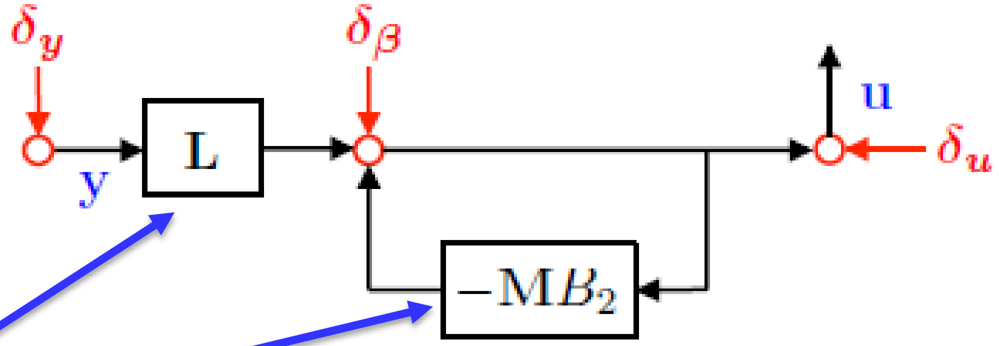
Q = L



(a) Internal Model Control

May be dense

$$\begin{bmatrix} x \\ u \end{bmatrix} = \begin{bmatrix} R & N & RB_2 & (zI - A)^{-1}B_2 \\ M & L & I + MB_2 & I \end{bmatrix} \begin{bmatrix} \delta_x \\ \delta_y \\ \delta_u \\ \delta_\beta \end{bmatrix}$$

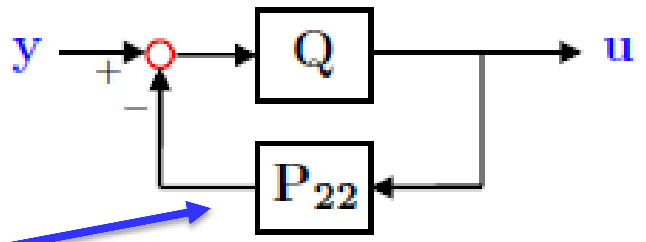


(b) Structure 1

Can be made sparse

$$\begin{bmatrix} x \\ u \end{bmatrix} = \begin{bmatrix} R & N \\ M & L \end{bmatrix} \begin{bmatrix} \delta_x \\ \delta_y \end{bmatrix}$$

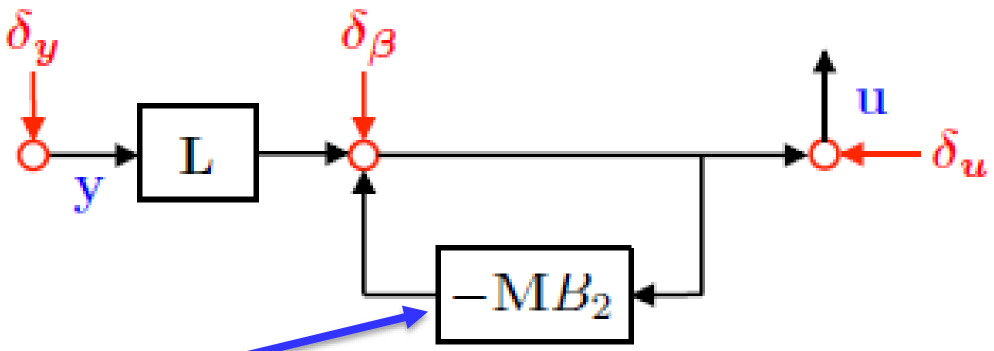
Q = L



(a) Internal Model Control

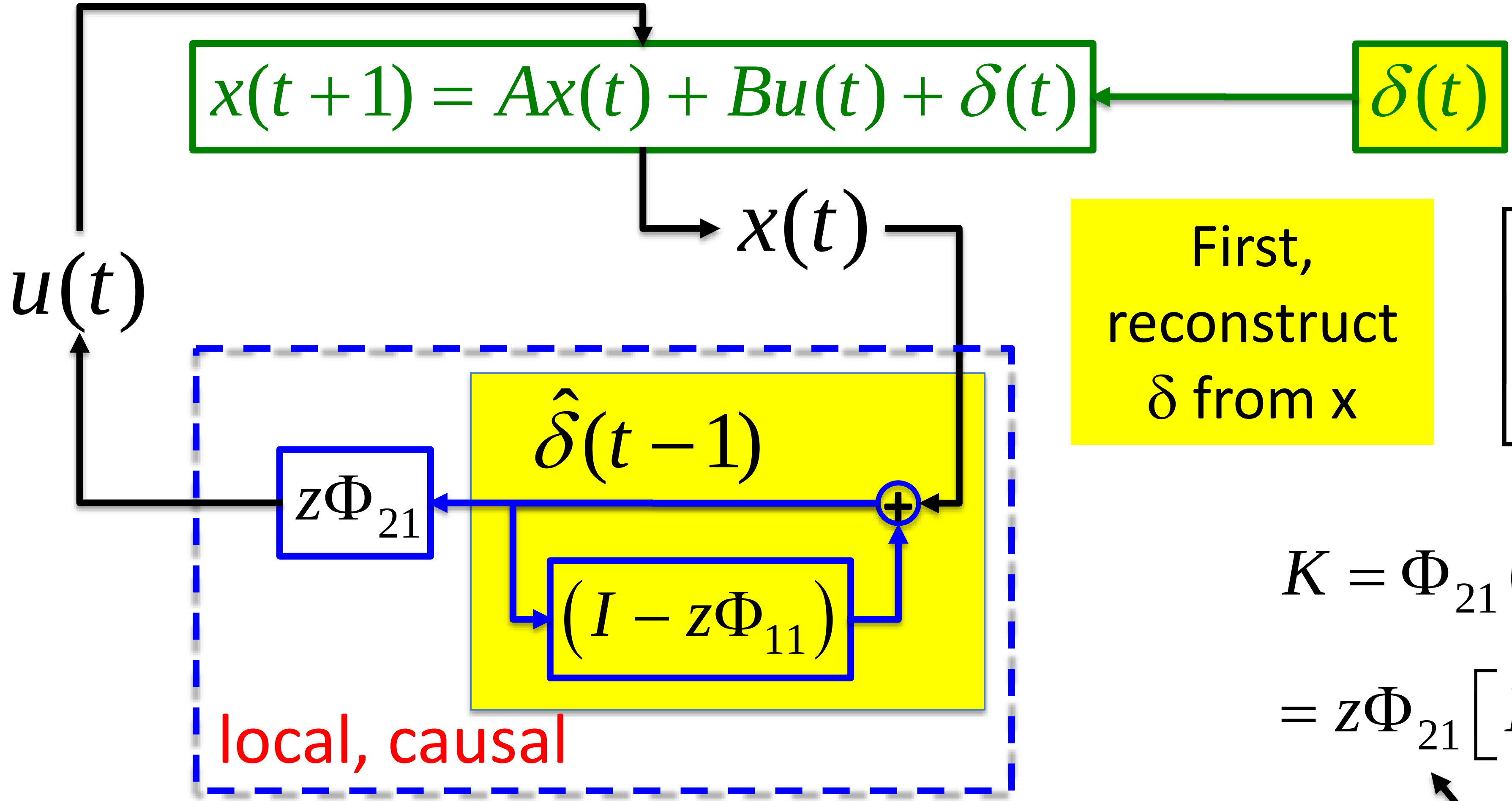
Cancels feedback from P

$$\begin{bmatrix} x \\ u \end{bmatrix} = \begin{bmatrix} R & N & RB_2 & (zI - A)^{-1}B_2 \\ M & L & I + MB_2 & I \end{bmatrix} \begin{bmatrix} \delta_x \\ \delta_y \\ \delta_u \\ \delta_\beta \end{bmatrix}$$



(b) Structure 1

Cancels feedback from P



First, reconstruct δ from x

$$\begin{bmatrix} x \\ u \end{bmatrix} = \begin{bmatrix} \Phi_{11} \\ \Phi_{21} \end{bmatrix} \delta x$$

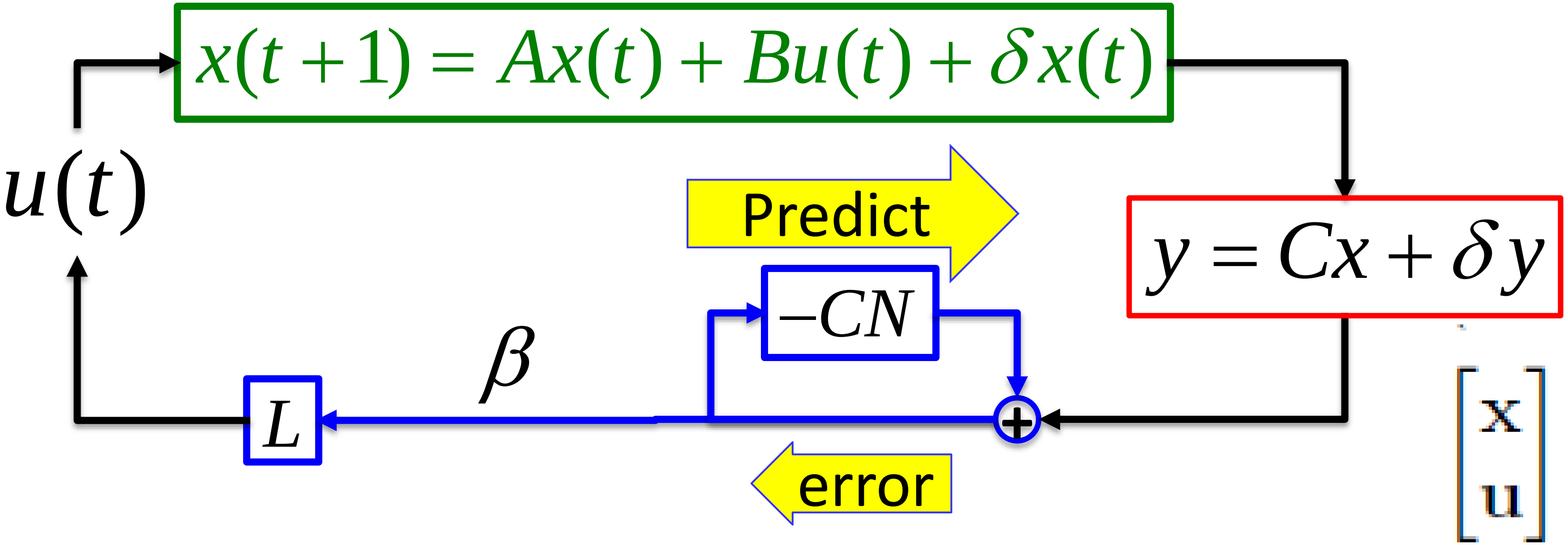
$$K = \Phi_{21}(\Phi_{11})^{-1}$$

$$K = \Phi_{21}(\Phi_{11})^{-1}$$

$$= z\Phi_{21}\left[I - (I - z\Phi_{11})\right]^{-1}$$

local, causal

State feedback

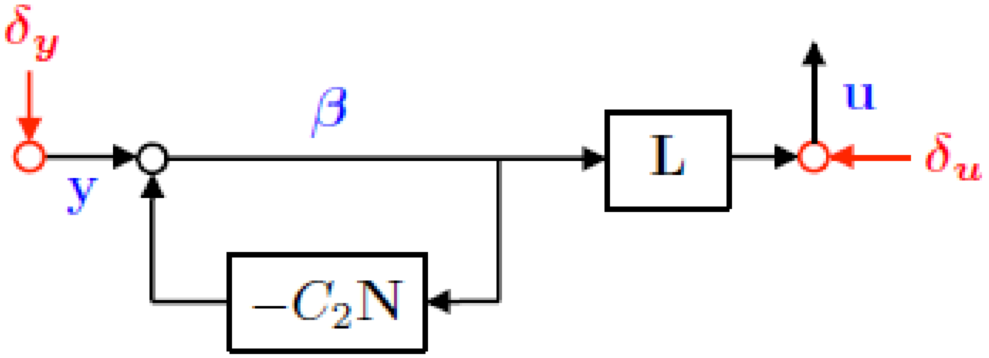


$$\begin{bmatrix} \mathbf{x} \\ \mathbf{u} \end{bmatrix} = \begin{bmatrix} \mathbf{R} & \mathbf{N} \\ \mathbf{M} & \mathbf{L} \end{bmatrix} \begin{bmatrix} \delta_x \\ \delta_y \end{bmatrix}$$

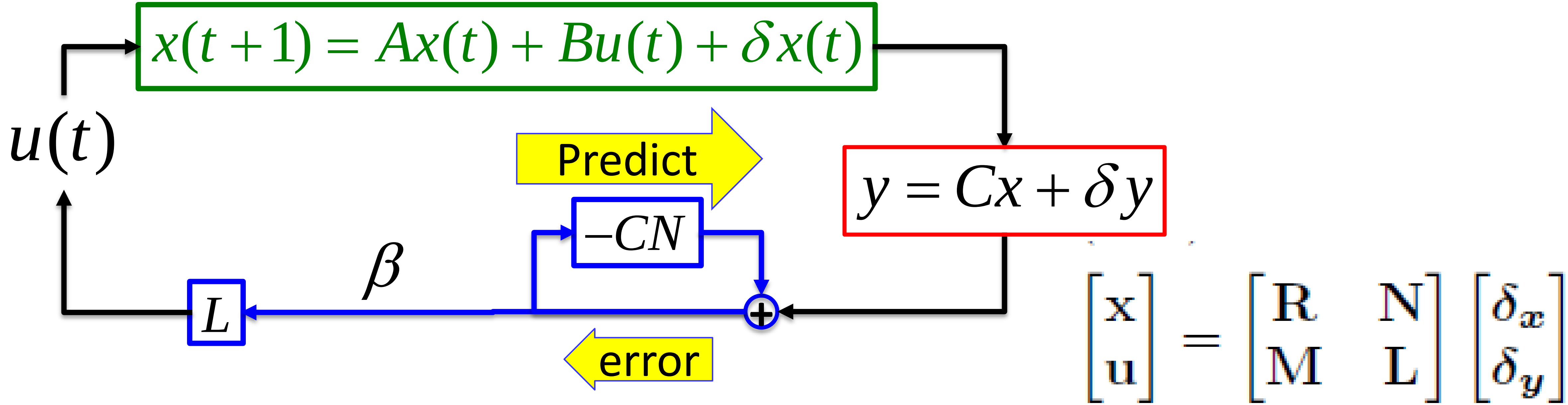
$$N = (zI - A)^{-1} BL \qquad \Rightarrow CN = C(zI - A)^{-1} BL = P_{22} L$$

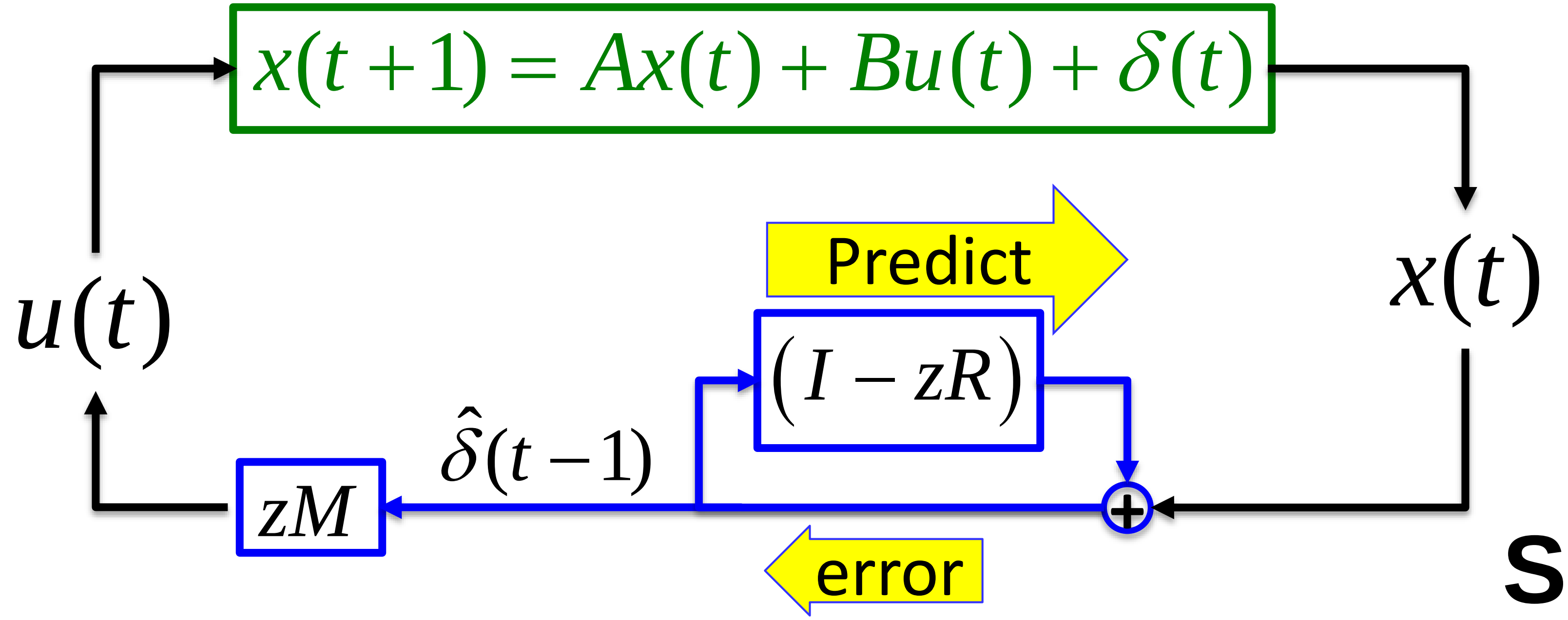
$$\begin{bmatrix} zI - A & -B_2 \end{bmatrix} \begin{bmatrix} \mathbf{R} & \mathbf{N} \\ \mathbf{M} & \mathbf{L} \end{bmatrix} = \begin{bmatrix} I & 0 \end{bmatrix}$$

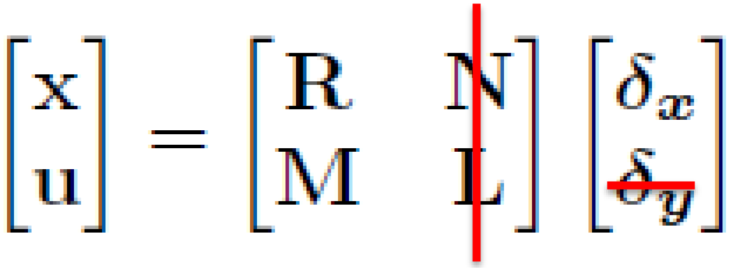
$$\begin{bmatrix} \mathbf{x} \\ \mathbf{u} \end{bmatrix} = \begin{bmatrix} \mathbf{R} & \mathbf{N} \\ \mathbf{M} & \mathbf{L} \end{bmatrix} \begin{bmatrix} \delta_x \\ \delta_y \end{bmatrix}$$



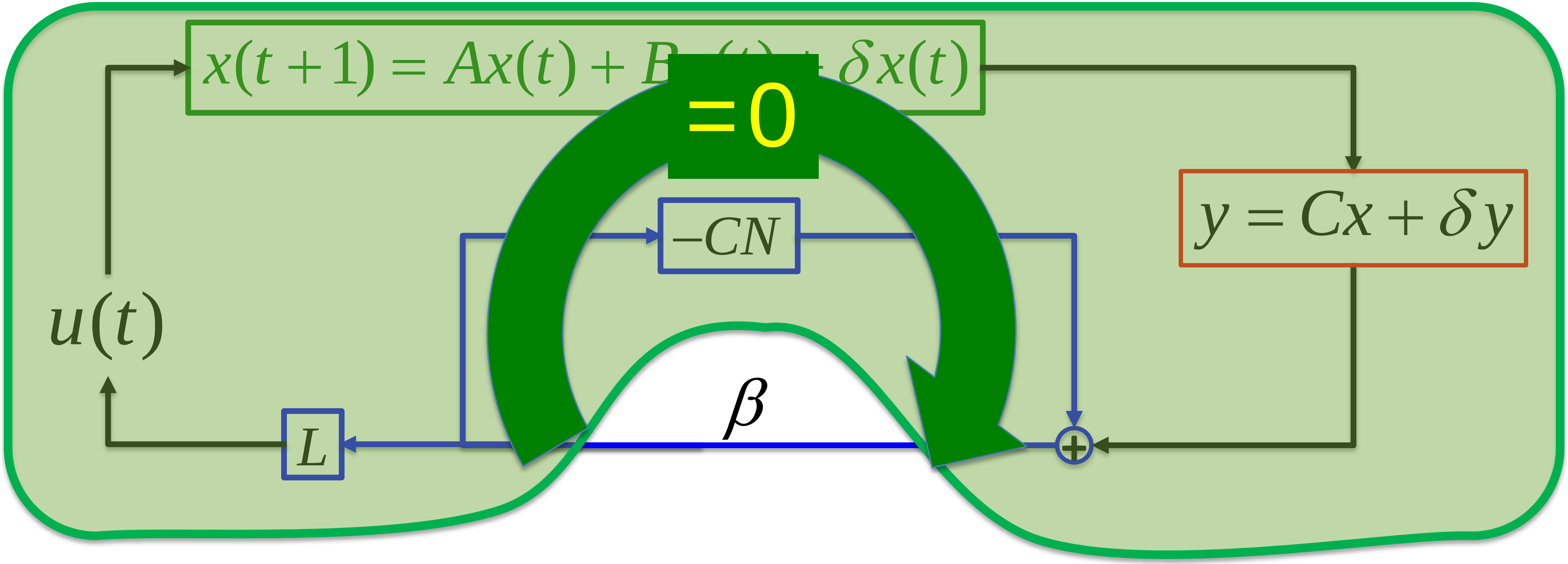
(c) Structure 2





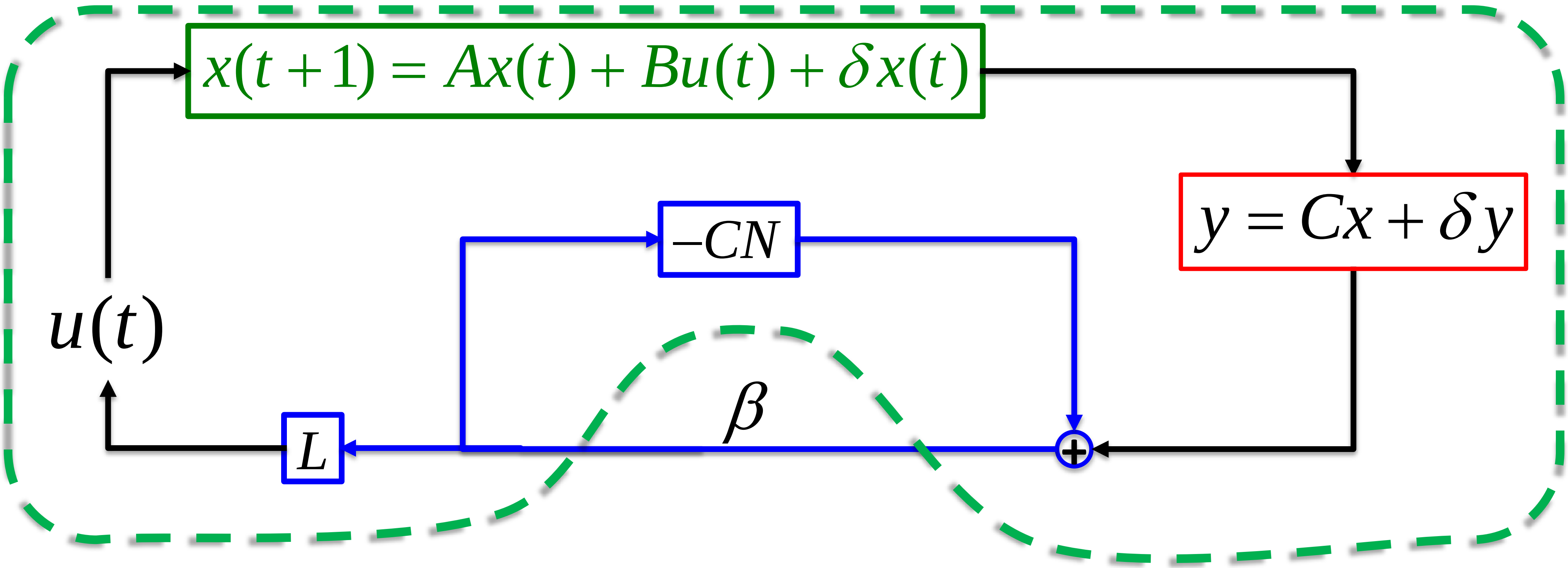


State feedback



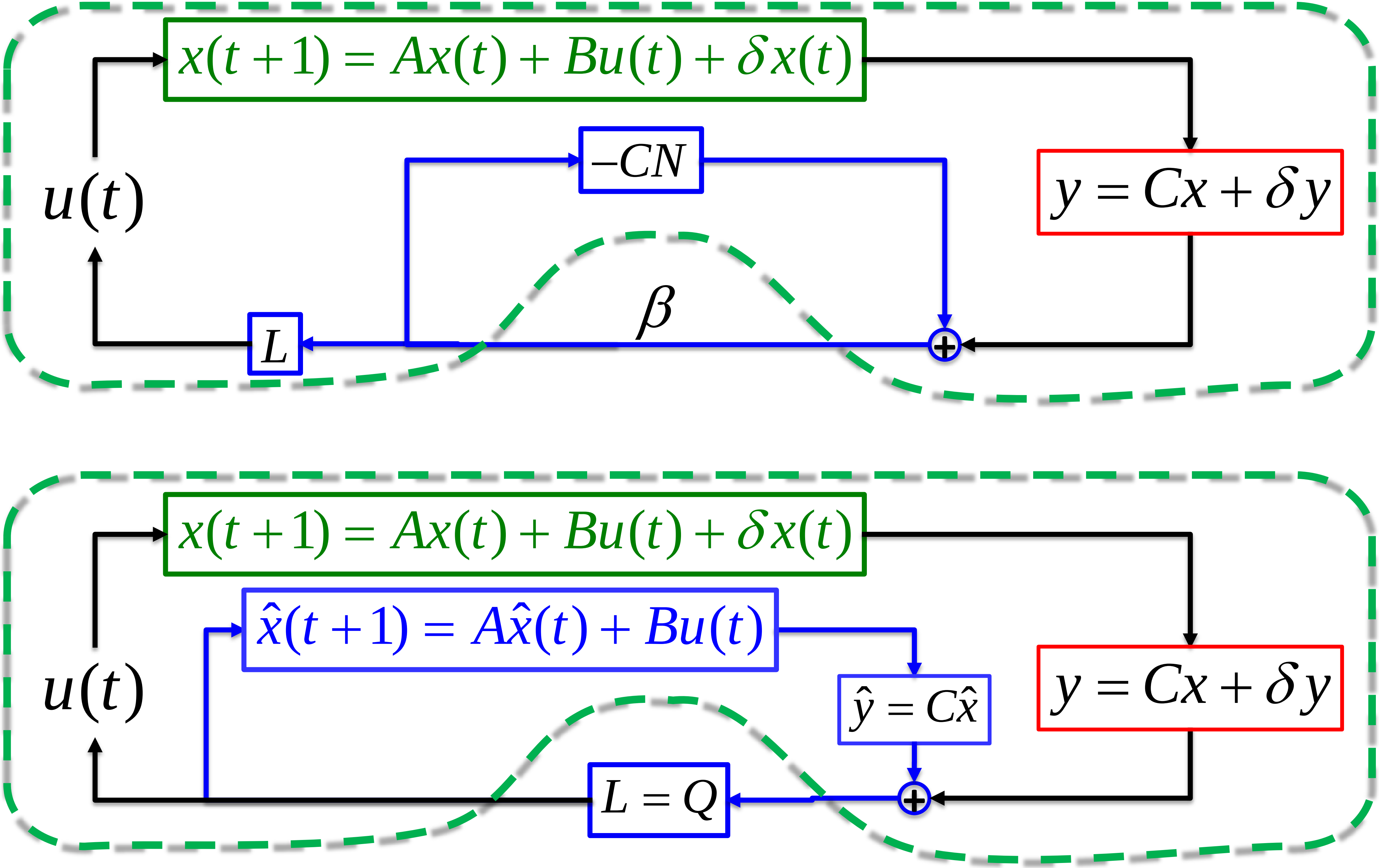
$$-CN + C\left(zI - A\right)^{-1} BL = 0$$

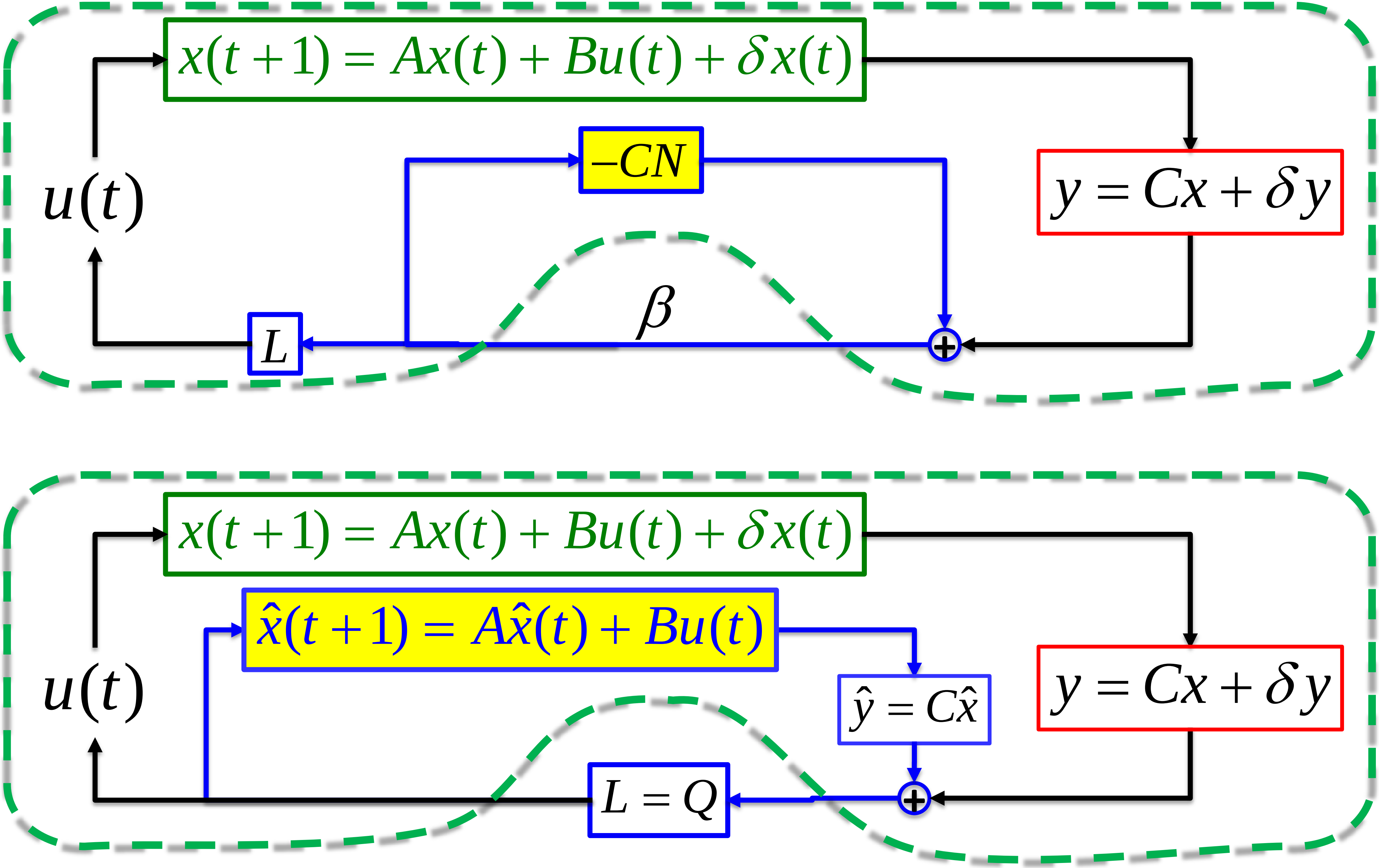
$$N = \left(zI - A\right)^{-1} BL \qquad \Rightarrow CN = C\left(zI - A\right)^{-1} BL = P_{22}L$$



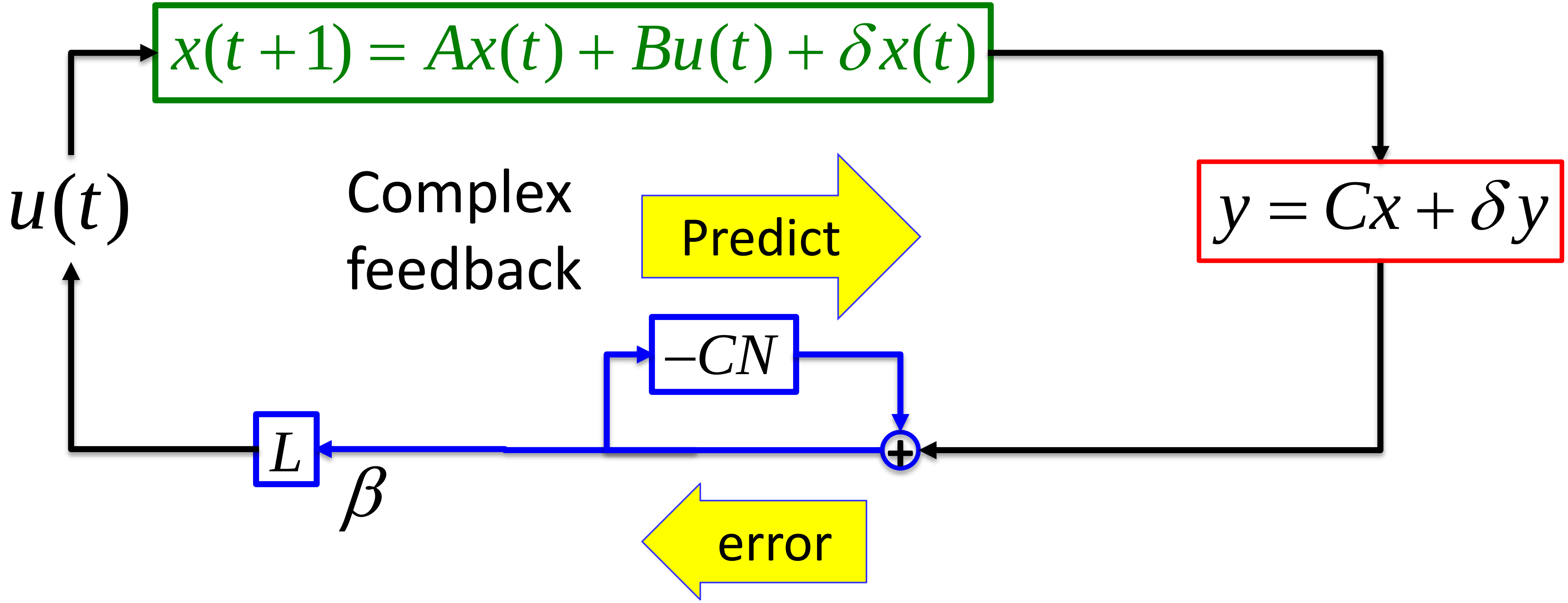
$$-CN + C\left(zI - A\right)^{-1} BL = 0$$

$$N = \left(zI - A\right)^{-1} BL \qquad \Rightarrow CN = C\left(zI - A\right)^{-1} BL = P_{22}L$$


$x(t+1) = Ax(t) + Bu(t) + \delta x(t)$
$-CN$
$y = Cx + \delta y$
$u(t)$
β
L
$x(t+1) = Ax(t) + Bu(t) + \delta x(t)$
$\hat{x}(t+1) = A\hat{x}(t) + Bu(t)$
$\hat{y} = C\hat{x}$
$y = Cx + \delta y$
$u(t)$
$L = Q$

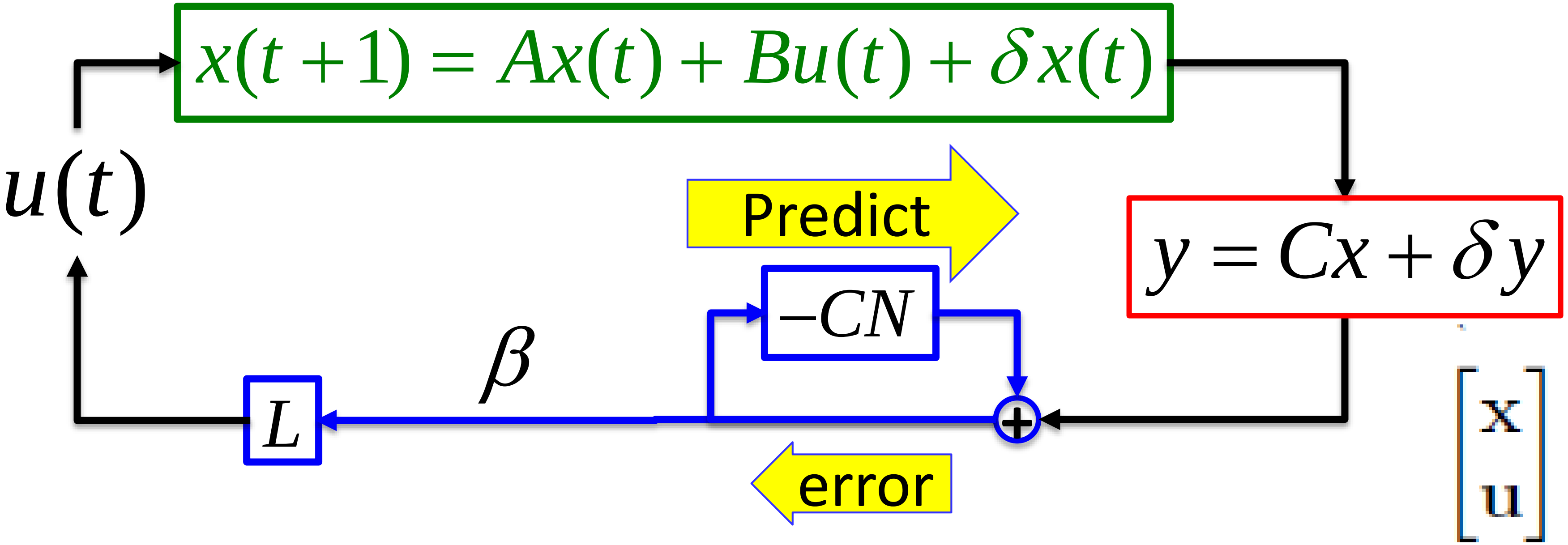


$x(t+1) = Ax(t) + Bu(t) + \delta x(t)$
$-CN$
$u(t)$
$y = Cx + \delta y$
β
L
$x(t+1) = Ax(t) + Bu(t) + \delta x(t)$
$\hat{x}(t+1) = A\hat{x}(t) + Bu(t)$
$u(t)$
$\hat{y} = C\hat{x}$
$y = Cx + \delta y$
$L = Q$

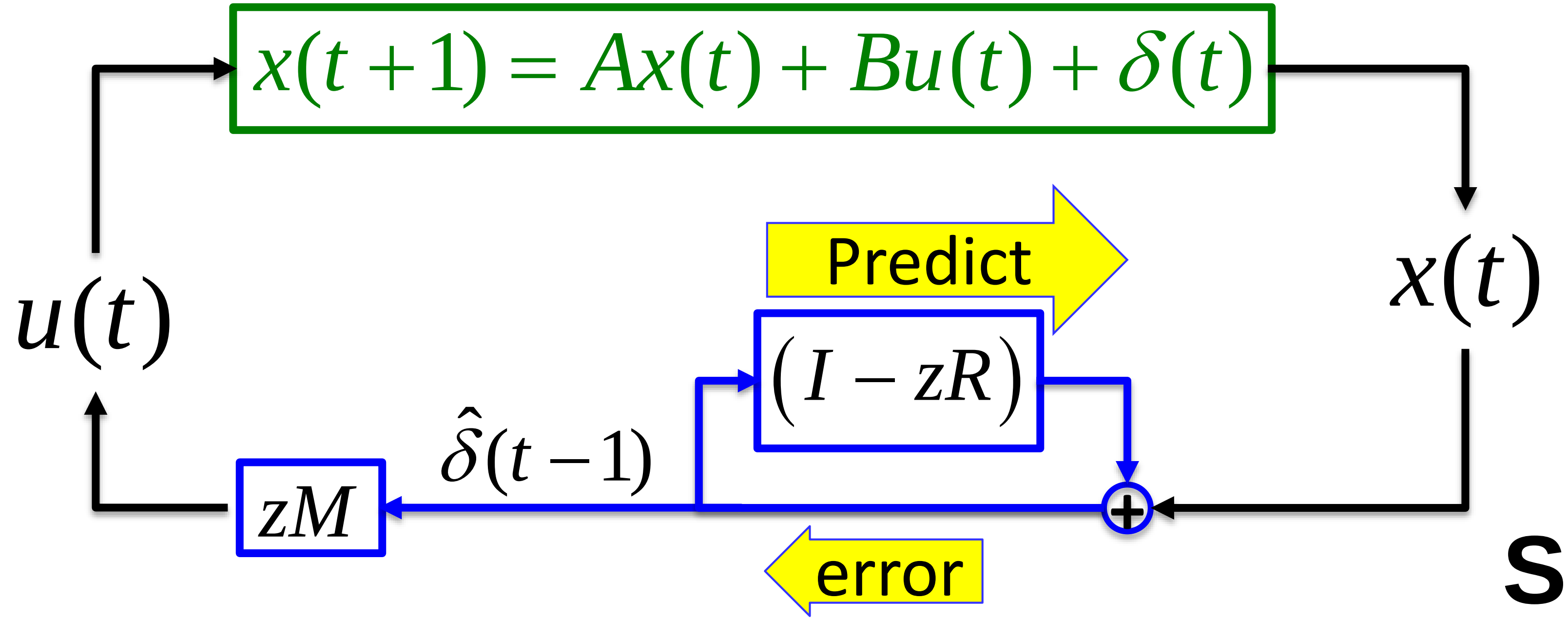


Simple feedforward (fast?)

$$N = (zI - A)^{-1} BL \qquad \Rightarrow CN = C(zI - A)^{-1} BL = P_{22} L$$



$$\begin{bmatrix} \mathbf{x} \\ \mathbf{u} \end{bmatrix} = \begin{bmatrix} \mathbf{R} & \mathbf{N} \\ \mathbf{M} & \mathbf{L} \end{bmatrix} \begin{bmatrix} \delta_x \\ \delta_y \end{bmatrix}$$

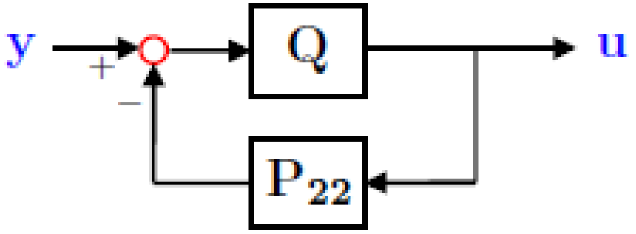


$$\begin{bmatrix} \mathbf{x} \\ \mathbf{u} \end{bmatrix} = \begin{bmatrix} \mathbf{R} & \cancel{\mathbf{N}} \\ \mathbf{M} & \cancel{\mathbf{L}} \end{bmatrix} \begin{bmatrix} \delta_x \\ \cancel{\delta_y} \end{bmatrix}$$

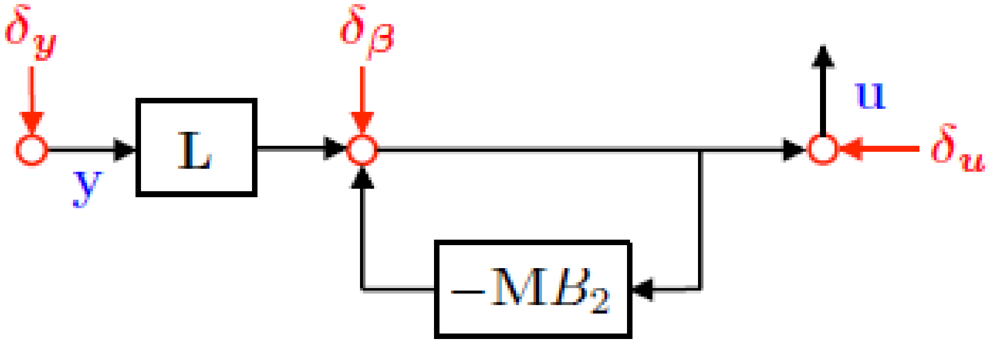
State feedback

$$\begin{bmatrix} \mathbf{x} \\ \mathbf{u} \end{bmatrix} = \begin{bmatrix} \mathbf{R} & \mathbf{N} \\ \mathbf{M} & \mathbf{L} \end{bmatrix} \begin{bmatrix} \delta_x \\ \delta_y \end{bmatrix}$$

Q = L

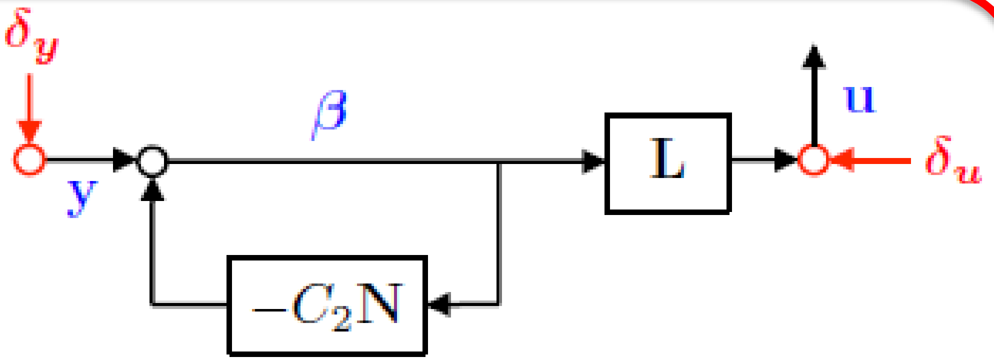


(a) Internal Model Control

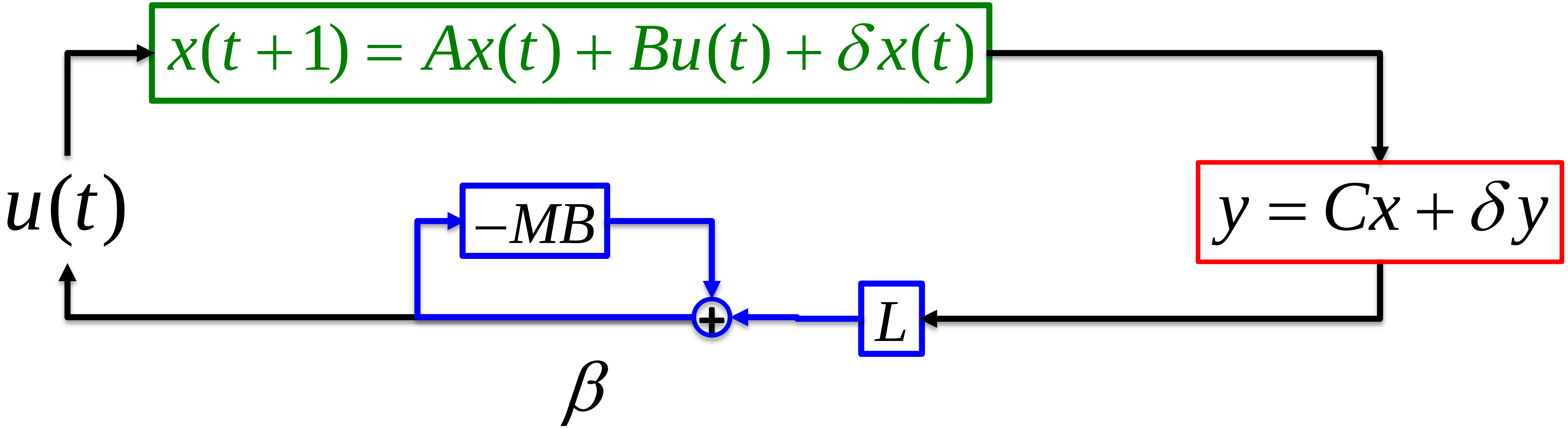


(b) Structure 1

$$\begin{bmatrix} \mathbf{x} \\ \mathbf{u} \\ \beta \end{bmatrix} = \begin{bmatrix} \mathbf{R} & \mathbf{N} & \mathbf{R}B_2 \\ \mathbf{M} & \mathbf{L} & I + \mathbf{M}B_2 \\ C_2(zI - A)^{-1} & I & C_2(zI - A)^{-1}B_2 \end{bmatrix} \begin{bmatrix} \delta_x \\ \delta_y \\ \delta_u \end{bmatrix}$$



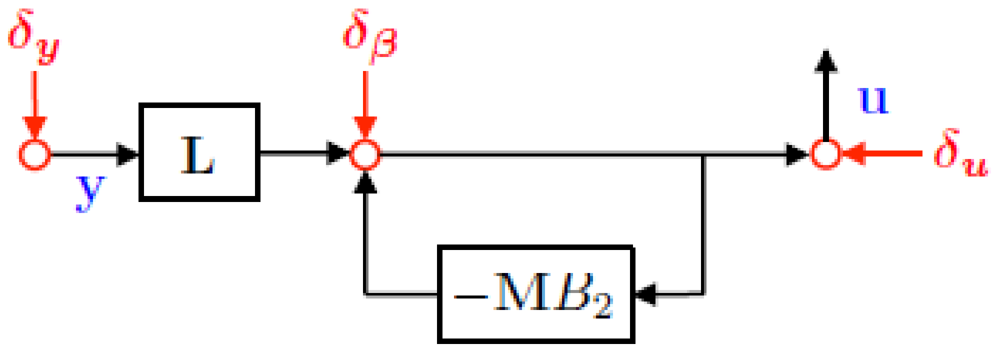
(c) Structure 2

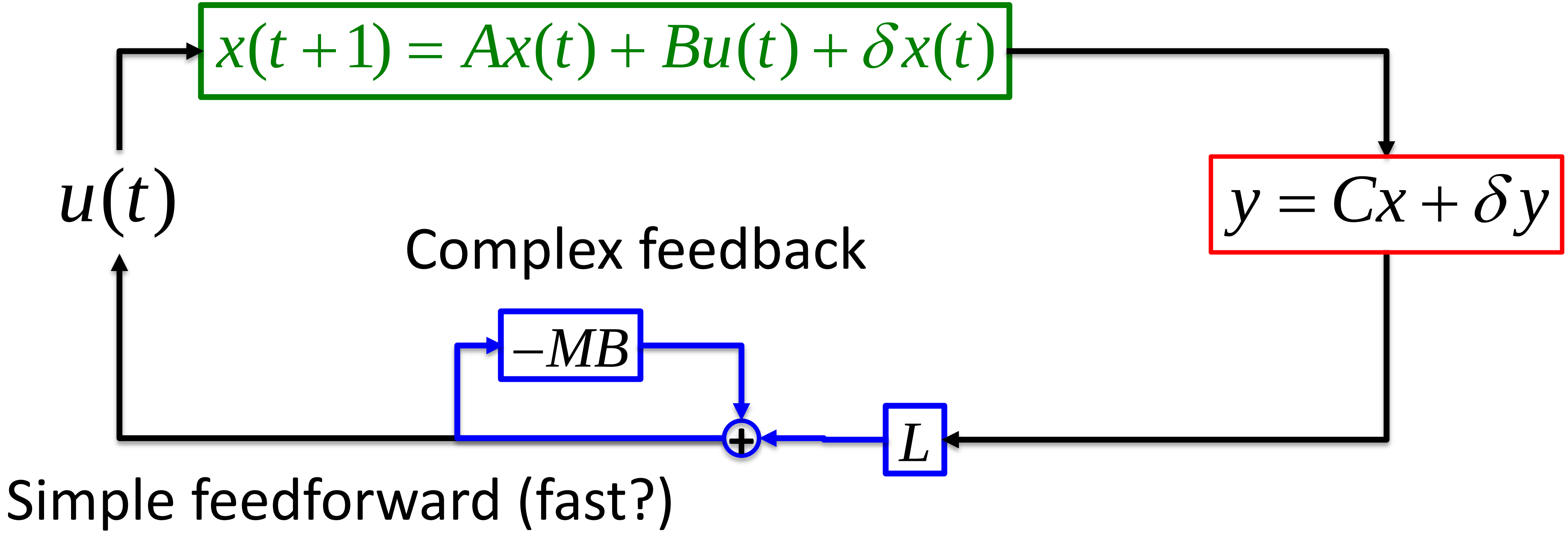


$$M = LC(zI - A)^{-1} \quad \Rightarrow MB = LC(zI - A)^{-1}B = LP_{22}$$

$$\begin{bmatrix} \mathbf{R} & \mathbf{N} \\ \mathbf{M} & \mathbf{L} \end{bmatrix} \begin{bmatrix} zI - A \\ -C_2 \end{bmatrix} = \begin{bmatrix} I \\ 0 \end{bmatrix}$$

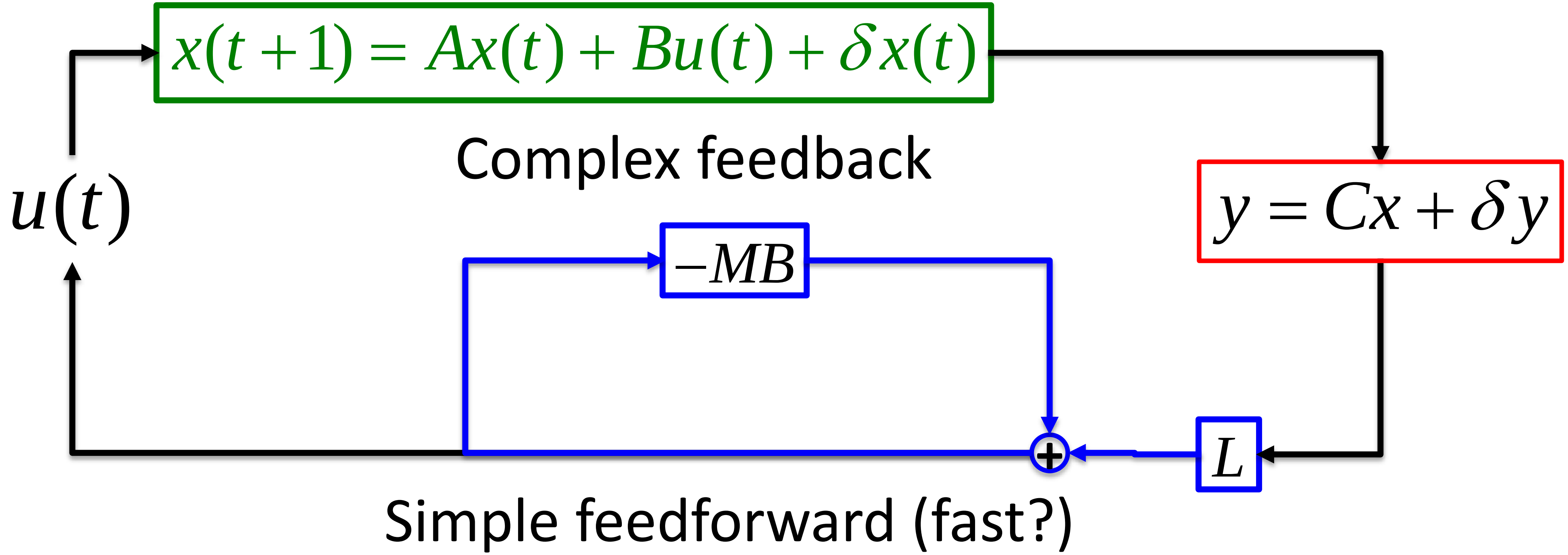
$$\begin{bmatrix} \mathbf{x} \\ \mathbf{u} \end{bmatrix} = \begin{bmatrix} \mathbf{R} & \mathbf{N} \\ \mathbf{M} & \mathbf{L} \end{bmatrix} \begin{bmatrix} \delta_x \\ \delta_y \end{bmatrix}$$





$$M = LC\left(zI - A\right)^{-1} \qquad \Rightarrow MB = LC\left(zI - A\right)^{-1} B = LP_{22}$$

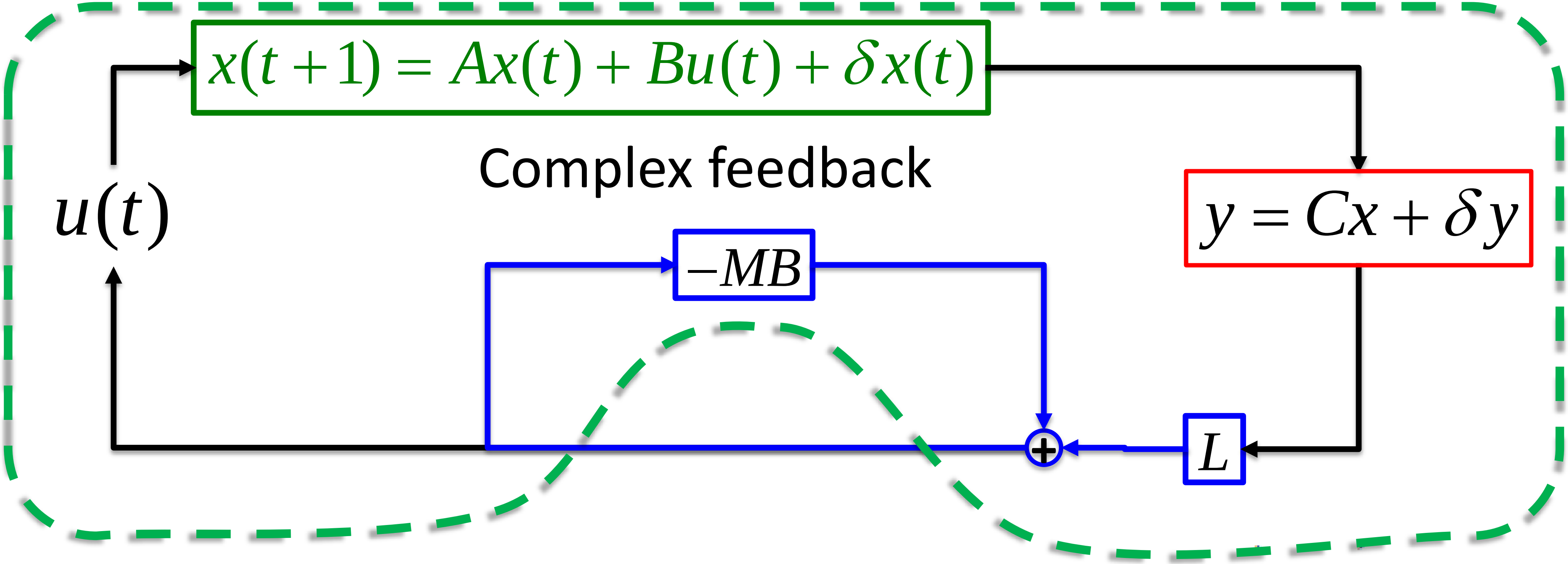
$$\begin{bmatrix} \mathbf{x} \\ \mathbf{u} \end{bmatrix} = \begin{bmatrix} \mathbf{R} & \mathbf{N} \\ \mathbf{M} & \mathbf{L} \end{bmatrix} \begin{bmatrix} \delta_x \\ \delta_y \end{bmatrix}$$



$$-MB + LC(zI - A)^{-1}B = 0$$

$$\begin{bmatrix} \mathbf{x} \\ \mathbf{u} \end{bmatrix} = \begin{bmatrix} \mathbf{R} & \mathbf{N} \\ \mathbf{M} & \mathbf{L} \end{bmatrix} \begin{bmatrix} \delta_x \\ \delta_y \end{bmatrix}$$

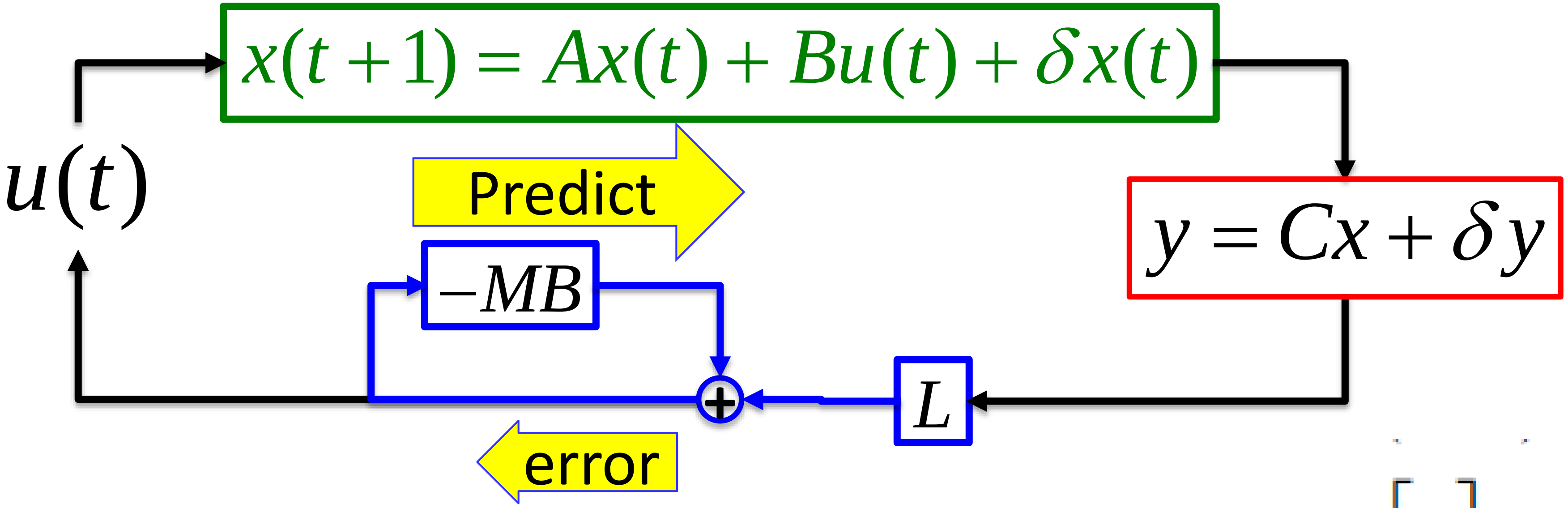
$$M = LC(zI - A)^{-1} \quad \Rightarrow MB = LC(zI - A)^{-1}B = LP_{22}$$



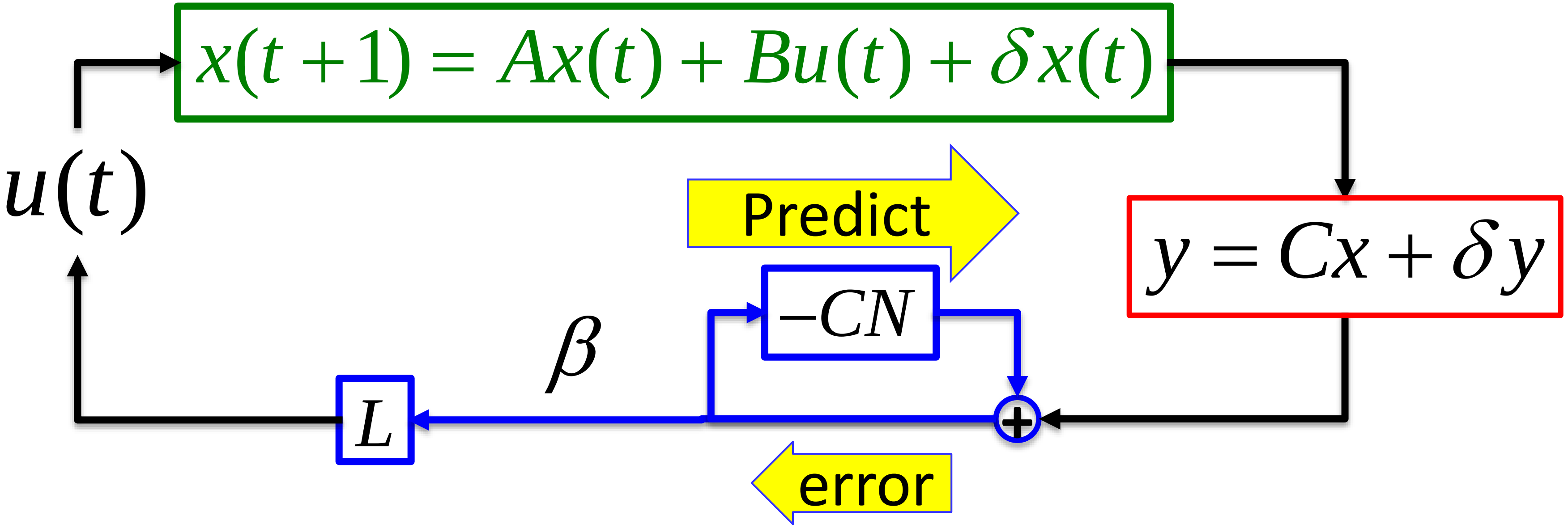
$$-MB + LC\left(zI - A\right)^{-1} B = 0$$

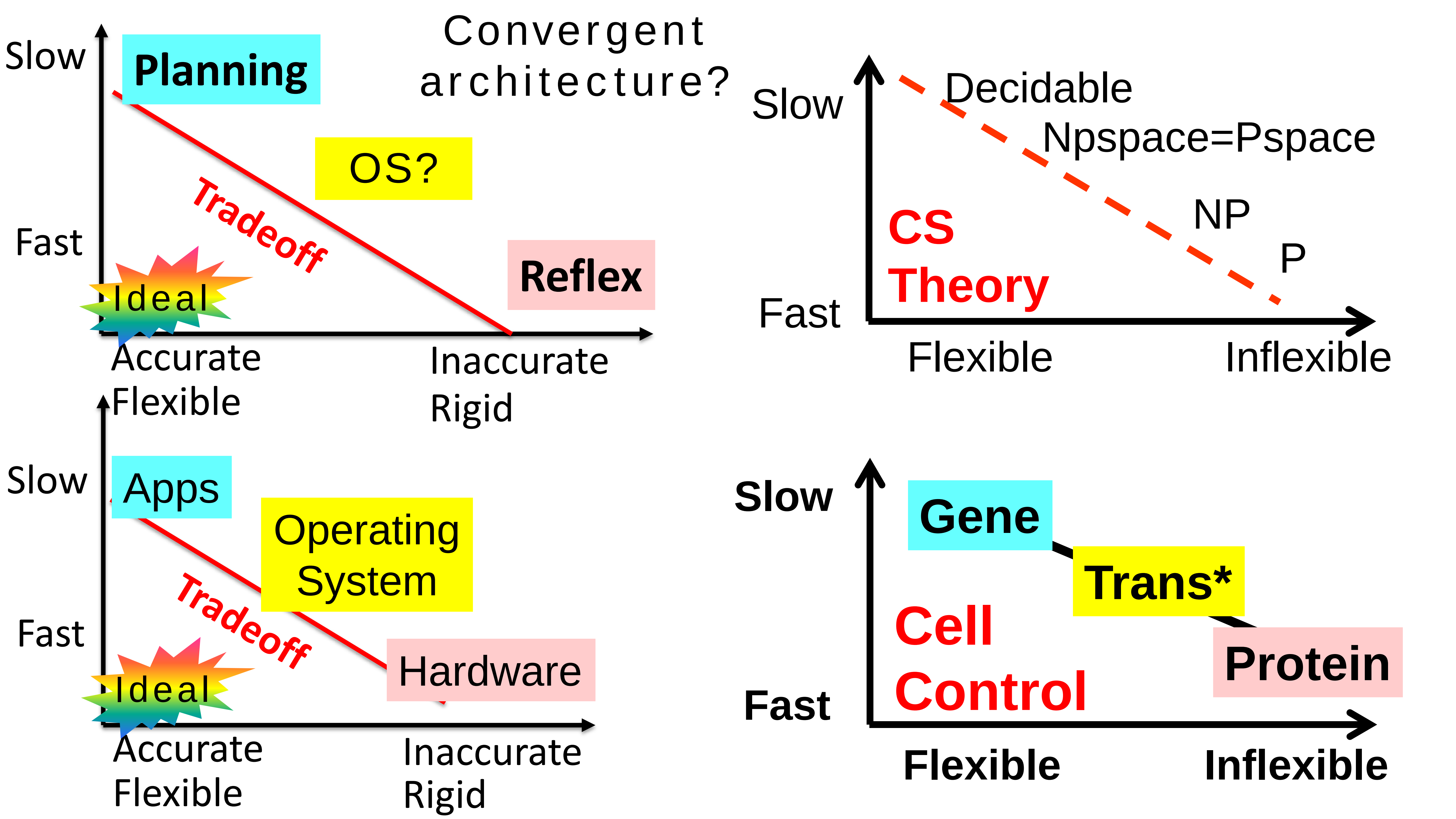
$$\begin{bmatrix} \mathbf{x} \\ \mathbf{u} \end{bmatrix} = \begin{bmatrix} \mathbf{R} & \mathbf{N} \\ \mathbf{M} & \mathbf{L} \end{bmatrix} \begin{bmatrix} \delta_x \\ \delta_y \end{bmatrix}$$

$$M = LC\left(zI - A\right)^{-1} \quad \Rightarrow MB = LC\left(zI - A\right)^{-1} B = LP_{22}$$

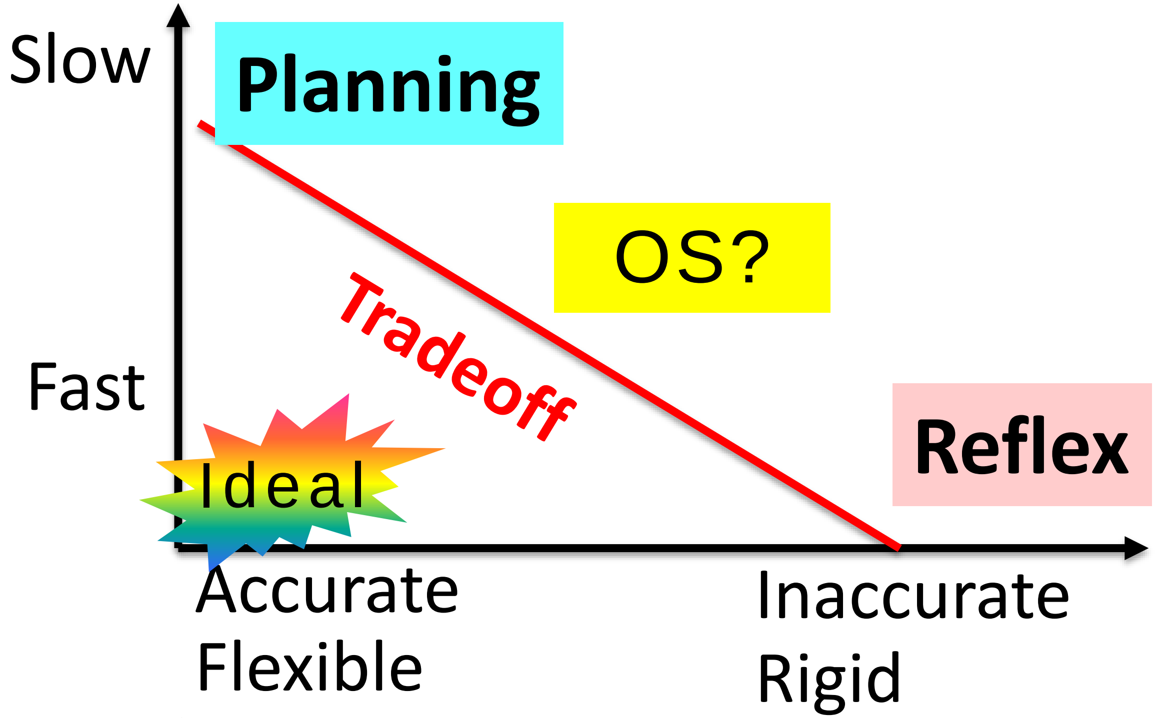


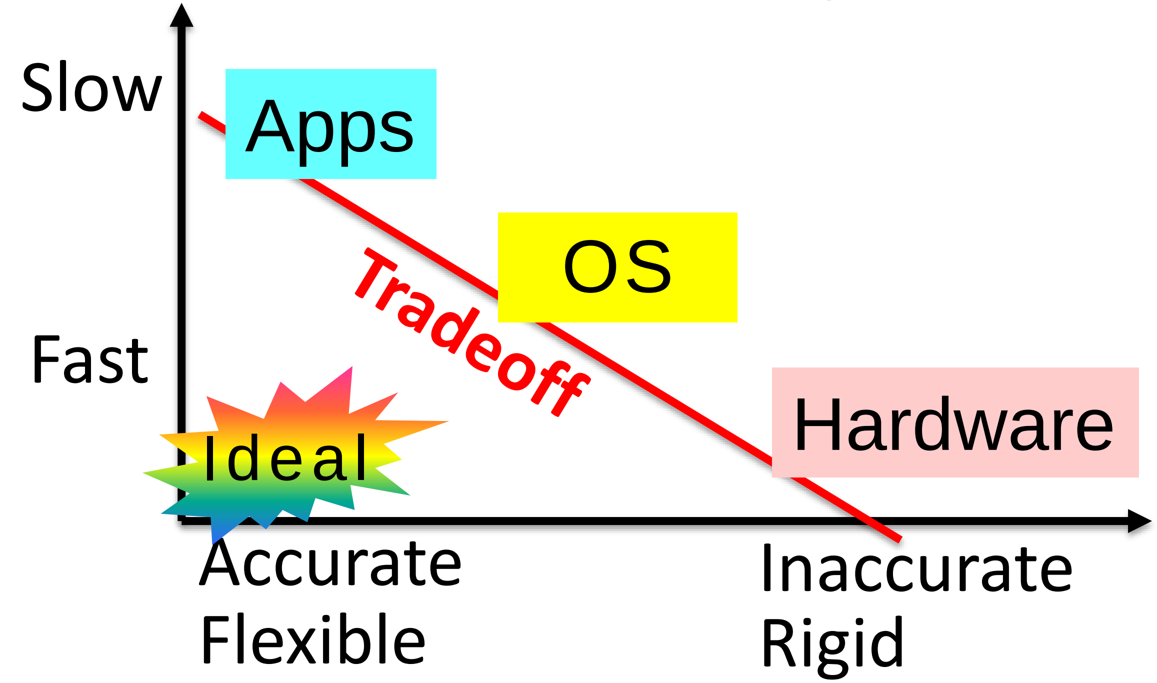
$$\begin{bmatrix} \mathbf{x} \\ \mathbf{u} \end{bmatrix} = \begin{bmatrix} \mathbf{R} & \mathbf{N} \\ \mathbf{M} & \mathbf{L} \end{bmatrix} \begin{bmatrix} \delta_x \\ \delta_y \end{bmatrix}$$

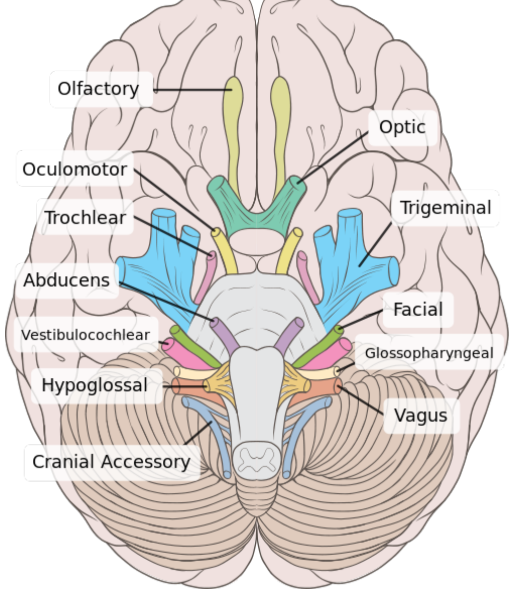




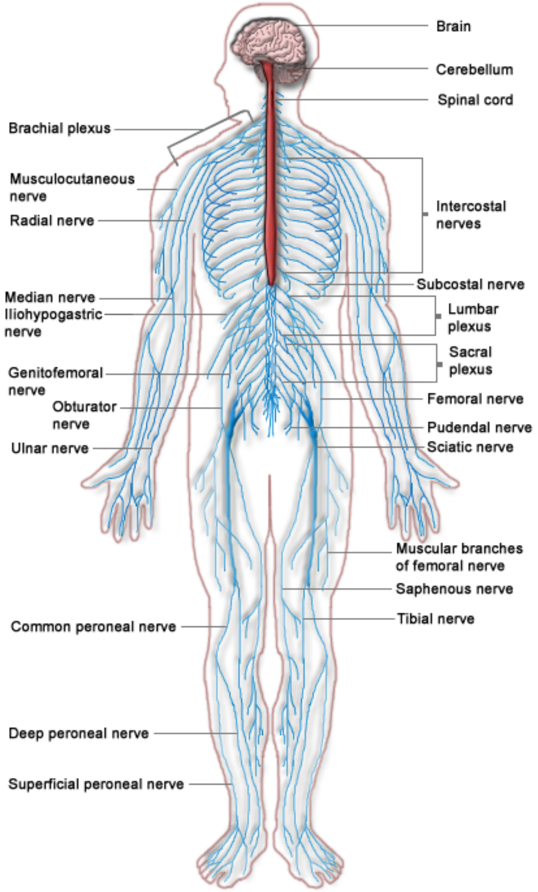
Convergent architecture?
Slow
Planning
OS?
Tradeoff
Fast
Reflex
Ideal
Accurate
Flexible
Inaccurate
Rigid
Slow
Decidable
Npspace=Pspace
NP
P
CS Theory
Fast
Flexible
Inflexible
Slow
Apps
Operating System
Tradeoff
Fast
Hardware
Ideal
Accurate
Flexible
Inaccurate
Rigid
Slow
Gene
Trans*
Cell Control
Protein
Fast
Flexible
Inflexible

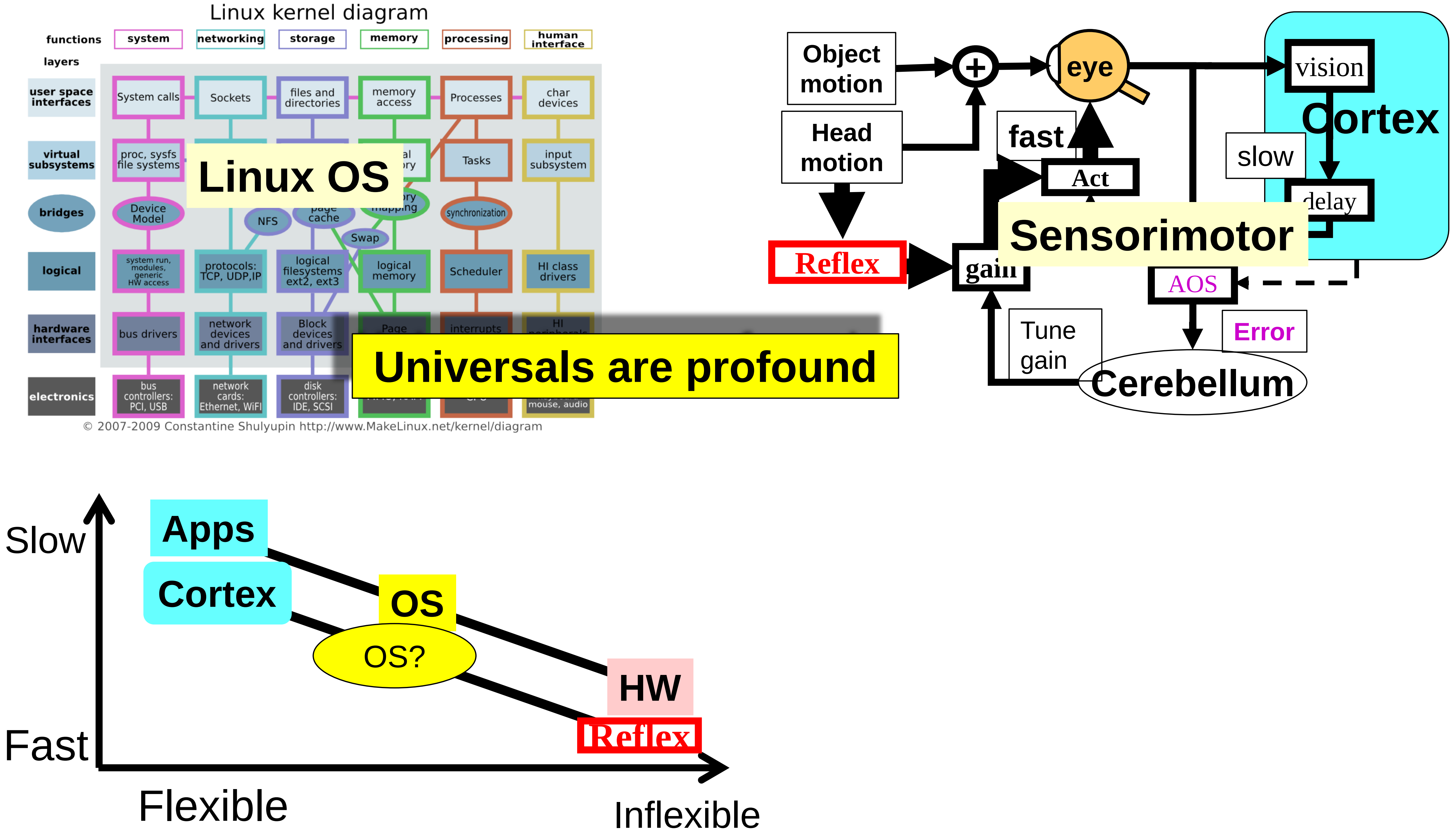




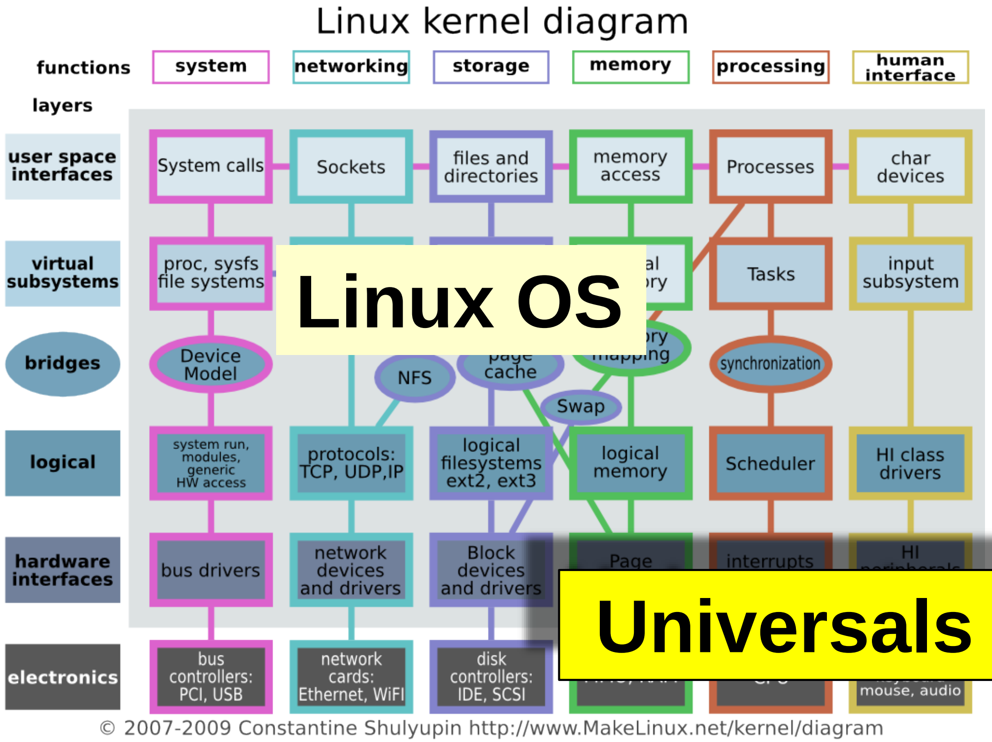


Convergent architecture?

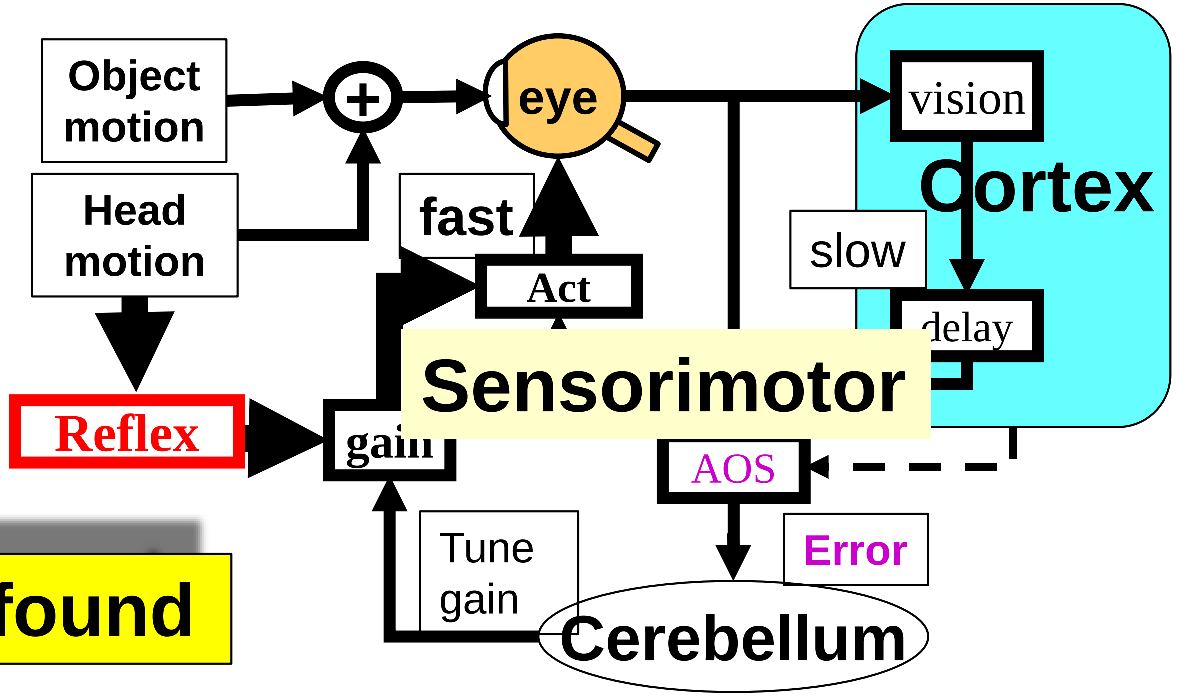


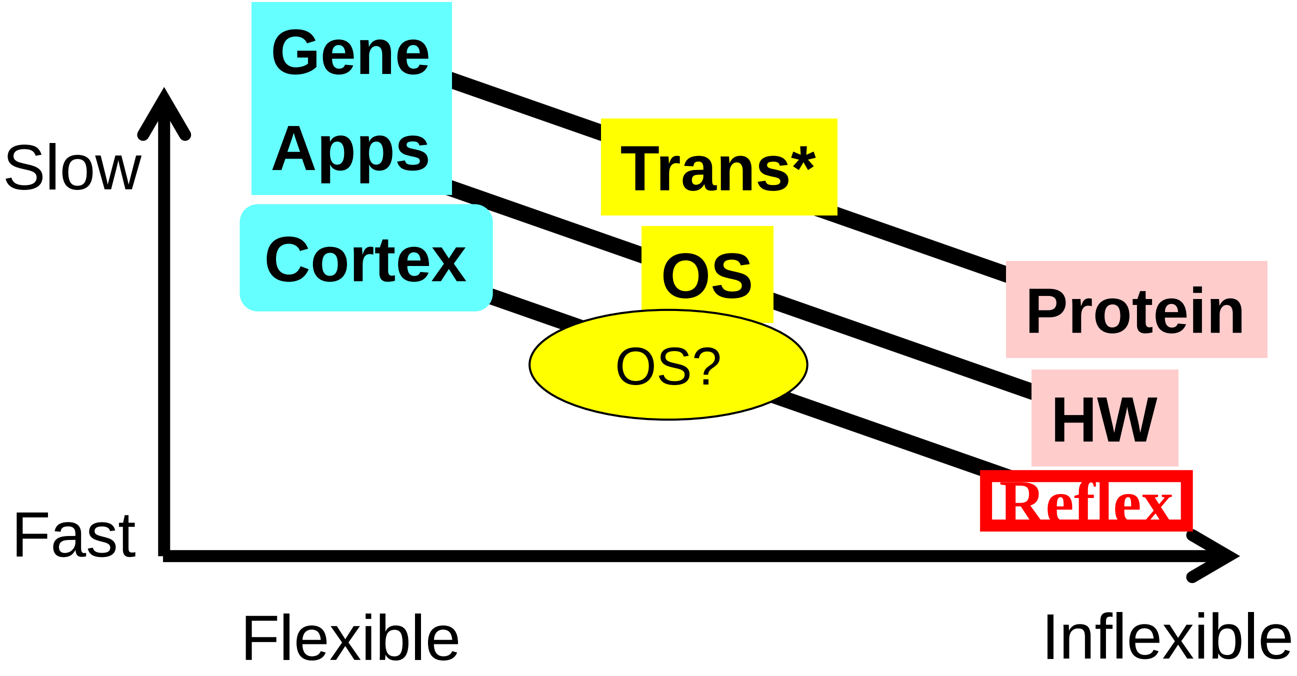


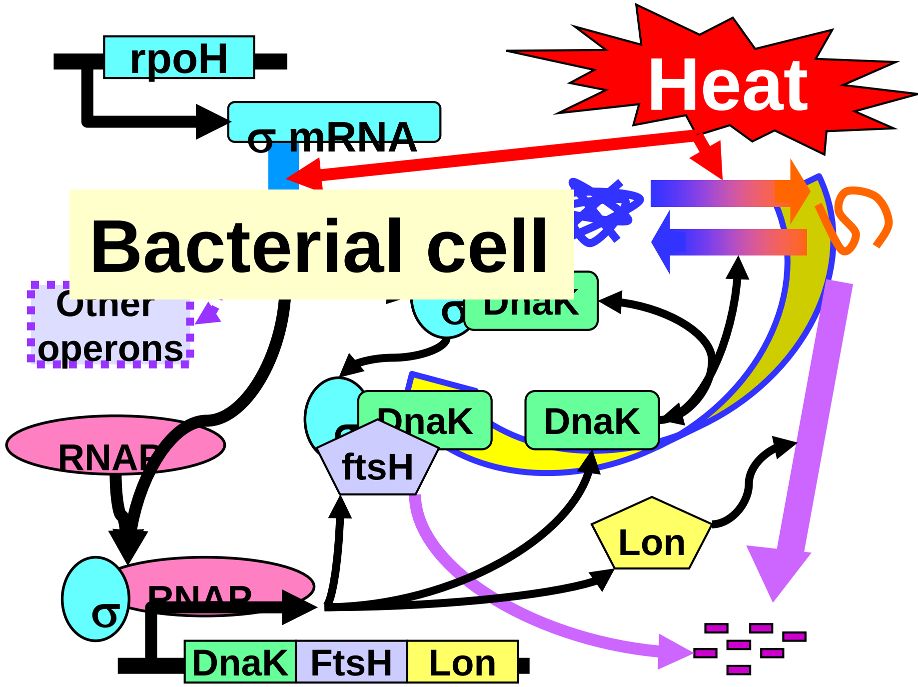
Linux kernel diagram
functions
system
networking
storage
memory
processing
human interface
layers
user space interfaces
virtual subsystems
bridges
logical
hardware interfaces
electronics
System calls
Sockets
files and directories
memory access
Processes
char devices
proc, sysfs file systems
Tasks
input subsystem
Device Model
NFS
page cache
Swap
synchronization
system run, modules, generic HW access
protocols: TCP, UDP, IP
logical filesystems ext2, ext3
logical memory
Scheduler
HI class drivers
bus drivers
network devices and drivers
Block devices and drivers
bus controllers: PCI, USB
network cards: Ethernet, WiFi
disk controllers: IDE, SCSI
mouse, audio
© 2007-2009 Constantine Shulyupin http://www.MakeLinux.net/kernel/diagram
Linux OS
Universals are profound
Object motion
Head motion
eye
vision
Cortex
fast
slow
Act
delay
Sensorimotor
Reflex
gain
AOS
Error
Tune gain
Cerebellum
Slow
Fast
Flexible
Inflexible
Apps
Cortex
OS
OS?
HW
Reflex

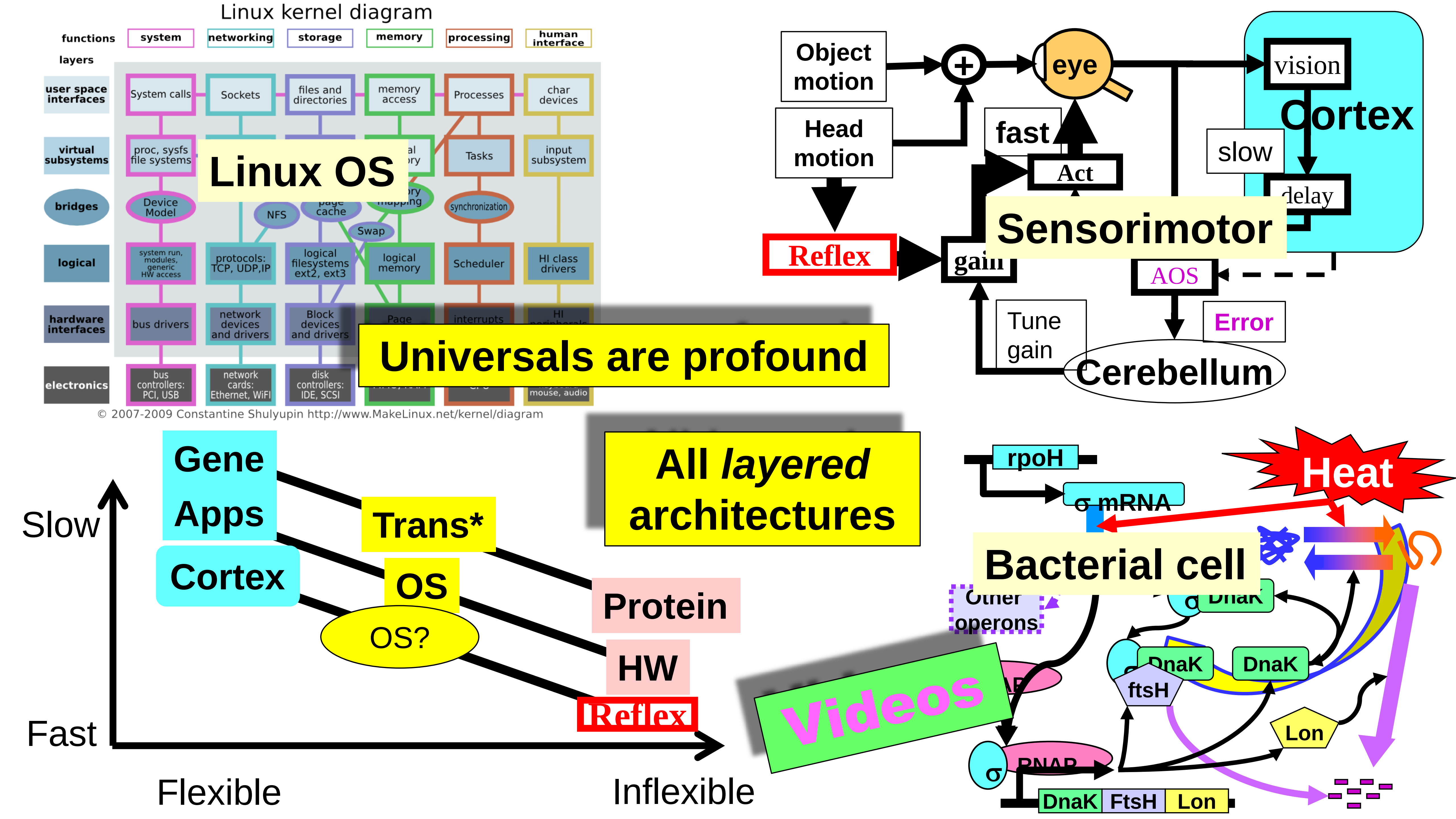


Universals are profound

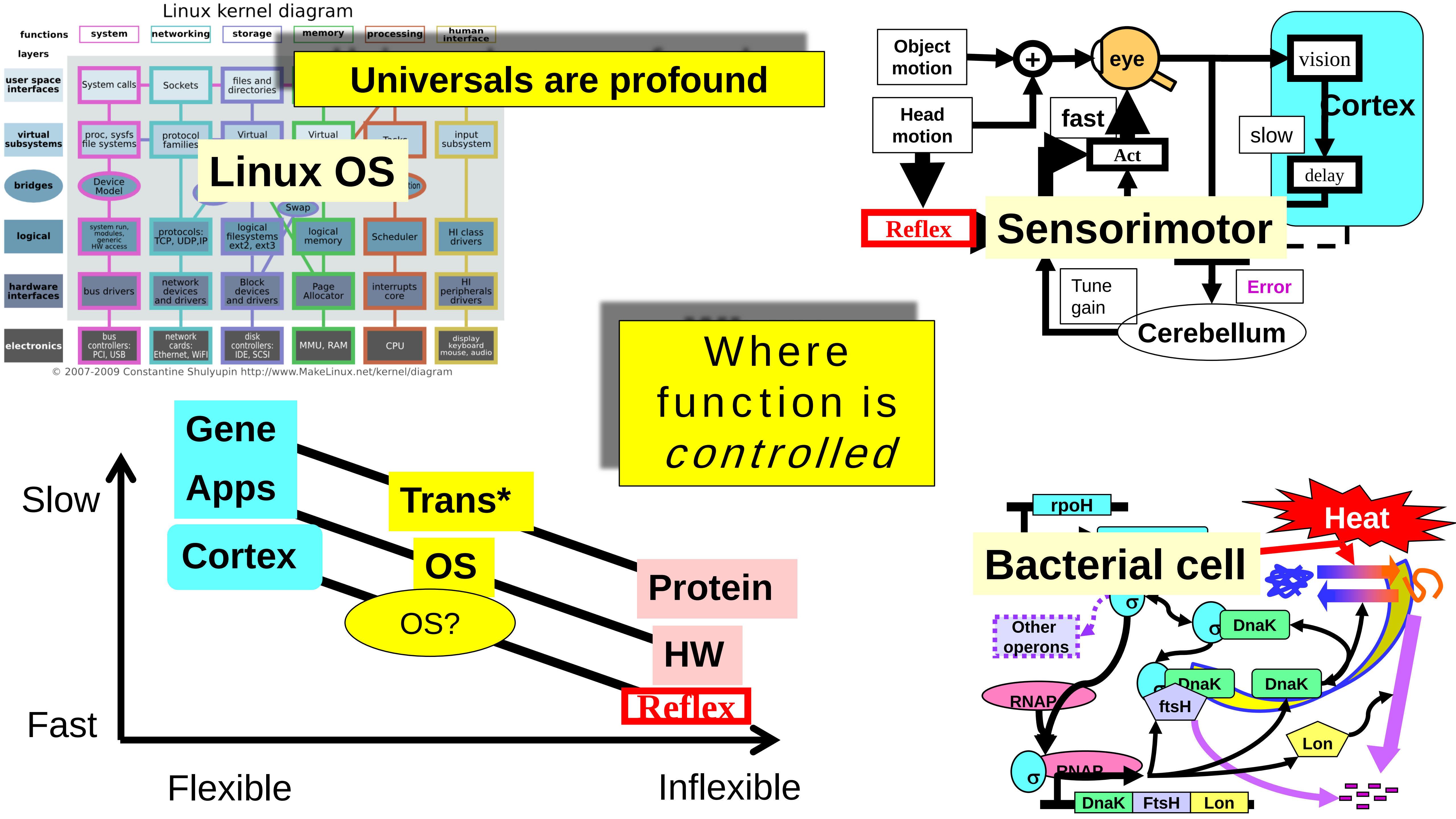




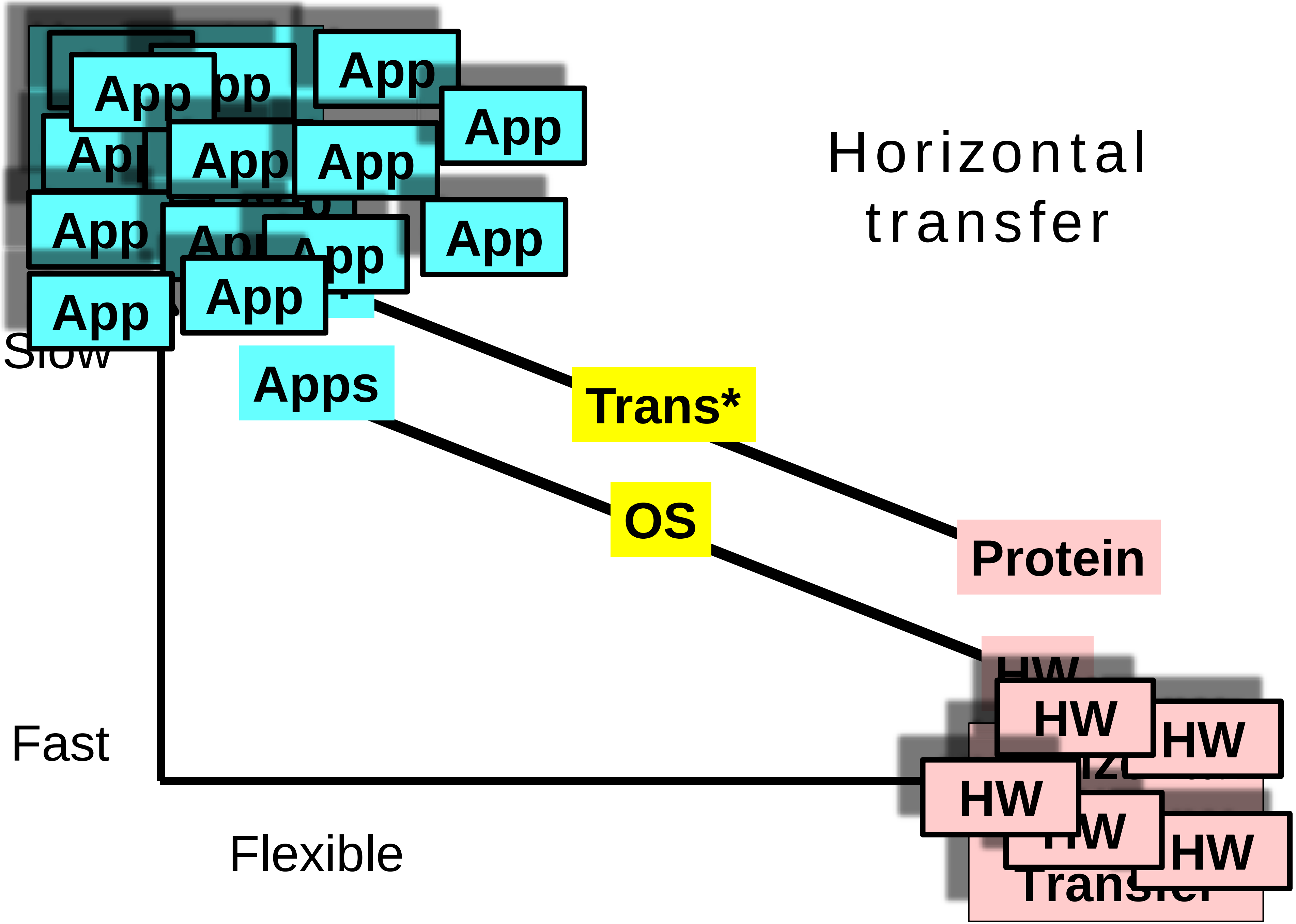




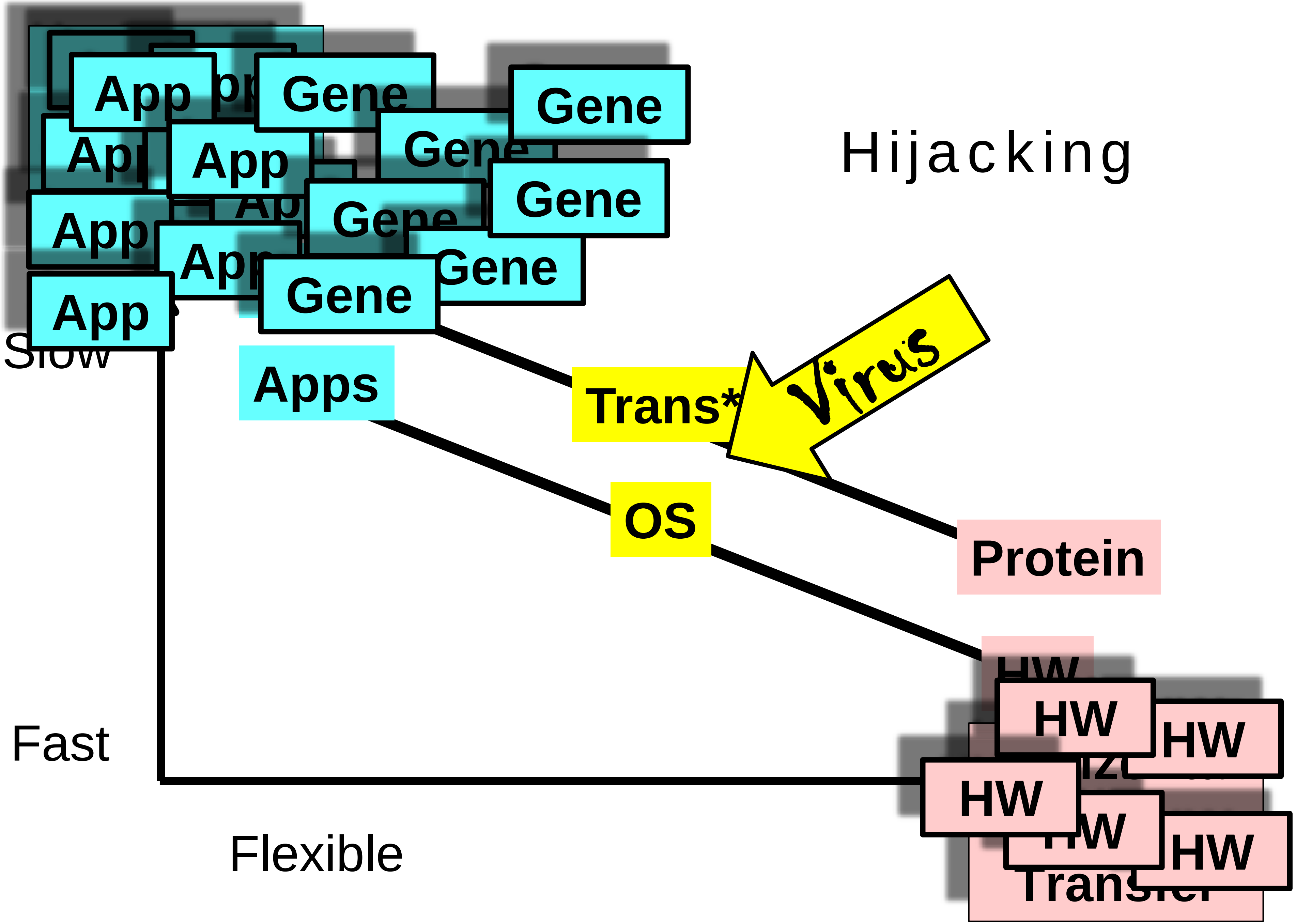
Linux kernel diagram
functions
system
networking
storage
memory
processing
human interface
layers
user space interfaces
virtual subsystems
bridges
logical
hardware interfaces
electronics
System calls
Sockets
files and directories
memory access
Processes
char devices
proc, sysfs file systems
Tasks
input subsystem
Device Model
NFS
page cache
Swap
synchronization
system run, modules, generic HW access
protocols: TCP, UDP,IP
logical filesystems ext2, ext3
logical memory
Scheduler
HI class drivers
bus drivers
network devices and drivers
Block devices and drivers
bus controllers: PCI, USB
network cards: Ethernet, WiFi
disk controllers: IDE, SCSI
mouse, audio
© 2007-2009 Constantine Shulyupin http://www.MakeLinux.net/kernel/diagram
Linux OS
Universals are profound
Object motion
Head motion
eye
vision
Cortex
fast
slow
Act
delay
Reflex
gain
Sensorimotor
AOS
Tune gain
Error
Cerebellum
Gene
Apps
Slow
Trans*
Cortex
OS
OS?
Protein
HW
Reflex
Fast
Flexible
Inflexible
All *layered* architectures
rpoH
σ mRNA
Heat
Bacterial cell
Other operons
DnaK
DnaK
ftsH
Lon
σ
Videos
DnaK
FtsH
Lon



Linux kernel diagram
functions
system
networking
storage
memory
processing
human interface
layers
user space interfaces
virtual subsystems
bridges
logical
hardware interfaces
electronics
System calls
Sockets
files and directories
proc, sysfs file systems
protocol families
Virtual
Virtual
input subsystem
Device Model
Swap
system run, modules, generic HW access
protocols: TCP, UDP,IP
logical filesystems ext2, ext3
logical memory
Scheduler
HI class drivers
bus drivers
network devices and drivers
Block devices and drivers
Page Allocator
interrupts core
HI peripherals drivers
bus controllers: PCI, USB
network cards: Ethernet, WiFi
disk controllers: IDE, SCSI
MMU, RAM
CPU
display keyboard mouse, audio
© 2007-2009 Constantine Shulyupin http://www.MakeLinux.net/kernel/diagram
Universals are profound
Linux OS
Object motion
Head motion
eye
vision
Cortex
fast
slow
Act
delay
Reflex
Sensorimotor
Tune gain
Error
Cerebellum
Where function is controlled
Gene
Apps
Slow
Trans*
Cortex
OS
Protein
OS?
HW
Reflex
Fast
Flexible
Inflexible
rpoH
Heat
Bacterial cell
σ
Other operons
σ
DnaK
DnaK
DnaK
RNAP
ftsH
Lon
σ
RNAP
DnaK
FtsH
Lon



Horizontal transfer
App
Apps
Trans*
OS
Protein
HW
Slow
Fast
Flexible



Hijacking
App
App
App
App
App
Gene
Gene
Gene
Gene
Gene
Gene
Gene
Slow
Apps
Trans*
Virus
OS
Protein
HW
HW
HW
HW
HW
Fast
Flexible

Predators don’t care about architecture

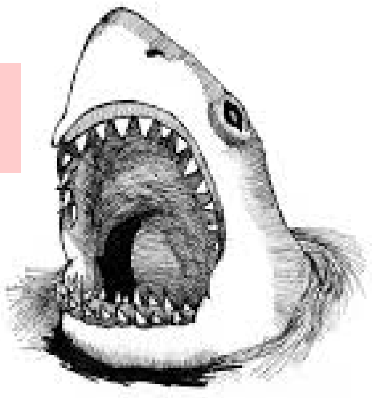
C

OK to ignore/destroy architecture

otein

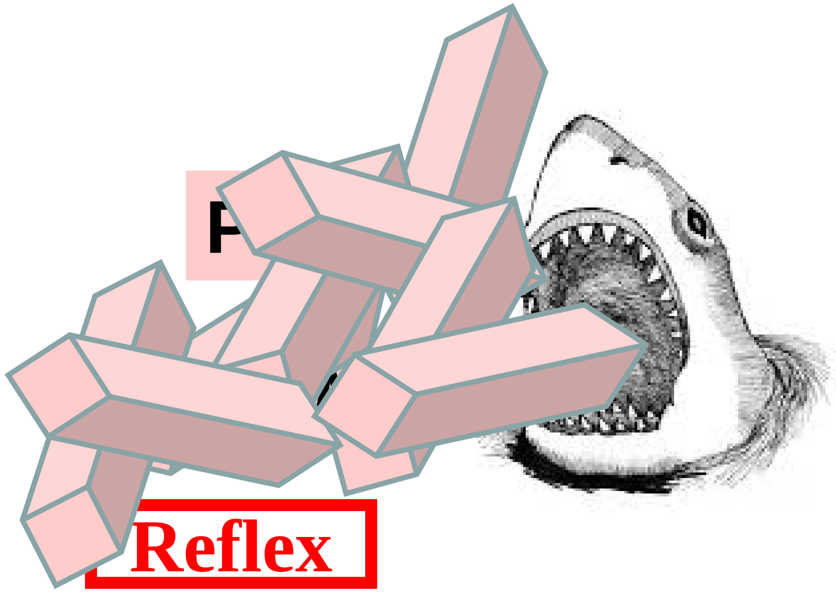
w

ex

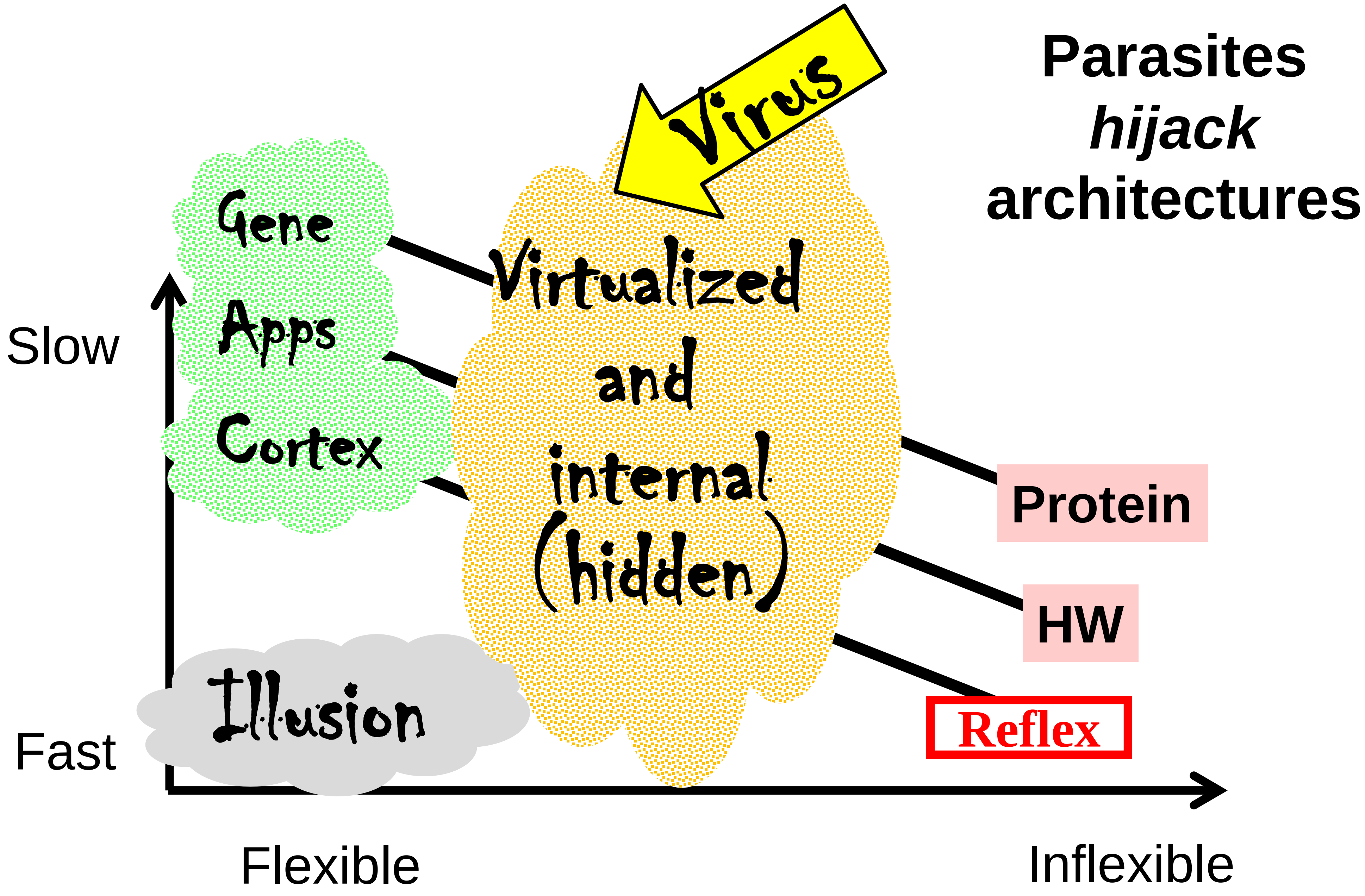


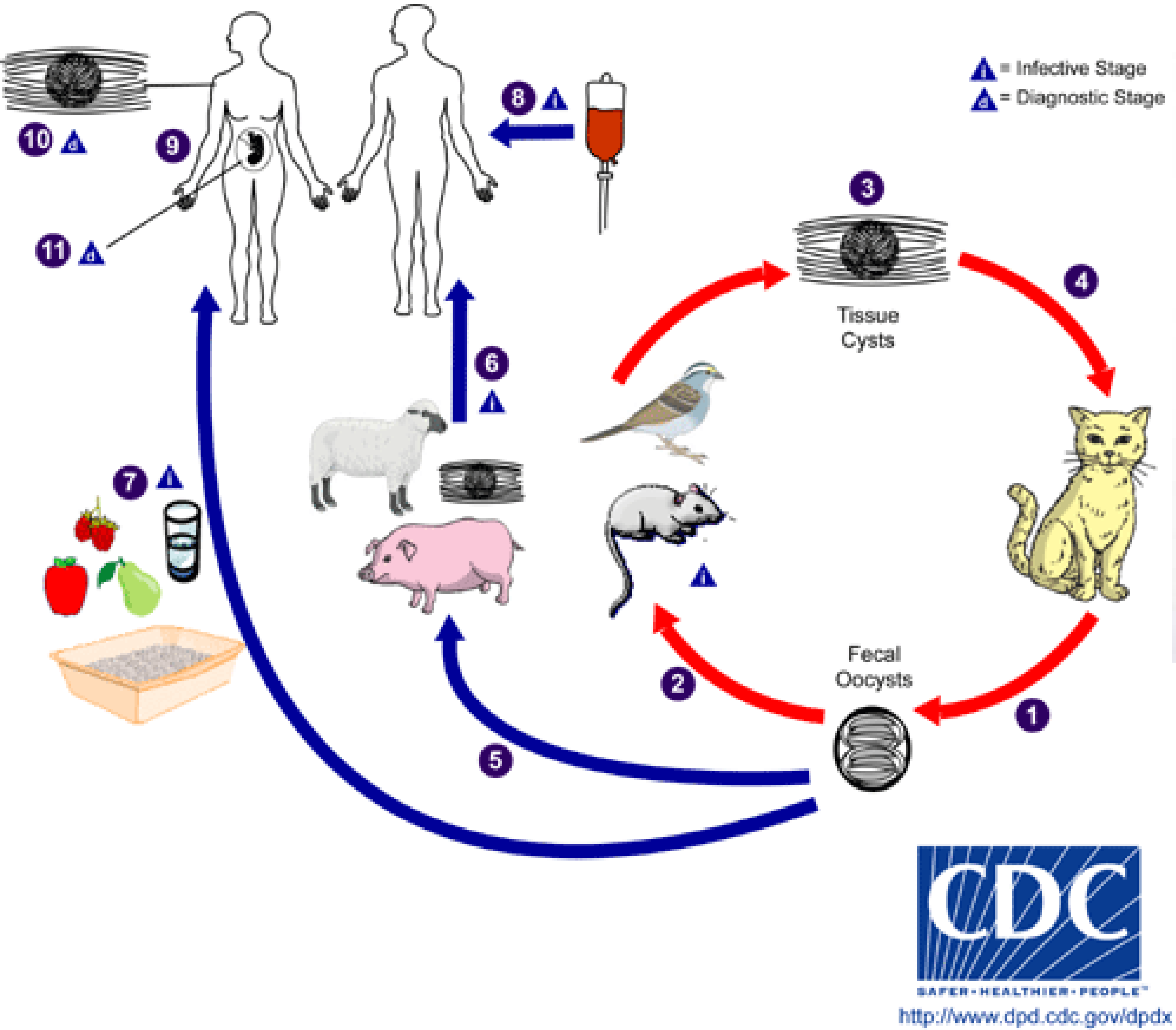
Predators don’t care about architecture

OK to ignore/destroy architecture

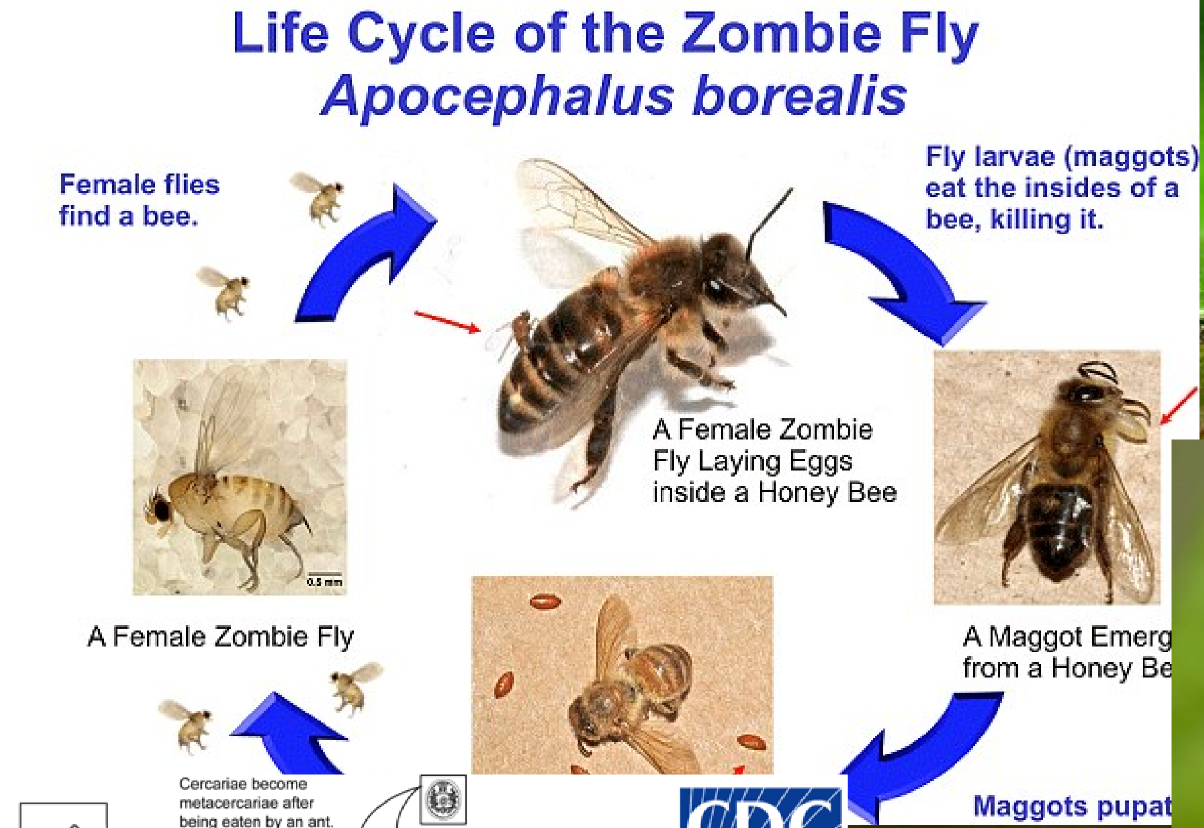


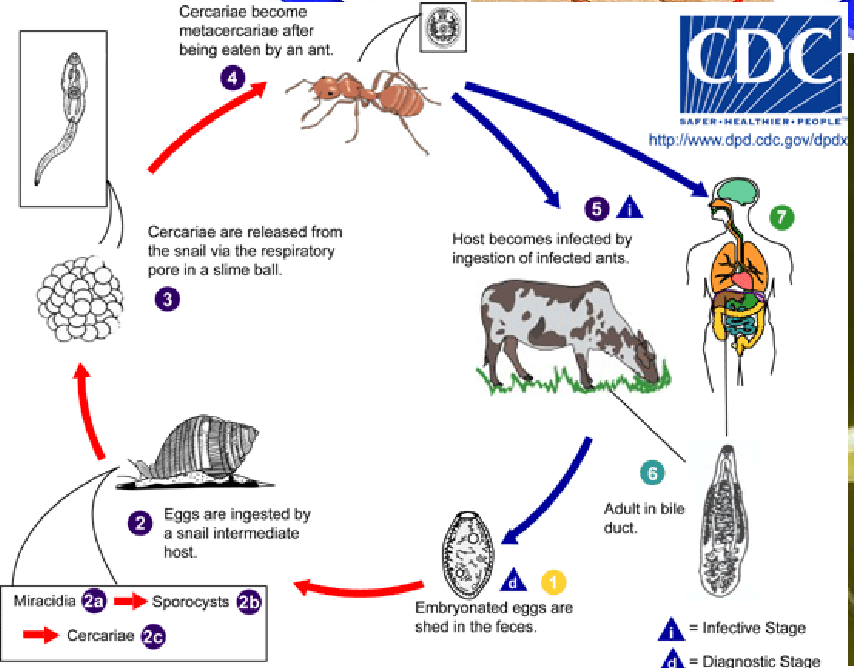
Consumes physical building blocks


Parasites
hijack
architectures
Virus
Gene
Apps
Cortex
Virtualized
and
internal
(hidden)
Protein
HW
Reflex
Illusion
Slow
Fast
Flexible
Inflexible



Zombie parasites





Zombie parasites

Zombie

Zombieness

Predator?

Parasite?

Zience fiction

Zombie

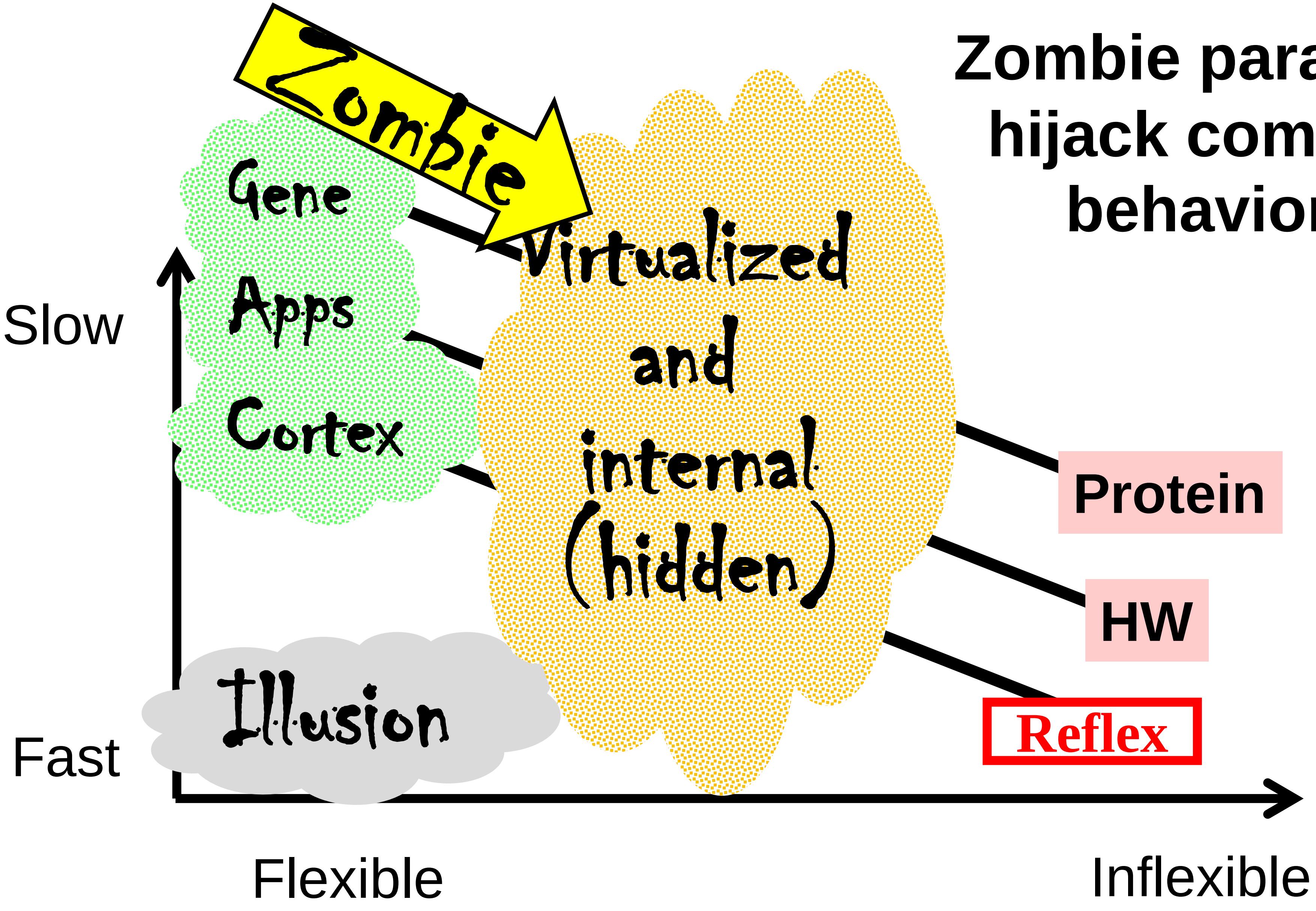
Predator?

Rabies

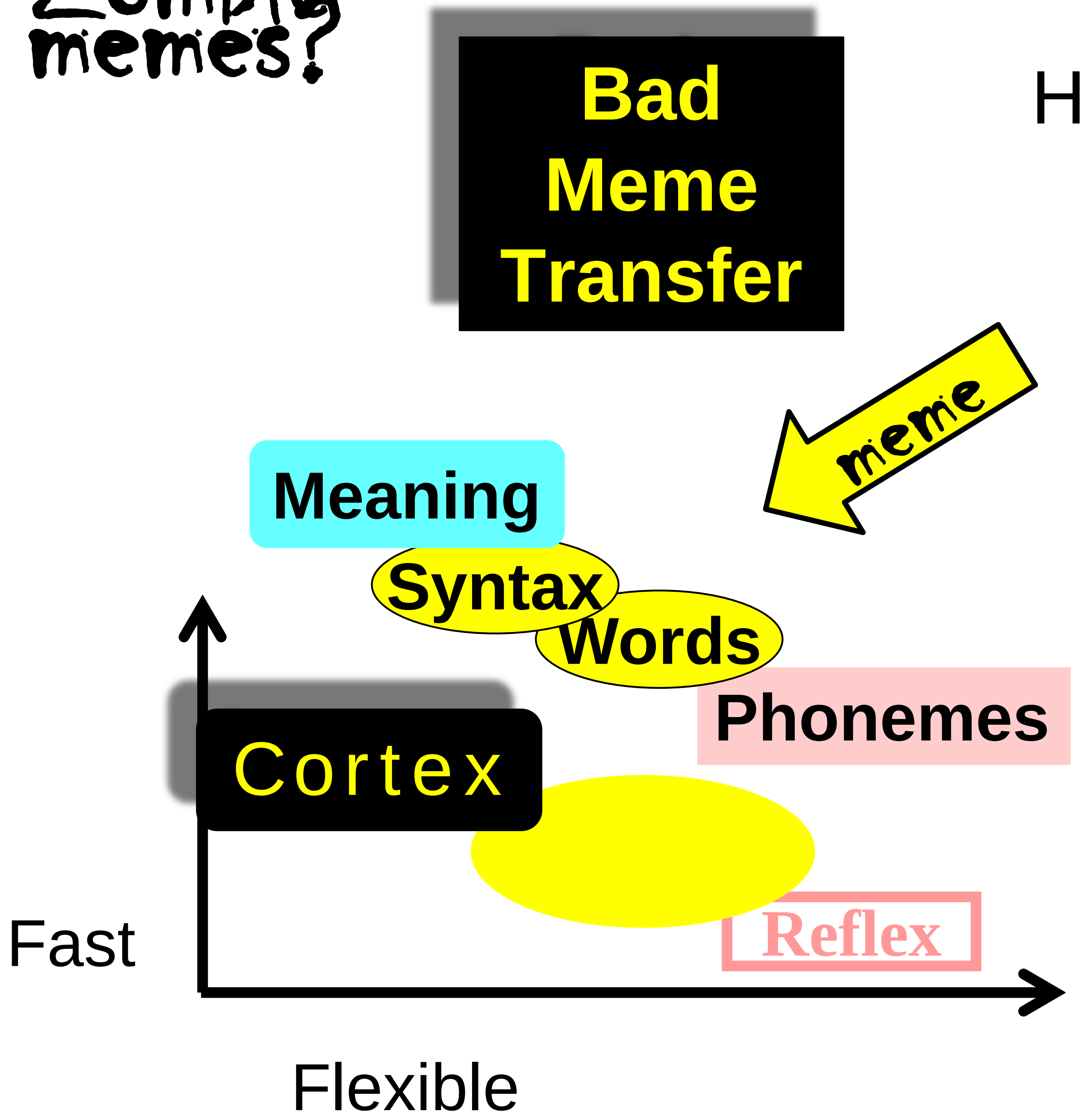
Zombieness

Parasite?

Zombie parasites hijack complex behaviors



Zombie memes?



Hijacking?

Beliefs

- Viral
- False
- Unhealthy
- Dangerous

Lifespan, violence, cancer, wound healing, and sociality

A control architecture perspective

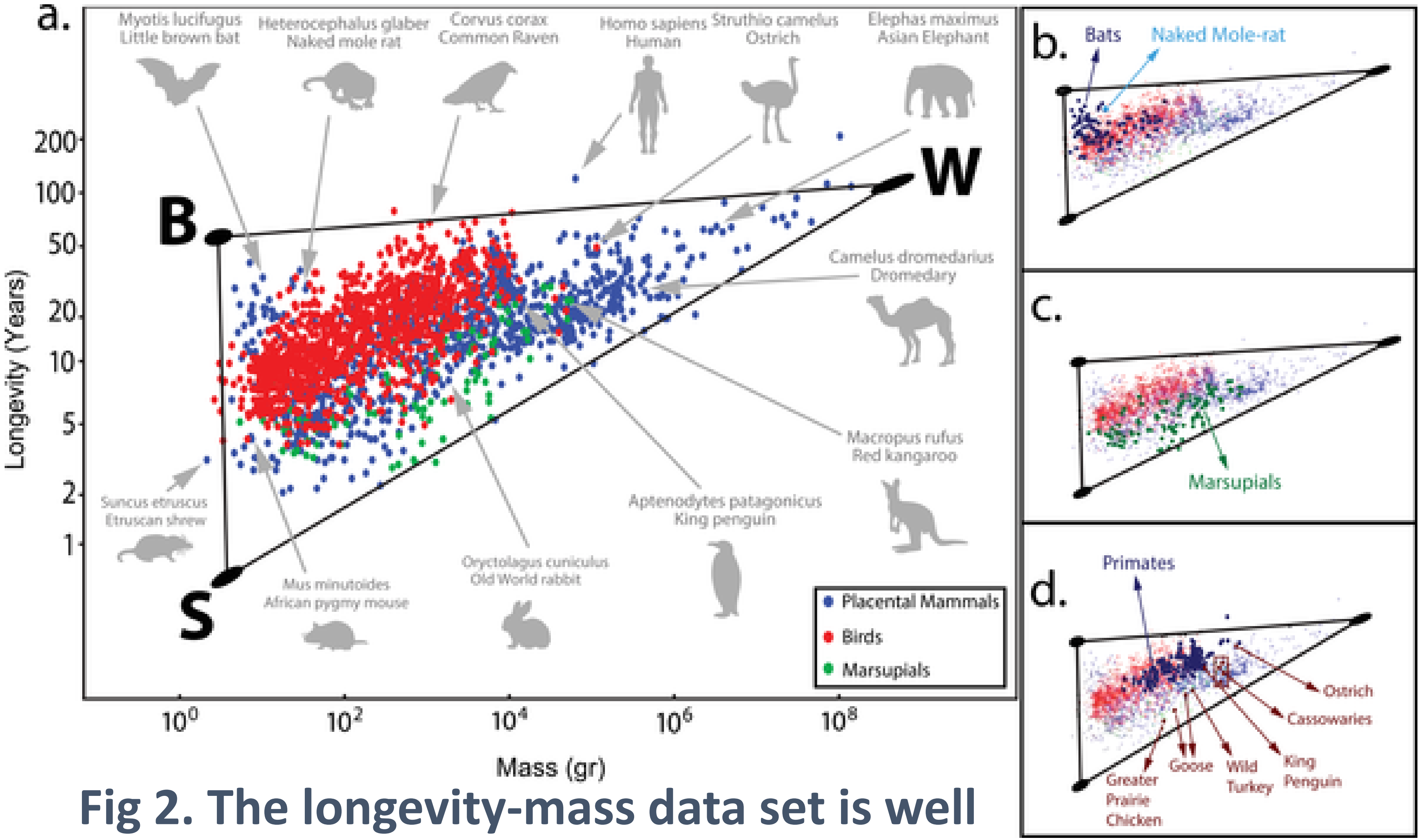


Fig 2. The longevity-mass data set is well described by a triangle in log space.

Szekely P, Korem Y, Moran U, Mayo A, Alon U (2015) The Mass-Longevity Triangle: Pareto Optimality and the Geometry of Life-History Trait Space. PLOS Computational Biology 11(10): e1004524. https://doi.org/10.1371/journal.pcbi.1004524
http://journals.plos.org/ploscompbiol/article?id=10.1371/journal.pcbi.1004524

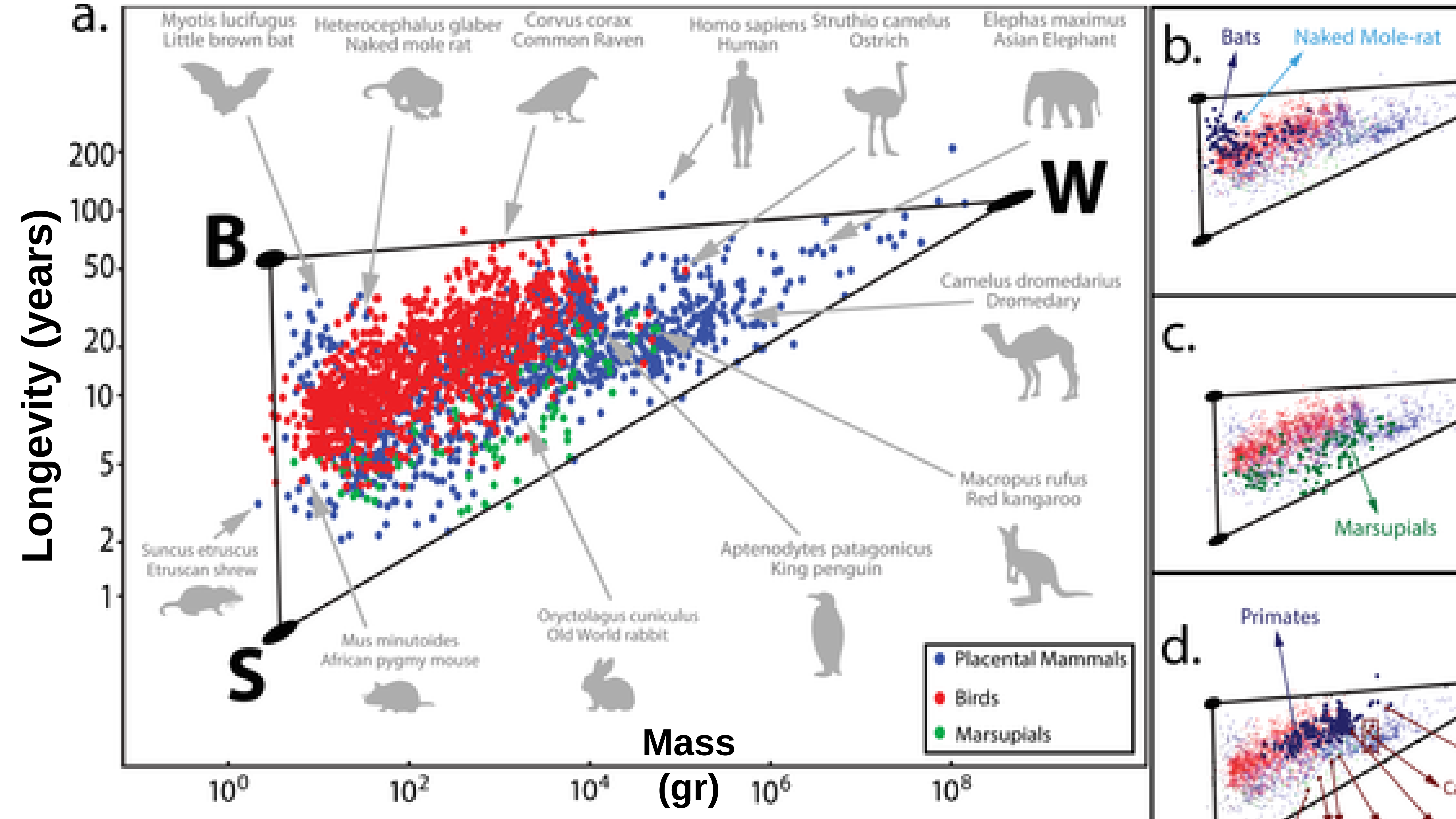
Szekely P, Korem Y, Moran U, Mayo A, Alon U (2015)

The Mass-Longevity Triangle: Pareto Optimality and the Geometry of Life-History Trait Space.

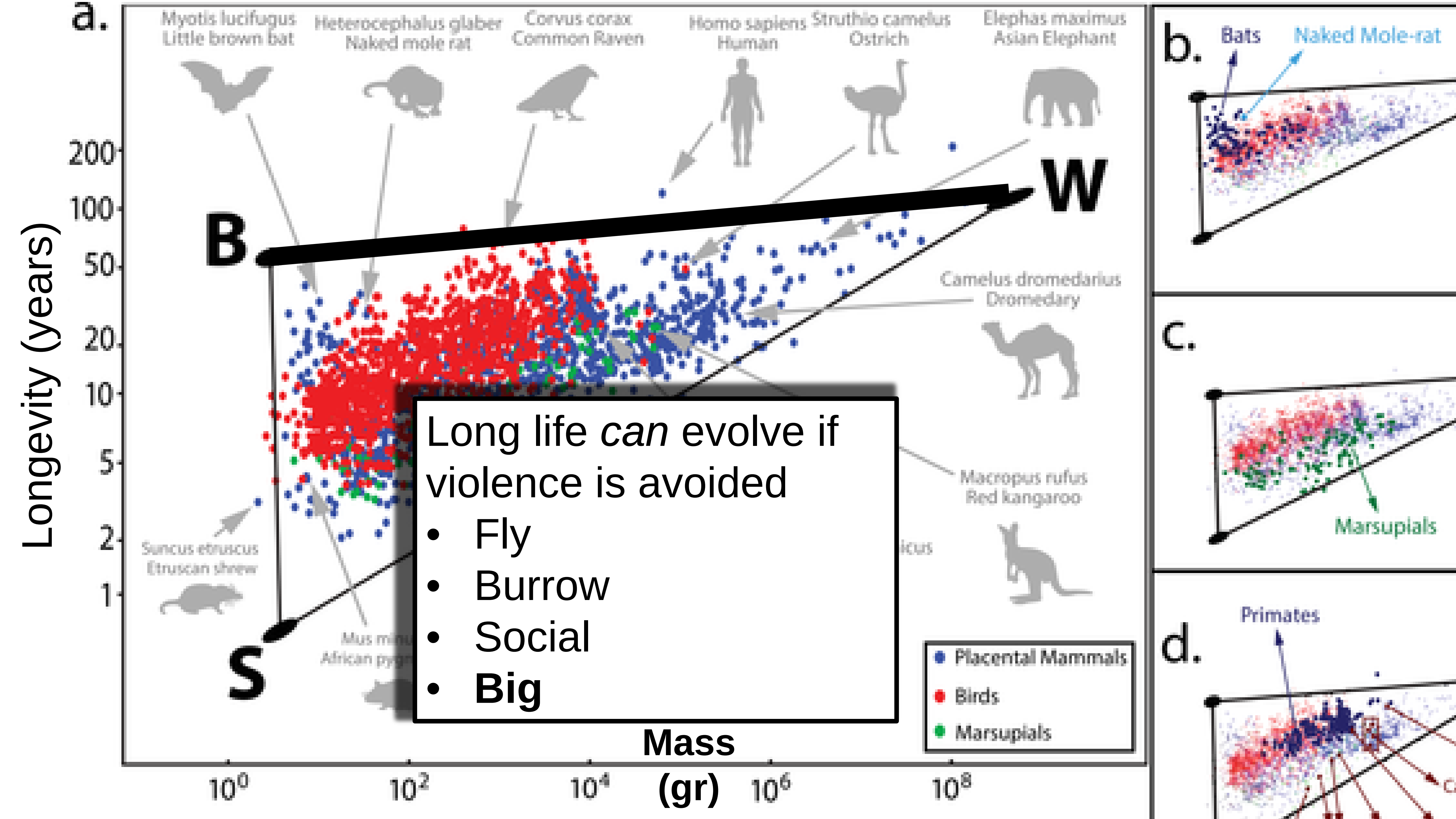
PLOS Computational Biology 11(10):

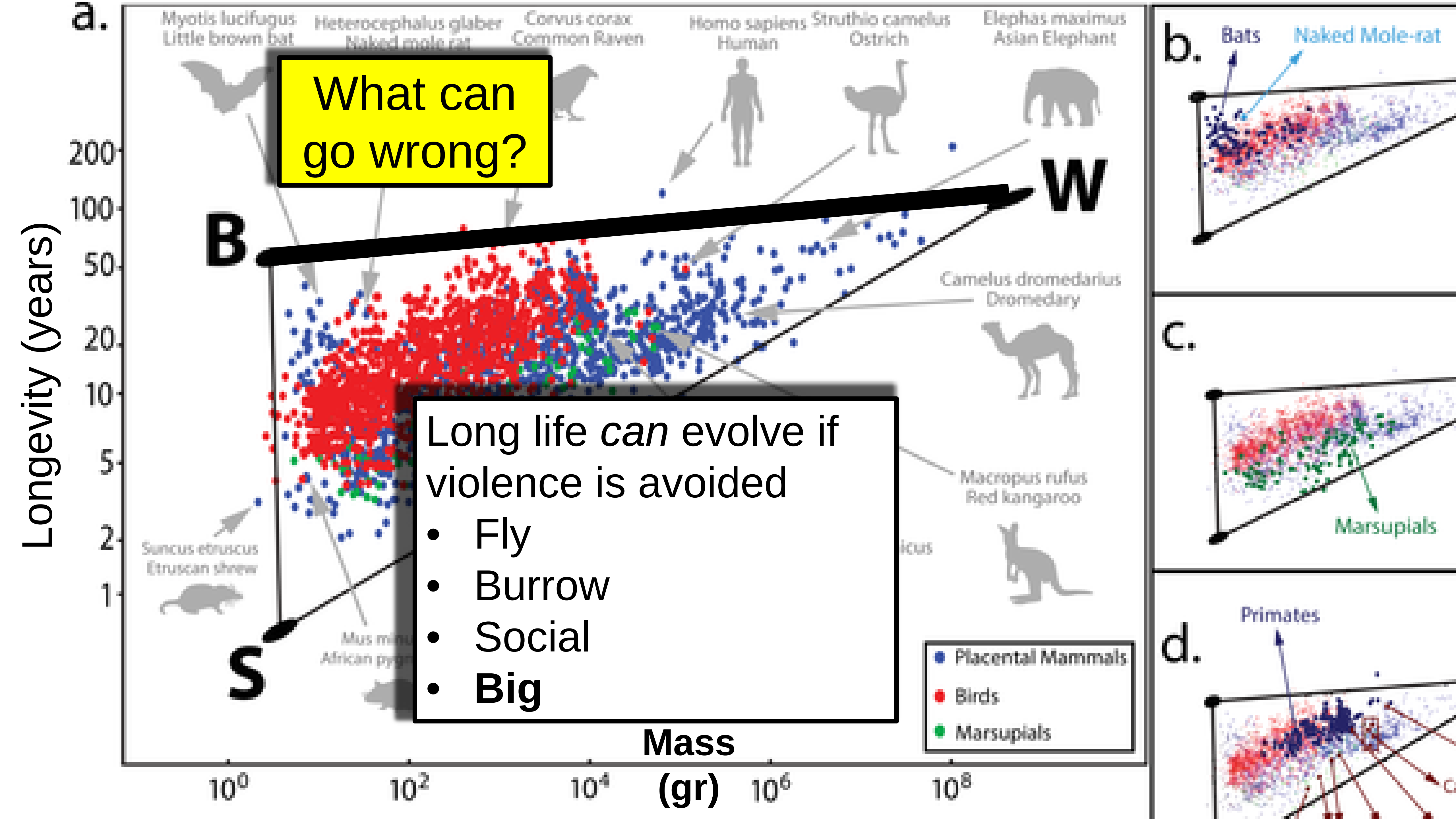
e1004524. https://doi.org/10.1371/journal.pcbi.1004524
http://journals.plos.org/ploscompbiol/article?id=10.1371/journal.pcbi.1004524

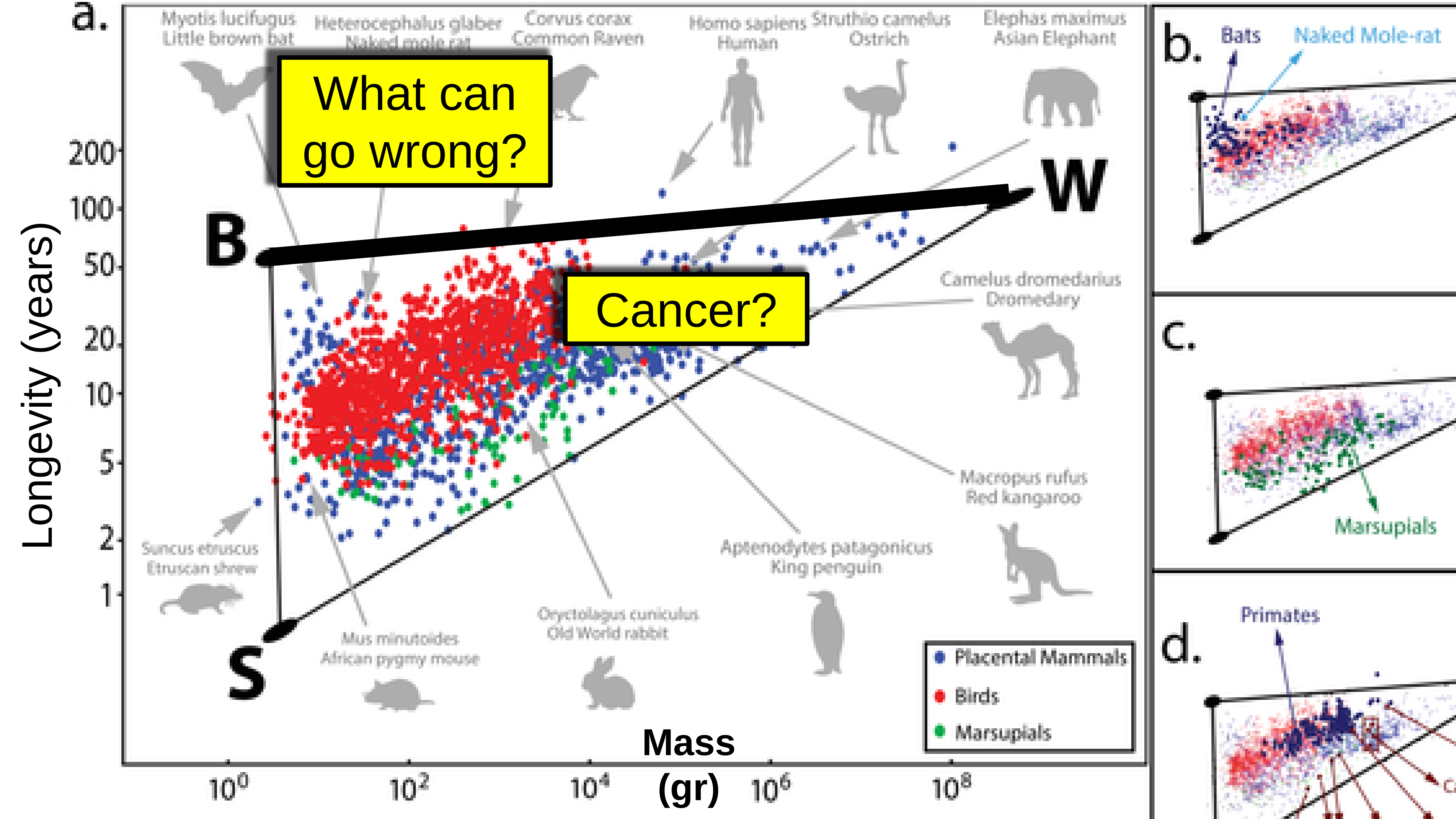
PLOS | COMPUTATIONAL BIOLOGY



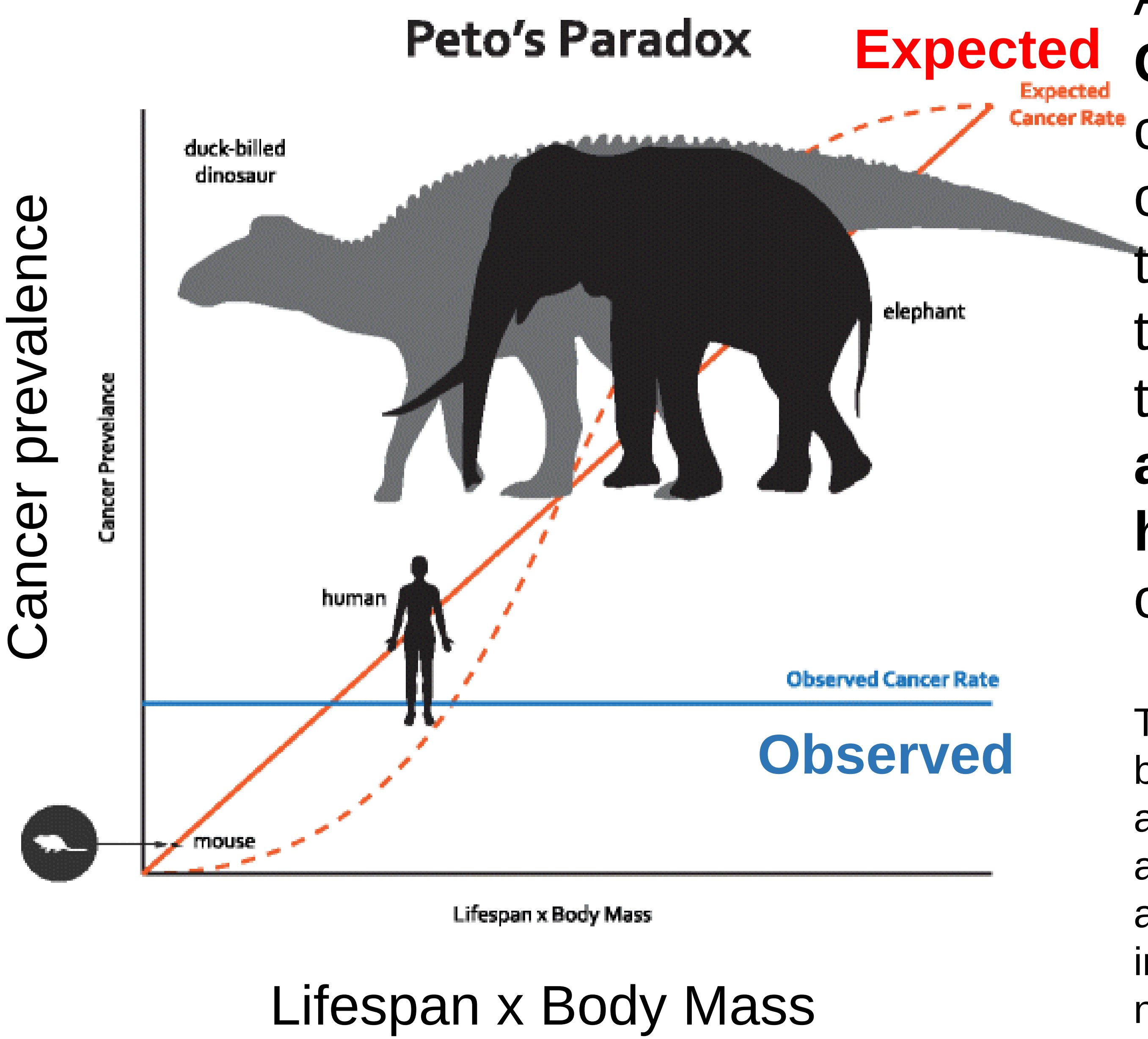
a.
Myotis lucifugus
Little brown bat
Heterocephalus glaber
Naked mole rat
Corvus corax
Common Raven
Homo sapiens
Human
Struthio camelus
Ostrich
Elephas maximus
Asian Elephant
Camelus dromedarius
Dromedary
Macropus rufus
Red kangaroo
Aptenodytes patagonicus
King penguin
Oryctolagus cuniculus
Old World rabbit
Mus minutoides
African pygmy mouse
Suncus etruscus
Etruscan shrew
B
W
S
Longevity (years)
200
100
50
20
10
5
2
1
Mass
(gr)
10^0
10^2
10^4
10^6
10^8
Placental Mammals
Birds
Marsupials
b.
Bats
Naked Mole-rat
c.
Marsupials
d.
Primates


a.
Myotis lucifugus
Little brown bat
Heterocephalus glaber
Naked mole rat
Corvus corax
Common Raven
Homo sapiens
Human
Struthio camelus
Ostrich
Elephas maximus
Asian Elephant
Camelus dromedarius
Dromedary
Macropus rufus
Red kangaroo
Suncus etruscus
Etruscan shrew
B
W
S
Longevity (years)
200
100
50
20
10
5
2
1
Mass
(gr)
10^0
10^2
10^4
10^6
10^8
Placental Mammals
Birds
Marsupials
Long life *can* evolve if violence is avoided
• Fly
• Burrow
• Social
• **Big**
b.
Bats
Naked Mole-rat
c.
Marsupials
d.
Primates


a.
Myotis lucifugus
Little brown bat
Heterocephalus glaber
Naked mole rat
Corvus corax
Common Raven
Homo sapiens
Human
Struthio camelus
Ostrich
Elephas maximus
Asian Elephant
What can go wrong?
200
100
50
20
10
5
2
1
Longevity (years)
B
W
S
Camelus dromedarius
Dromedary
Macropus rufus
Red kangaroo
Suncus etruscus
Etruscan shrew
Long life *can* evolve if violence is avoided
• Fly
• Burrow
• Social
• **Big**
Placental Mammals
Birds
Marsupials
Mass (gr)
10^0
10^2
10^4
10^6
10^8
b.
Bats
Naked Mole-rat
c.
Marsupials
d.
Primates

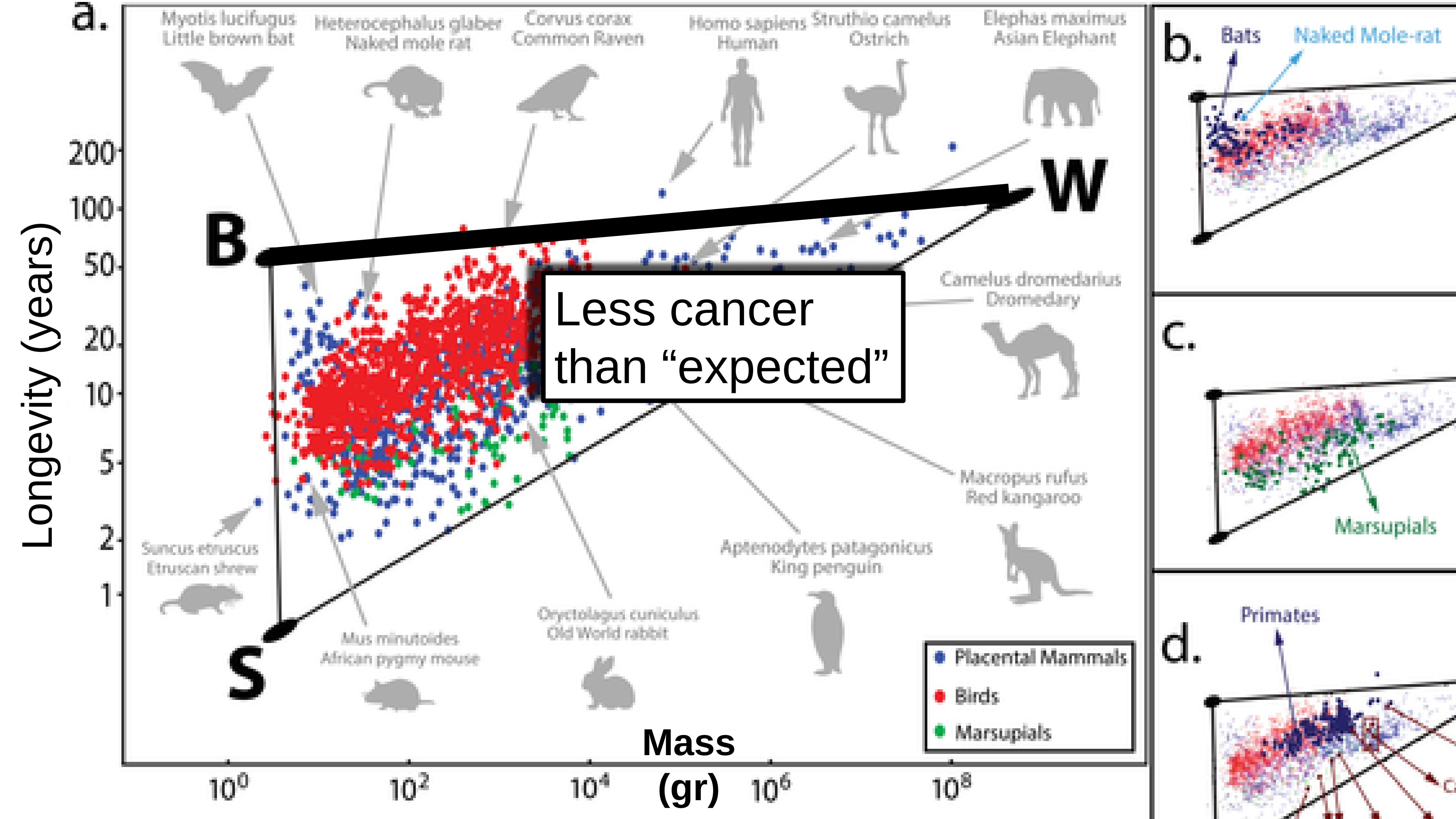


a.
Myotis lucifugus
Little brown bat
Heterocephalus glaber
Naked mole rat
Corvus corax
Common Raven
Homo sapiens
Human
Struthio camelus
Ostrich
Elephas maximus
Asian Elephant
What can go wrong?
Cancer?
B
W
S
Camelus dromedarius
Dromedary
Macropus rufus
Red kangaroo
Suncus etruscus
Etruscan shrew
Mus minutoides
African pygmy mouse
Oryctolagus cuniculus
Old World rabbit
Aptenodytes patagonicus
King penguin
Placental Mammals
Birds
Marsupials
Longevity (years)
Mass (gr)
b.
Bats
Naked Mole-rat
c.
Marsupials
d.
Primates

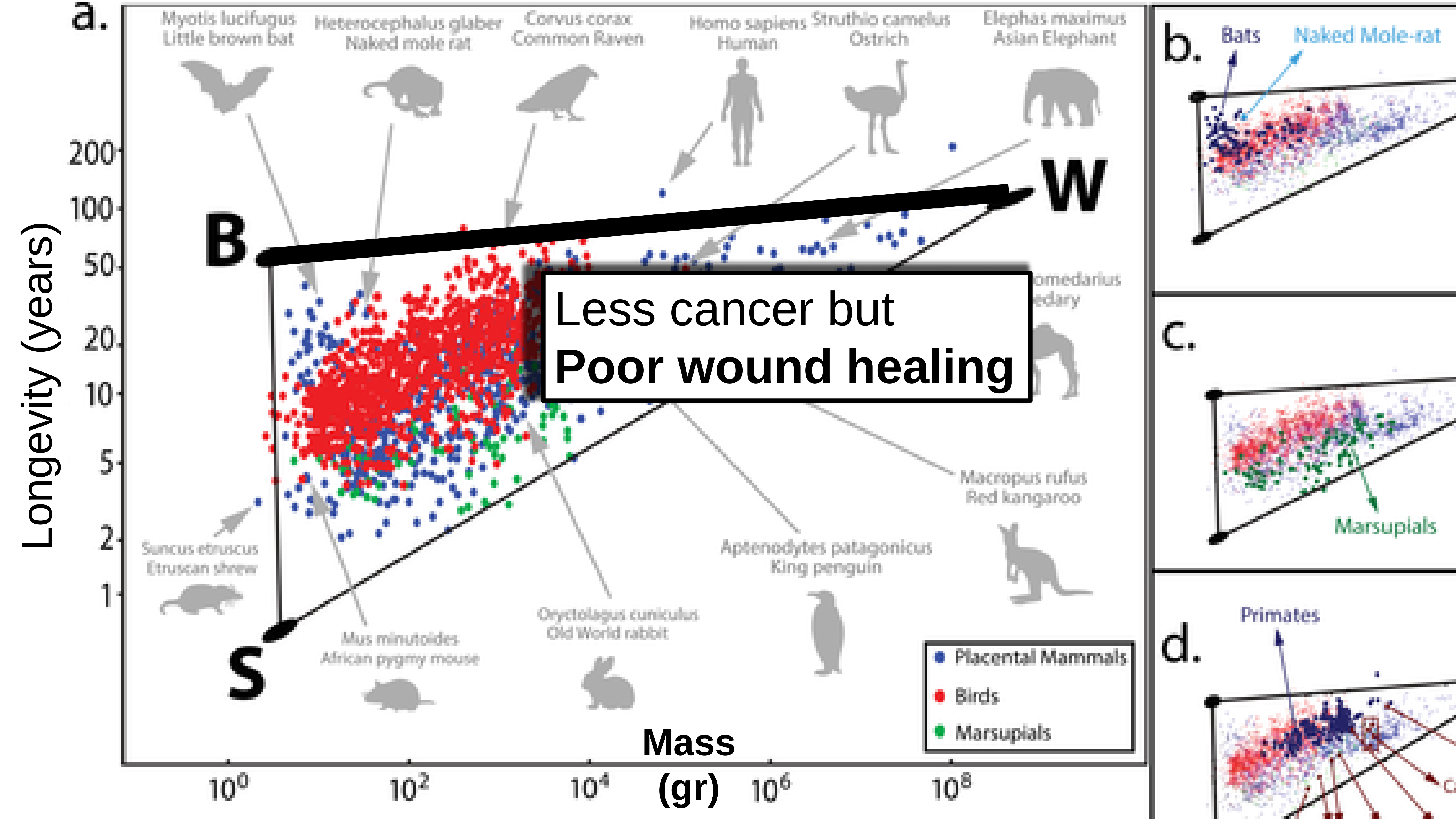


An illustration of **Peto's Paradox**. **Cancer** is a disease of uncontrolled cell growth and division, and the risk of developing cancer increases with the number of cell divisions during the lifetime of an organism. Thus, the expected **cancer rate for large and/or long-lived species is higher** than for smaller short-lived ones.

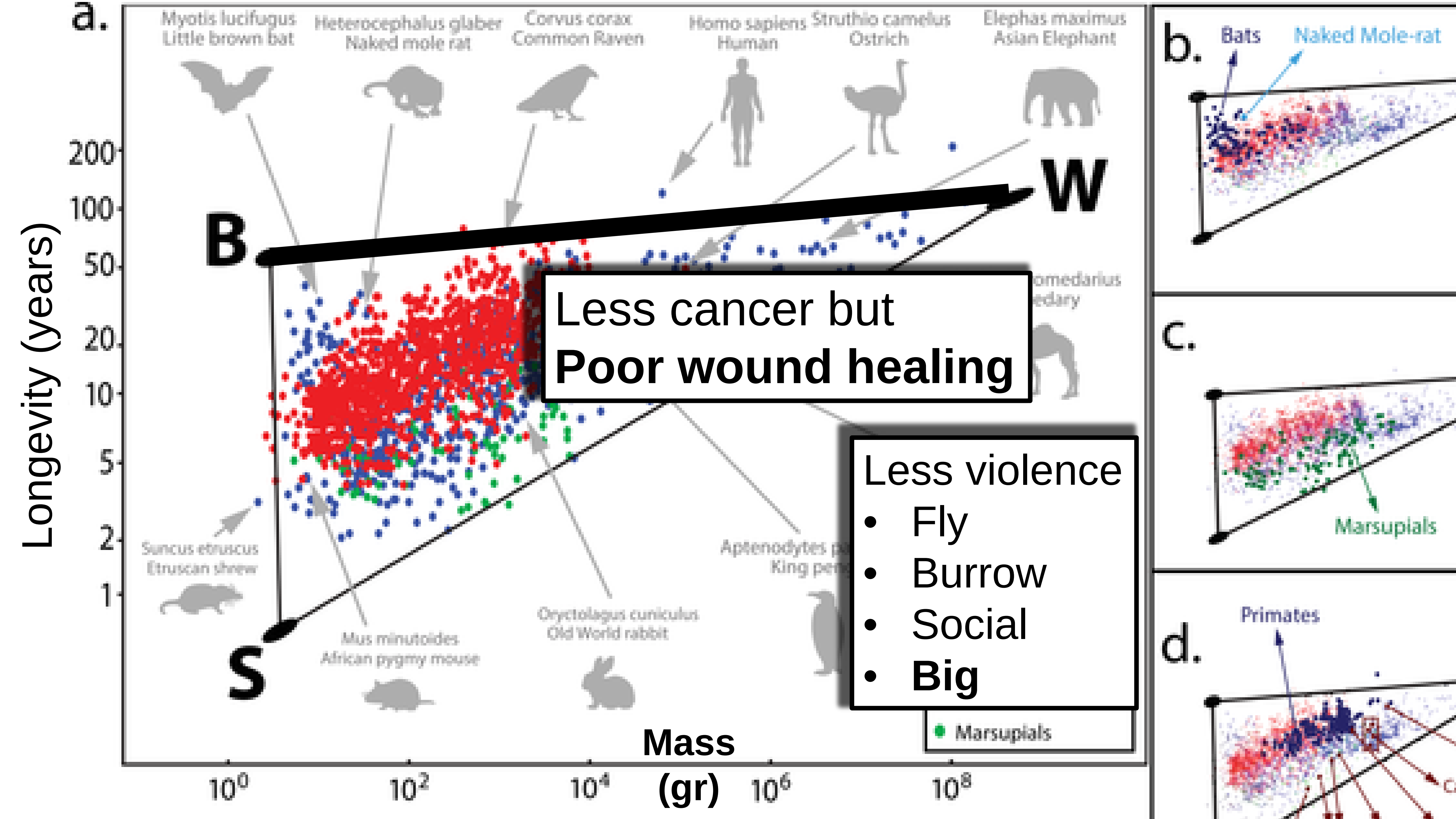
The *solid red line* indicates a linear relationship between cancer rate and (body mass)*(lifespan) and the *dashed red line* represents an approximation of the expected cancer rate assuming a model describing the probability of an individual developing colorectal cancer after a given number of cell divisions [4]. The *solid blue line* represents the observation that there is no relationship between cancer risk and (body



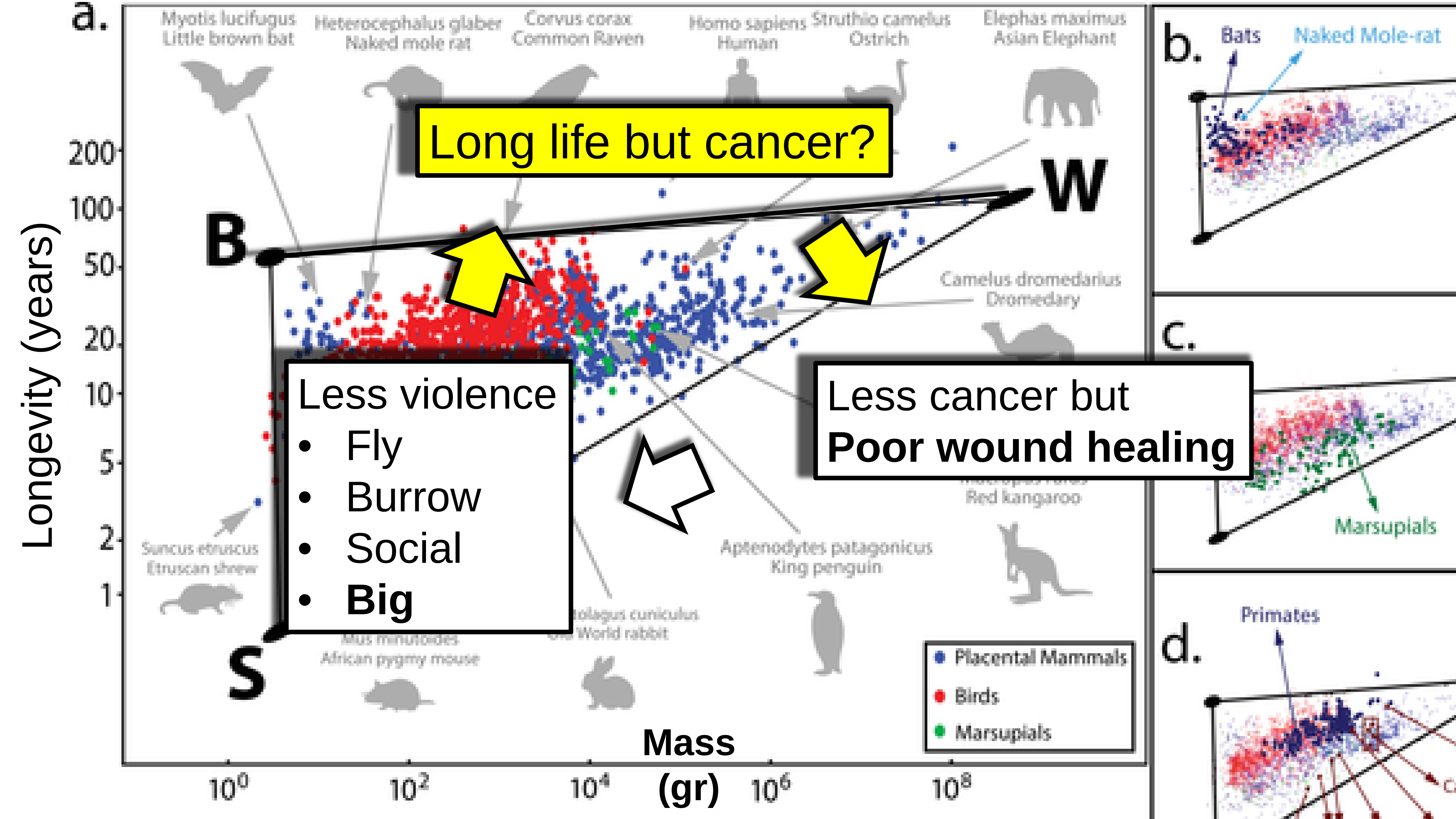
a.
Myotis lucifugus
Little brown bat
Heterocephalus glaber
Naked mole rat
Corvus corax
Common Raven
Homo sapiens
Human
Struthio camelus
Ostrich
Elephas maximus
Asian Elephant
B
W
S
Less cancer than "expected"
Camelus dromedarius
Dromedary
Macropus rufus
Red kangaroo
Aptenodytes patagonicus
King penguin
Suncus etruscus
Etruscan shrew
Mus minutoides
African pygmy mouse
Oryctolagus cuniculus
Old World rabbit
Longevity (years)
Mass (gr)
Placental Mammals
Birds
Marsupials
b.
Bats
Naked Mole-rat
c.
Marsupials
d.
Primates



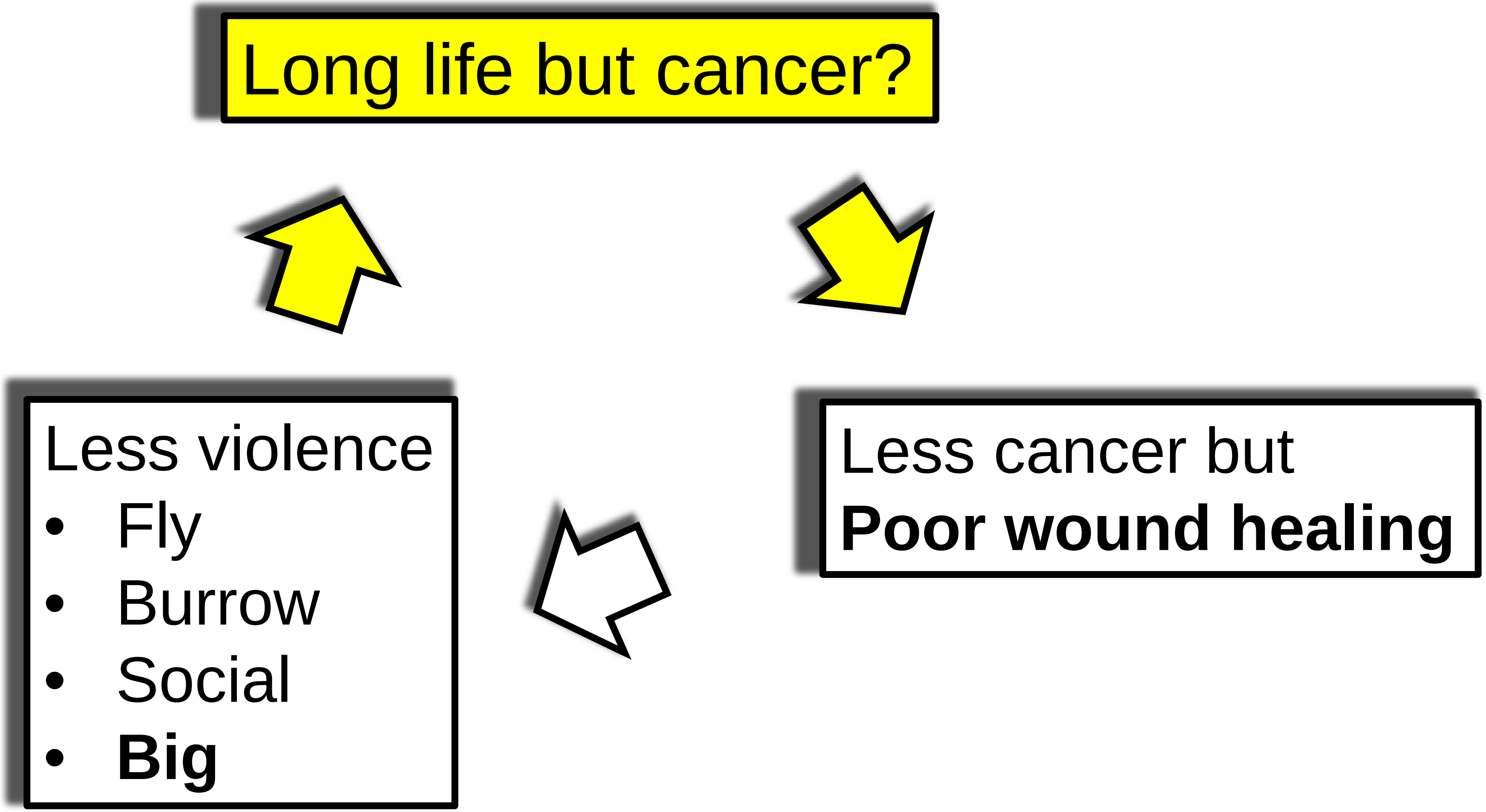
a.
Myotis lucifugus
Little brown bat
Heterocephalus glaber
Naked mole rat
Corvus corax
Common Raven
Homo sapiens
Human
Struthio camelus
Ostrich
Elephas maximus
Asian Elephant
B
W
S
Less cancer but
Poor wound healing
Macropus rufus
Red kangaroo
Suncus etruscus
Etruscan shrew
Mus minutoides
African pygmy mouse
Oryctolagus cuniculus
Old World rabbit
Aptenodytes patagonicus
King penguin
Placental Mammals
Birds
Marsupials
Longevity (years)
200
100
50
20
10
5
2
1
Mass
(gr)
10^0
10^2
10^4
10^6
10^8
b.
Bats
Naked Mole-rat
c.
Marsupials
d.
Primates

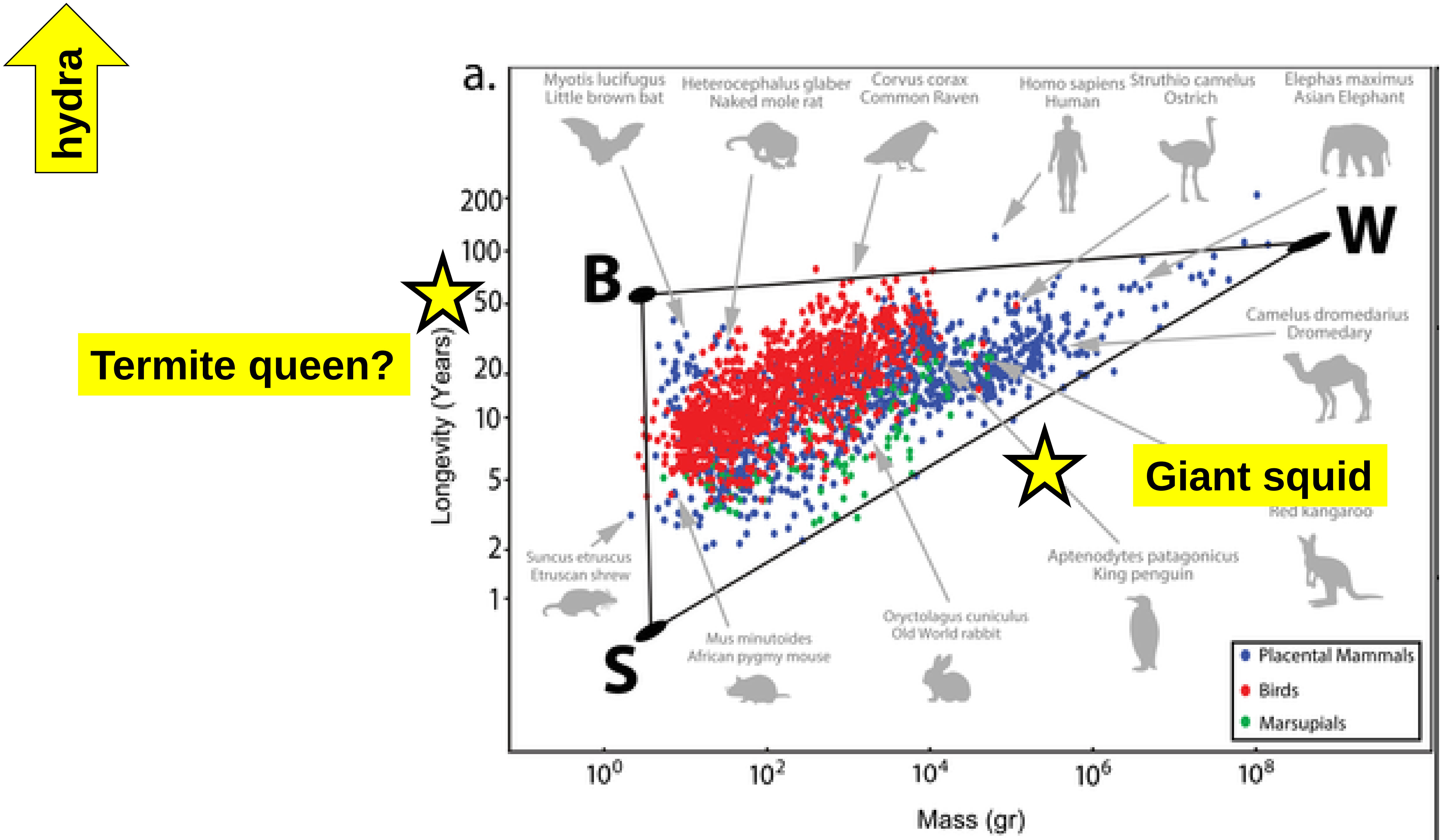


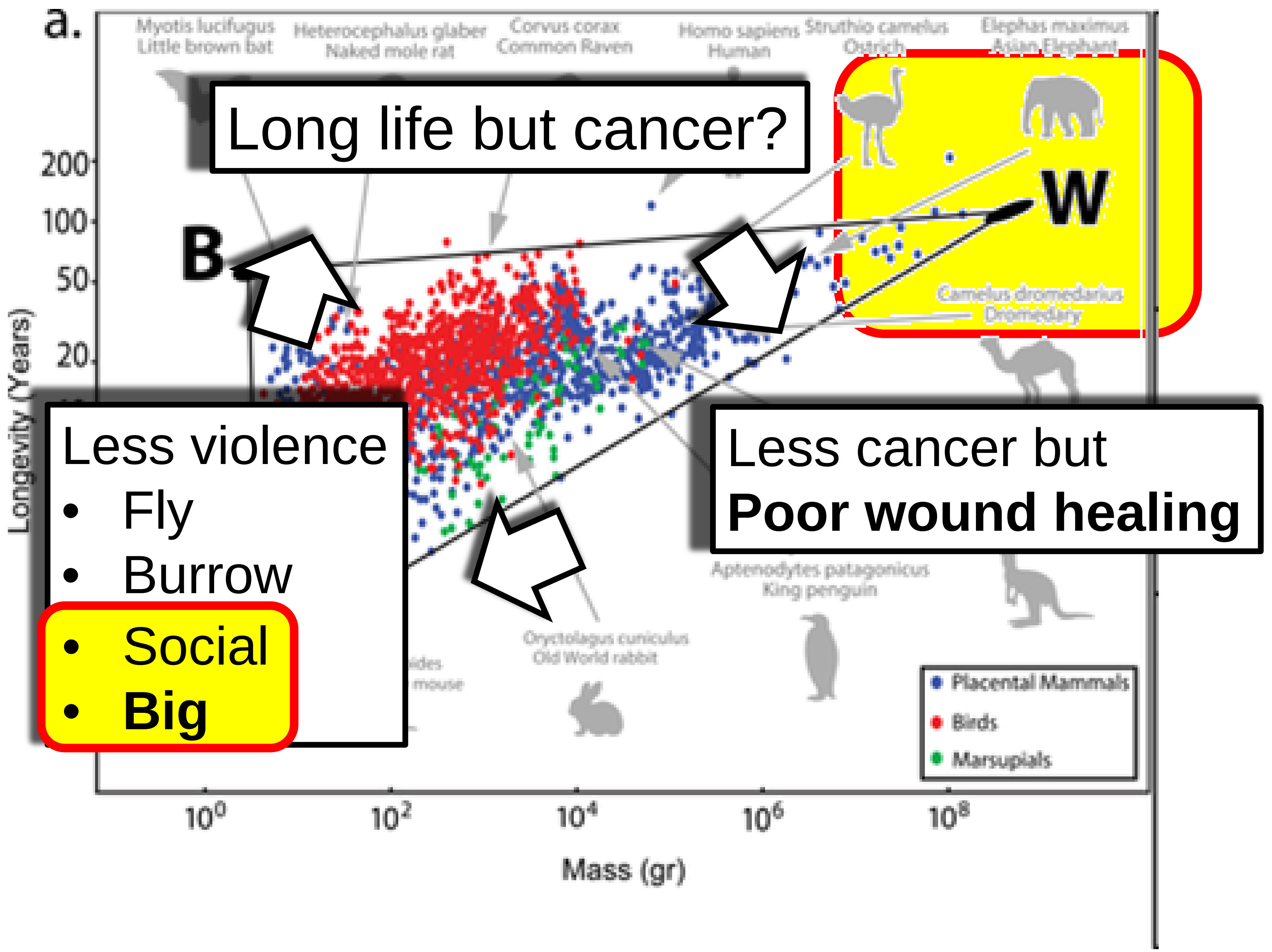
a.
Myotis lucifugus
Little brown bat
Heterocephalus glaber
Naked mole rat
Corvus corax
Common Raven
Homo sapiens
Human
Struthio camelus
Ostrich
Elephas maximus
Asian Elephant
200
100
50
20
10
5
2
1
Longevity (years)
B
W
S
Less cancer but
Poor wound healing
Less violence
Fly
Burrow
Social
Big
Suncus etruscus
Etruscan shrew
Mus minutoides
African pygmy mouse
Oryctolagus cuniculus
Old World rabbit
Marsupials
Mass
(gr)
10^0
10^2
10^4
10^6
10^8
b.
Bats
Naked Mole-rat
c.
Marsupials
d.
Primates



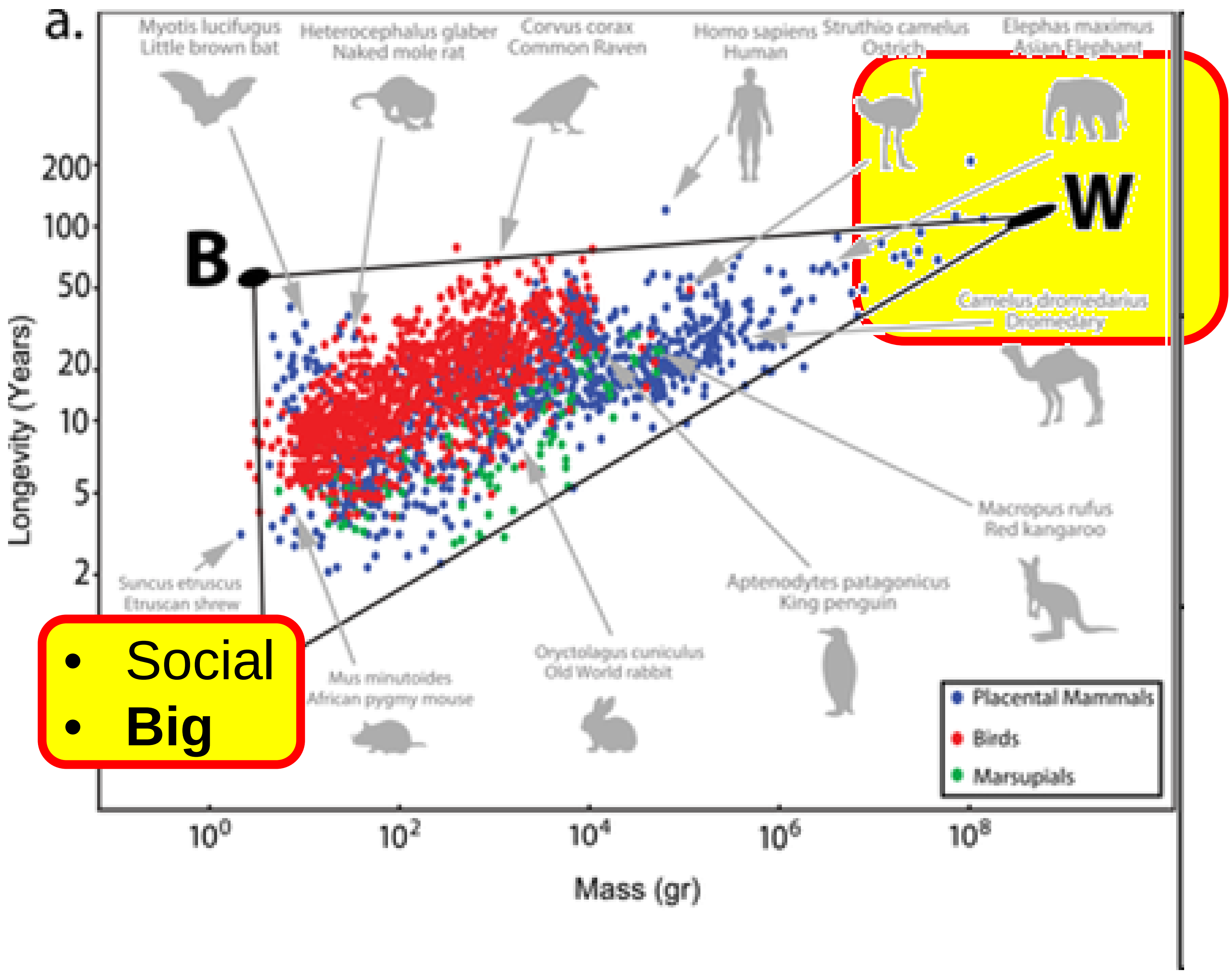
a.
Myotis lucifugus
Little brown bat
Heterocephalus glaber
Naked mole rat
Corvus corax
Common Raven
Homo sapiens
Human
Struthio camelus
Ostrich
Elephas maximus
Asian Elephant
Long life but cancer?
W
B
S
Camelus dromedarius
Dromedary
Less violence
• Fly
• Burrow
• Social
• **Big**
Less cancer but
Poor wound healing
Red kangaroo
Suncus etruscus
Etruscan shrew
Aptenodytes patagonicus
King penguin
African pygmy mouse
Placental Mammals
Birds
Marsupials
Longevity (years)
200
100
50
20
10
5
2
1
Mass
(gr)
10^0
10^2
10^4
10^6
10^8
b.
Bats
Naked Mole-rat
c.
Marsupials
d.
Primates


Long life but cancer?
Less cancer but
Poor wound healing
Less violence
Fly
Burrow
Social
Big


hydra
Termite queen?
Giant squid
a.
Myotis lucifugus
Little brown bat
Heterocephalus glaber
Naked mole rat
Corvus corax
Common Raven
Homo sapiens
Human
Struthio camelus
Ostrich
Elephas maximus
Asian Elephant
Camelus dromedarius
Dromedary
Red kangaroo
Aptenodytes patagonicus
King penguin
Oryctolagus cuniculus
Old World rabbit
Mus minutoides
African pygmy mouse
Suncus etruscus
Etruscan shrew
B
W
S
Longevity (Years)
200
100
50
20
10
5
2
1
Mass (gr)
10^0
10^2
10^4
10^6
10^8
Placental Mammals
Birds
Marsupials



a.
Myotis lucifugus
Little brown bat
Heterocephalus glaber
Naked mole rat
Corvus corax
Common Raven
Homo sapiens
Human
Struthio camelus
Ostrich
Elephas maximus
Asian Elephant
Long life but cancer?
W
B
Camelus dromedarius
Dromedary
Less violence
• Fly
• Burrow
• Social
• **Big**
Less cancer but
Poor wound healing
Aptenodytes patagonicus
King penguin
Oryctolagus cuniculus
Old World rabbit
Placental Mammals
Birds
Marsupials
200
100
50
20
Longevity (Years)
10^0
10^2
10^4
10^6
10^8
Mass (gr)

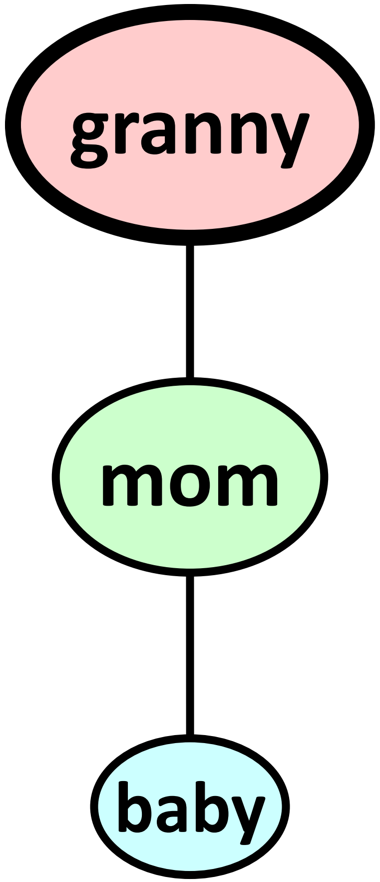


Elephants
Orcas

Social Architectures

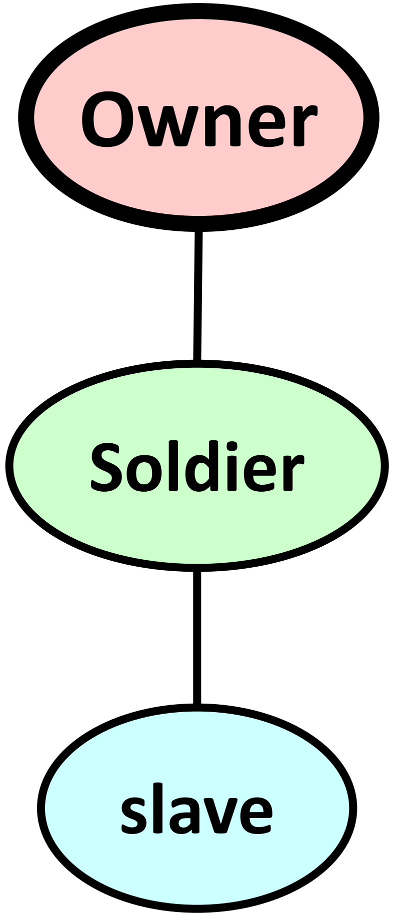
Bonobos
Elephants
Orcas
Baboons?

- Atomic network elements
- Human examples?
- Stability and robustness?
- Scalability?



Social Architectures

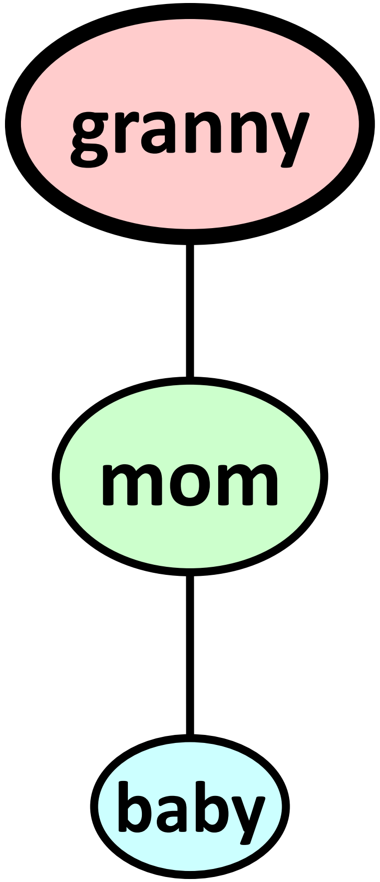
Chimps
Humans
Baboons?



- Atomic network elements
- Human examples
- Stability and robustness
- Scalability

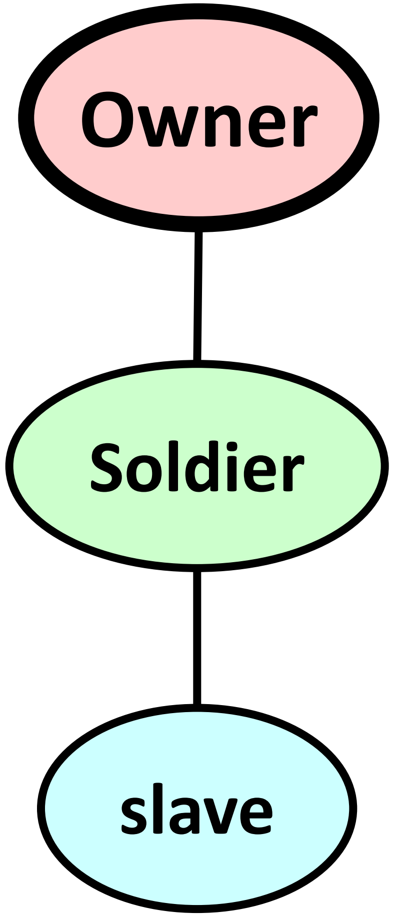
Warning: may be offensive to everyone, but especially humans

Bonobos
Elephants
Orcas
Baboons?



Chimps
Humans
Baboons?

Dominance



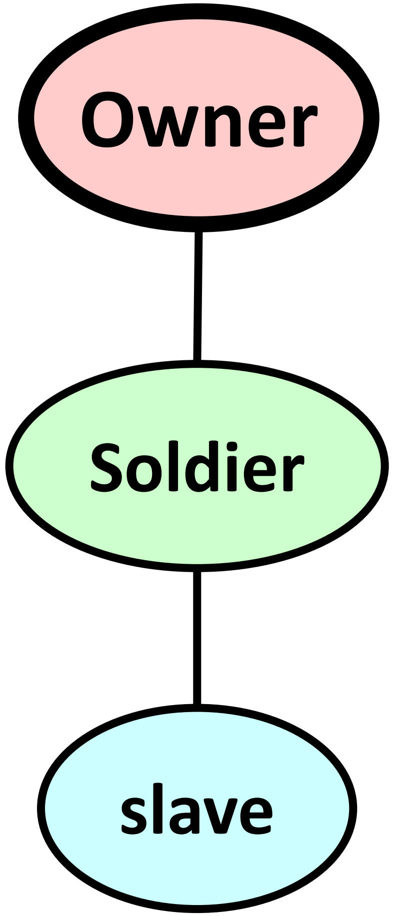
Near
term

Fear
Anger
Hatred
Violence

Atomic network elements

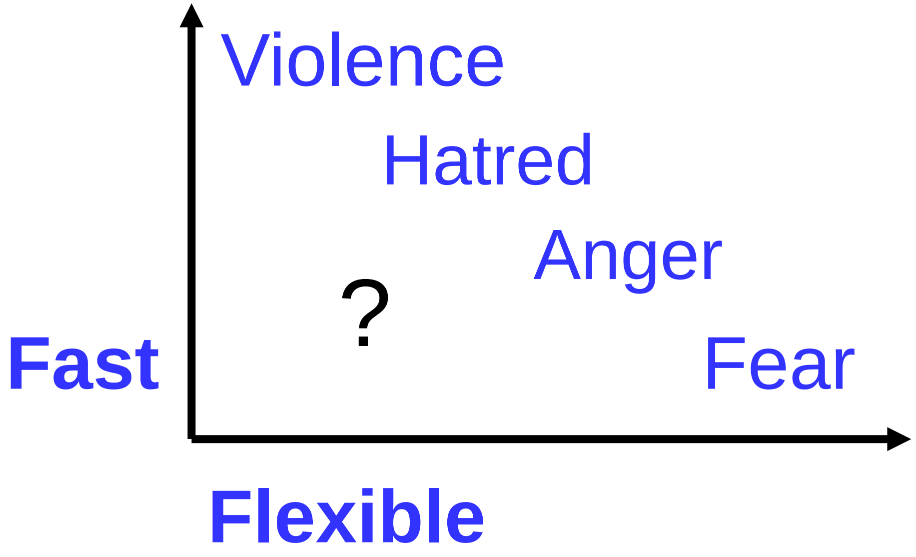
Dominance

Chimps
Humans
Baboons?

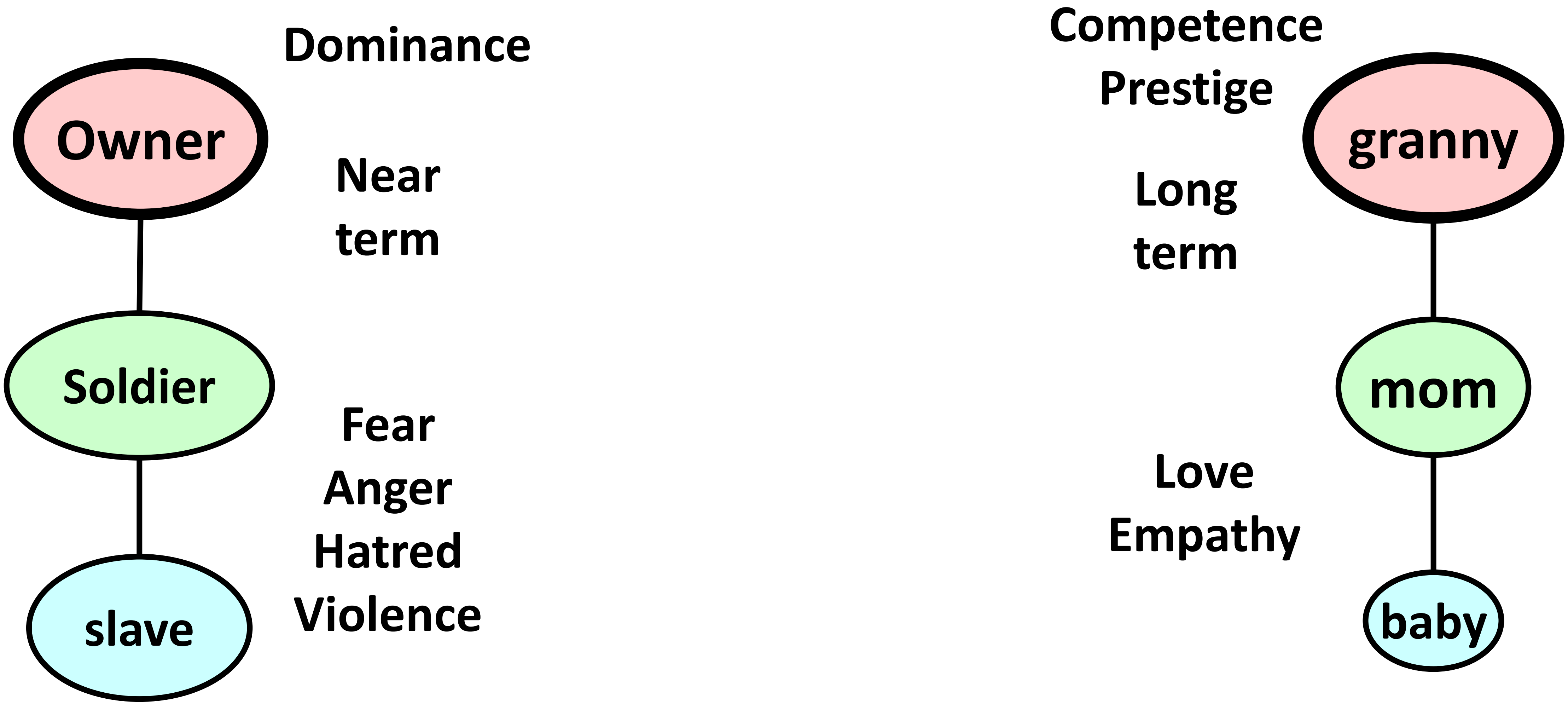


Near
term

Fear
Anger
Hatred
Violence

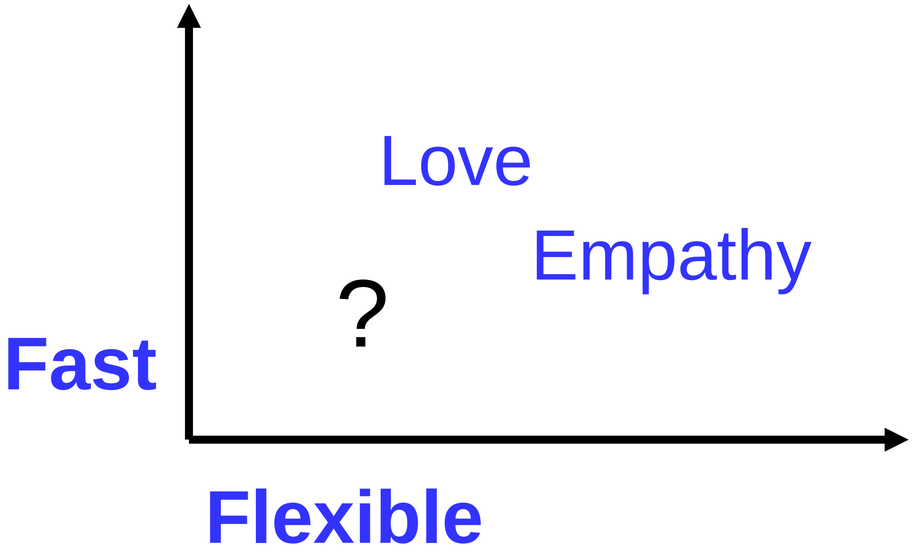


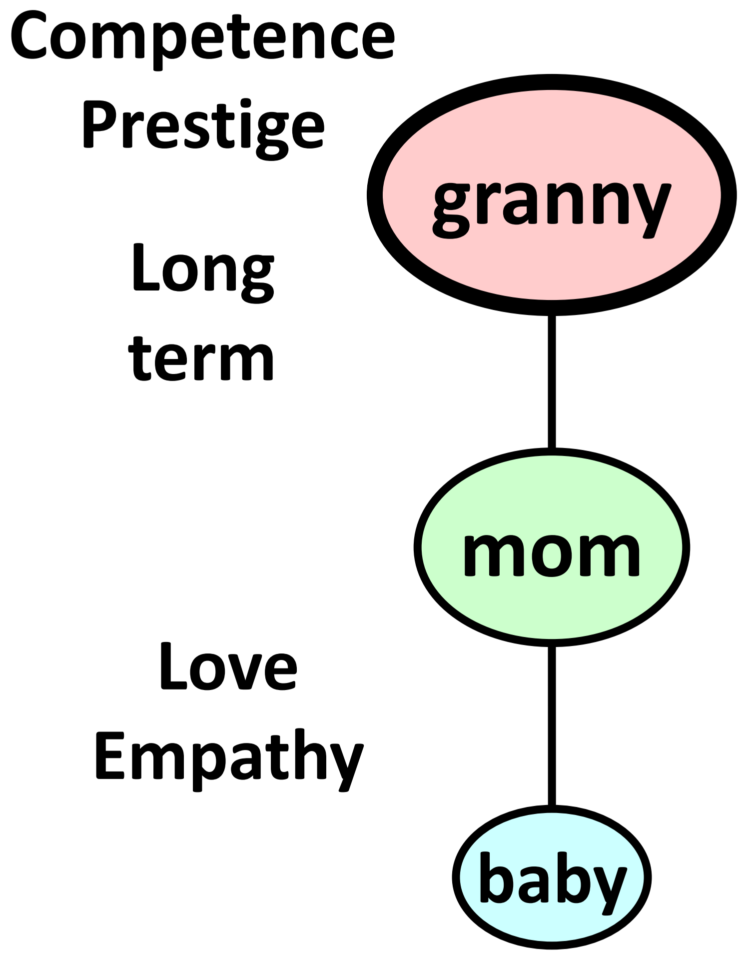
Atomic network elements



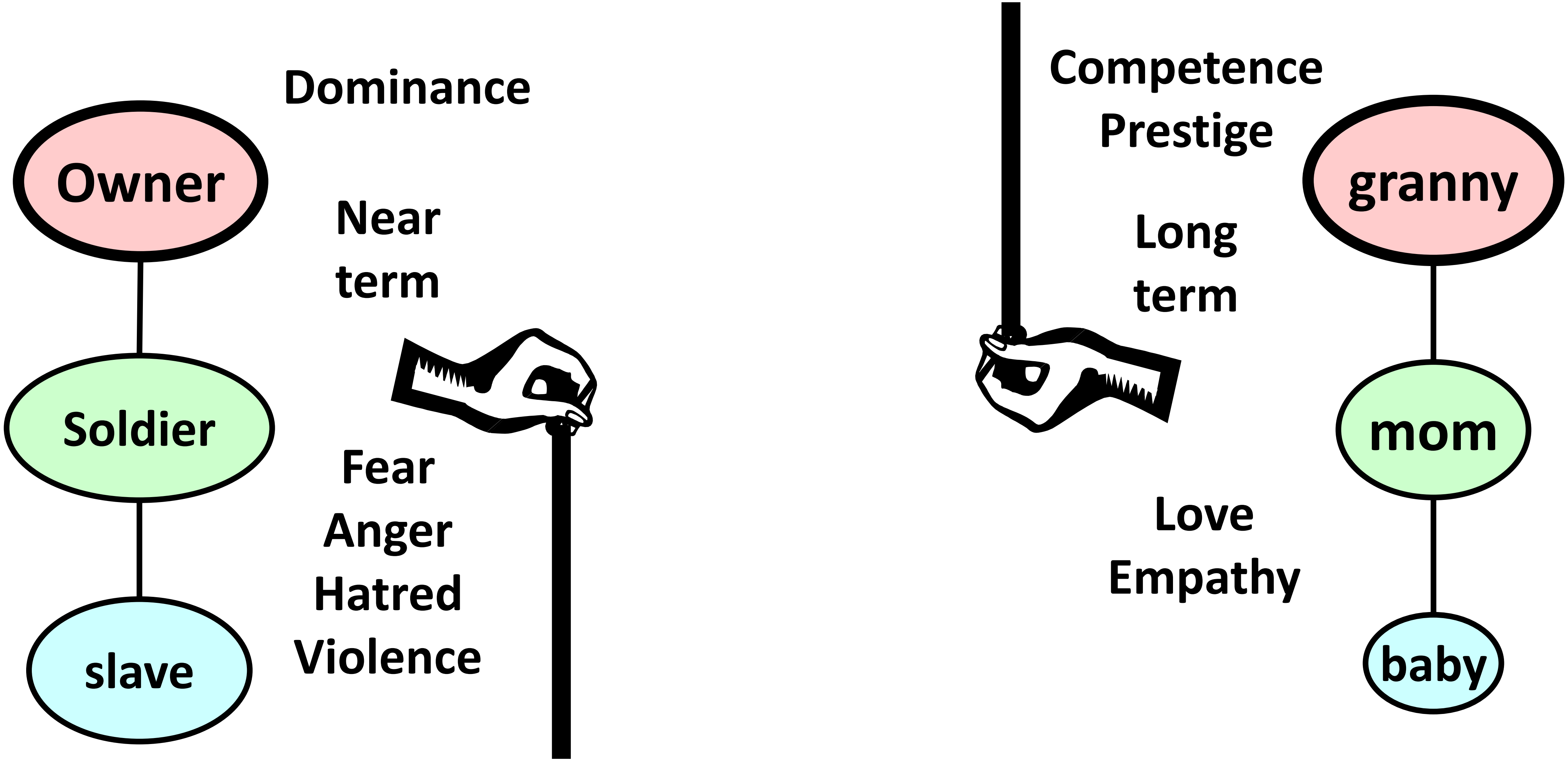
Atomic network elements

Bonobos
Elephants
Orcas
Baboons?

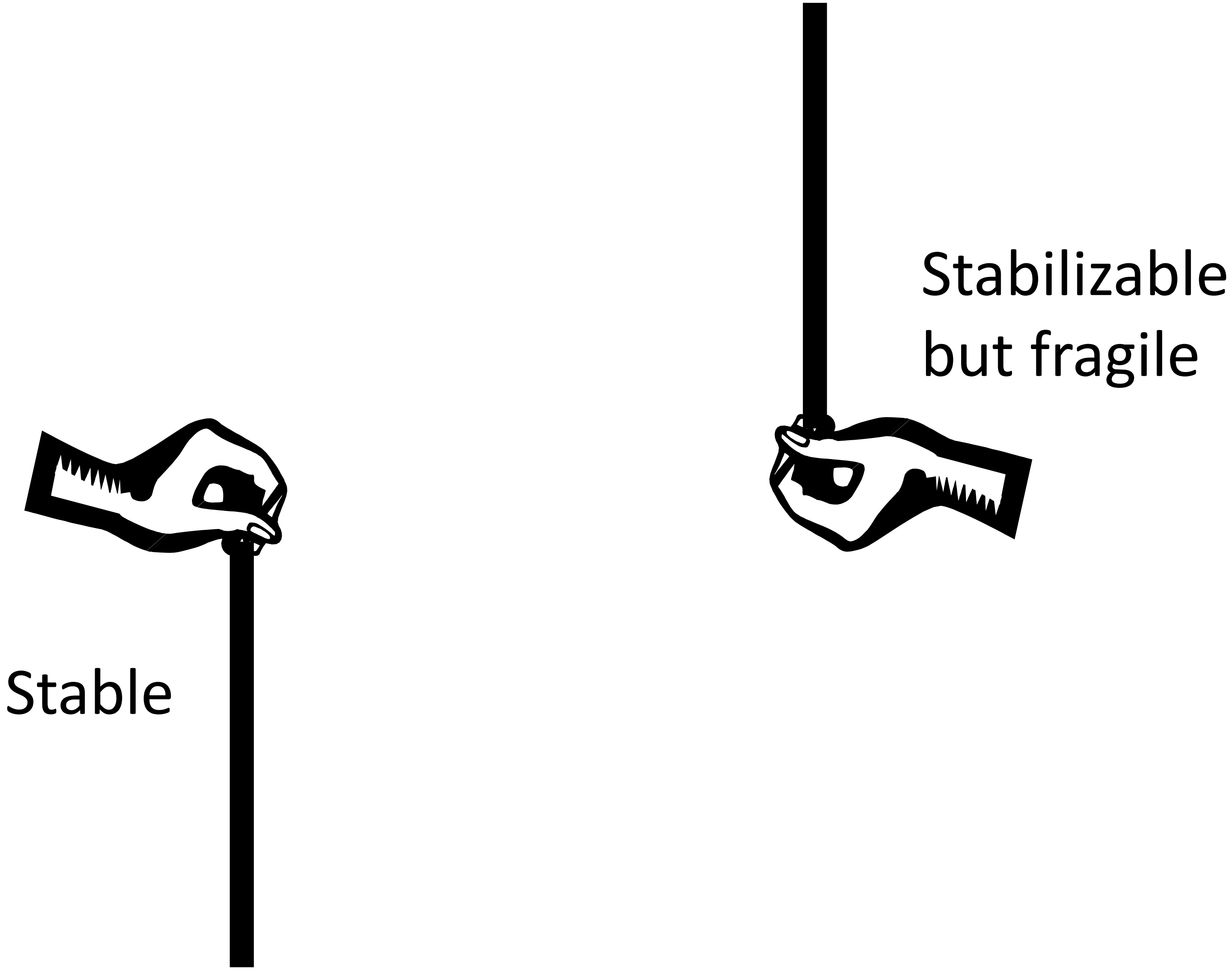




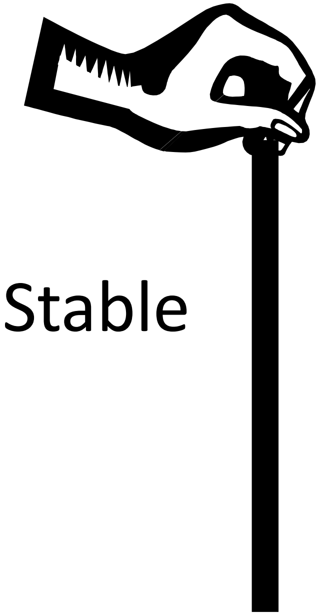
Atomic network elements



Atomic network elements


Stable
Stabilizable
but fragile

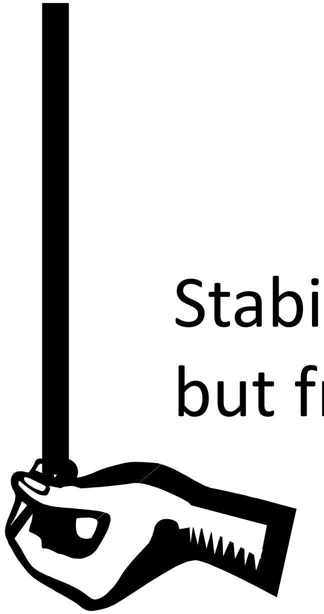
Other examples



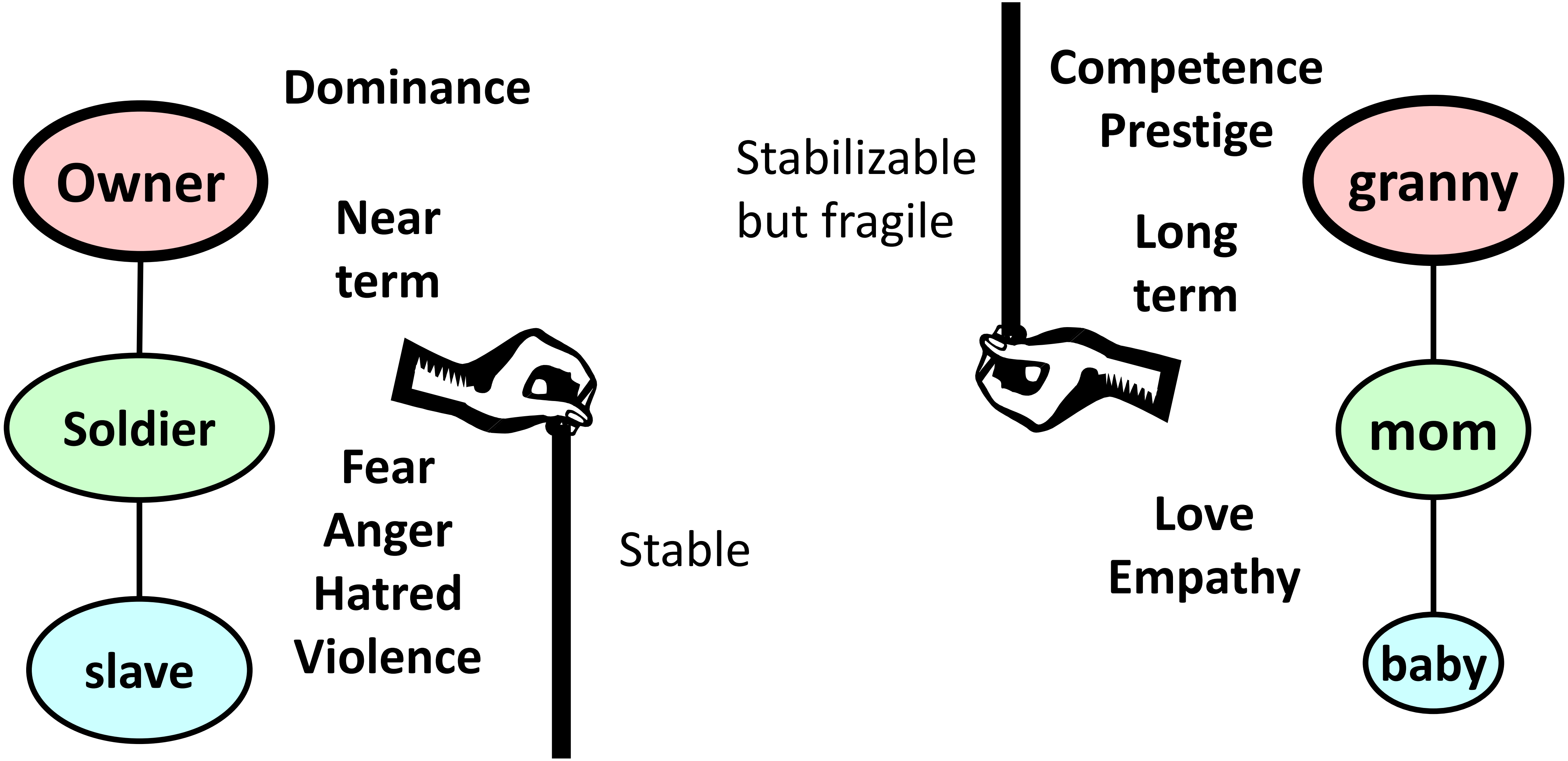
Stable

Death

Life

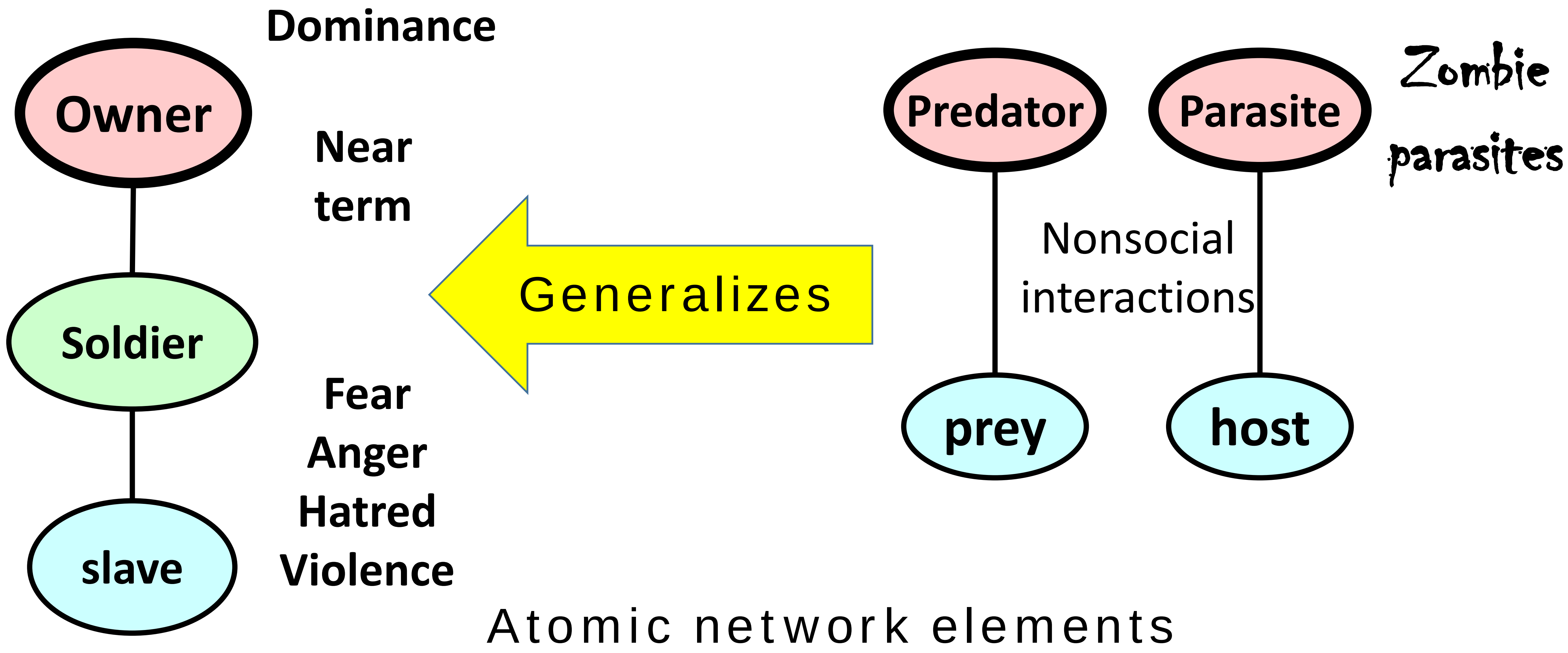


Stabilizable
but fragile

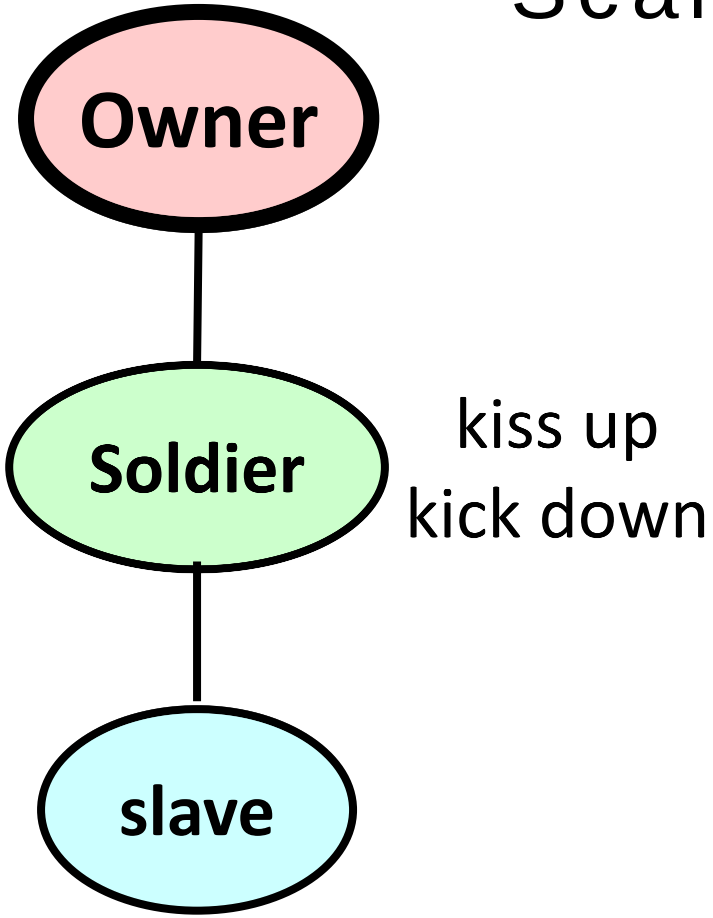


Atomic network elements

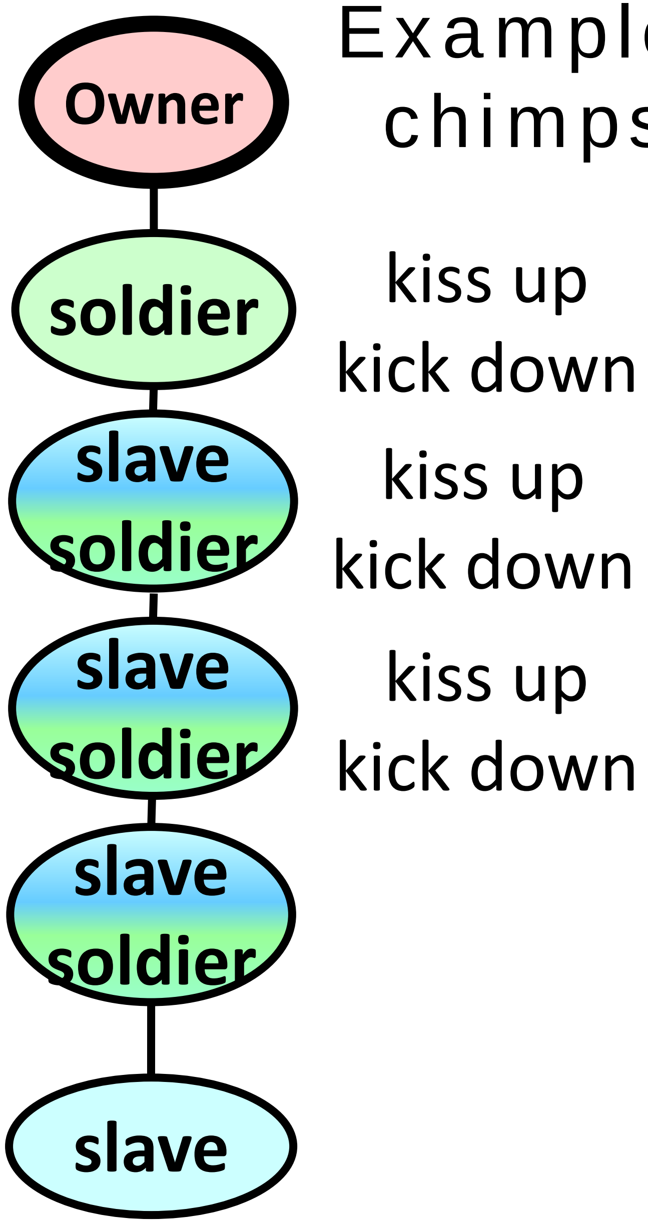
Owner = predator + parasite



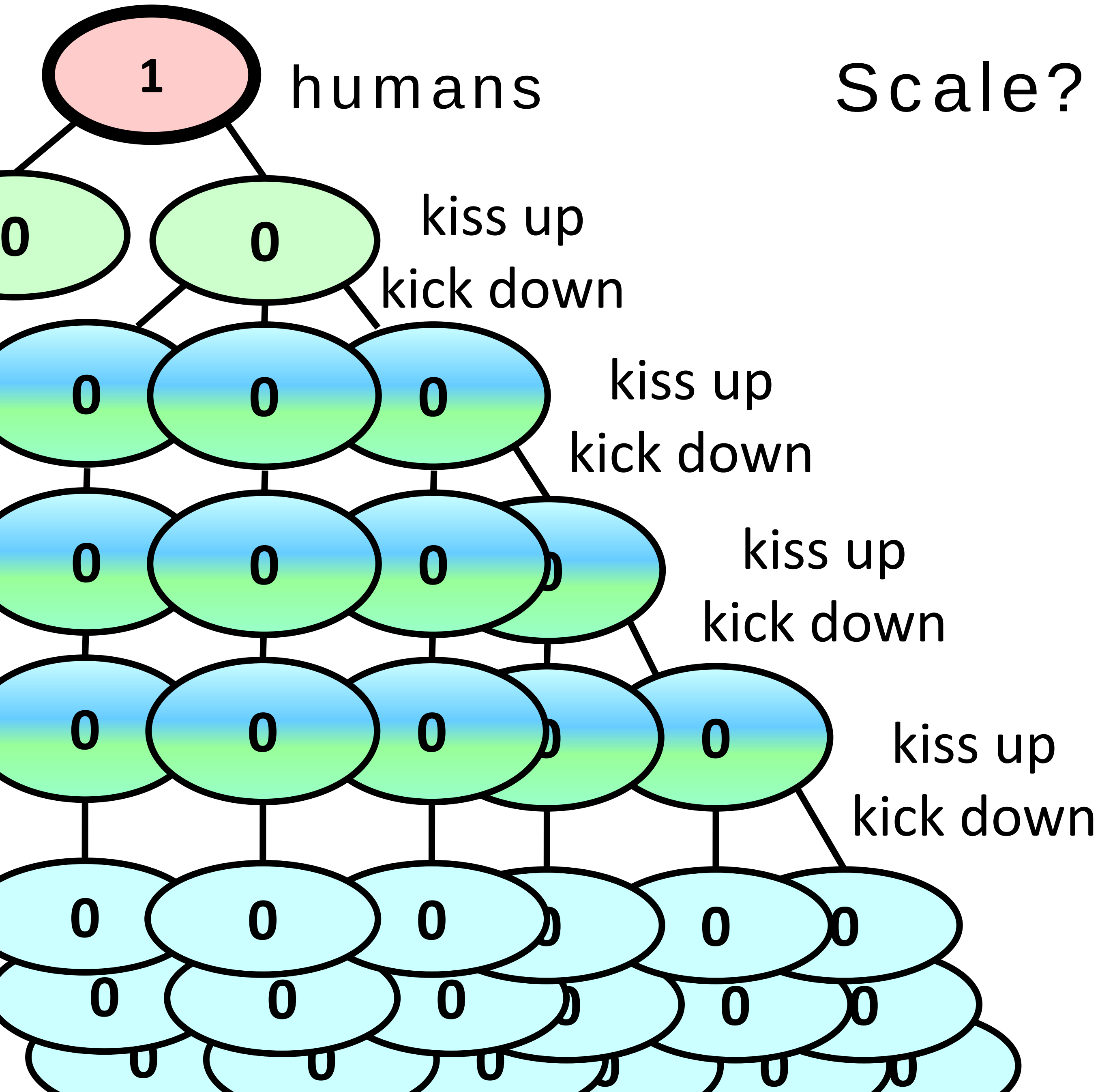
Scale?



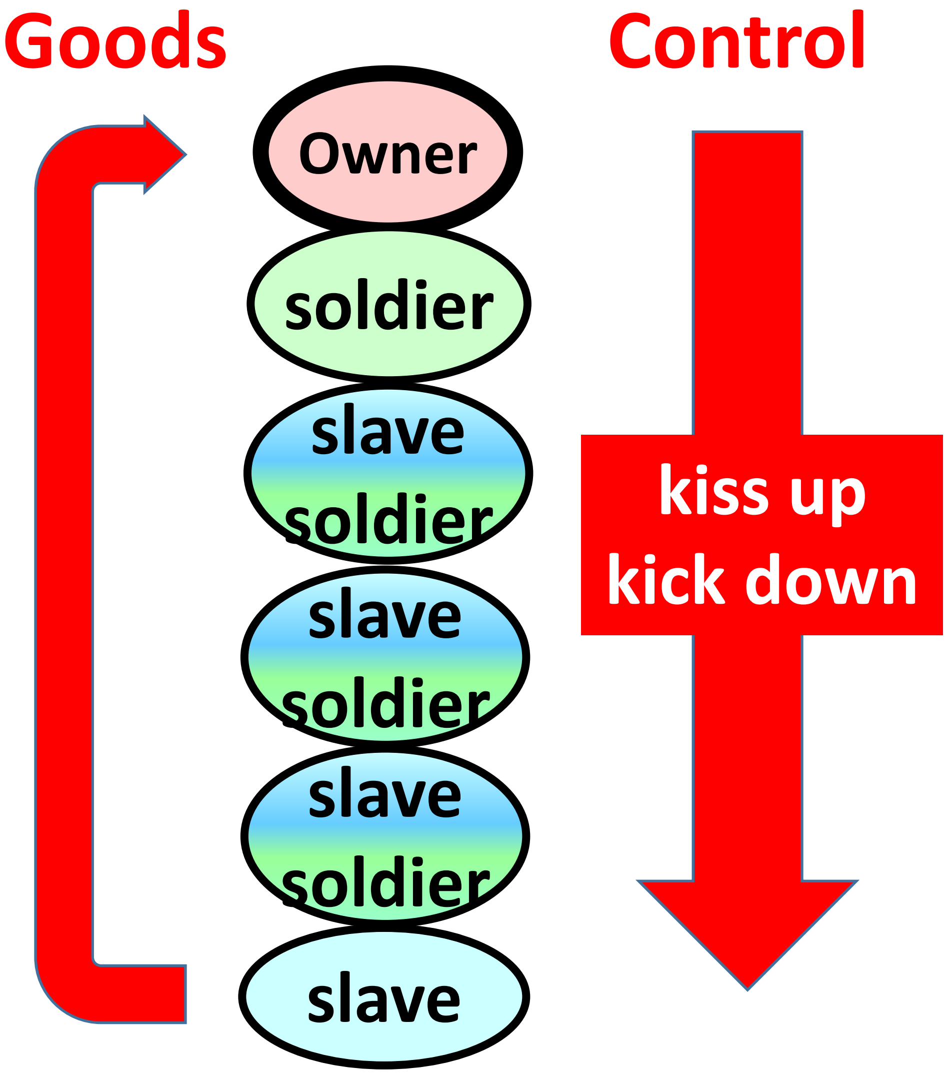
Example: chimps

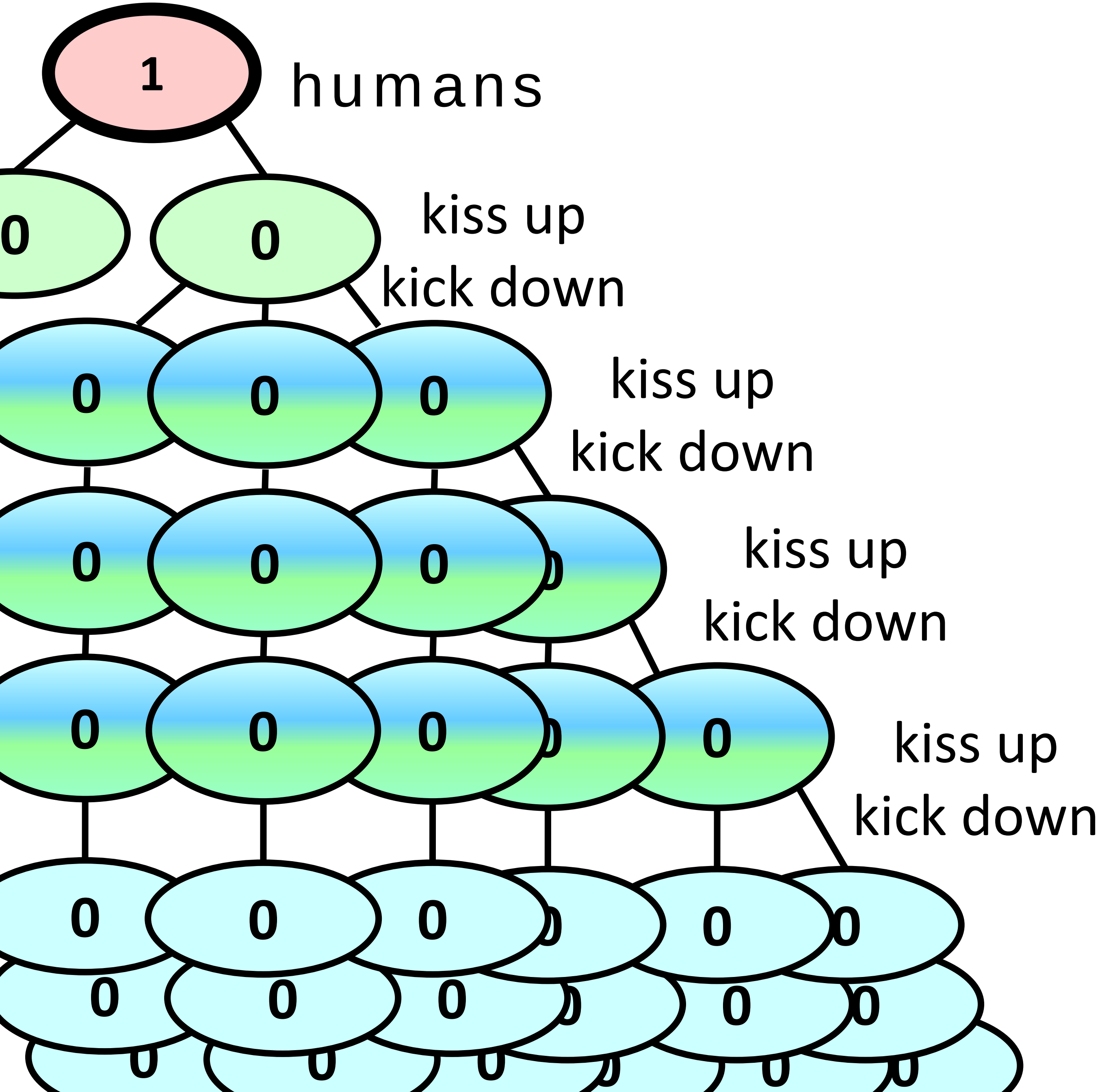


Scale?



Stable and scalable

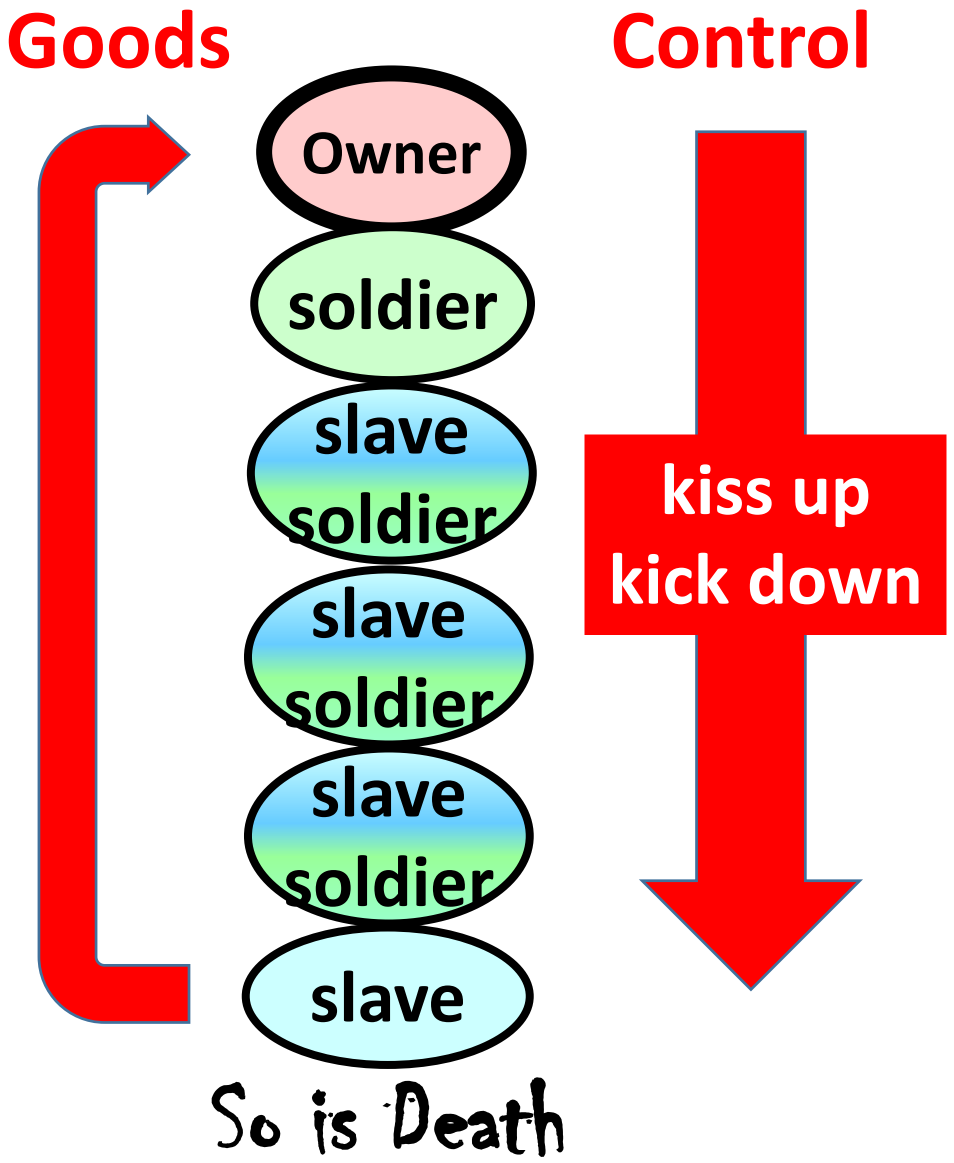




The biggest con

Empires

Stable and scalable



Stable but not scalable?