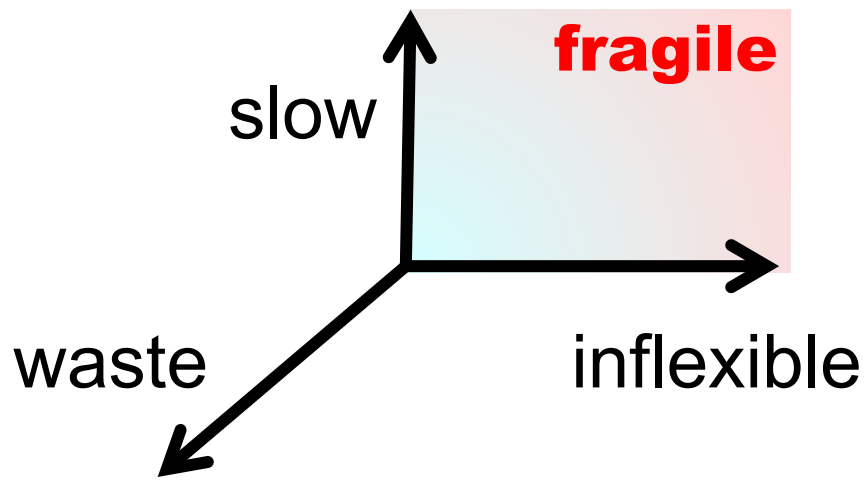
Universal laws and architectures:

Theory and lessons from

nets, grids, brains, bugs,
planes, docs, fire, fashion,
art, turbulence, music, buildings,
cities, earthquakes, bodies, running, throwing,
Synesthesia, spacecraft, statistical mechanics

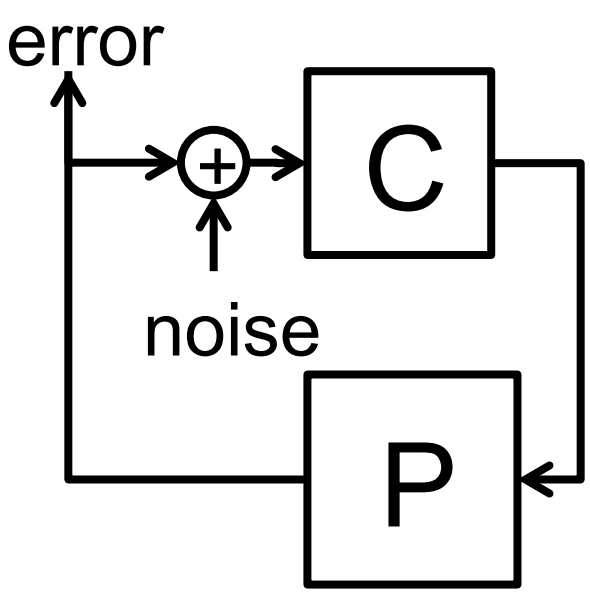


Understand this more deeply?

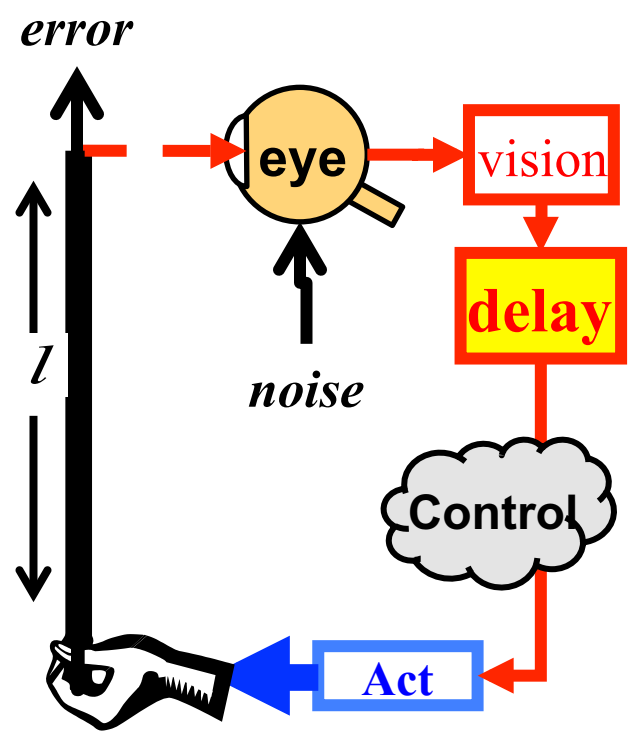
$$\left.\begin{array}{c}\exp\left(\int \ln|T|\right)\\ \|T\|_\infty\end{array}\right\} \geq \exp(p\tau)\left|\frac{z+p}{z-p}\right|$$

Mechanics+
Gravity +
Light +
Control theory

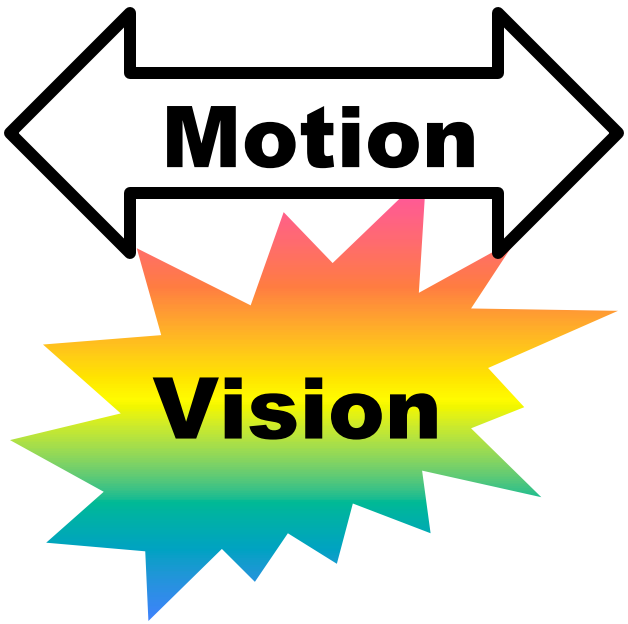
$$|T(j\omega)| = \left|\frac{E}{N}\right|$$



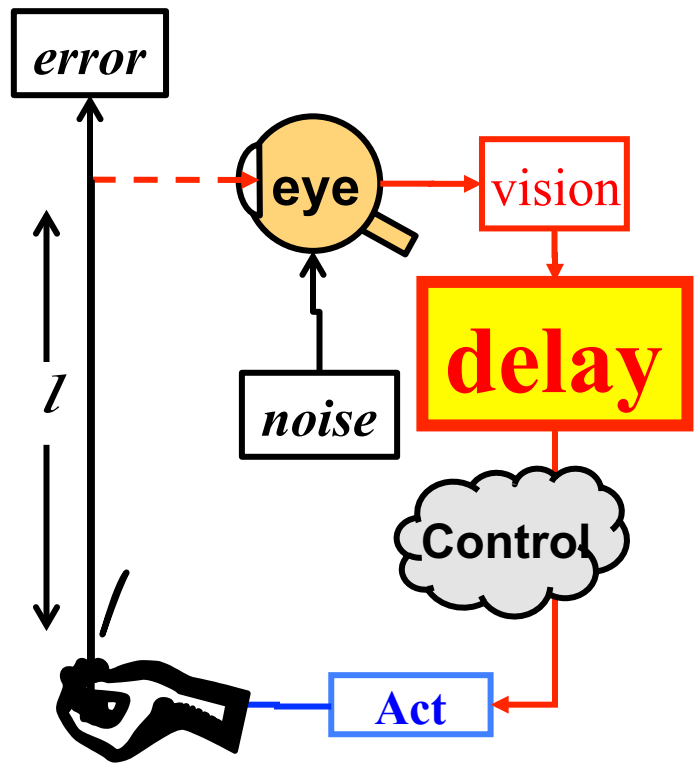
+ Neuroscience



Understand this more deeply?

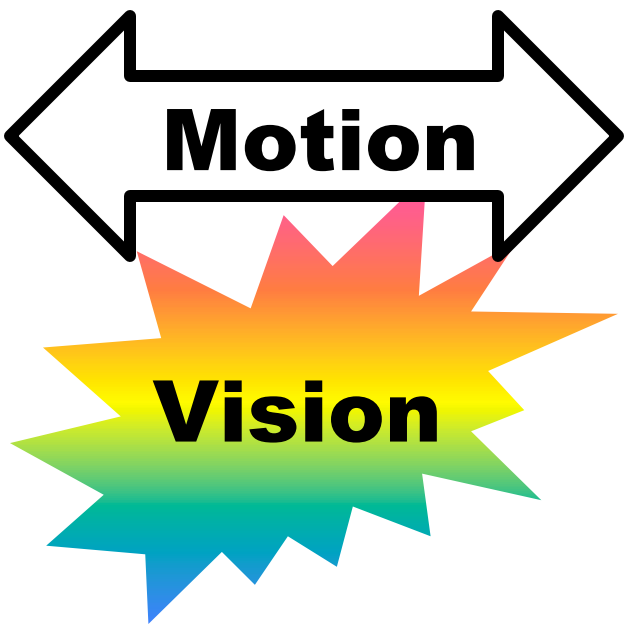


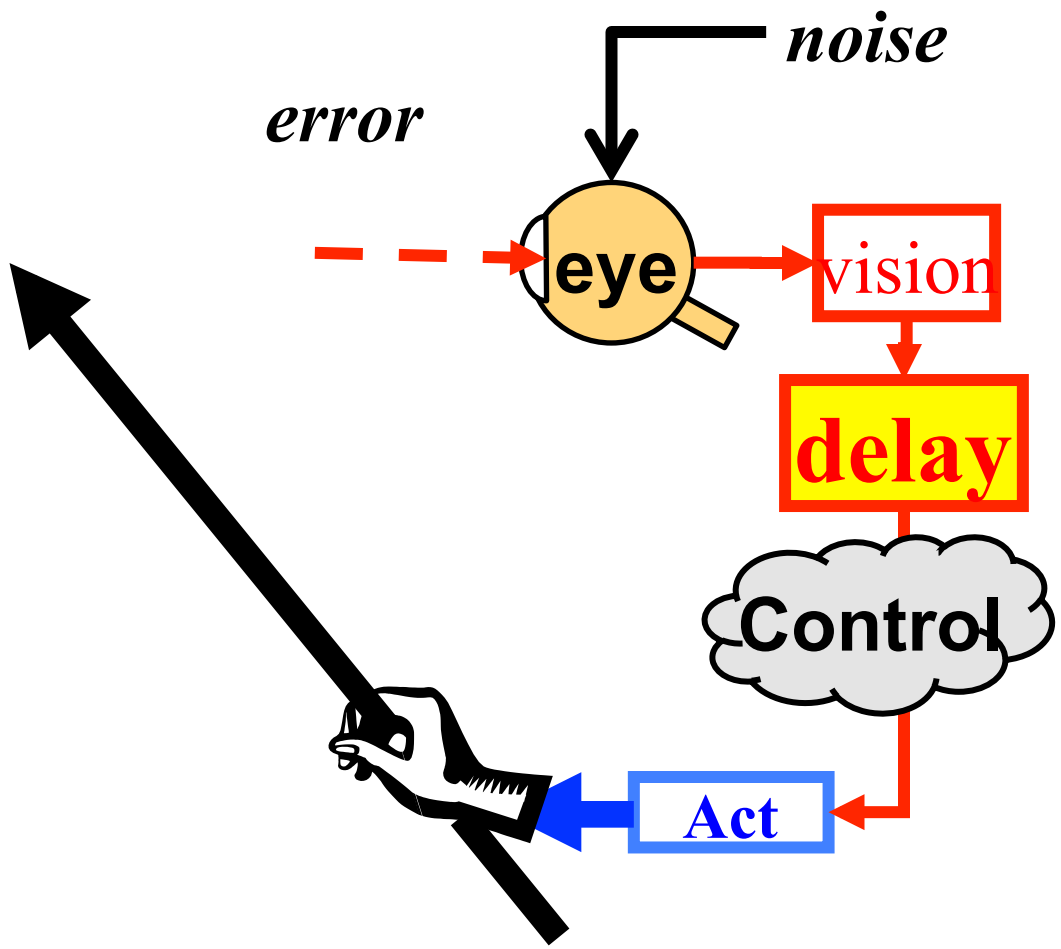
+ Neuroscience

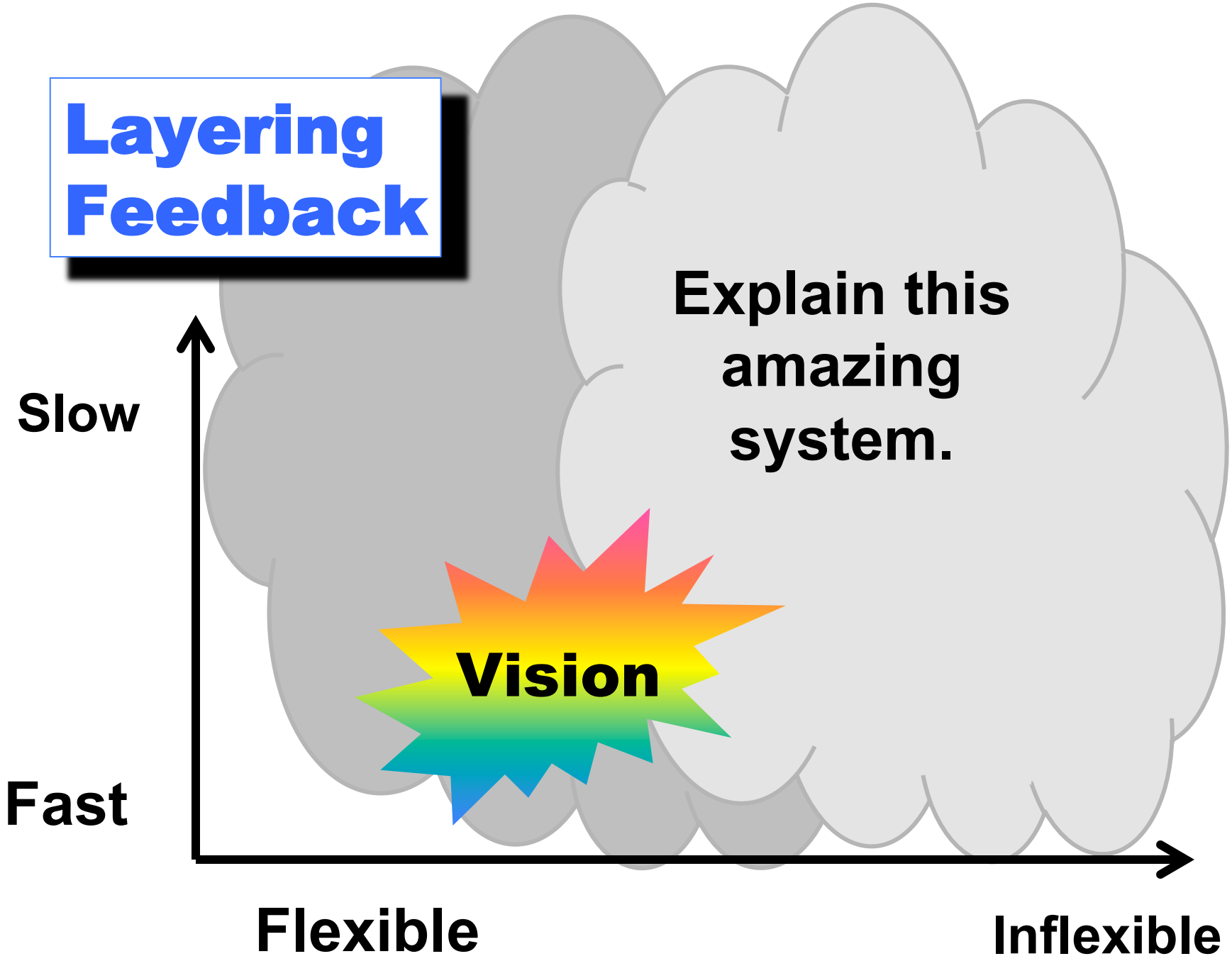


Robust vision w/motion

- Object motion
- Self motion






Layering Feedback
Explain this amazing system.
Vision
Slow
Fast
Flexible
Inflexible

Robust vision with

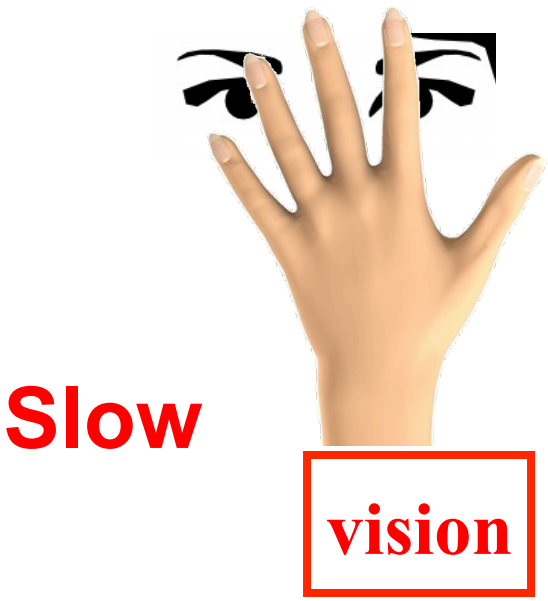
- Hand motion
- Head motion

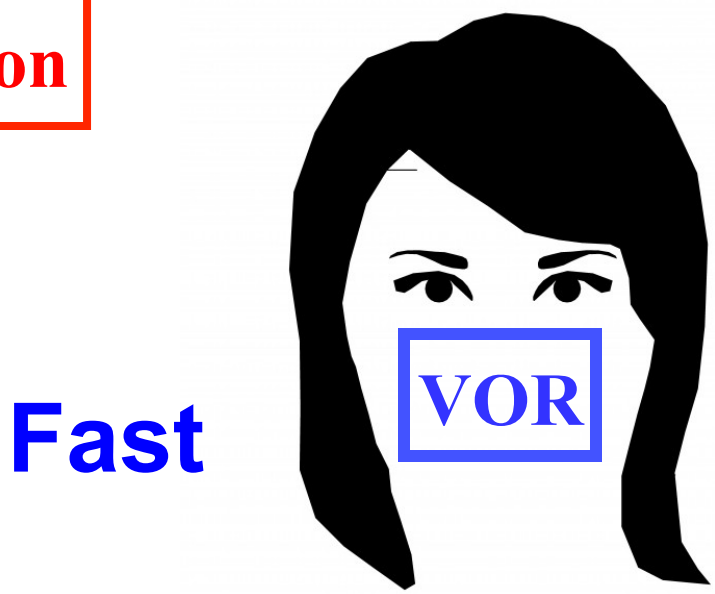
Experiment

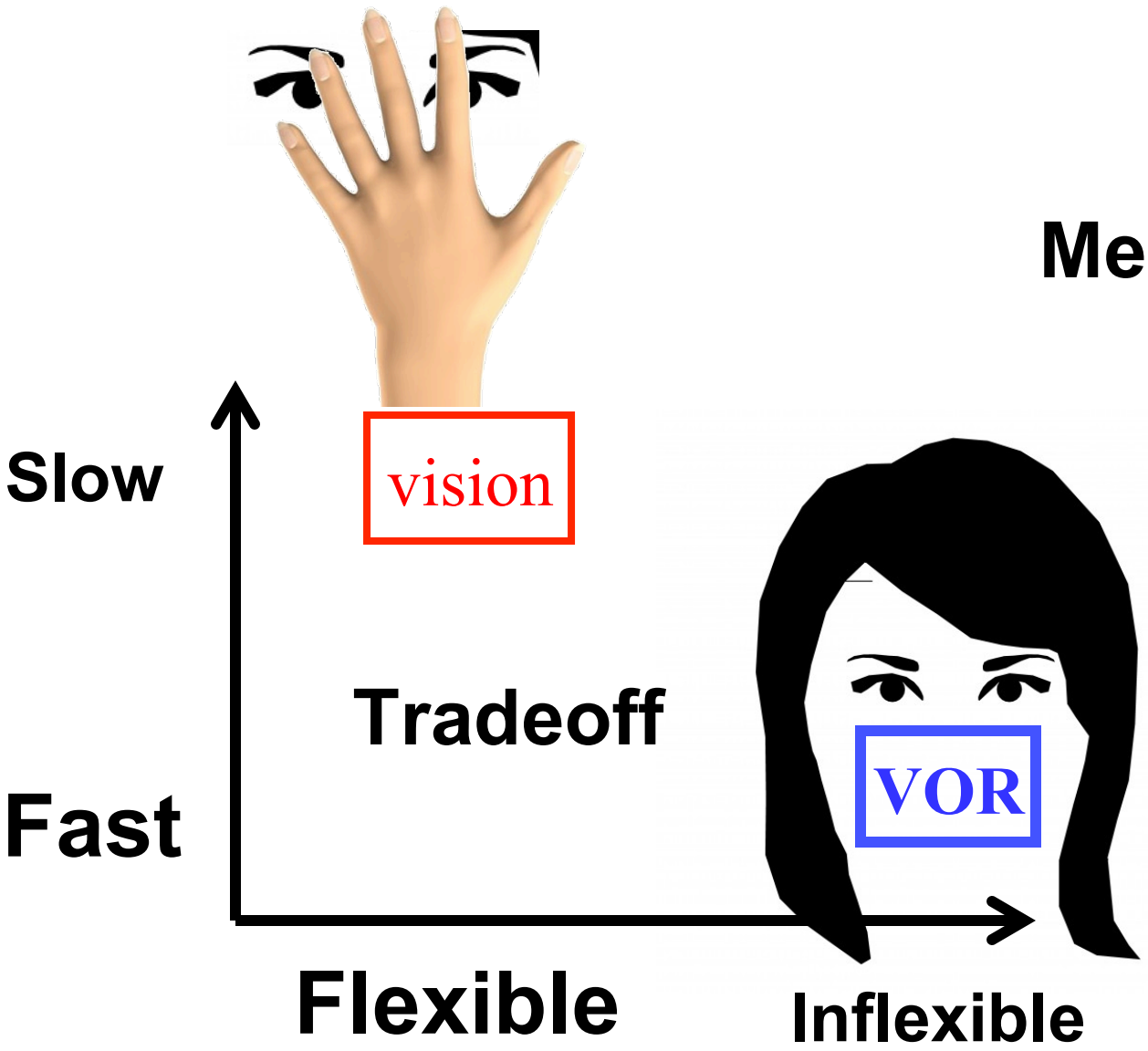
- Motion/vision control without blurring
- Which is easier and faster?

Why?

- Mechanism
- Tradeoff

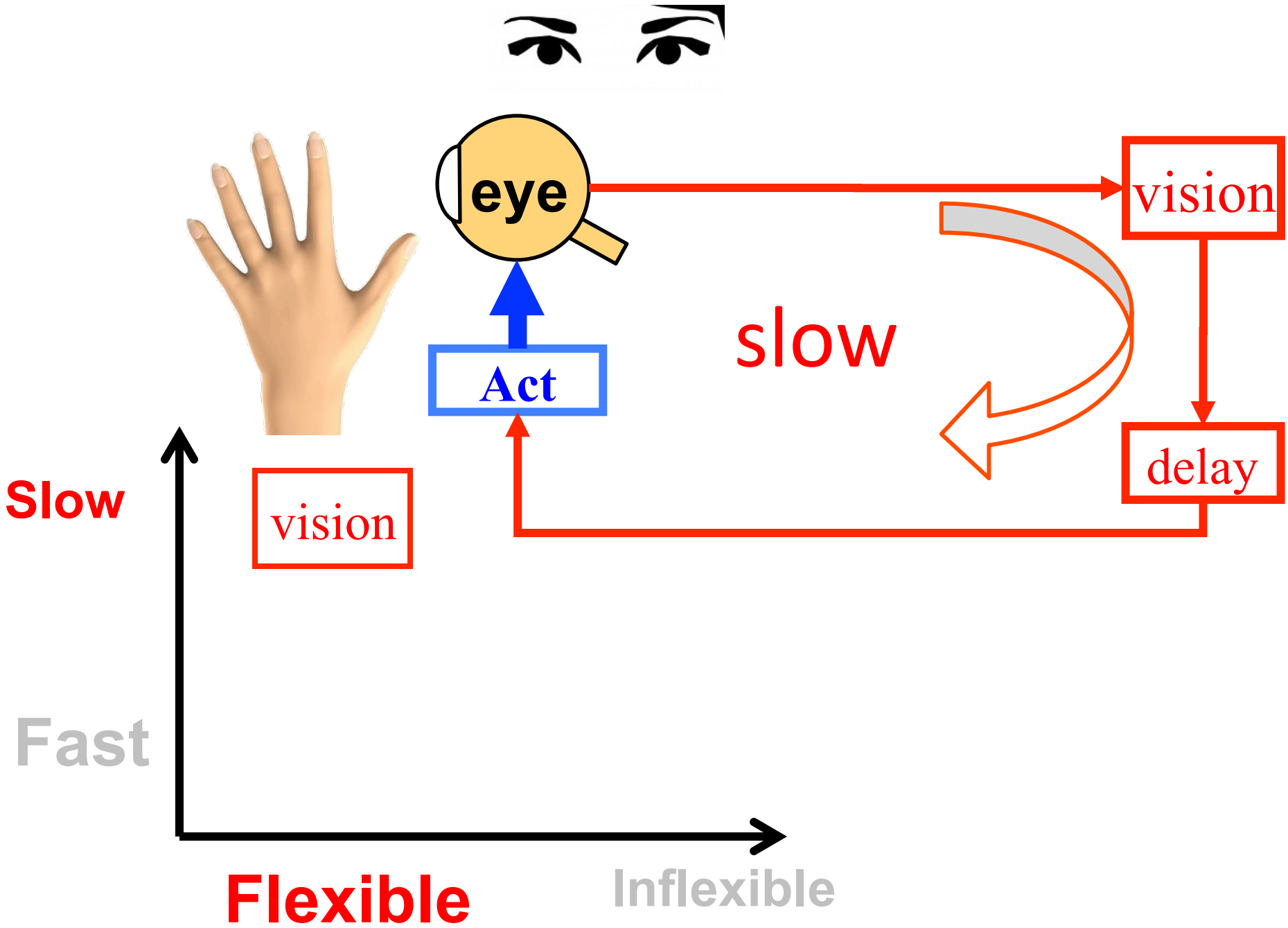


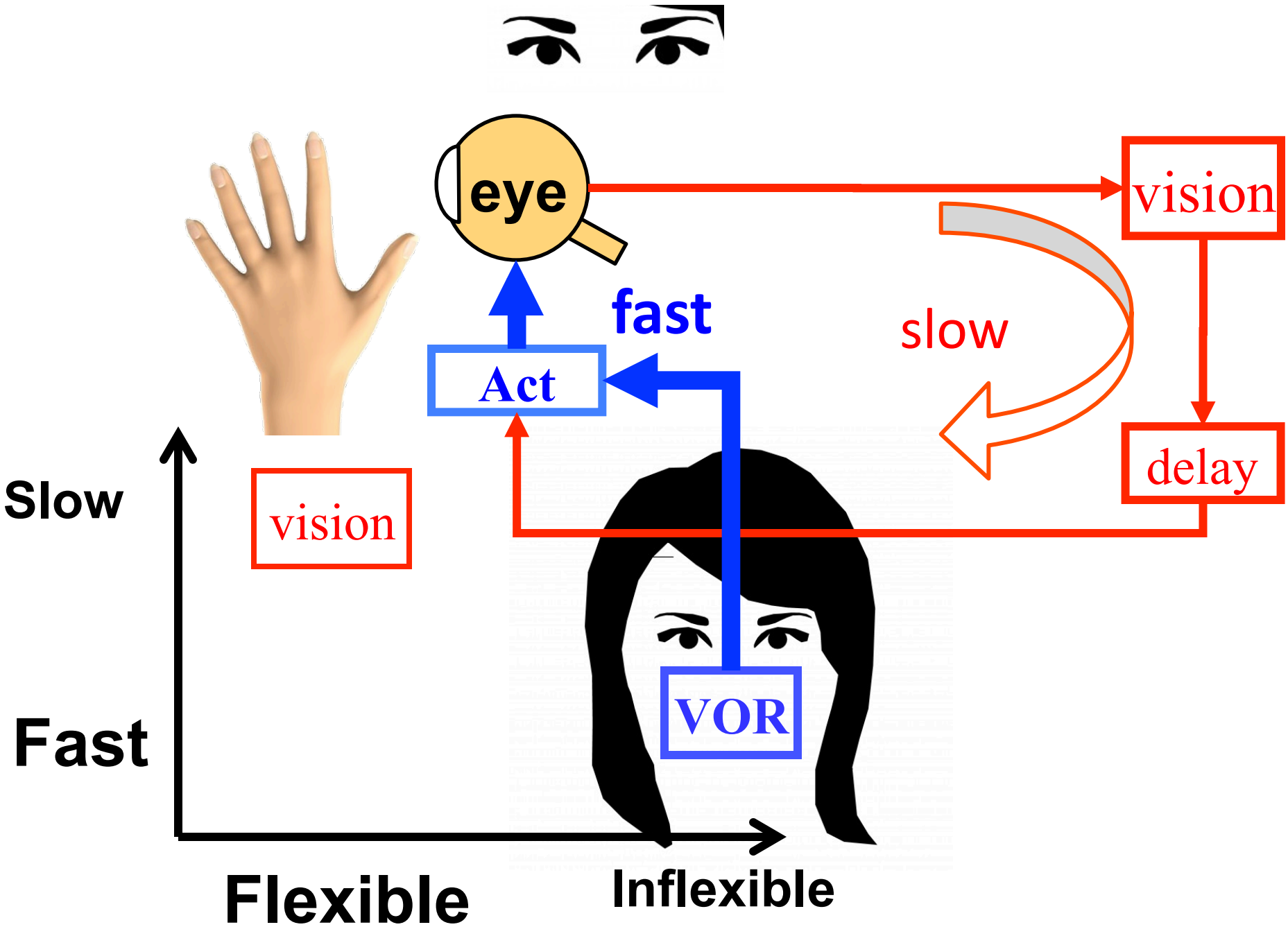


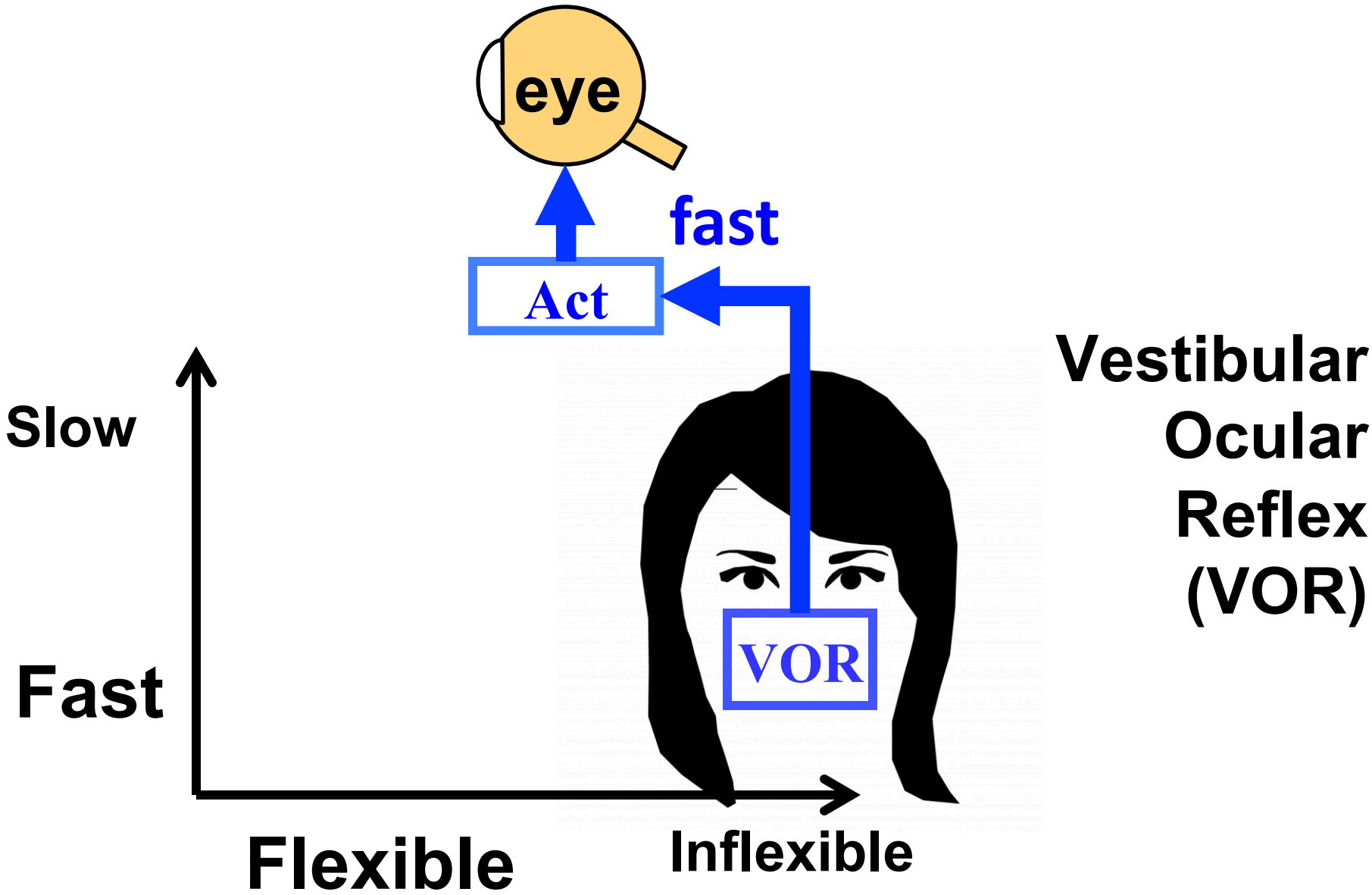


Mechanism

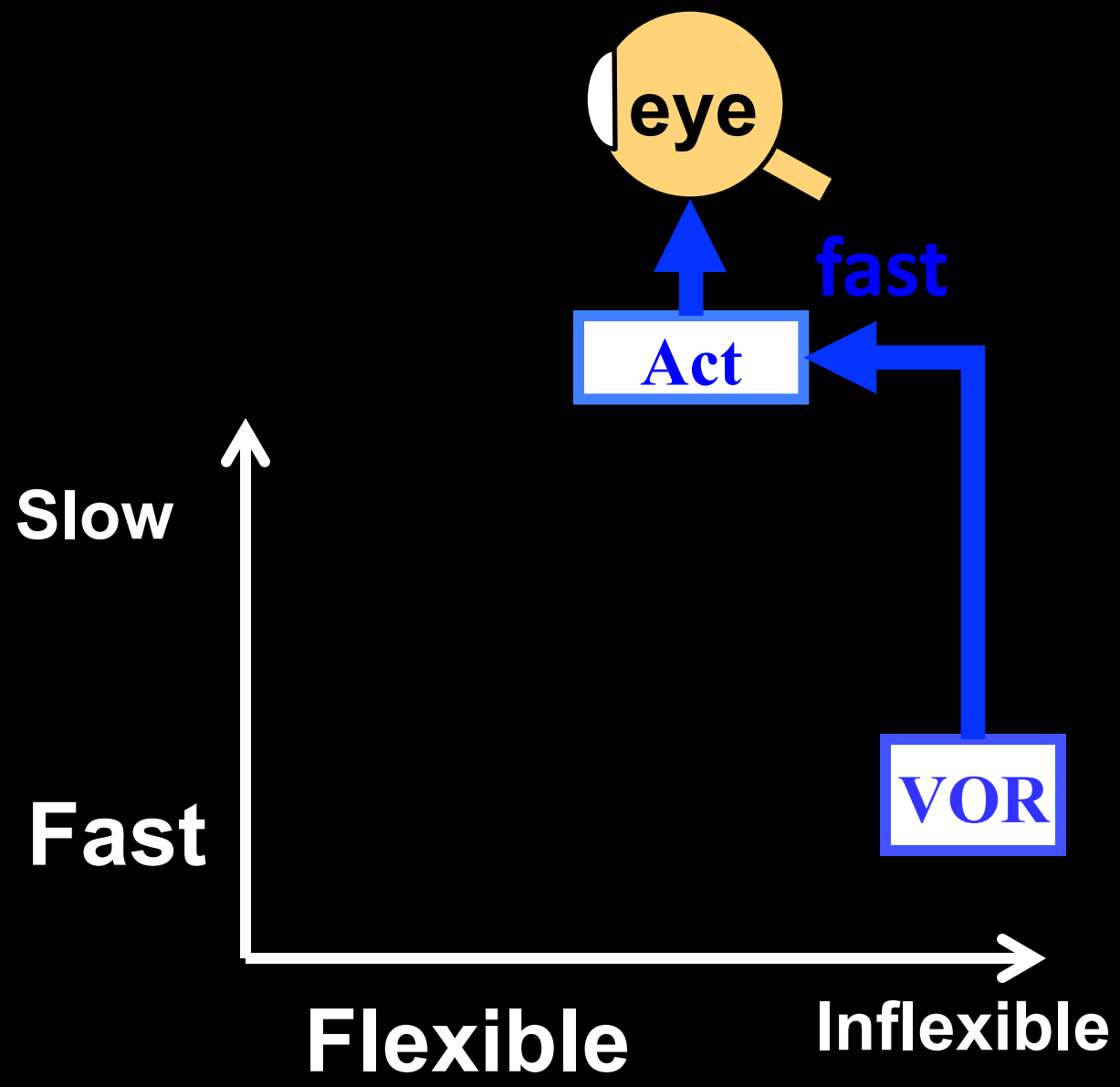
Vestibular Ocular Reflex (VOR)

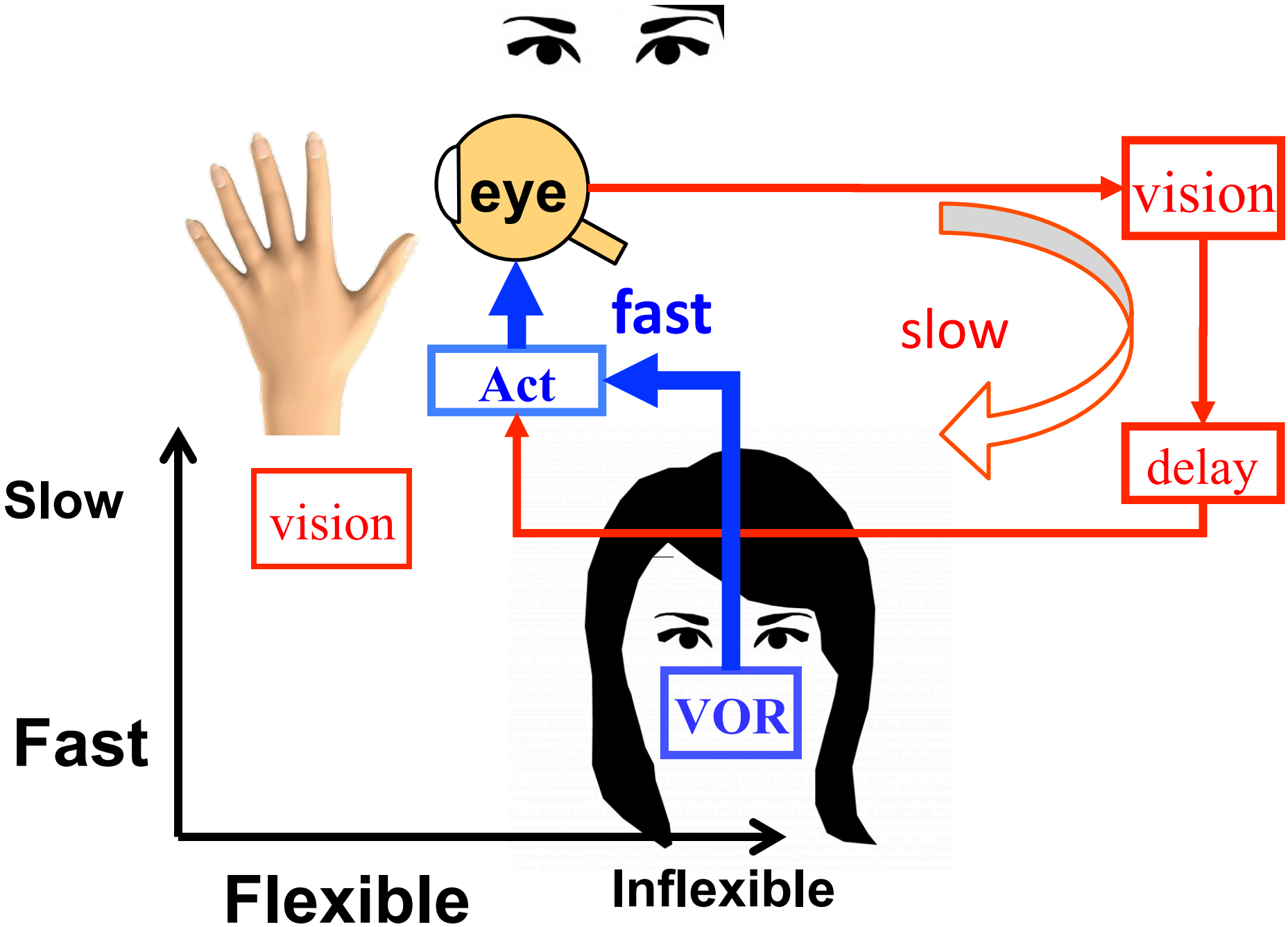

eye
vision
slow
Act
delay
vision
Slow
Fast
Flexible
Inflexible

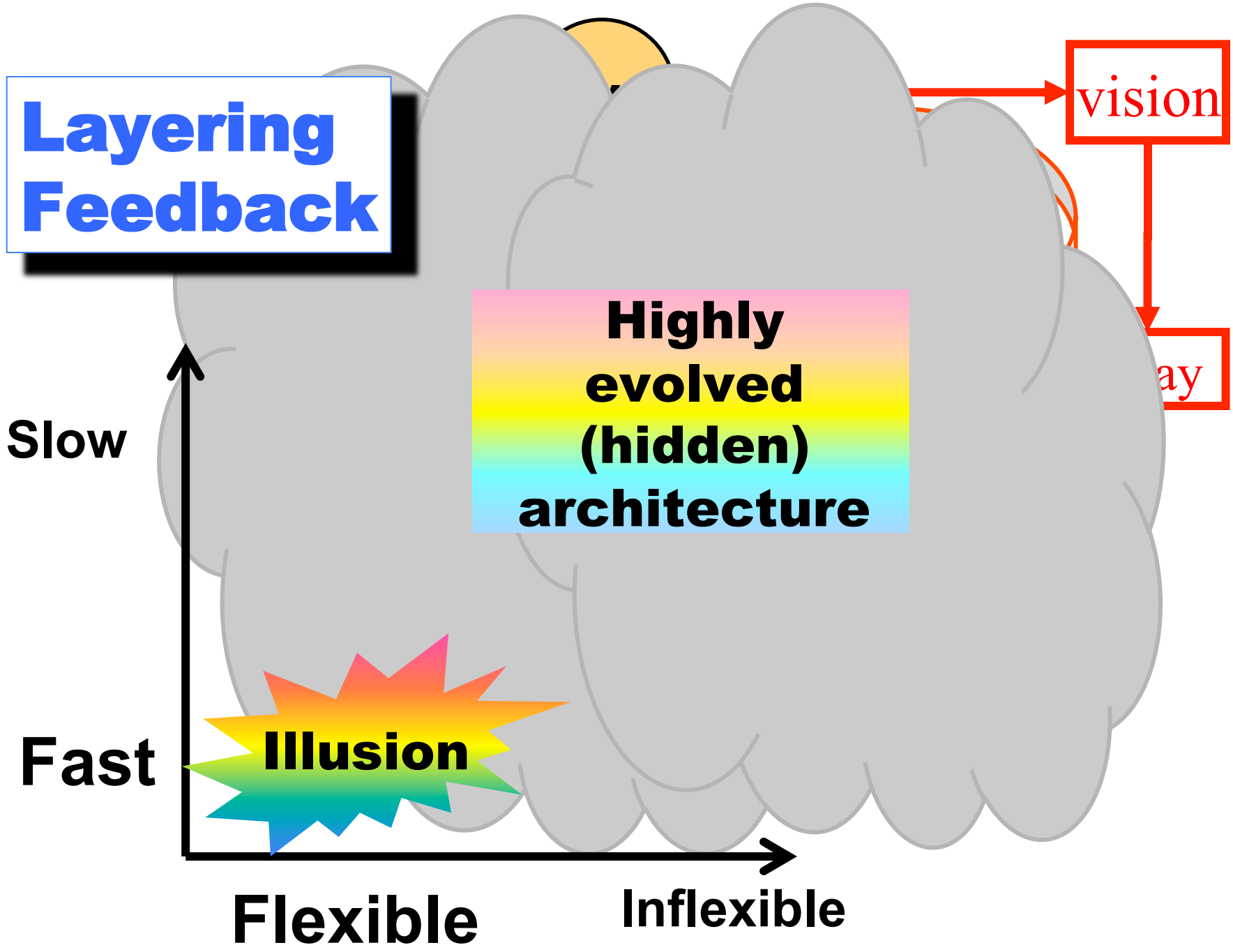

eye
vision
fast
slow
Act
delay
vision
Slow
Fast
VOR
Flexible
Inflexible


eye
fast
Act
Slow
Fast
VOR
Flexible
Inflexible
Vestibular
Ocular
Reflex
(VOR)

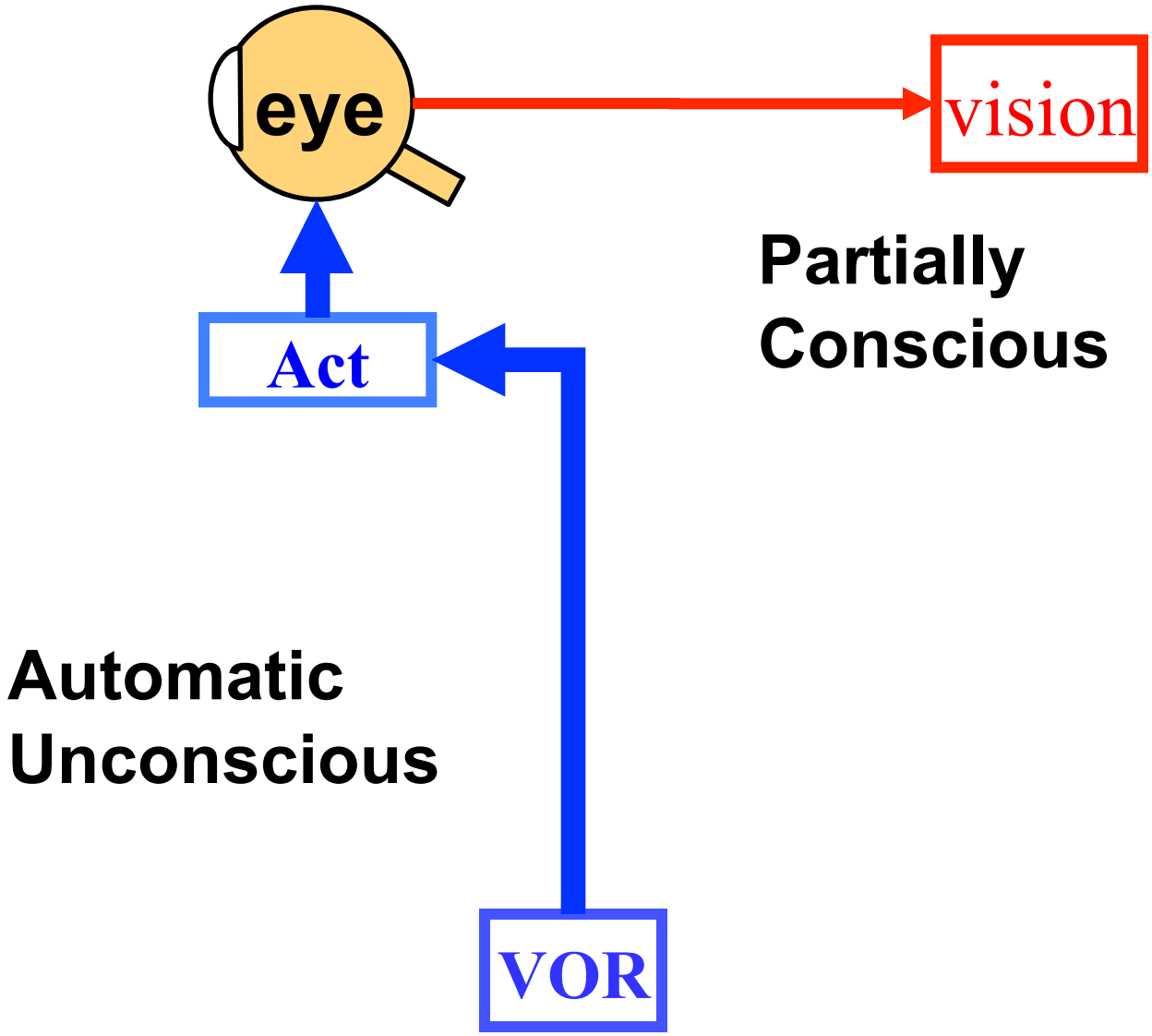
It works in the dark or with your eyes closed, but you can't tell.



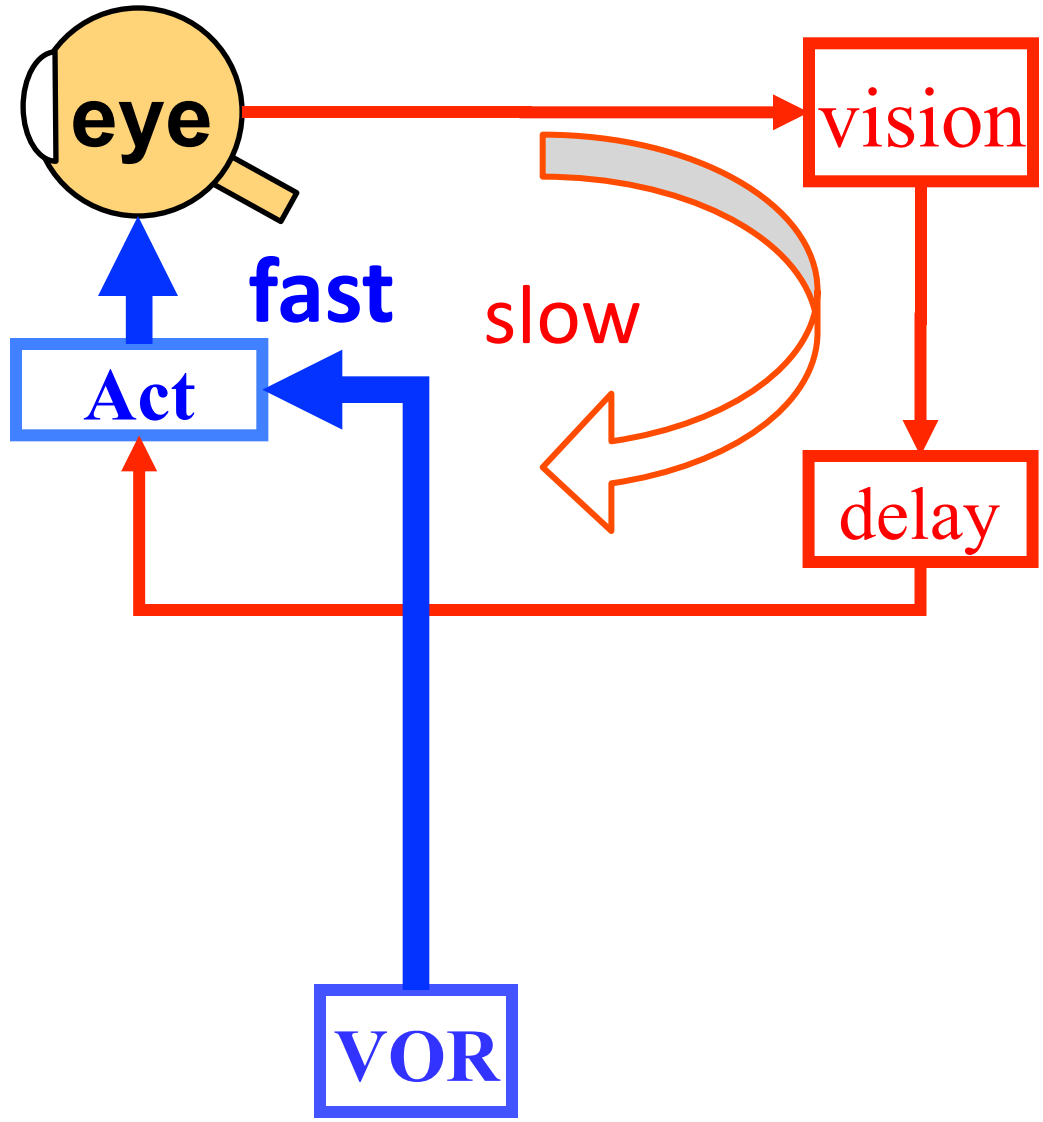

eye
vision
fast
slow
Act
delay
vision
Slow
Fast
VOR
Flexible
Inflexible


Layering
Feedback
vision
ay
Highly
evolved
(hidden)
architecture
Slow
Fast
Illusion
Flexible
Inflexible

Layering

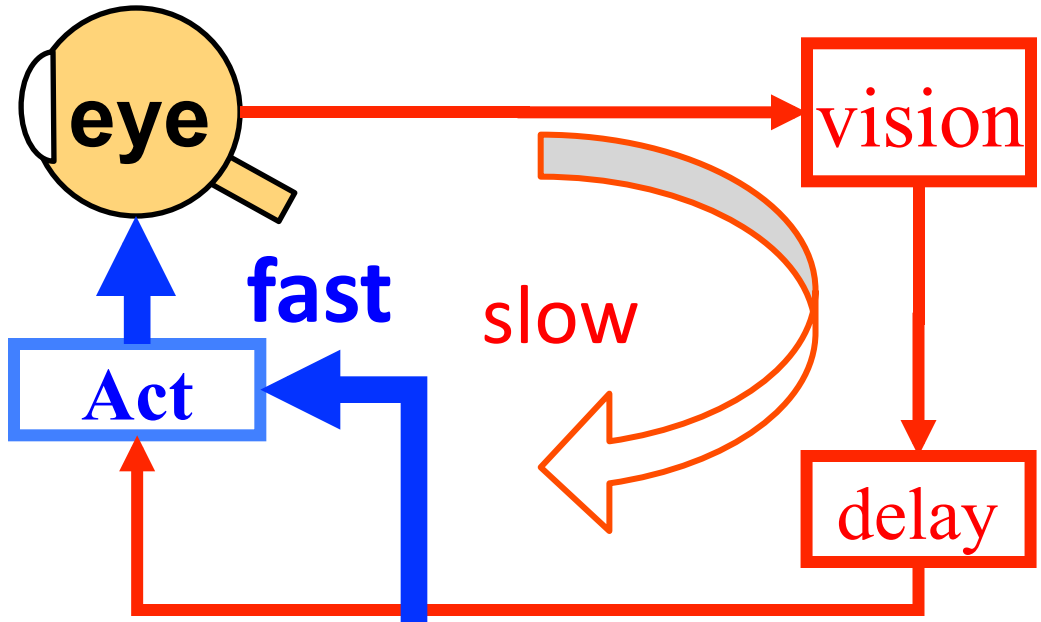

eye
vision
Partially
Conscious
Act
Automatic
Unconscious
VOR

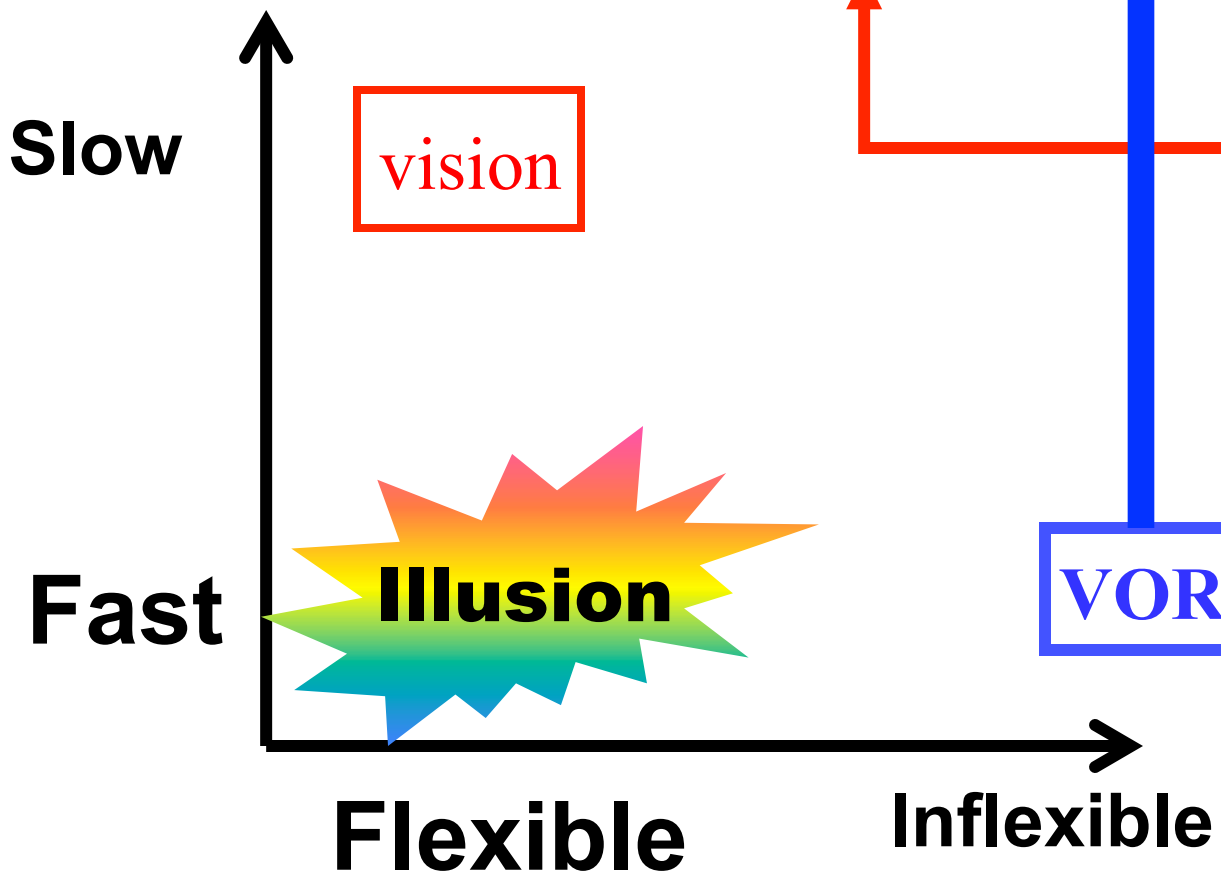
Layering Feedback



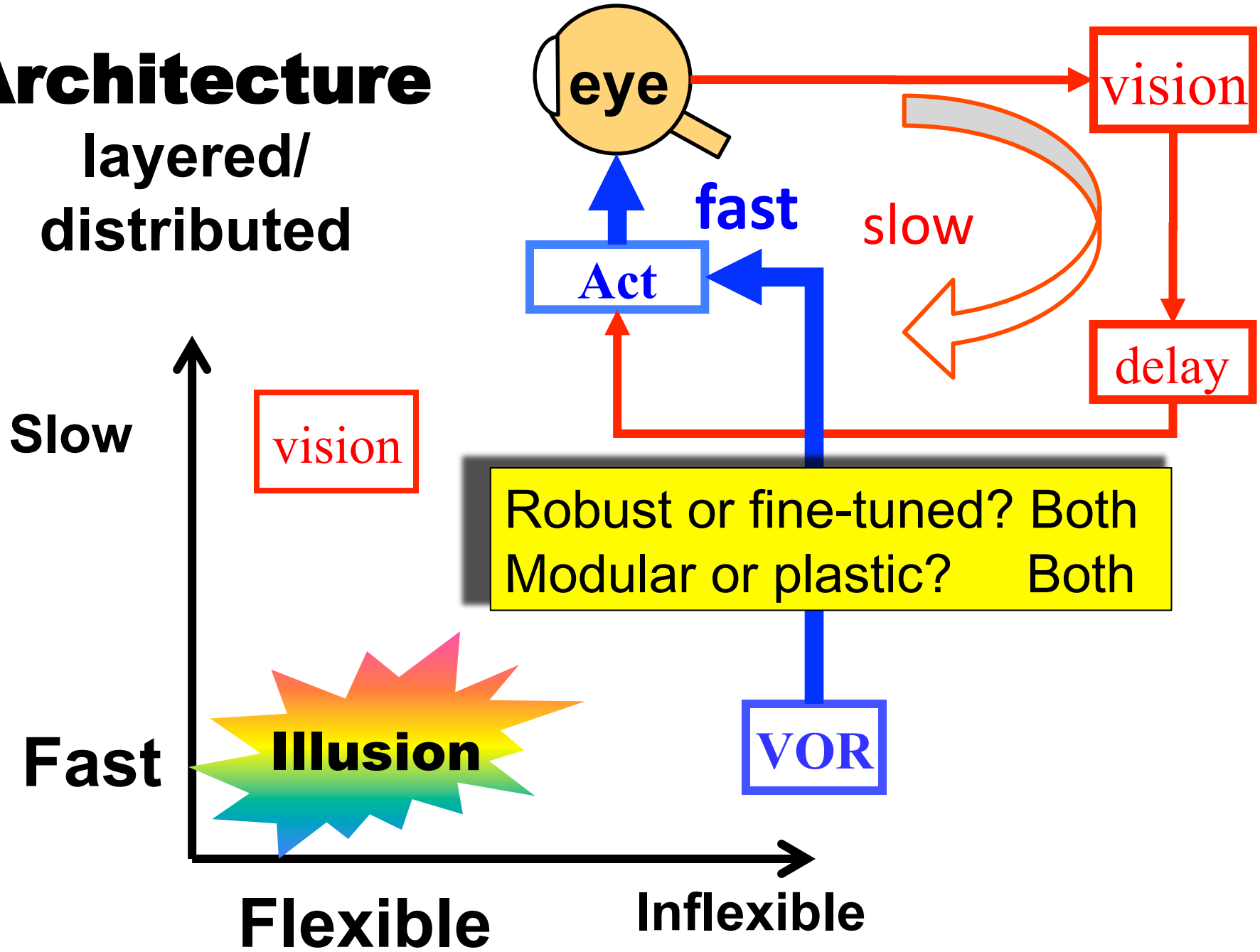
Architecture

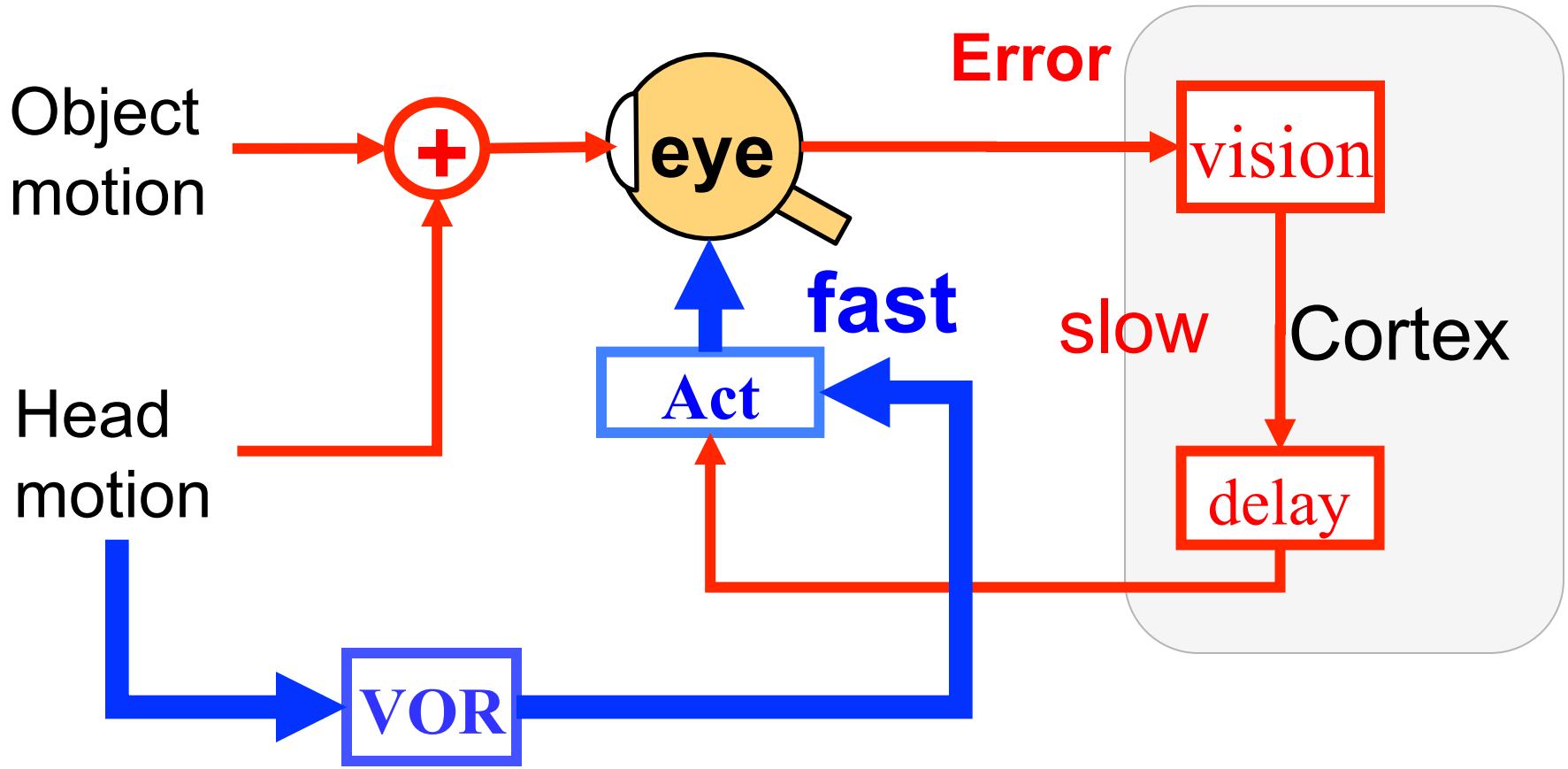
layered/
distributed



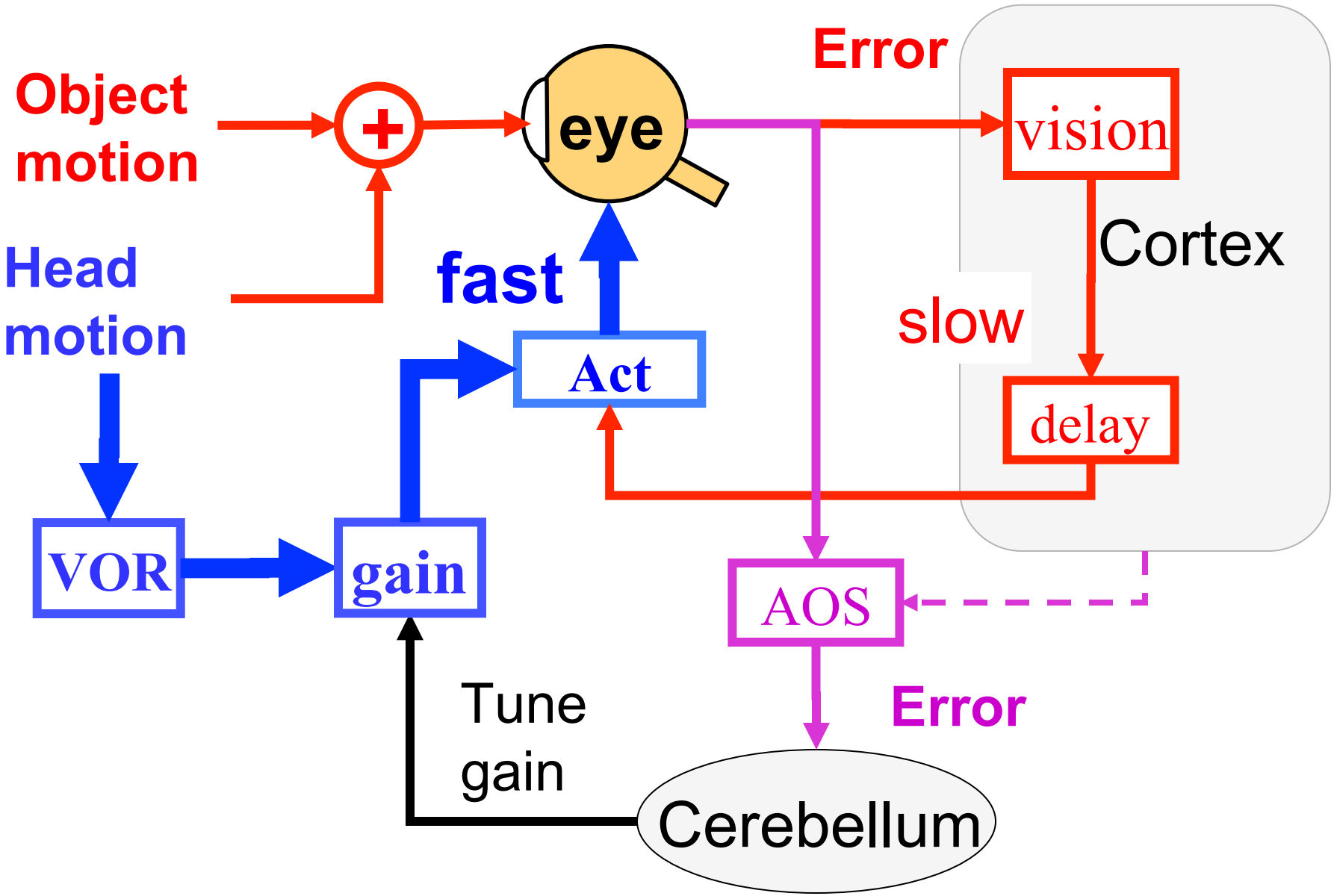


Architecture
layered/
distributed



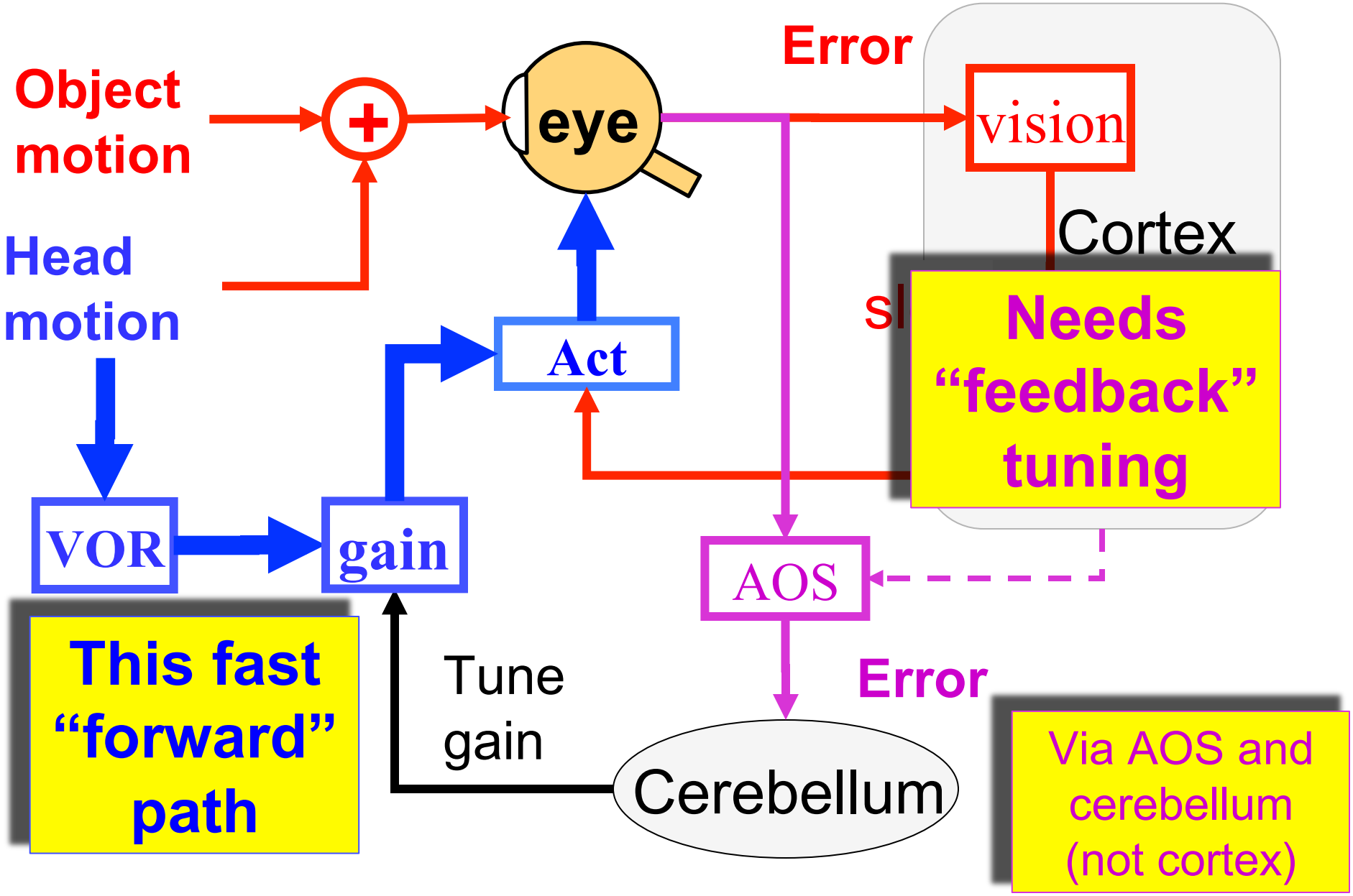


Very rough cartoon



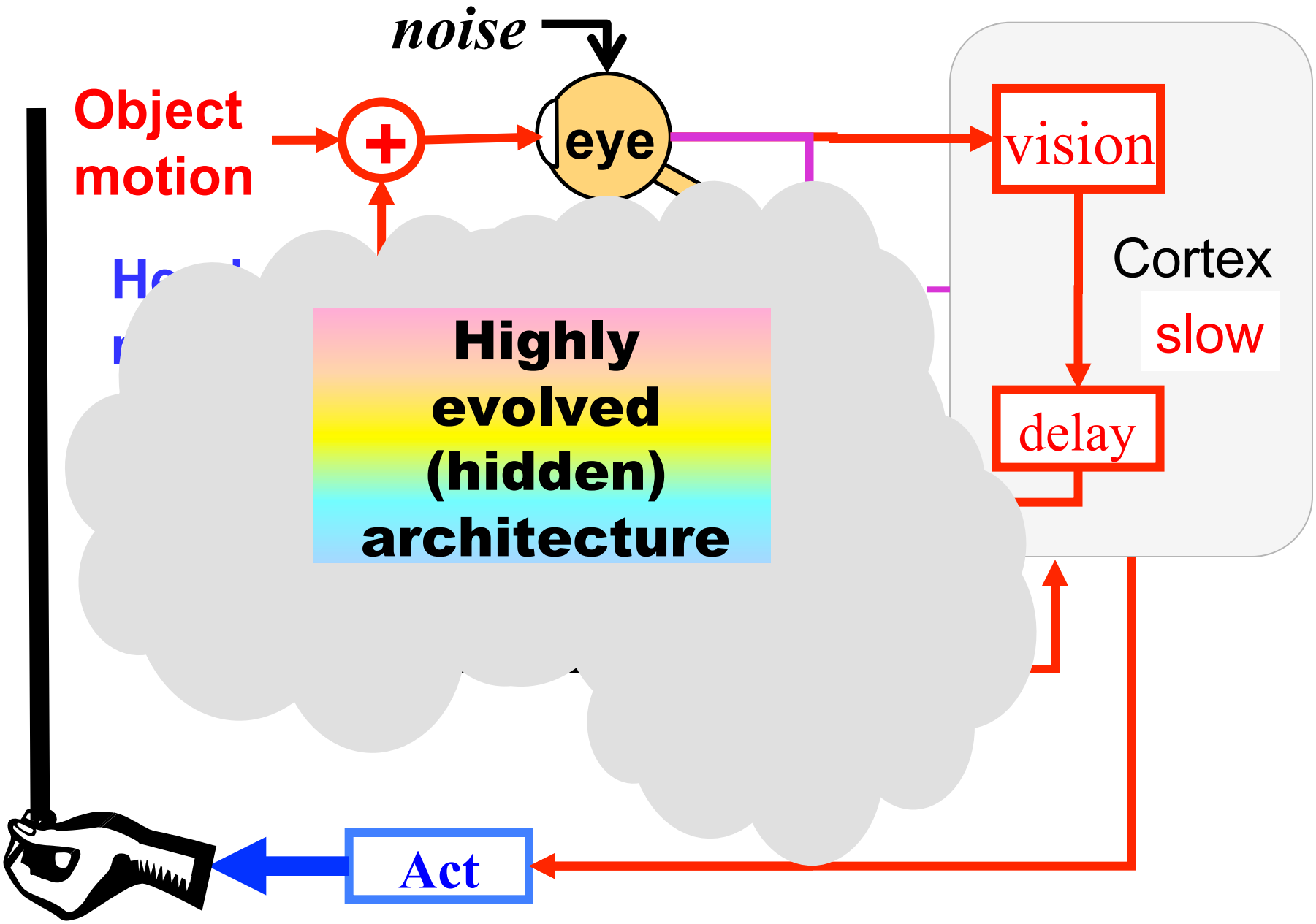
Slightly better

AOS = Accessory Optical system

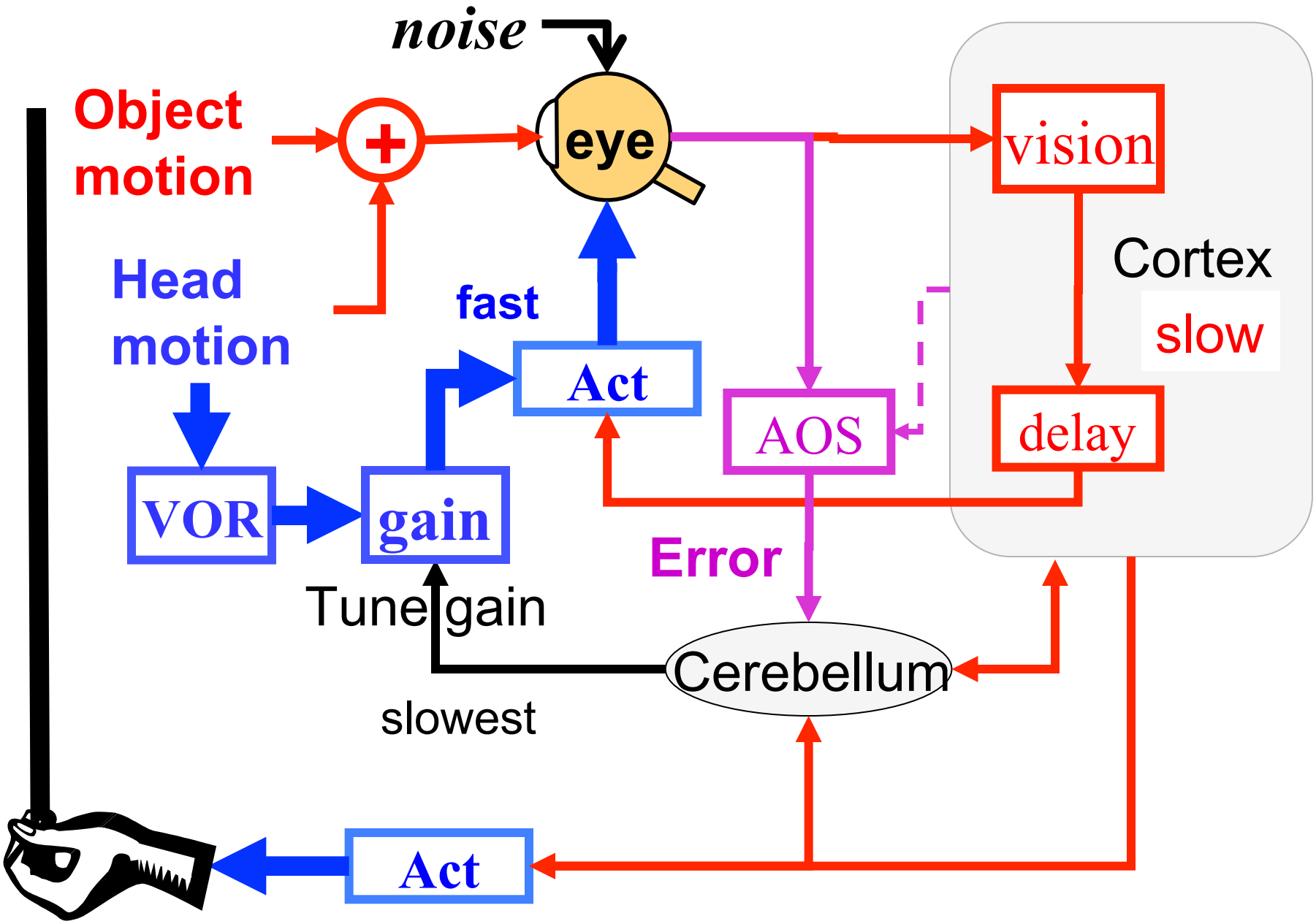


Slightly better

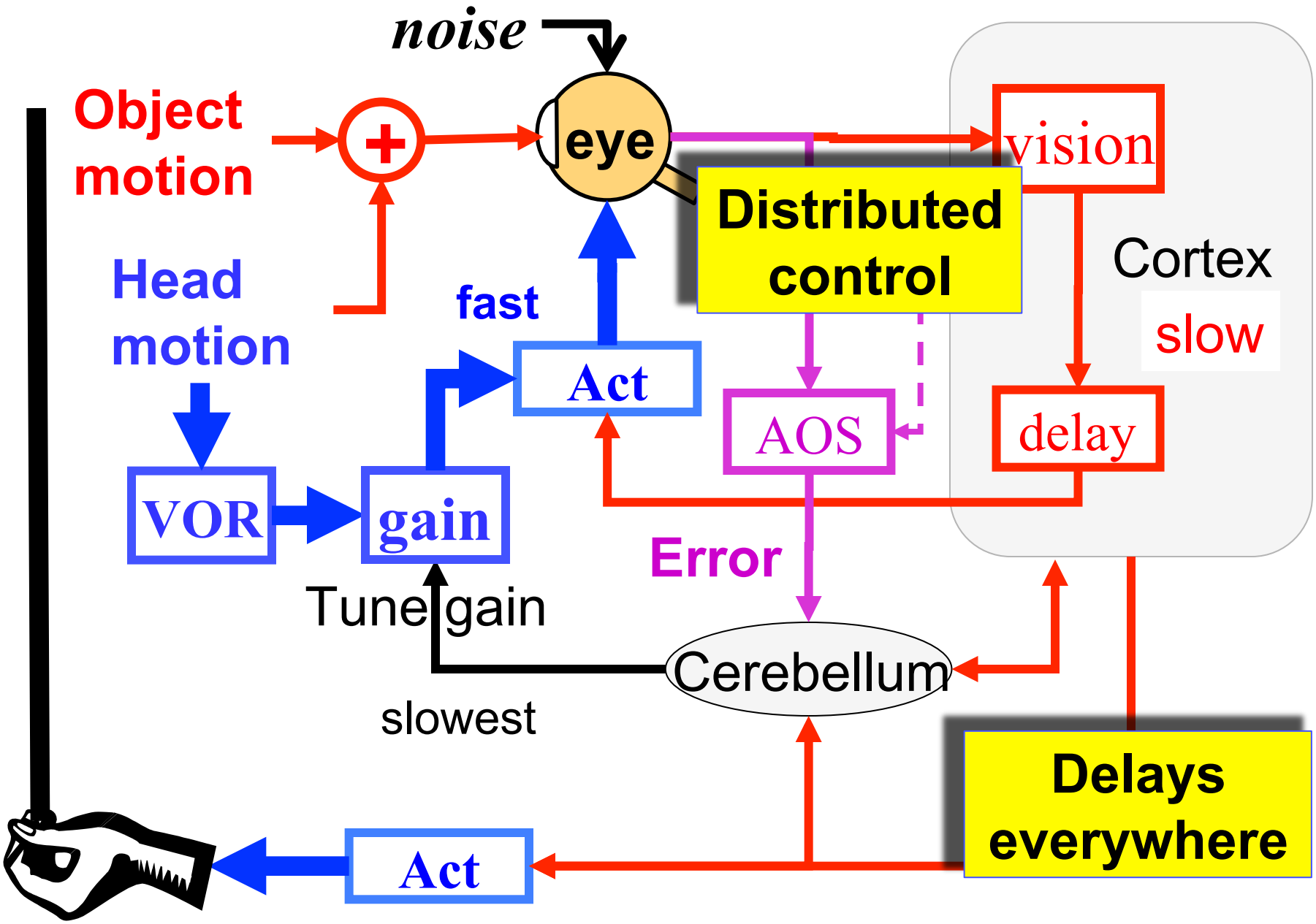
AOS = Accessory Optical system



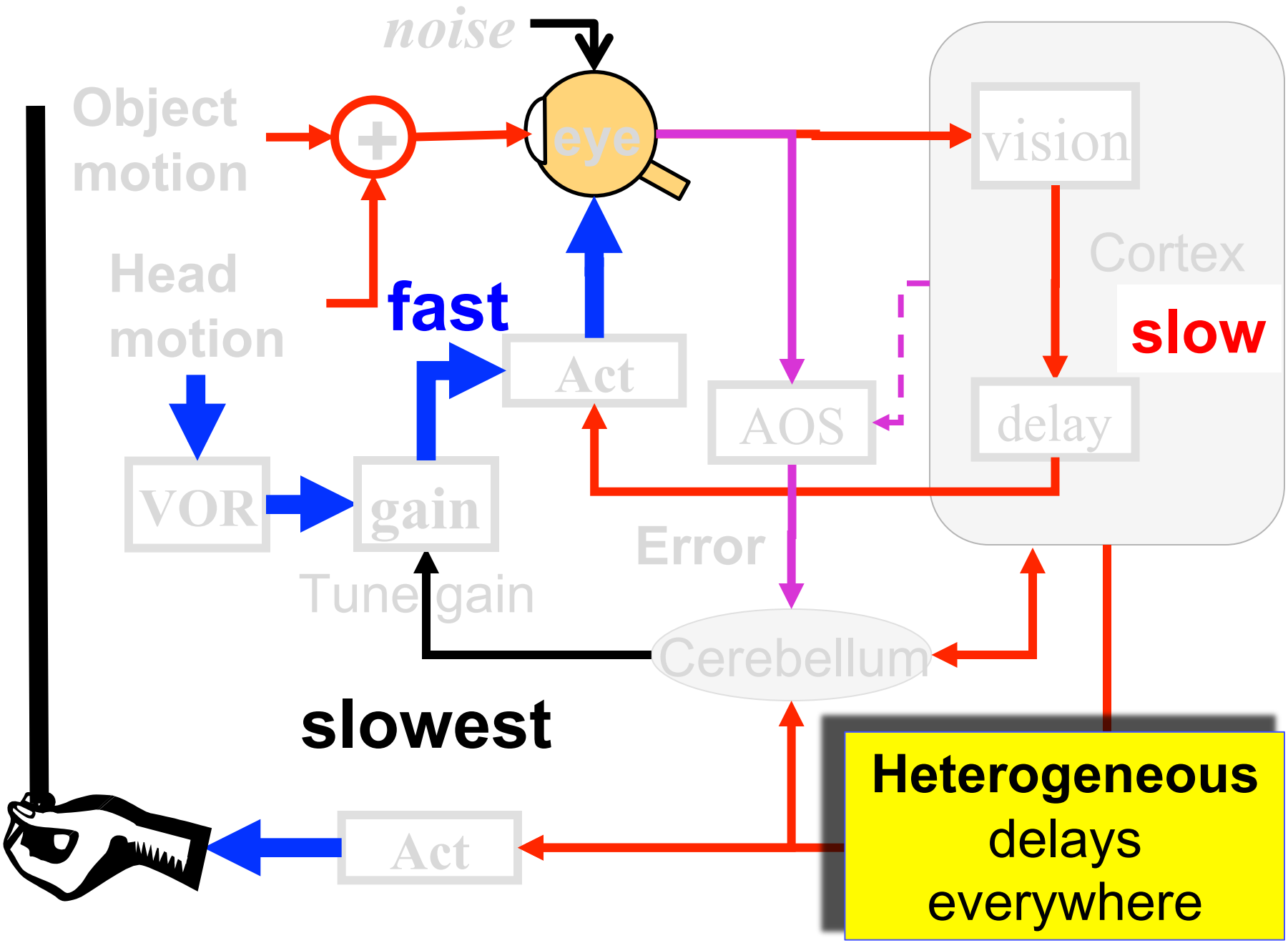
AOS = Accessory Optical system

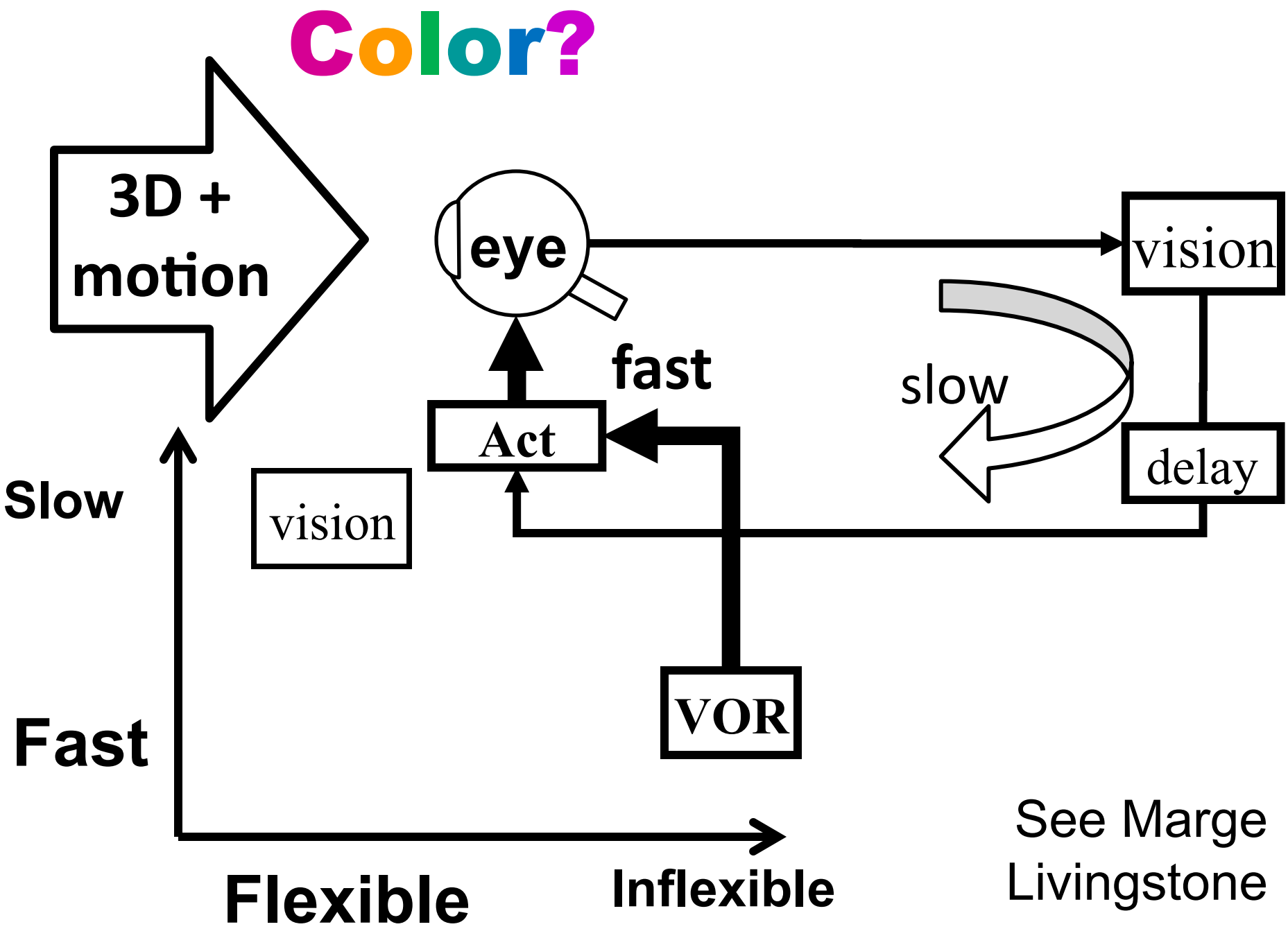


AOS = Accessory Optical system

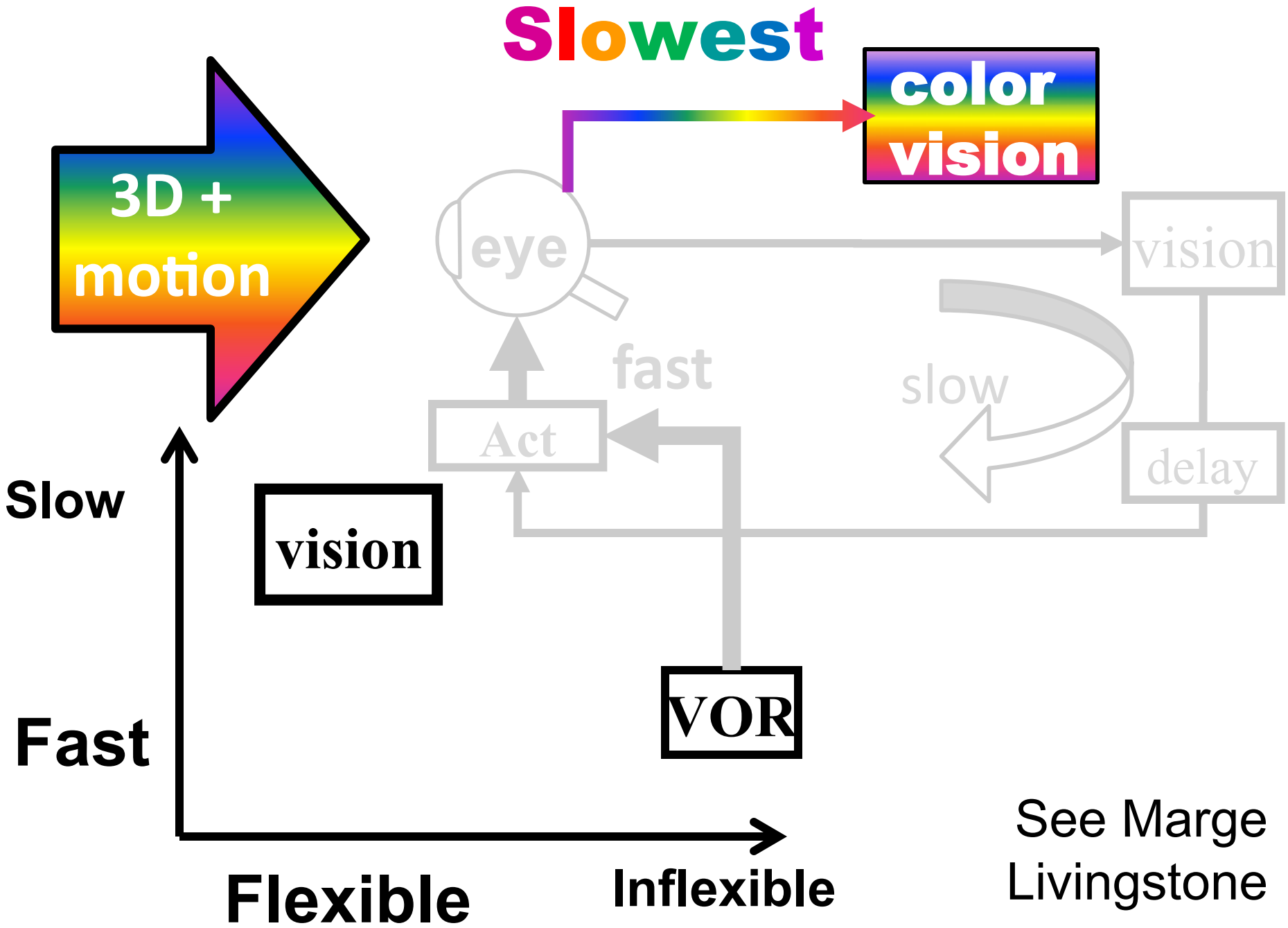


AOS = Accessory Optical system

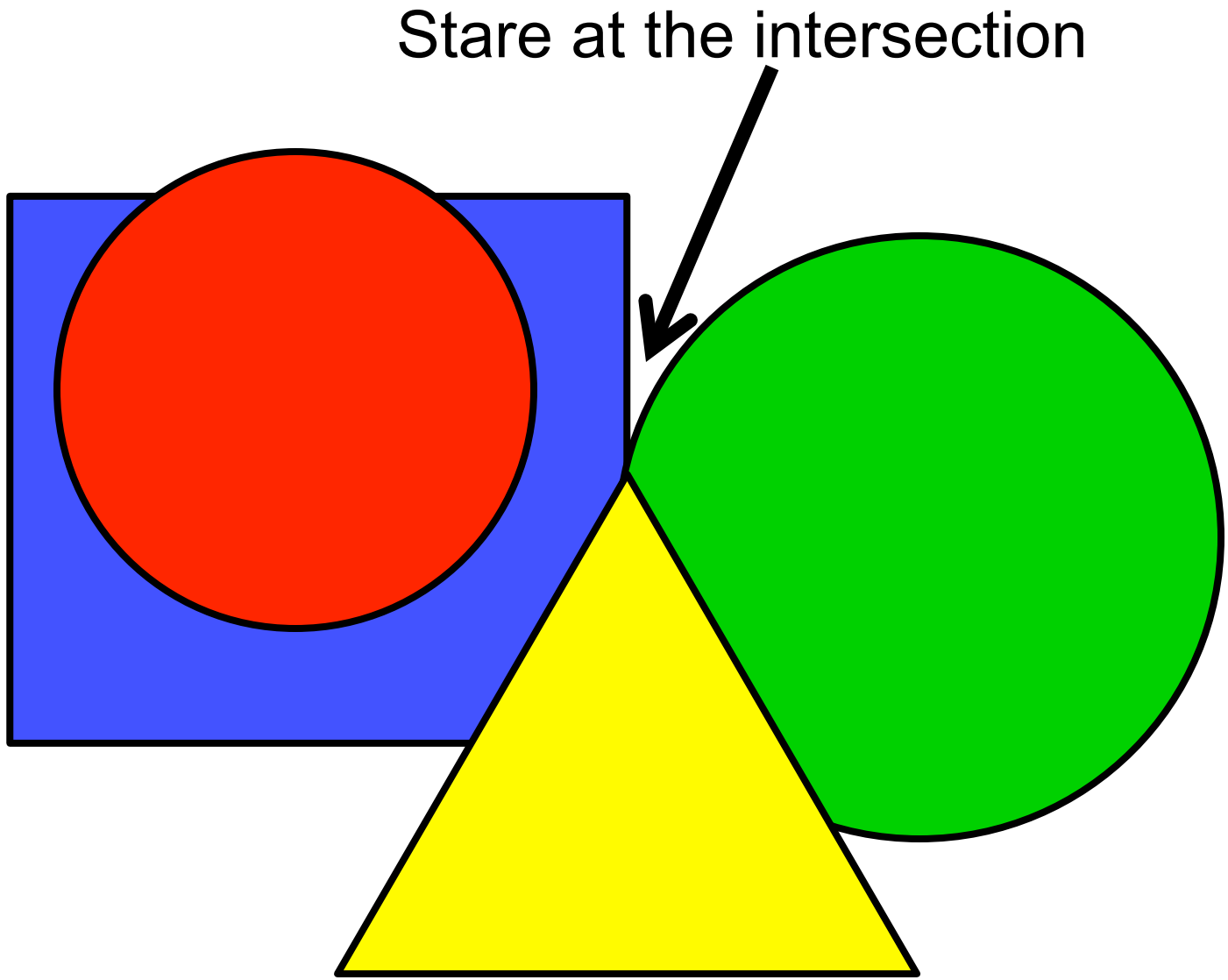

noise
Object motion
eye
vision
Cortex
slow
Head motion
fast
Act
AOS
delay
VOR
gain
Error
Tune gain
Cerebellum
slowest
Act
Heterogeneous delays everywhere

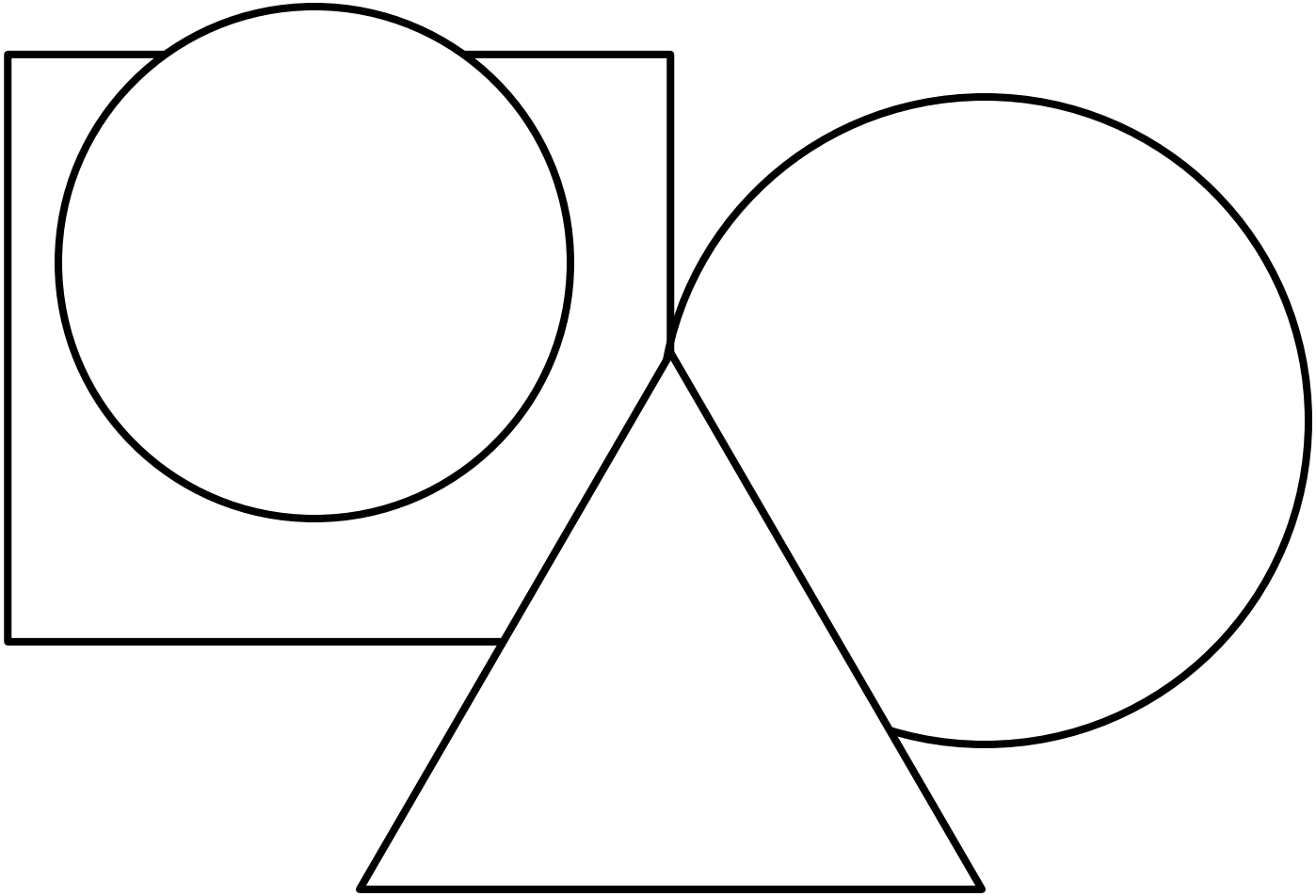


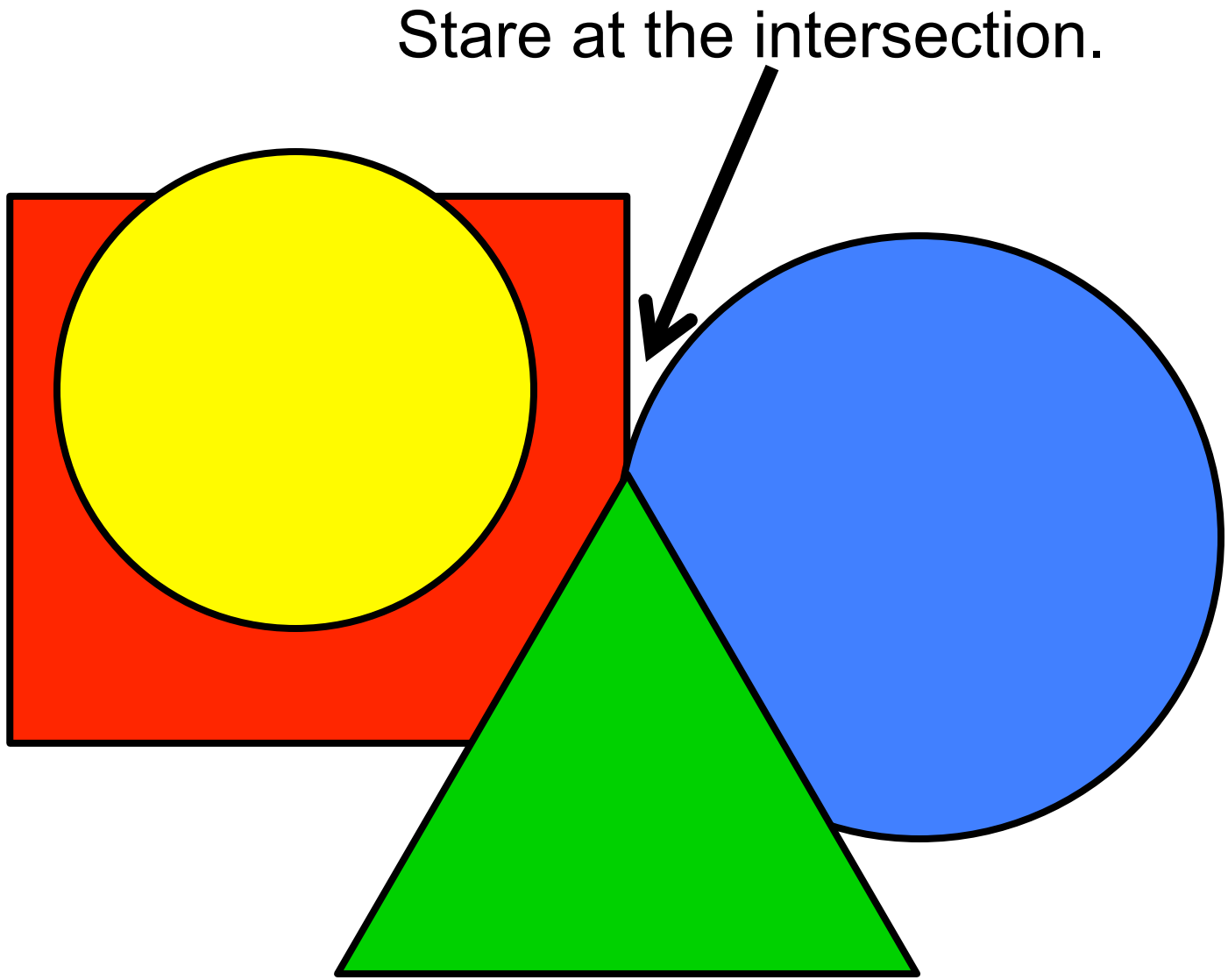
See Marge Livingstone

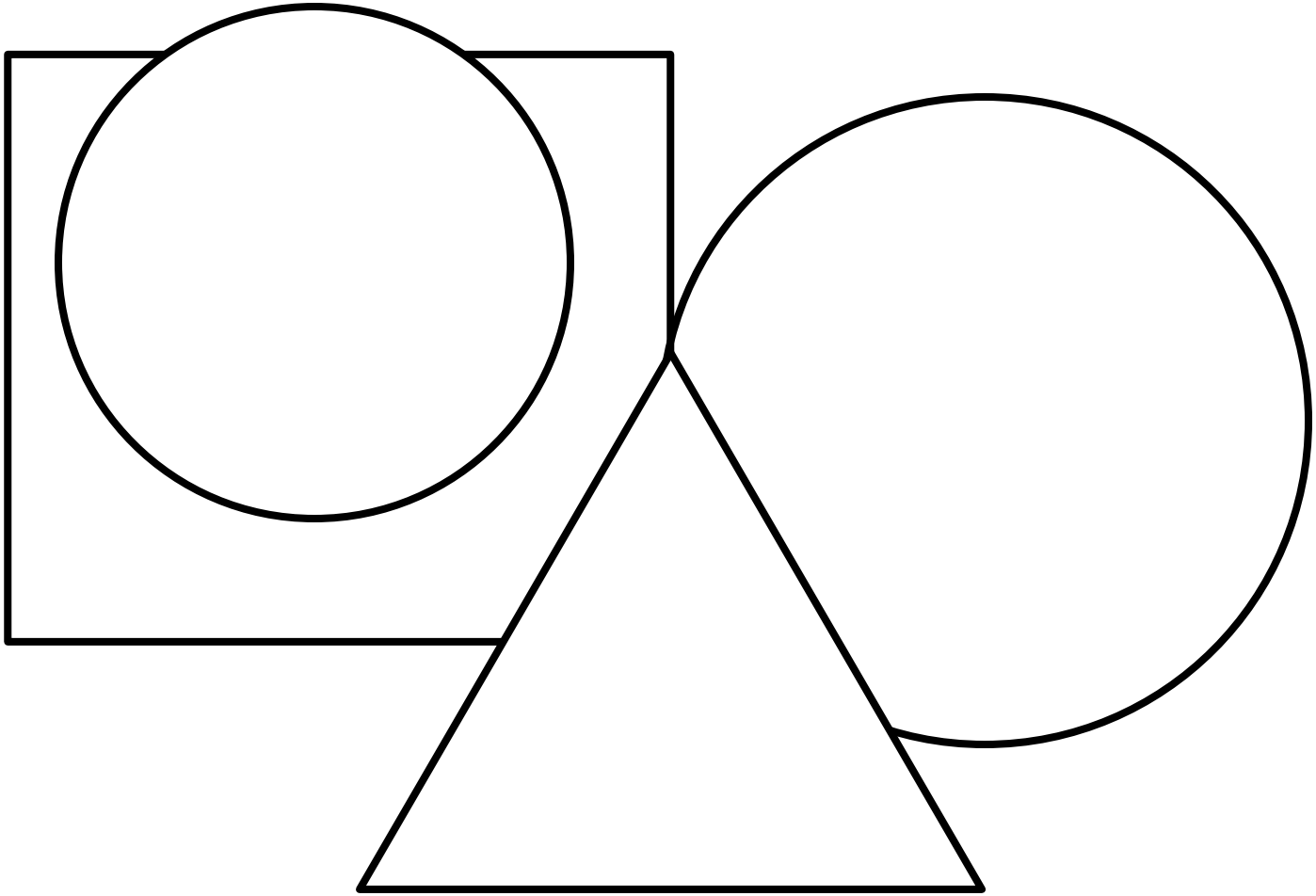


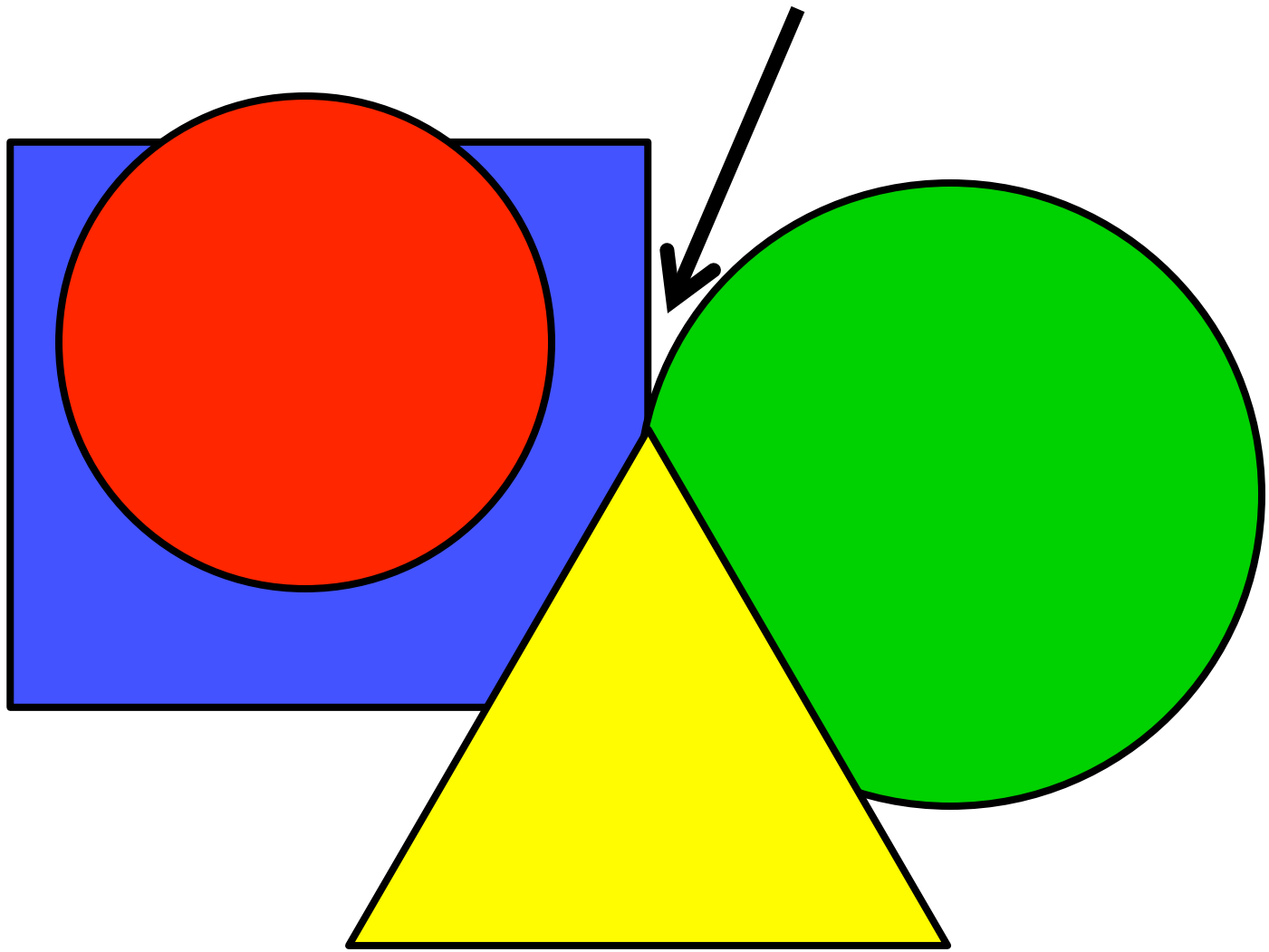
See Marge Livingstone

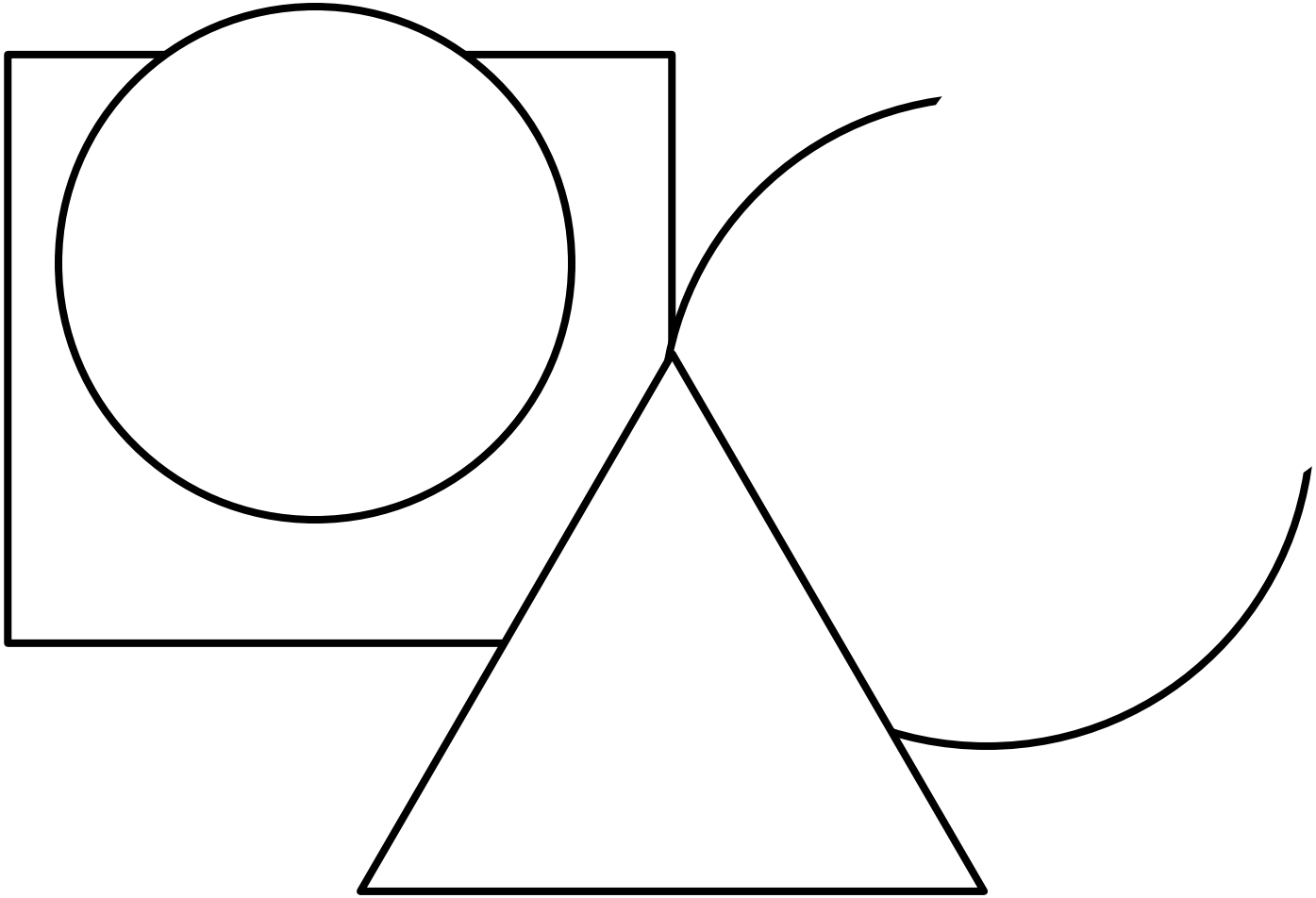

Stare at the intersection

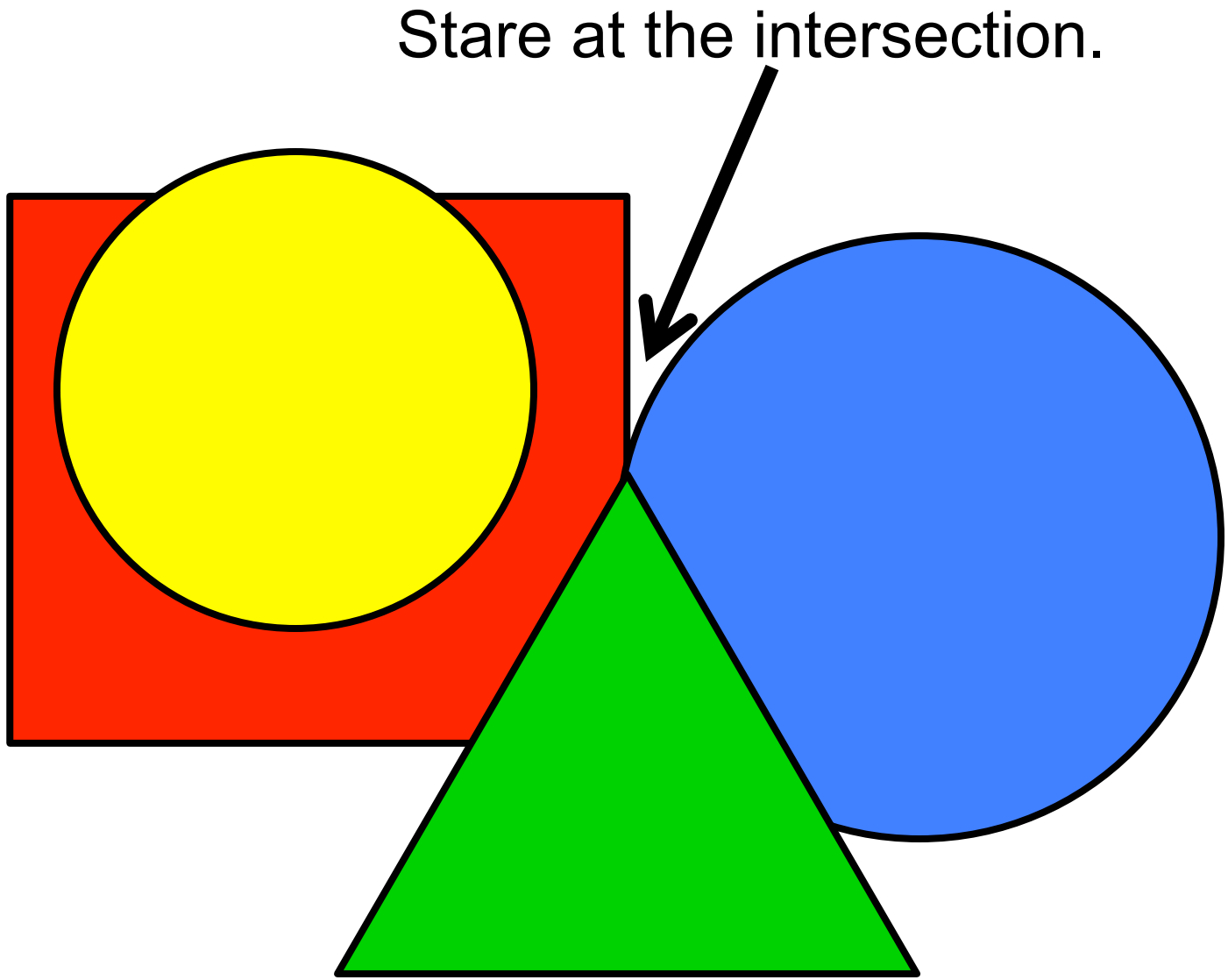


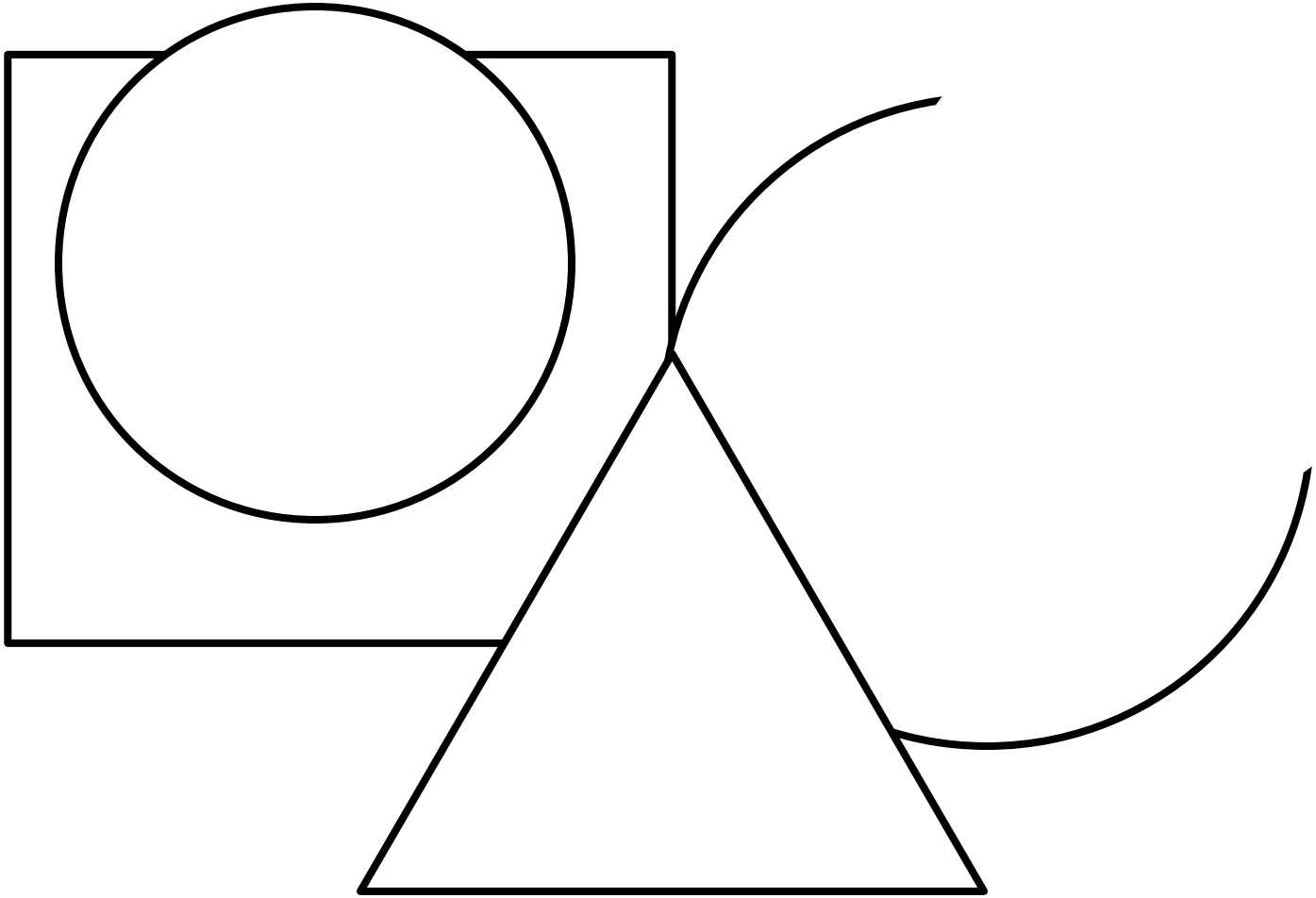

Stare at the intersection.

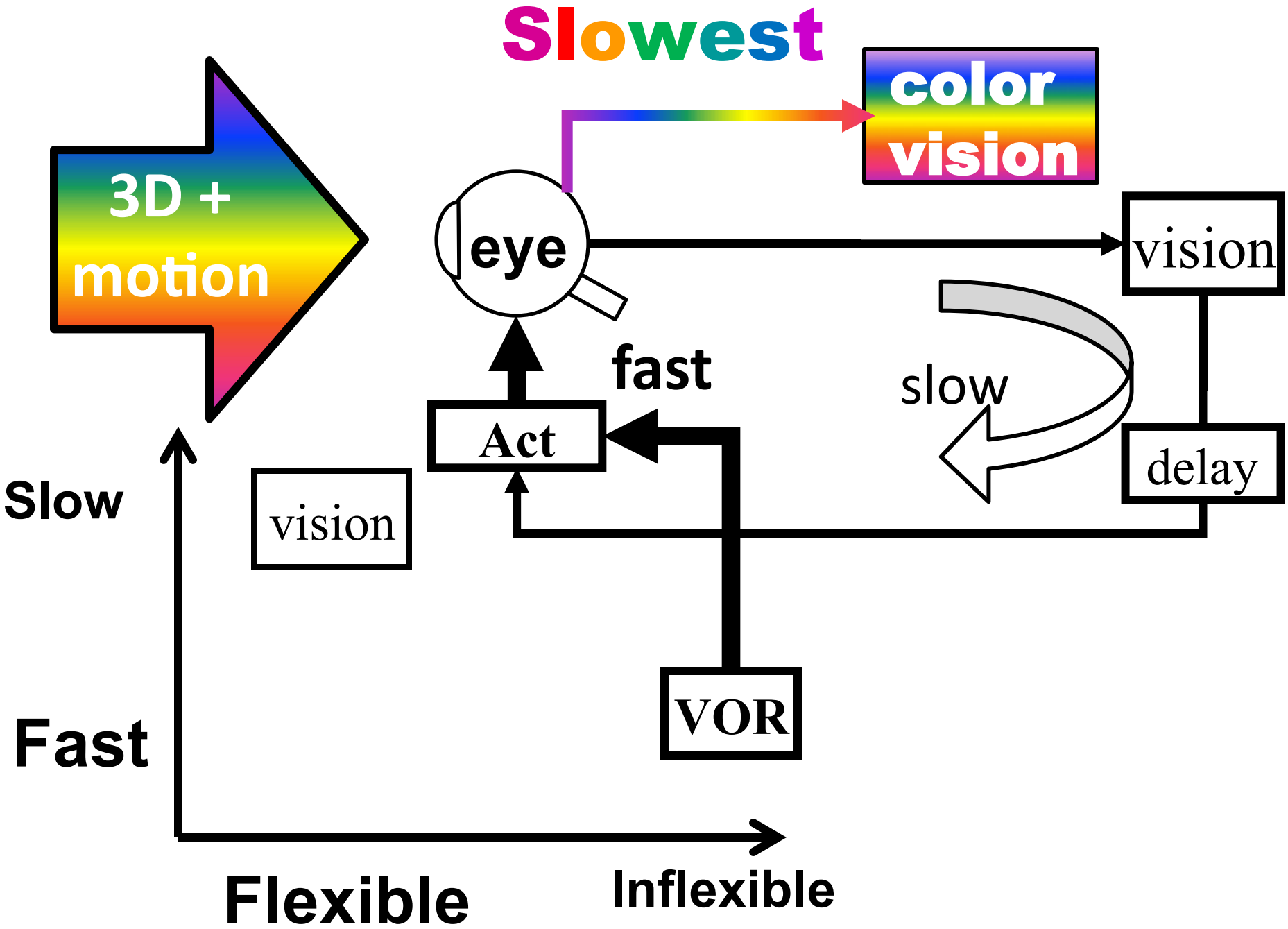






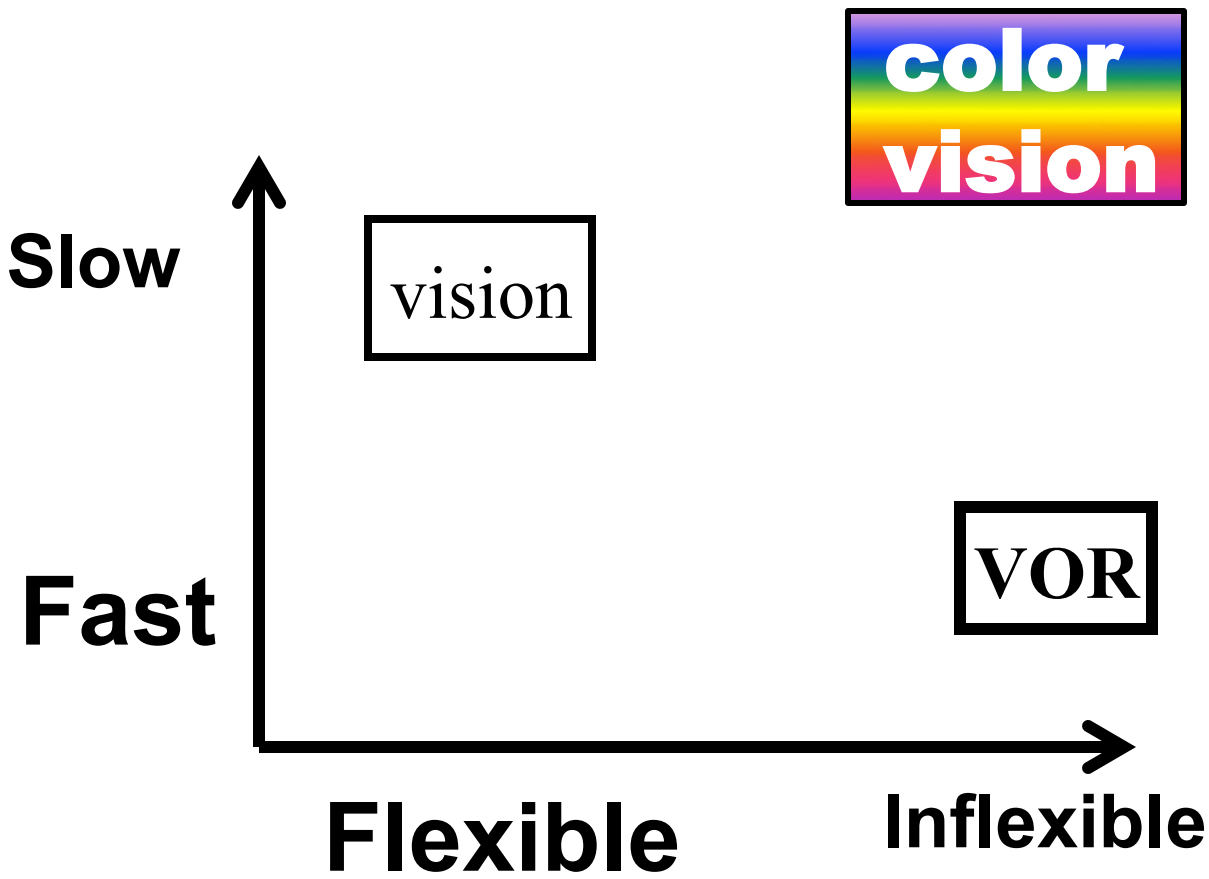

Stare at the intersection.

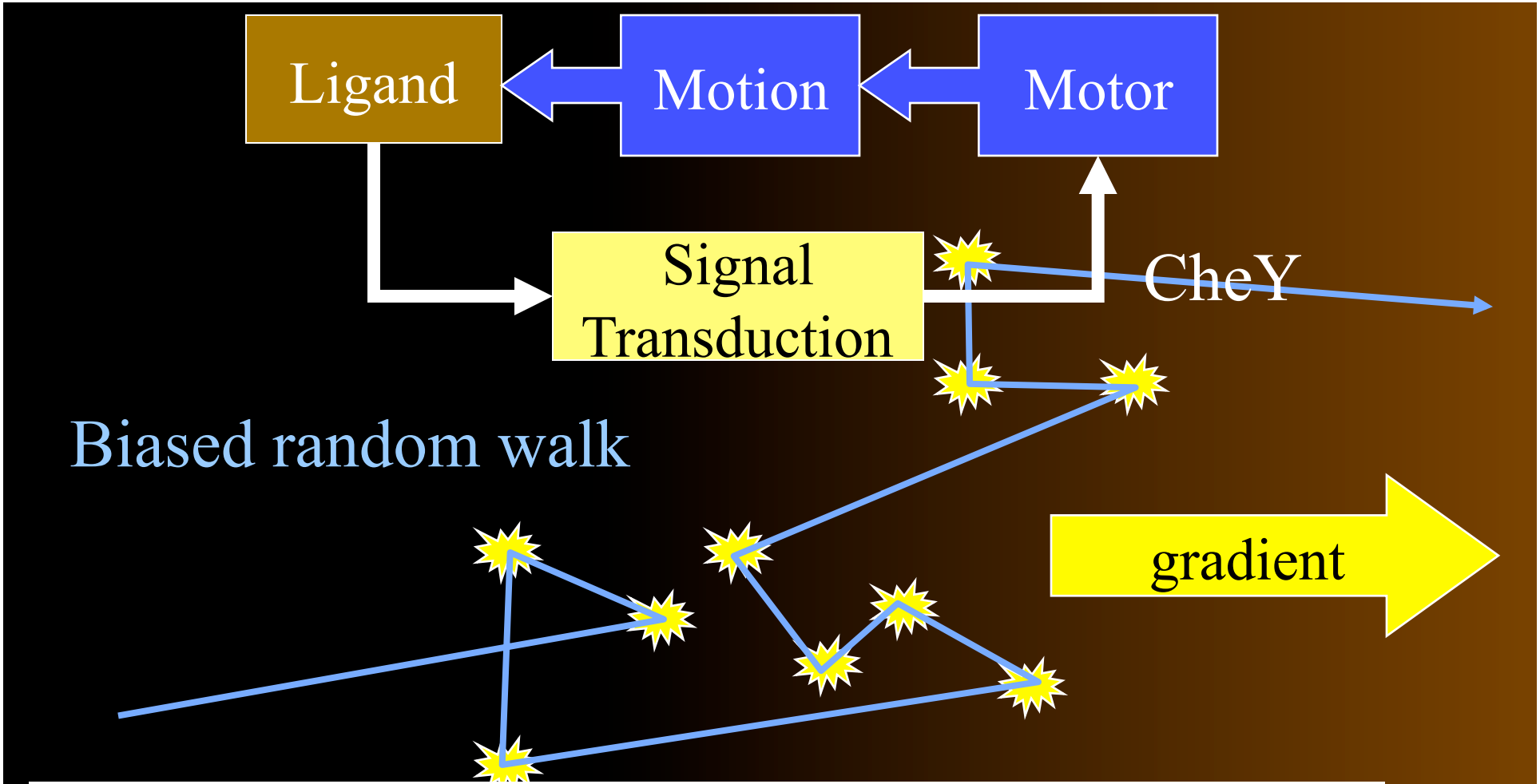



Slowest
color vision
3D + motion
eye
vision
fast
slow
Act
delay
vision
Slow
VOR
Fast
Flexible
Inflexible

Seeing is dreaming

- is simulation
- requiring "internal model"





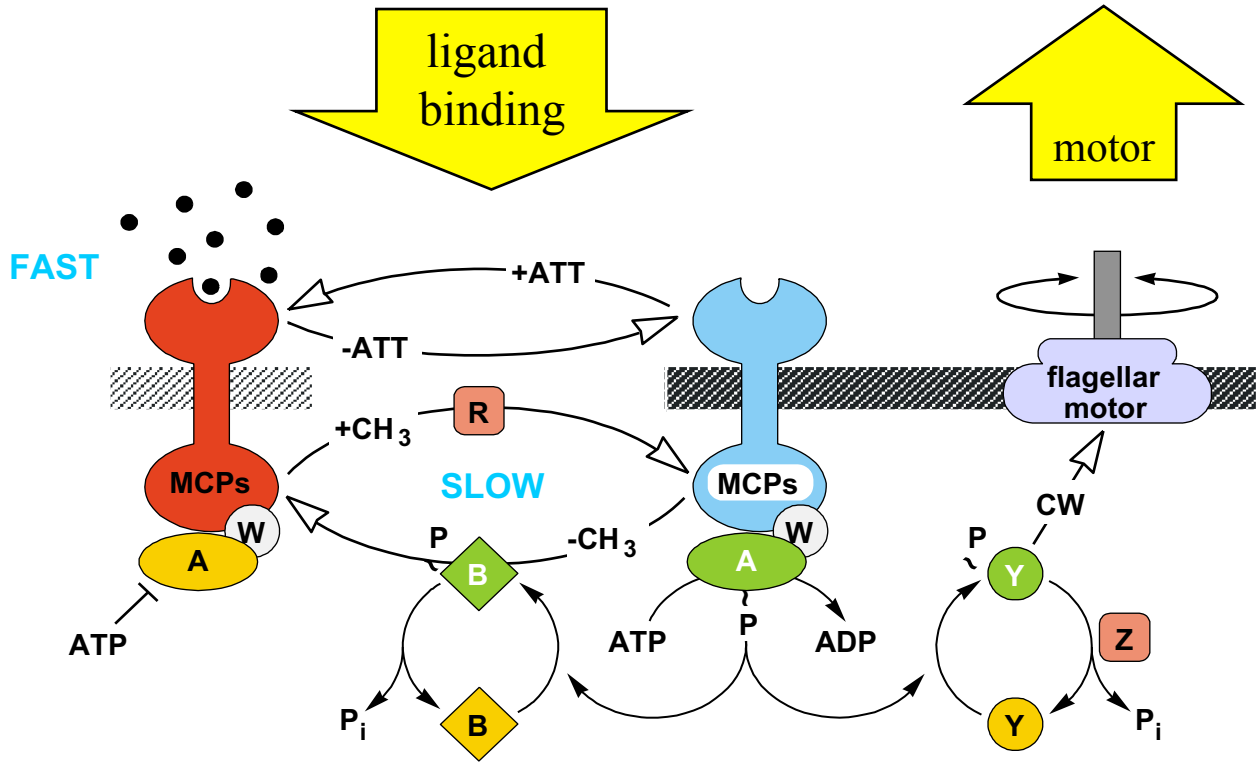
Robust perfect adaptation in bacterial chemotaxis through integral feedback control

Tau-Mu Yi*†, Yun Huang†‡, Melvin I. Simon*§, and John Doyle‡

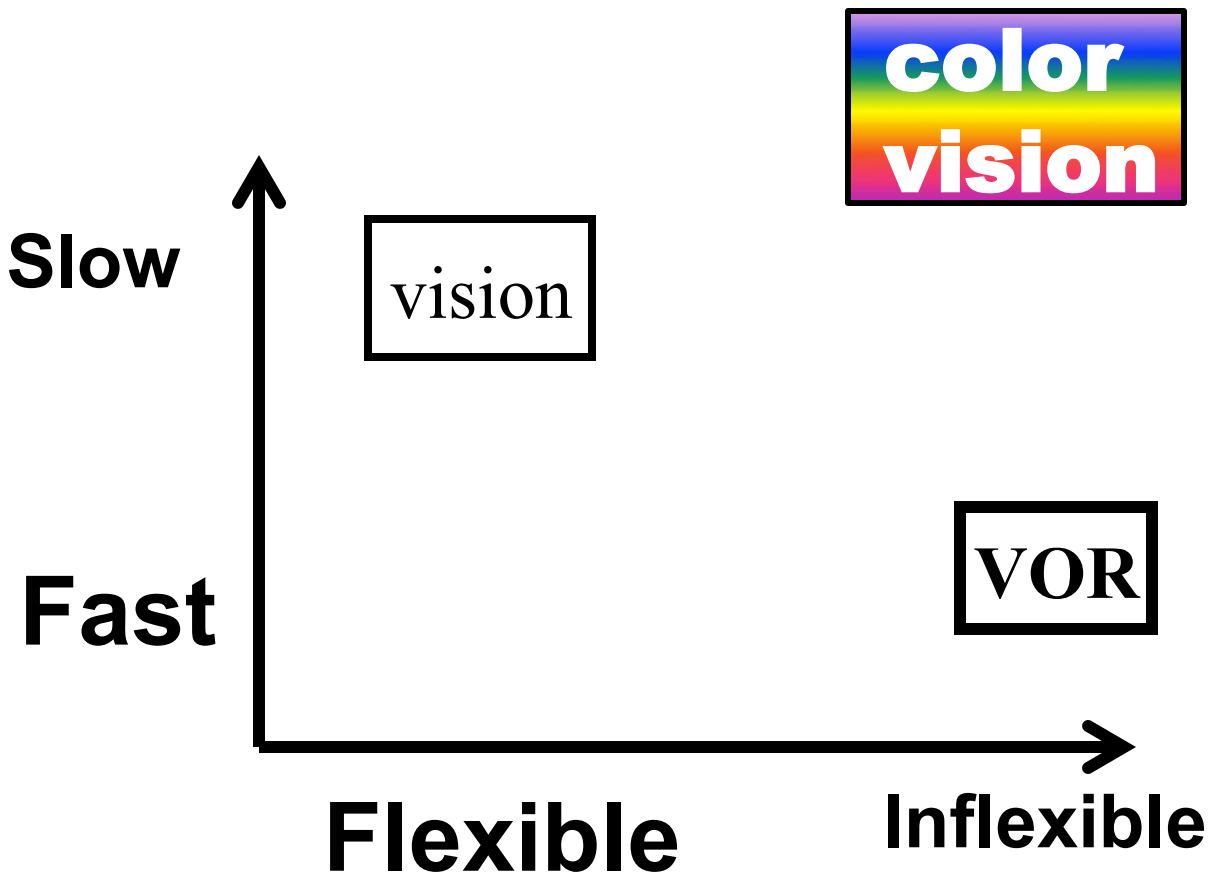
PNAS | April 25, 2000 | vol. 97 | no. 9 | 4649–4653

Bacterial chemotaxis

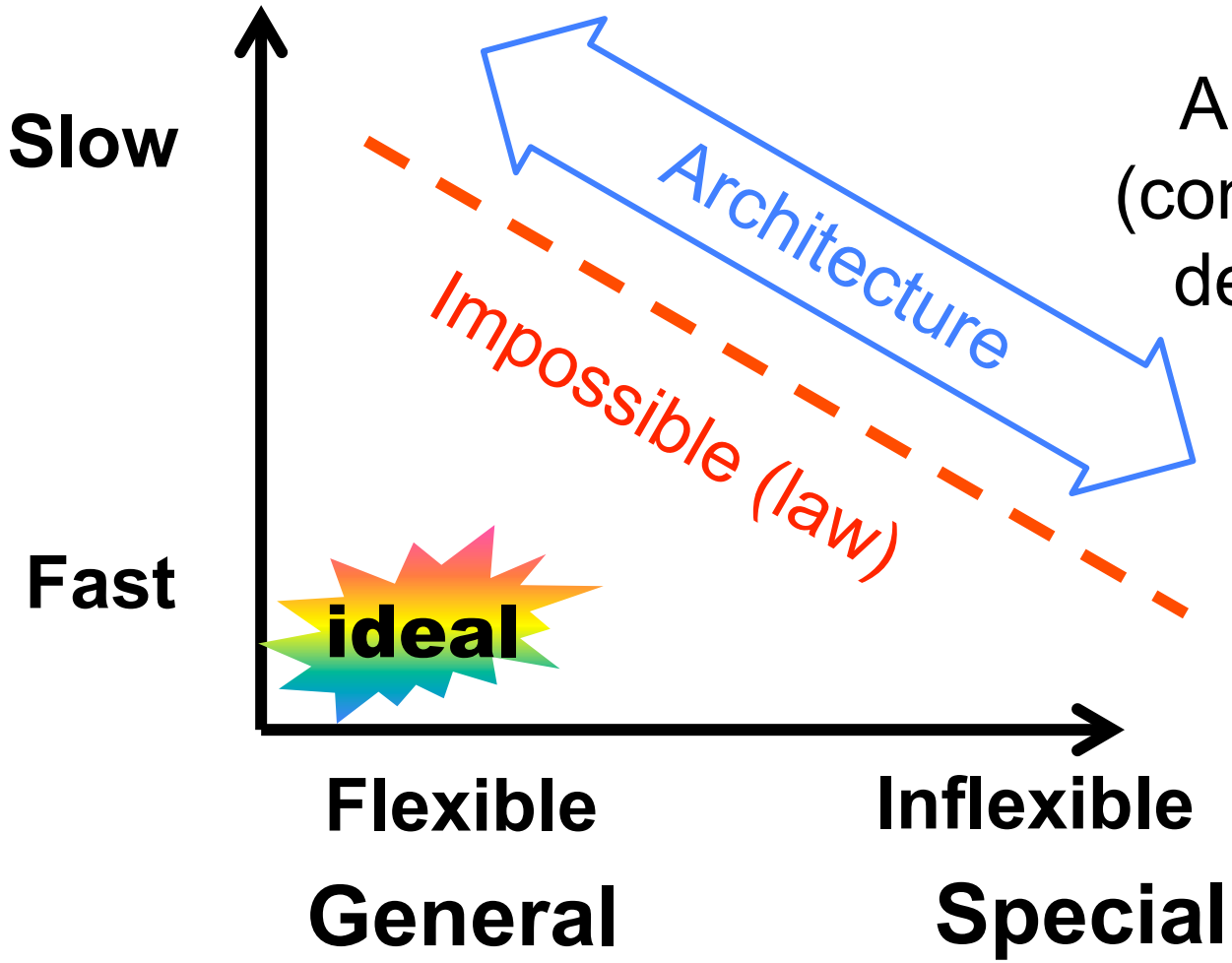
- Internal model *necessary* for robust chemotaxis
- Reality is 3d, but…
- Internal model *virtual* and 1d



Layering Distributed Feedback

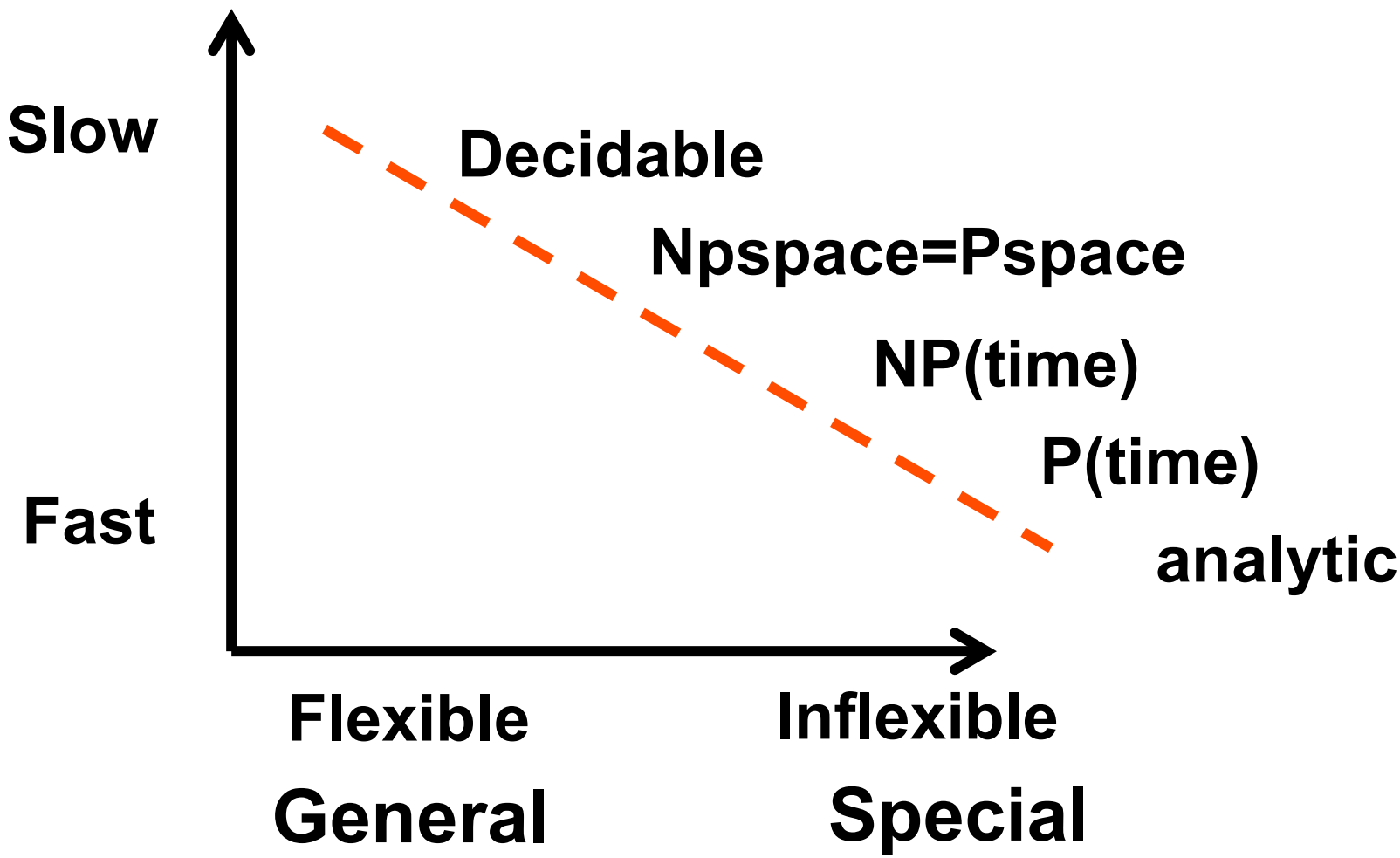


Universal laws and architectures (Turing)



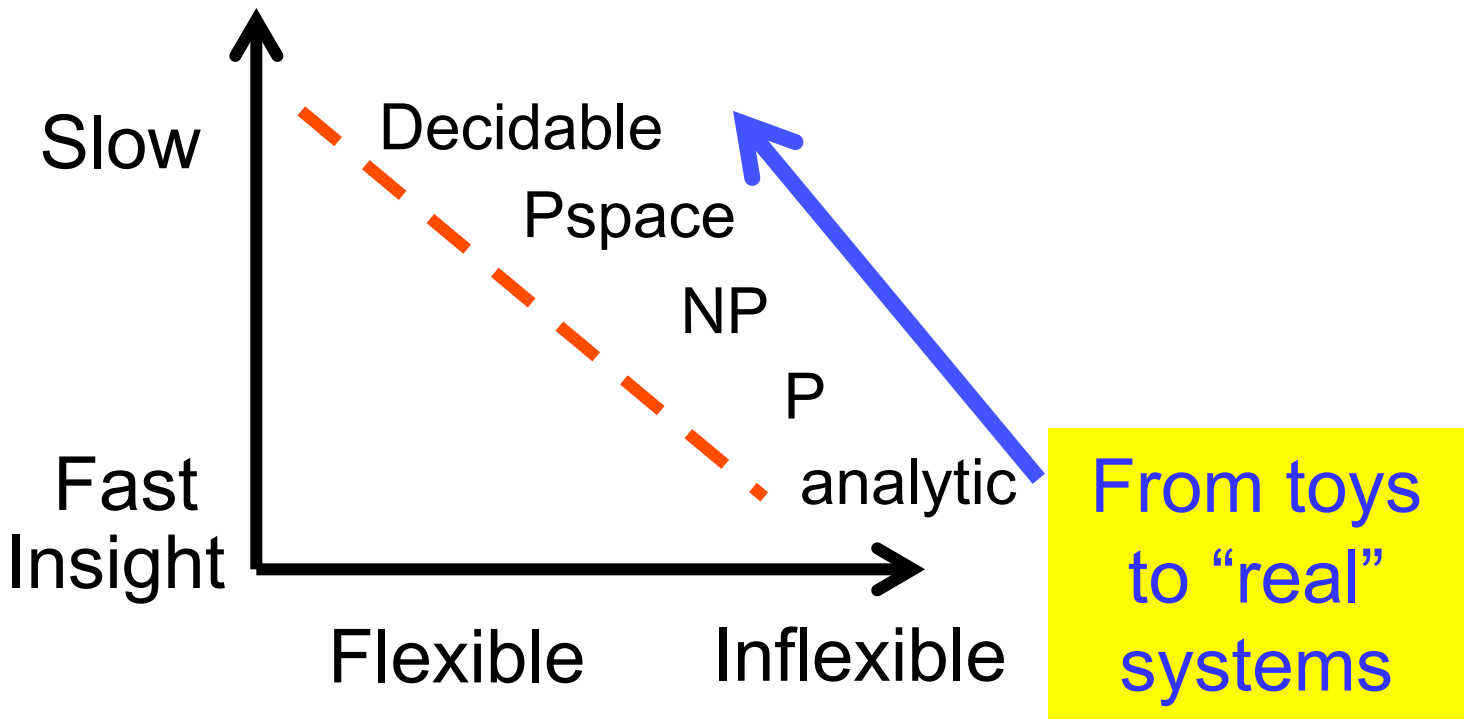
Architecture (constraints that deconstrain)

Computation
(on and off-line)



Compute

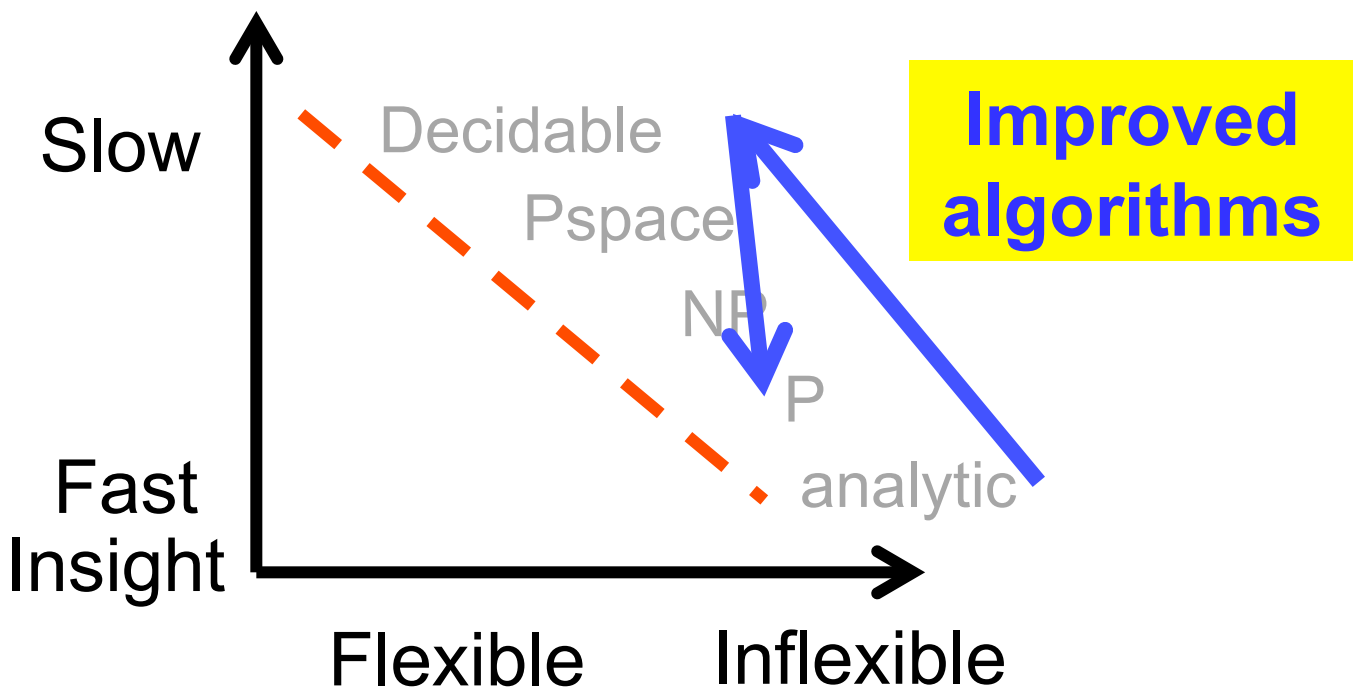
Research progress



Control, OR

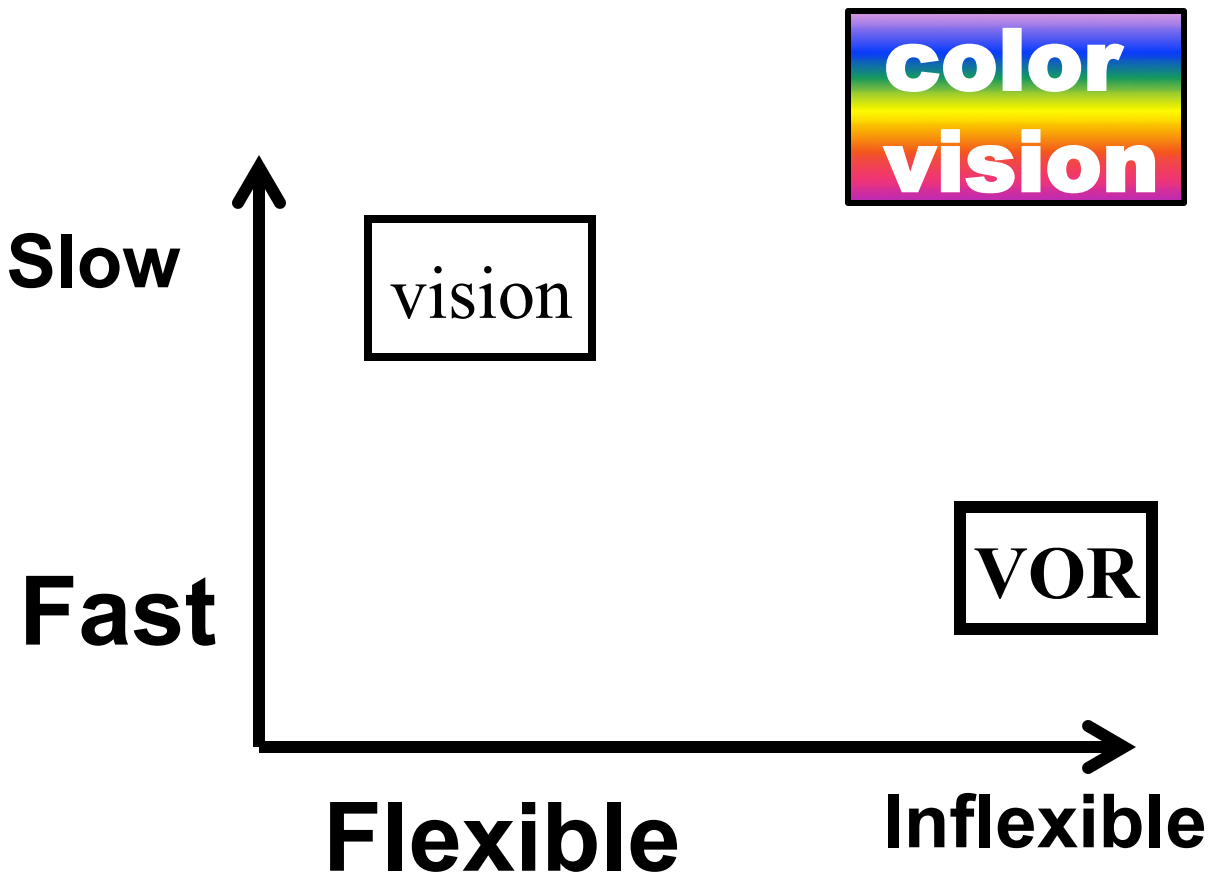
Compute

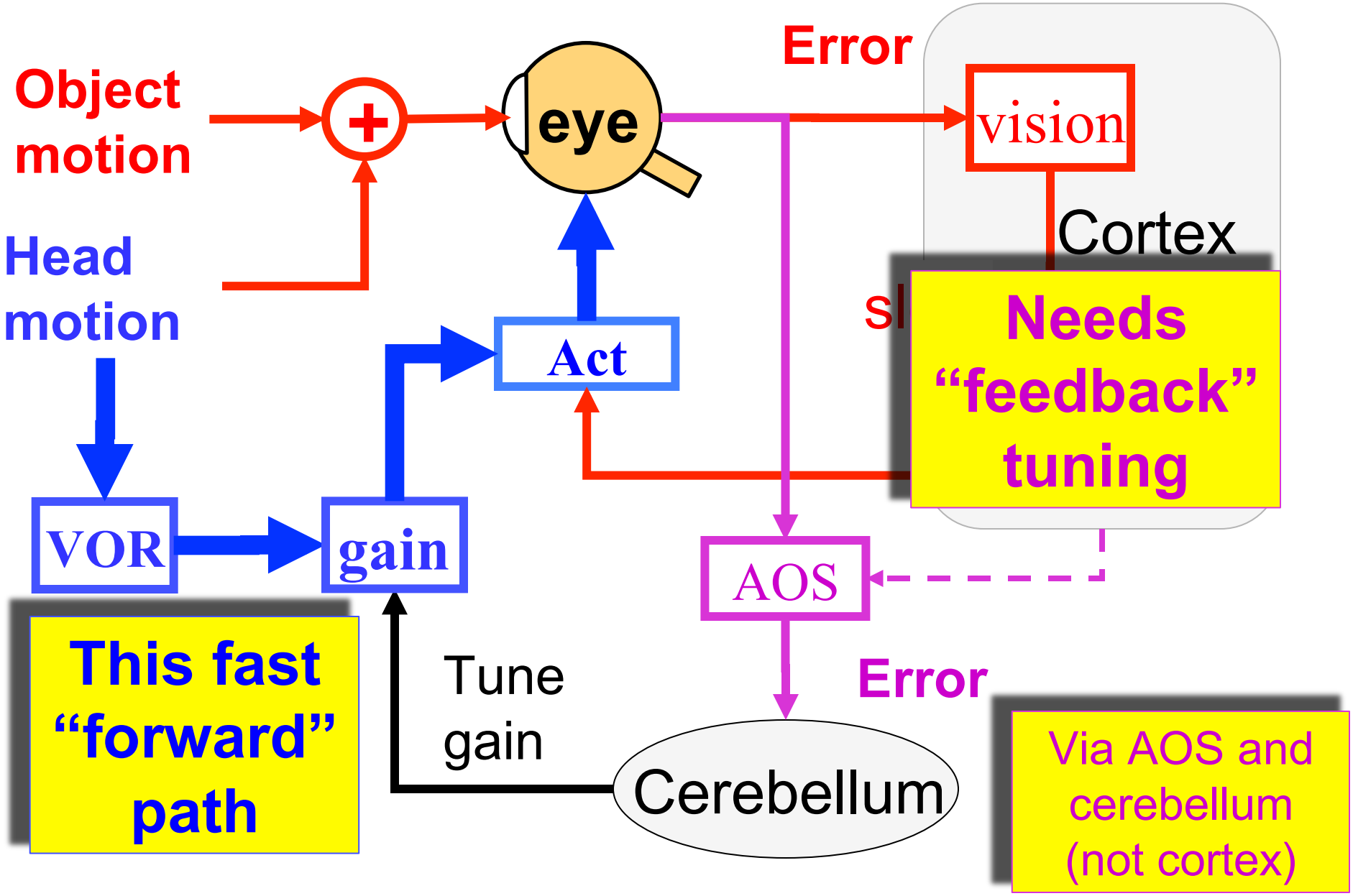
Research progress



Control, OR

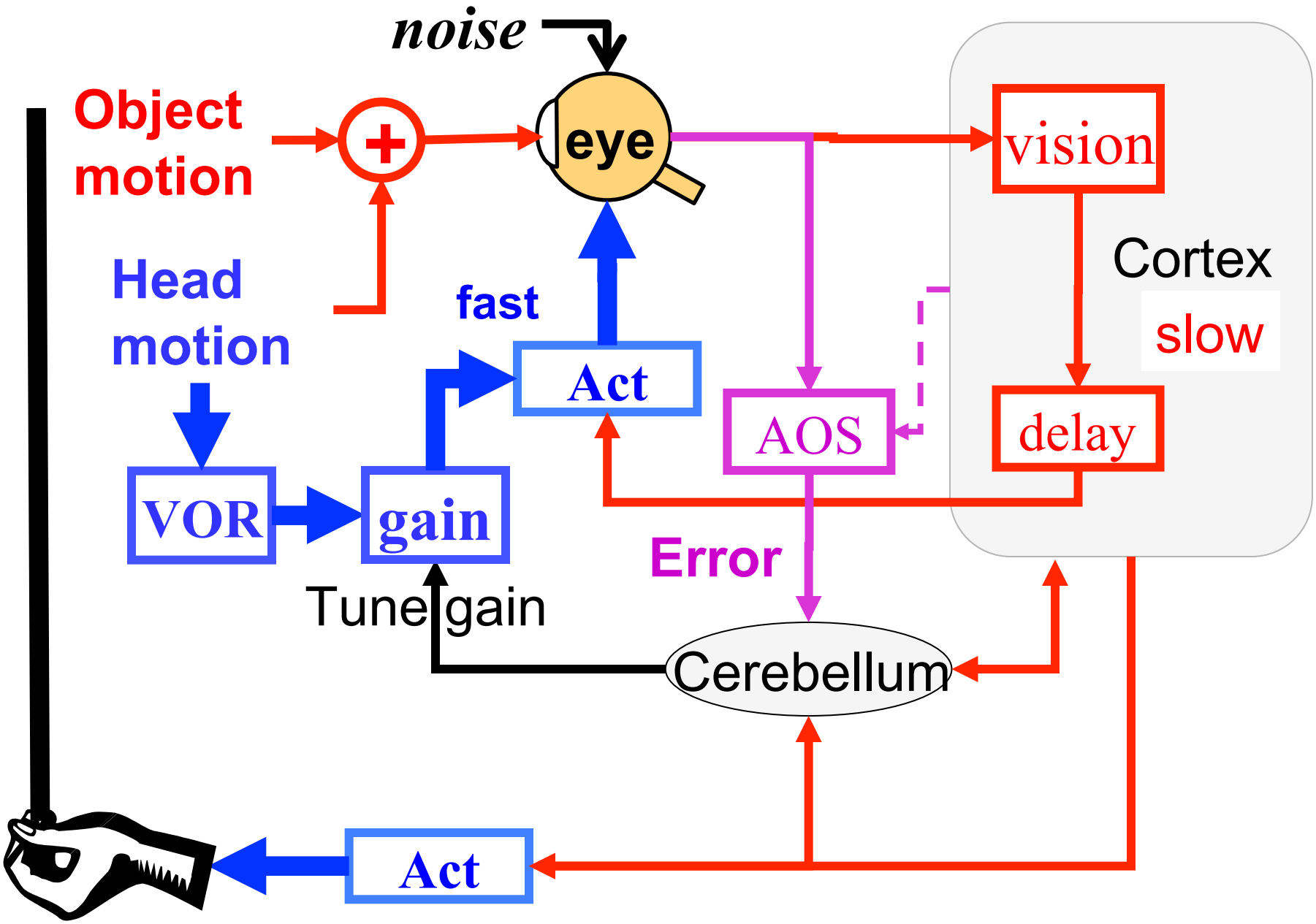
Layering Distributed Feedback





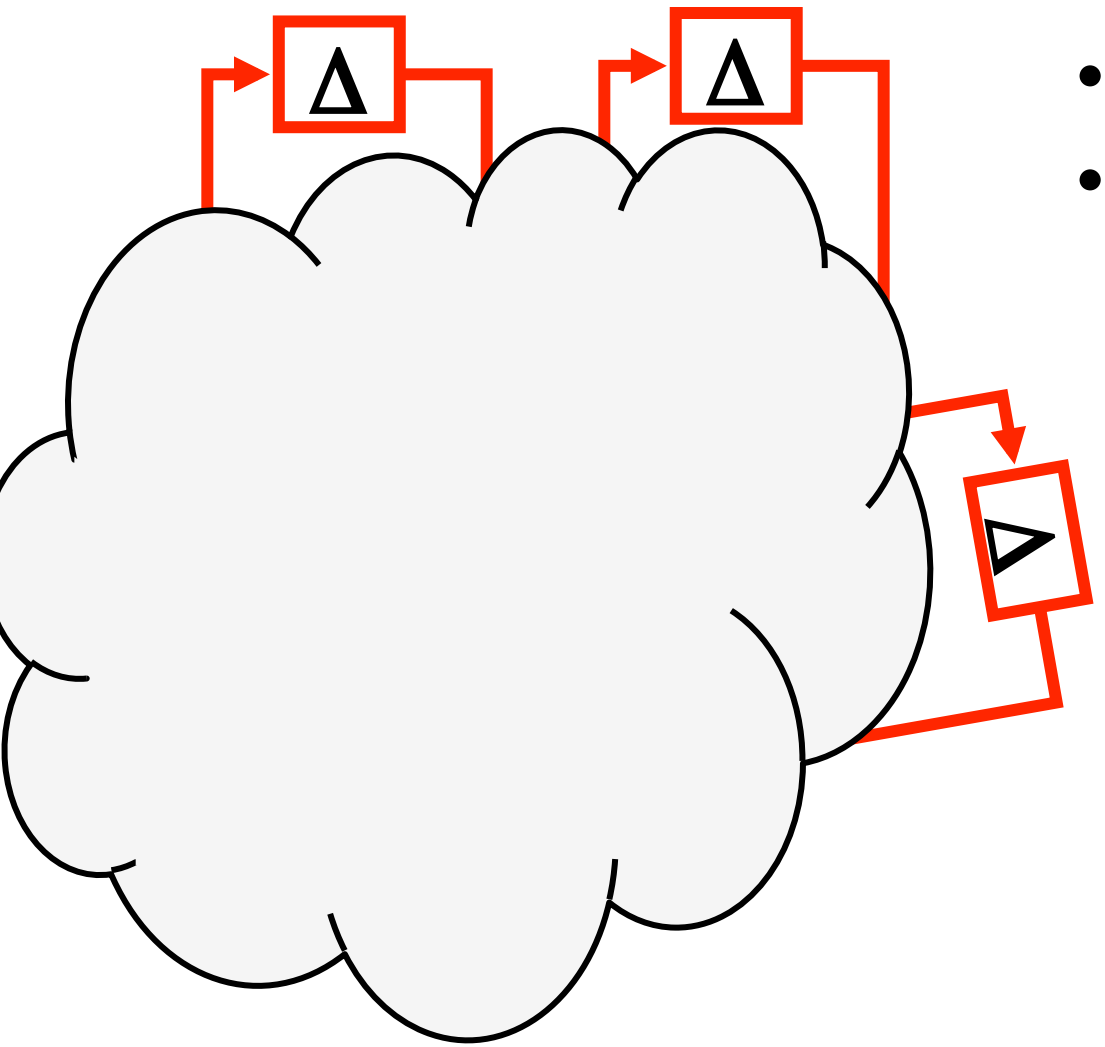
Slightly better

AOS = Accessory Optical system



AOS = Accessory Optical system

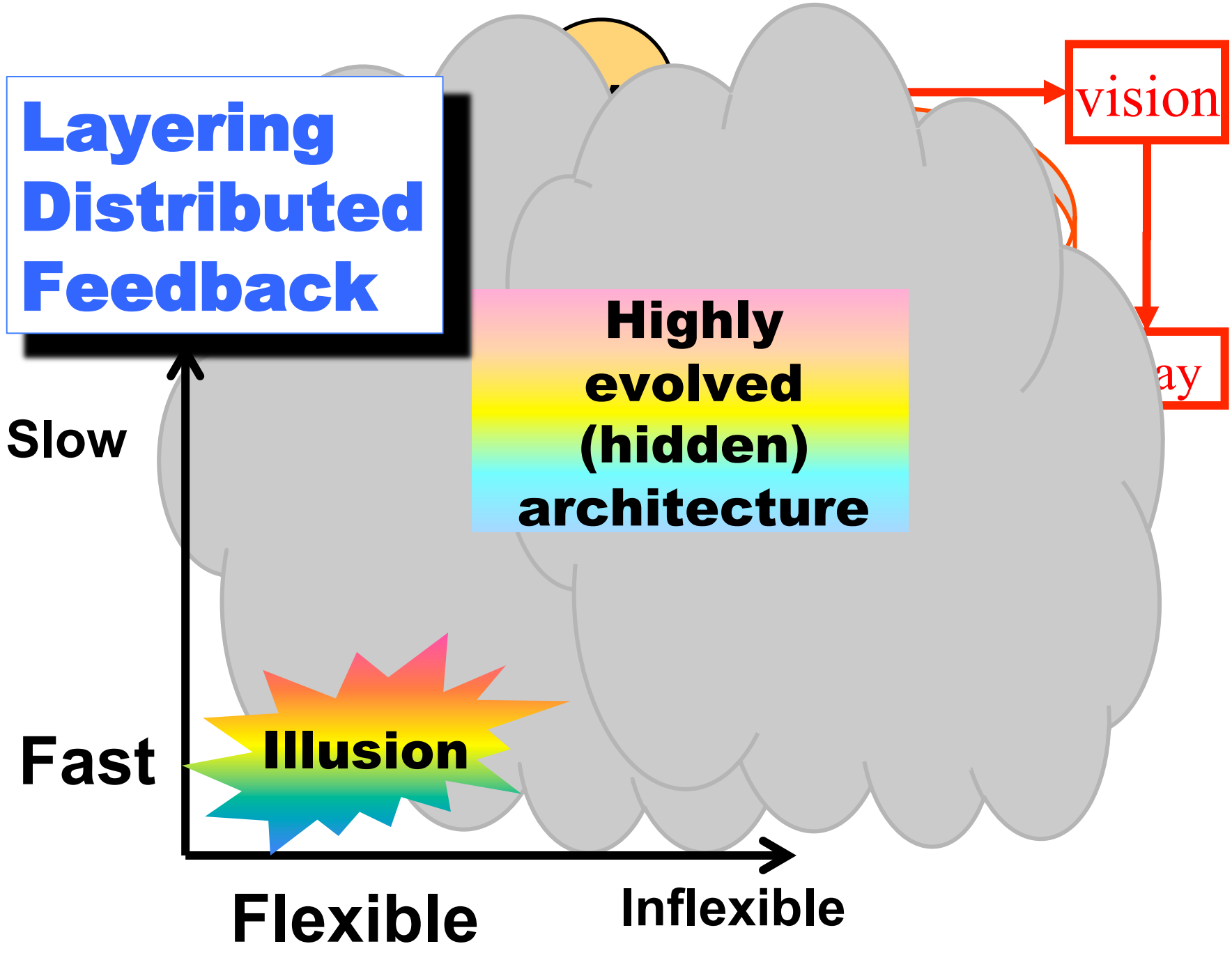
$$\sup_{\Delta} \left| T(\Delta) \right| ?$$

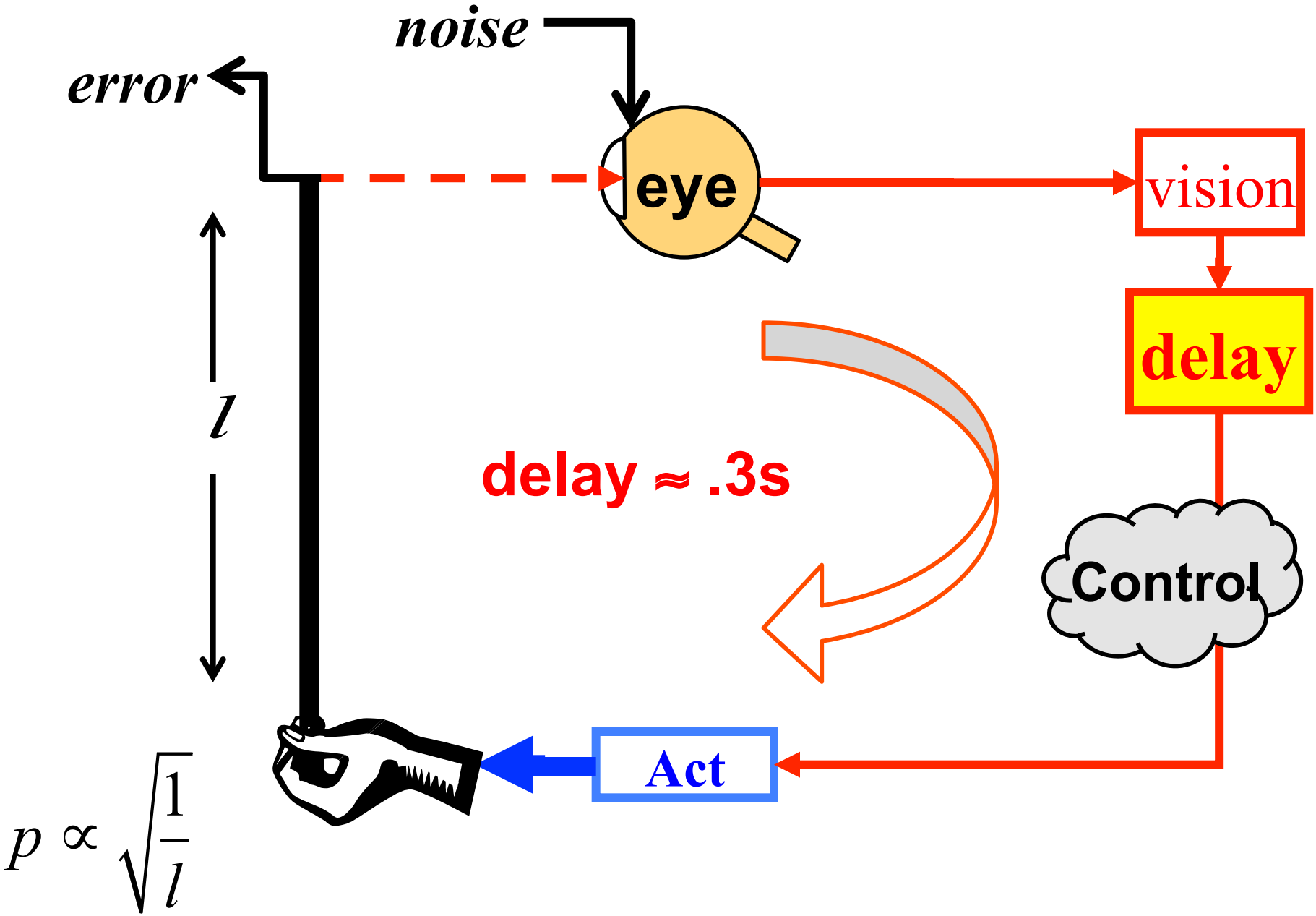


Scale with dimension?

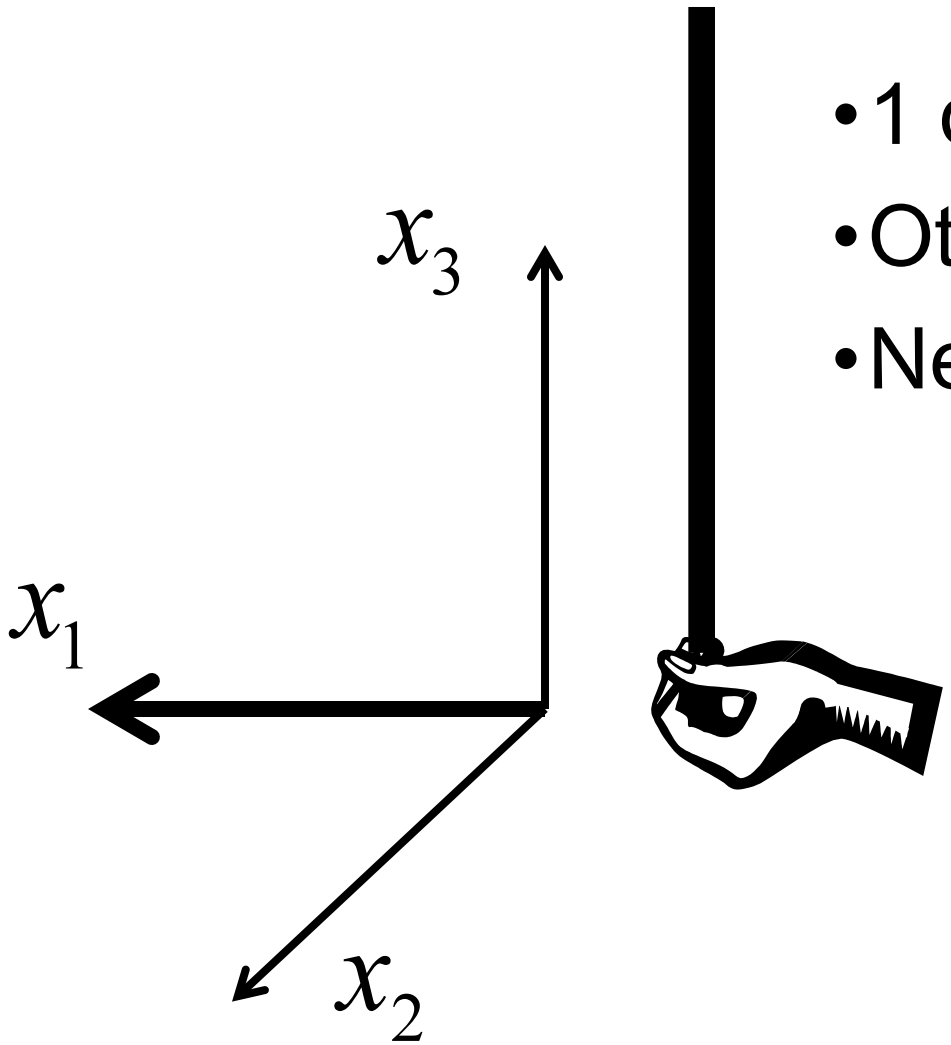
Uncertainty everywhere

- Real (NP hard)
- Complex = LTI (??)
- Operator valued or Noncomm (P)

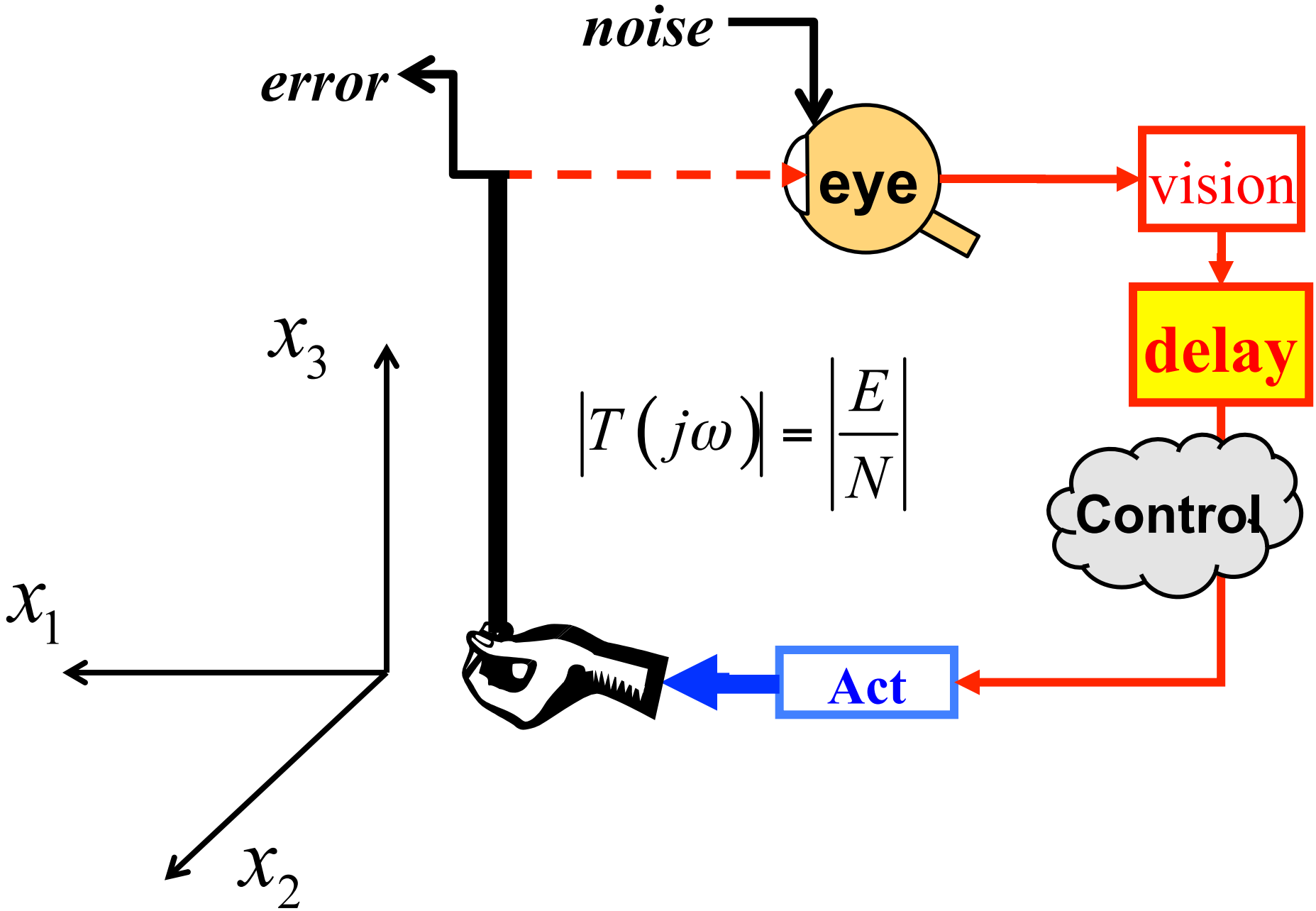

Layering
Distributed
Feedback
vision
ay
Highly
evolved
(hidden)
architecture
Slow
Fast
Illusion
Flexible
Inflexible

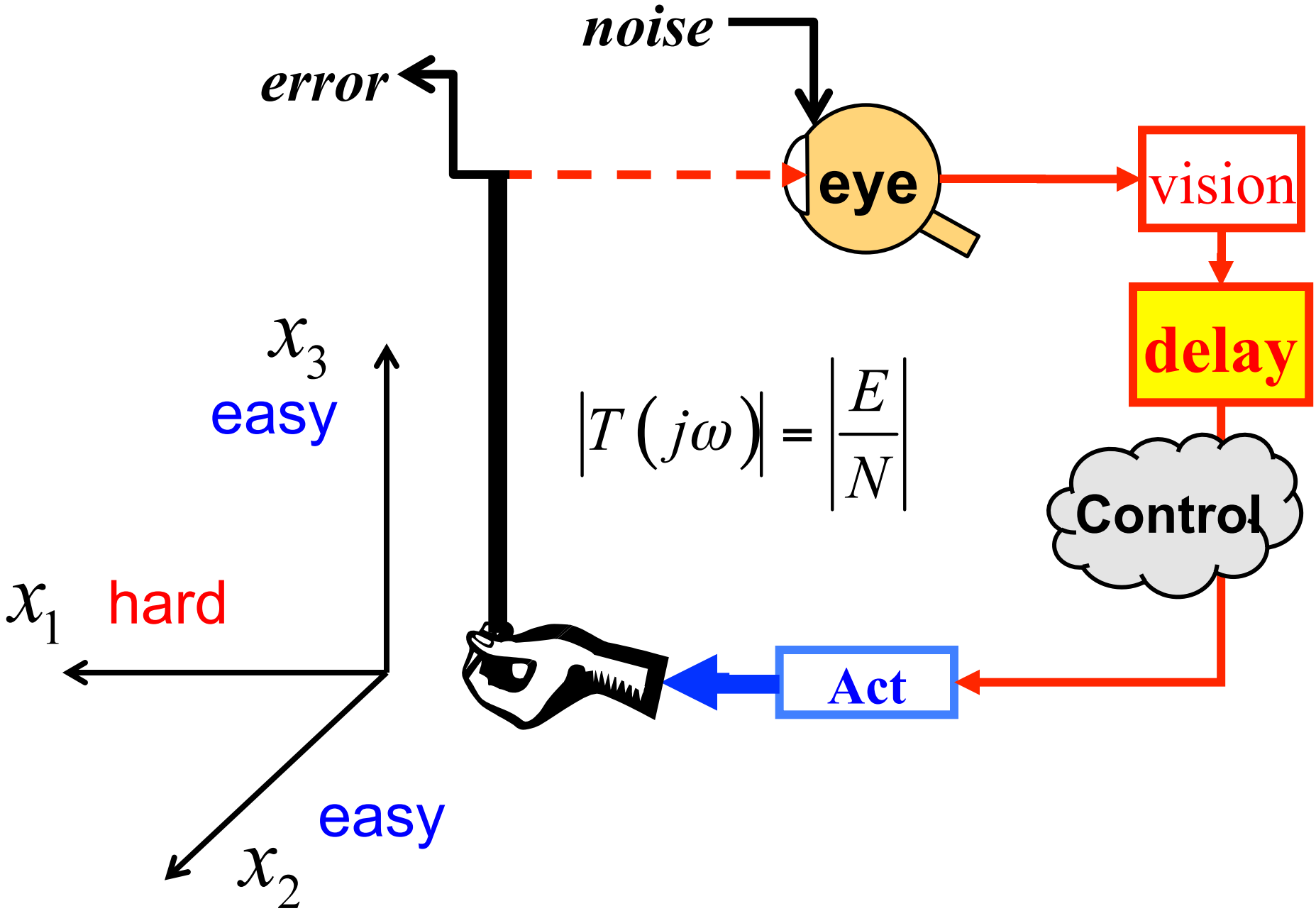

noise
error
eye
vision
delay
l
delay ≈ .3s
Control
Act
$p \propto \sqrt{\frac{1}{l}}$

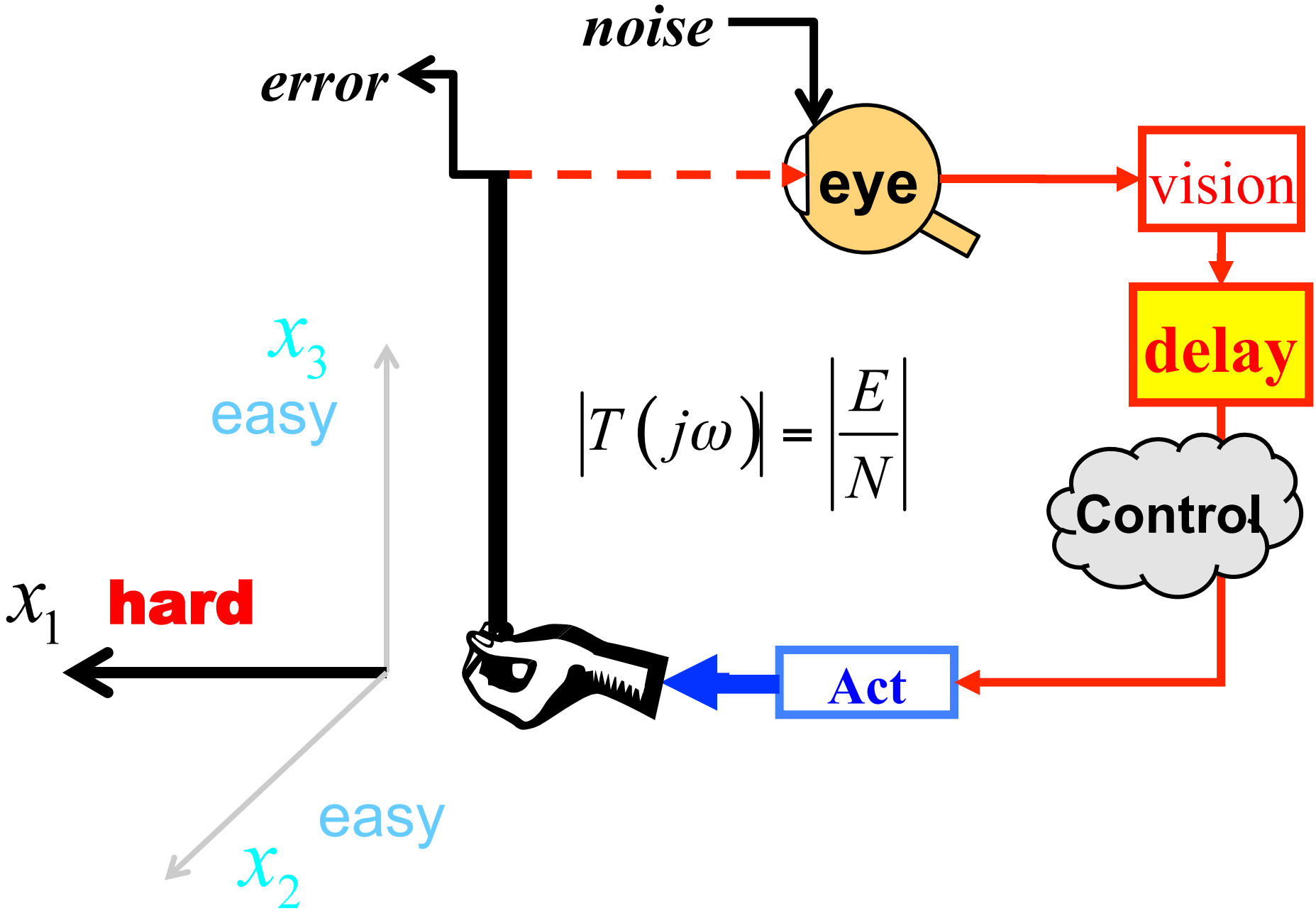
Model?

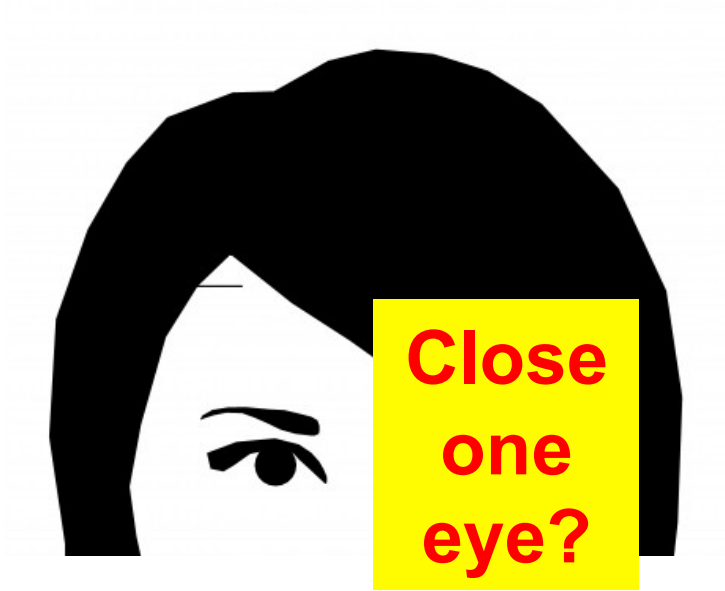


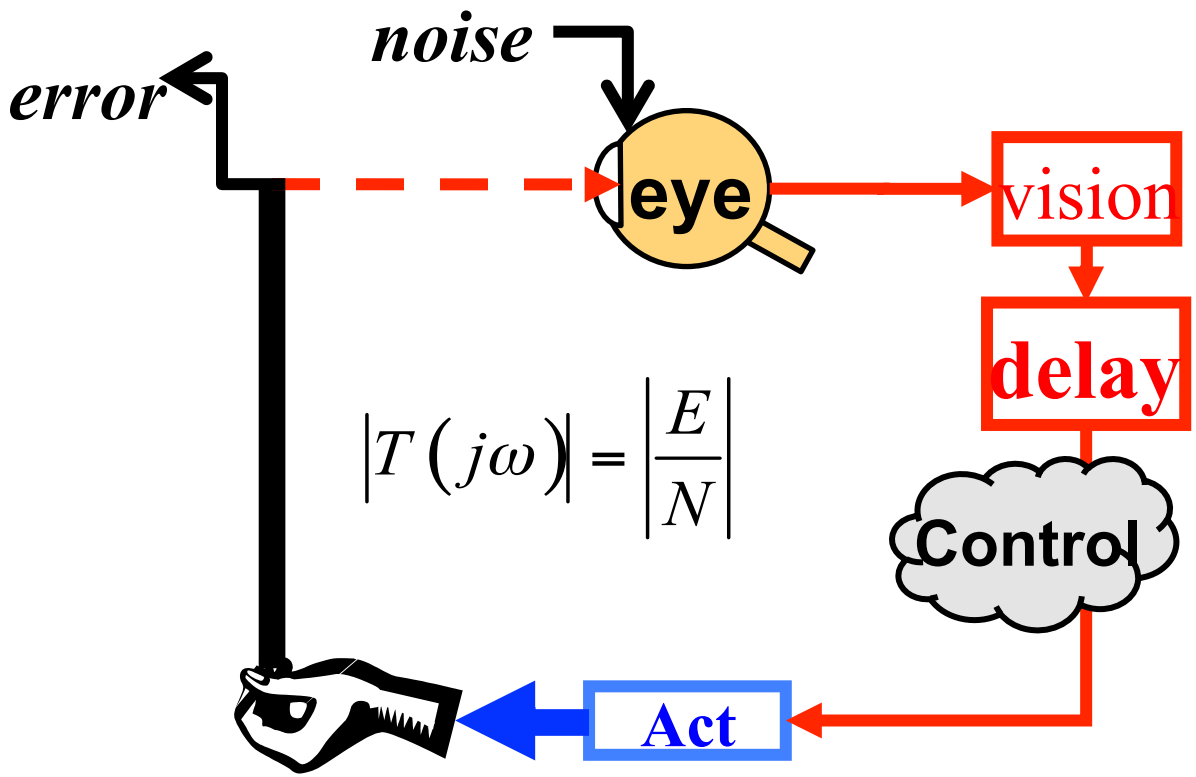
- 1 dimension, 4 states?
- Other 2 dimensions?
- New issues arise


noise
error
eye
vision
delay
Control
Act
x_3
x_1
x_2
$|T(j\omega)| = \left|\frac{E}{N}\right|$

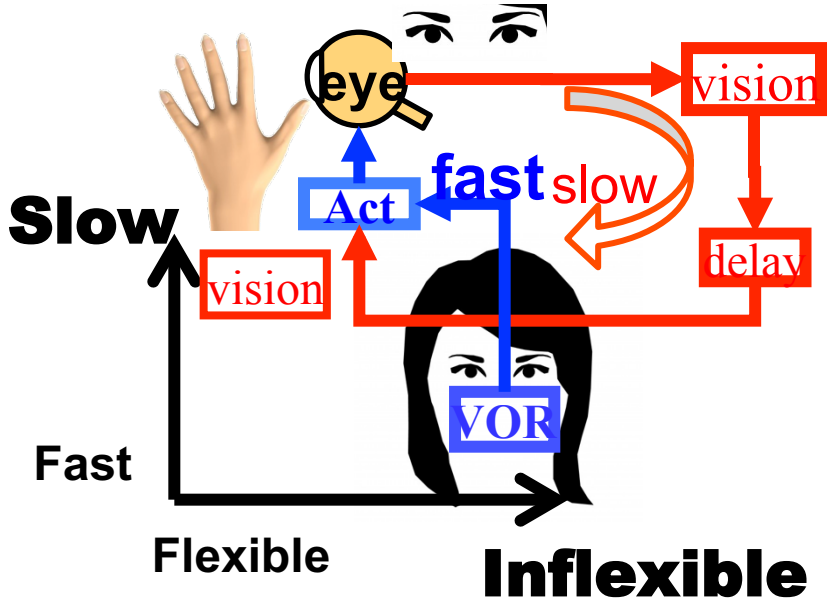

noise
error
eye
vision
delay
Control
Act
x_3
easy
x_1
hard
x_2
easy
$|T(j\omega)| = \left|\frac{E}{N}\right|$


noise
error
eye
vision
delay
Control
Act
$|T(j\omega)| = \left|\frac{E}{N}\right|$
x_3
easy
x_1
hard
easy
x_2

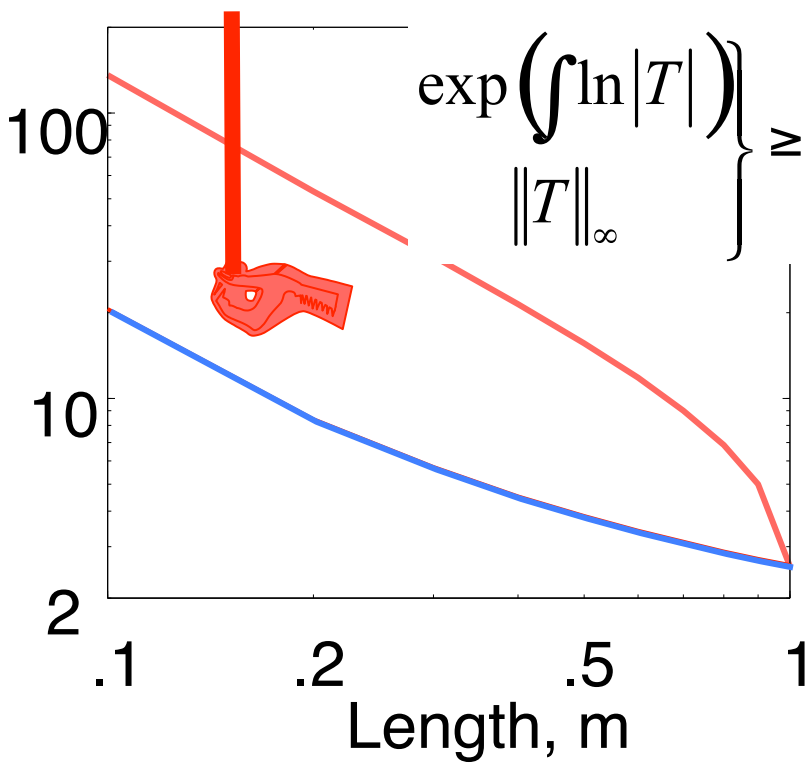




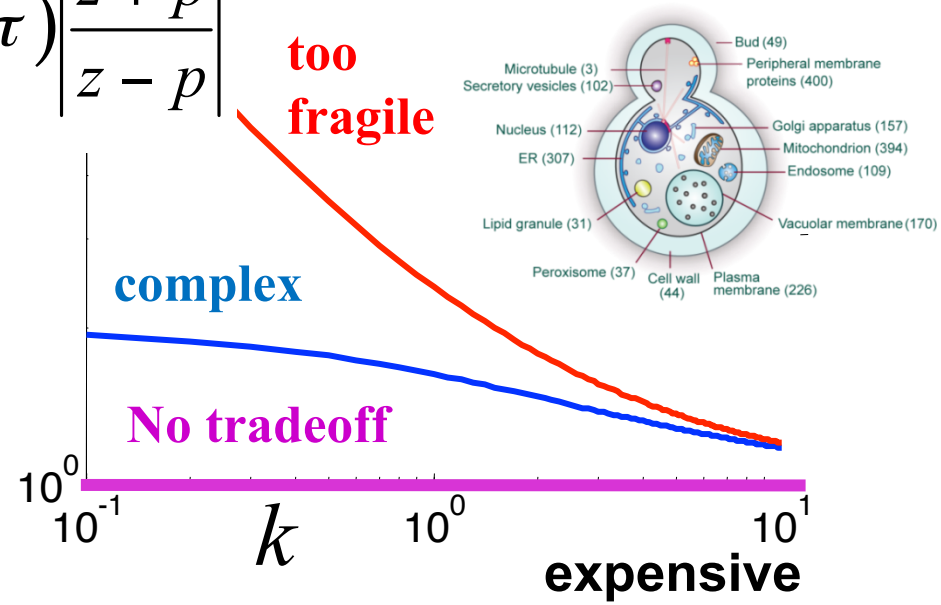
$$\left|T(j\omega)\right| = \left|\frac{E}{N}\right|$$

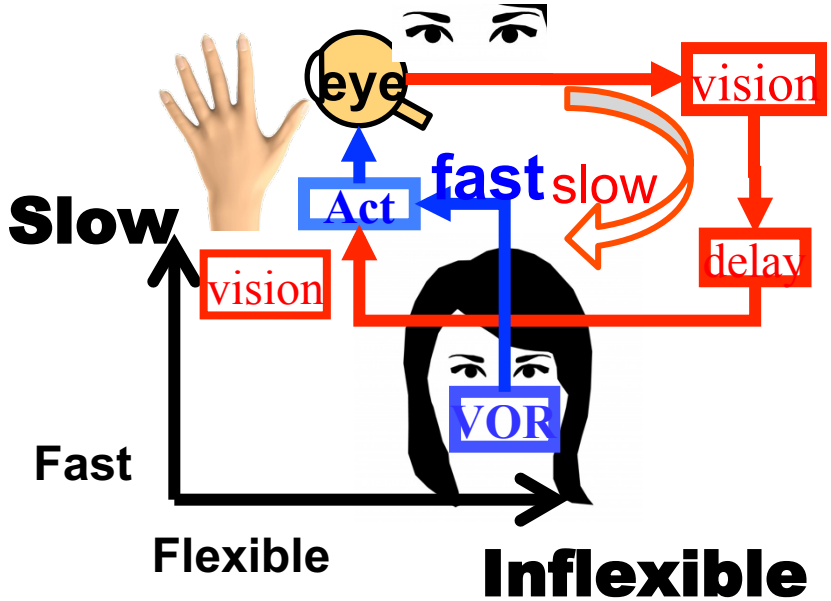


Universal laws?

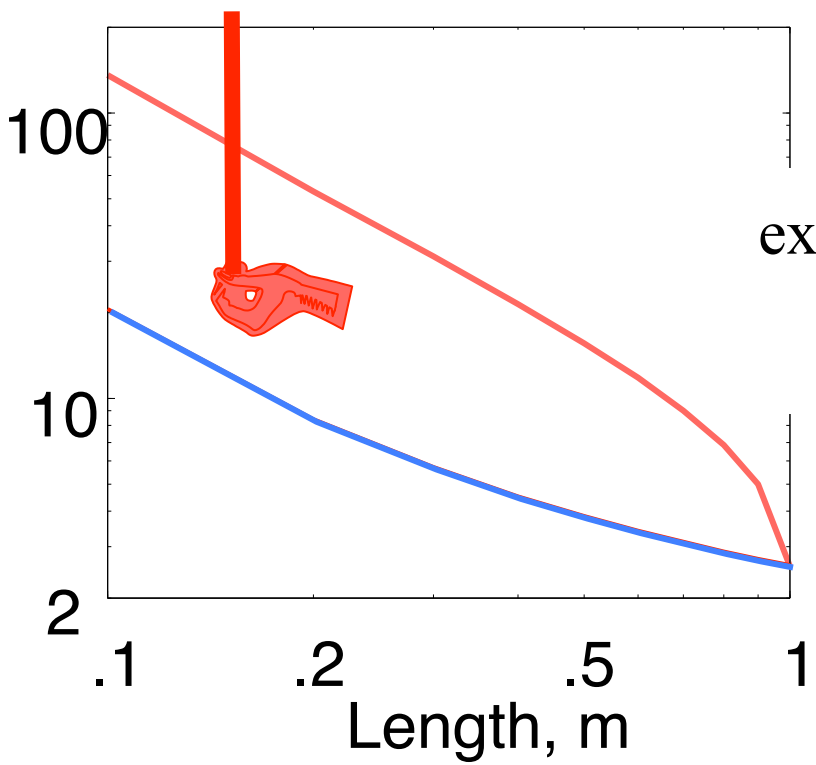


$$\left.\begin{matrix}\exp\left(\int \ln|T|\right) \\ \|T\|_\infty\end{matrix}\right\} \geq \exp(p\tau)\left|\frac{z+p}{z-p}\right|$$



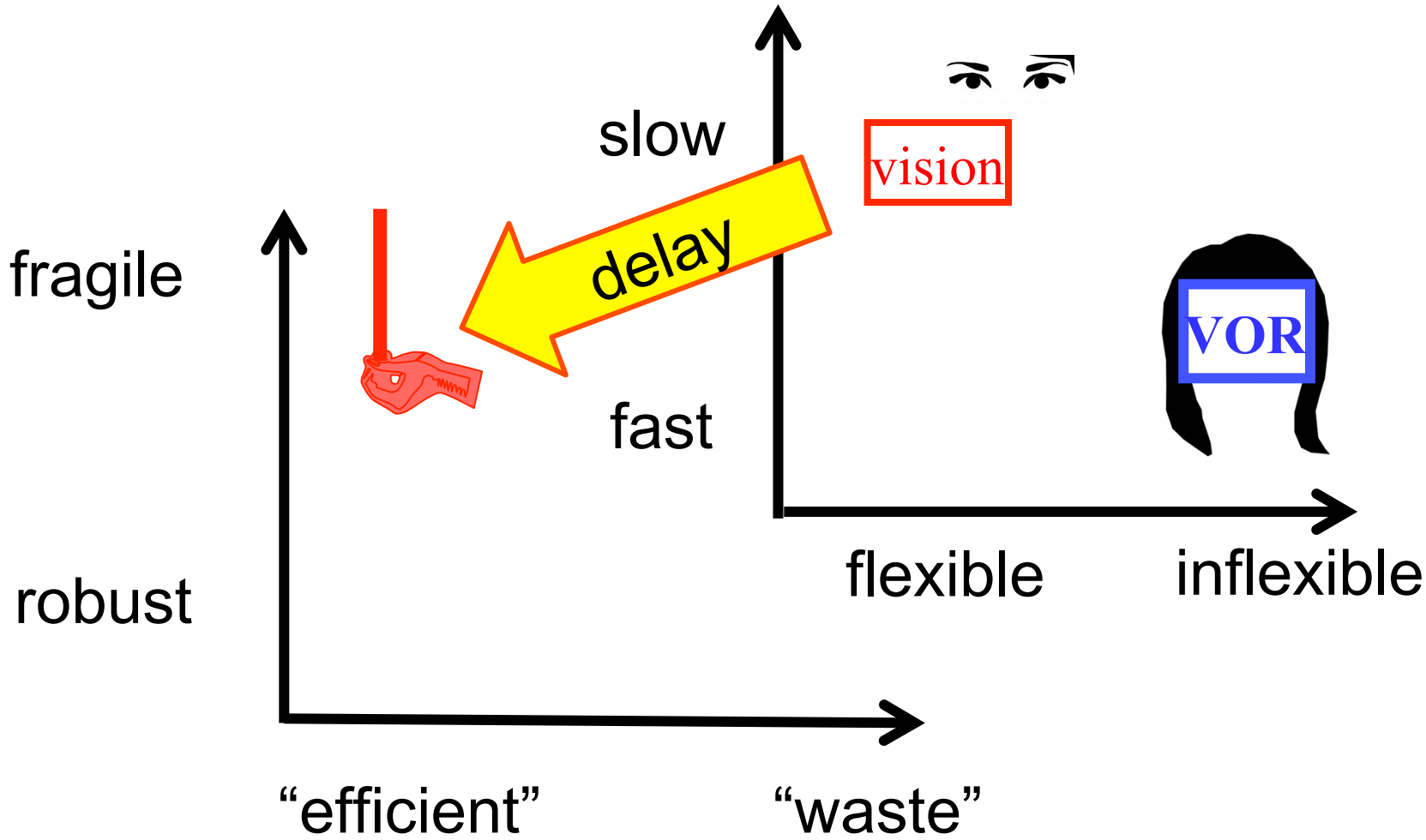


How do these fit together?

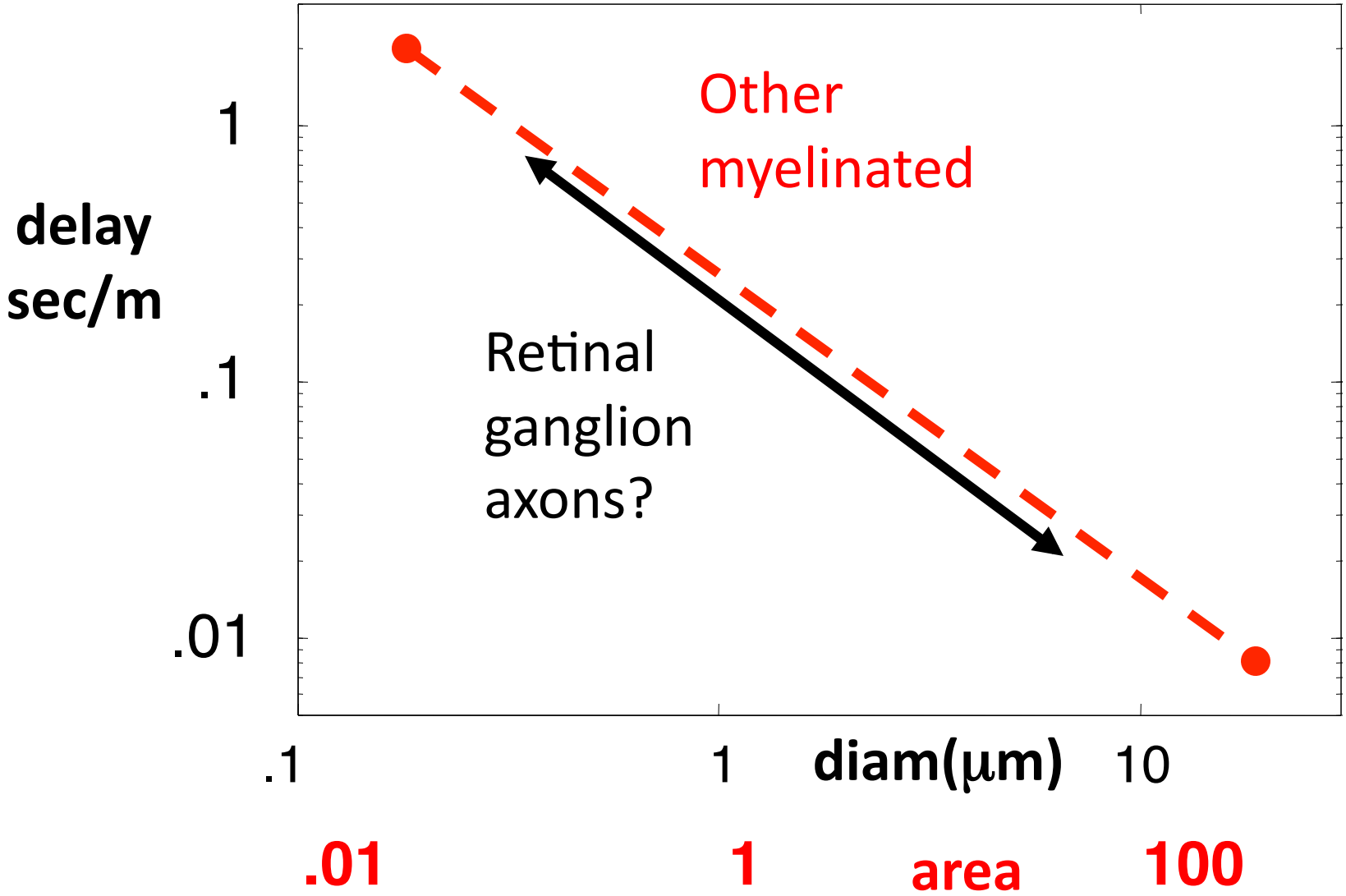


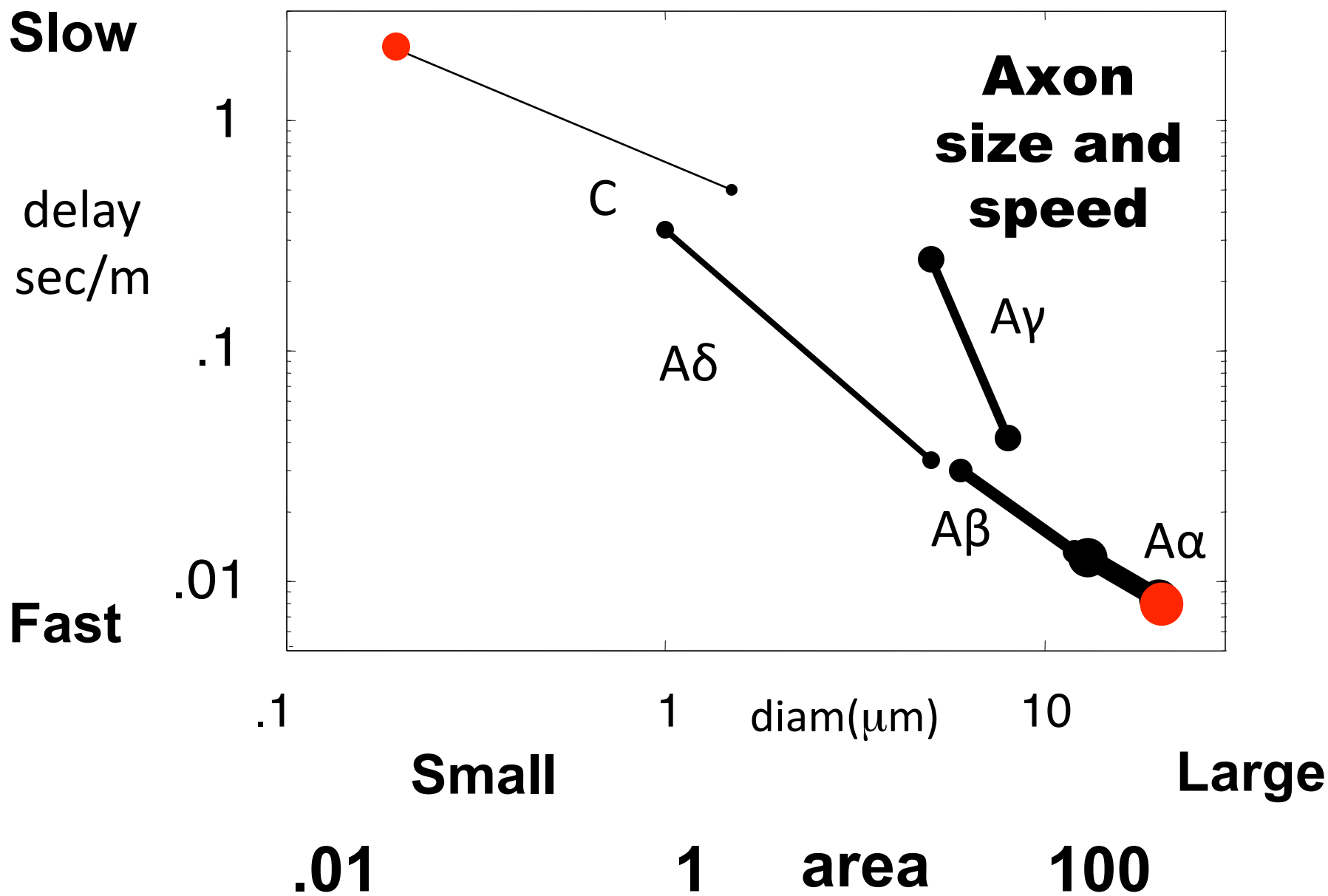
$$\left.\begin{matrix} \exp\left(\int \ln|T|\right) \\ \|T\|_\infty \end{matrix}\right\} \geq \exp(p\tau)\left|\frac{z+p}{z-p}\right|$$

How do these fit together?

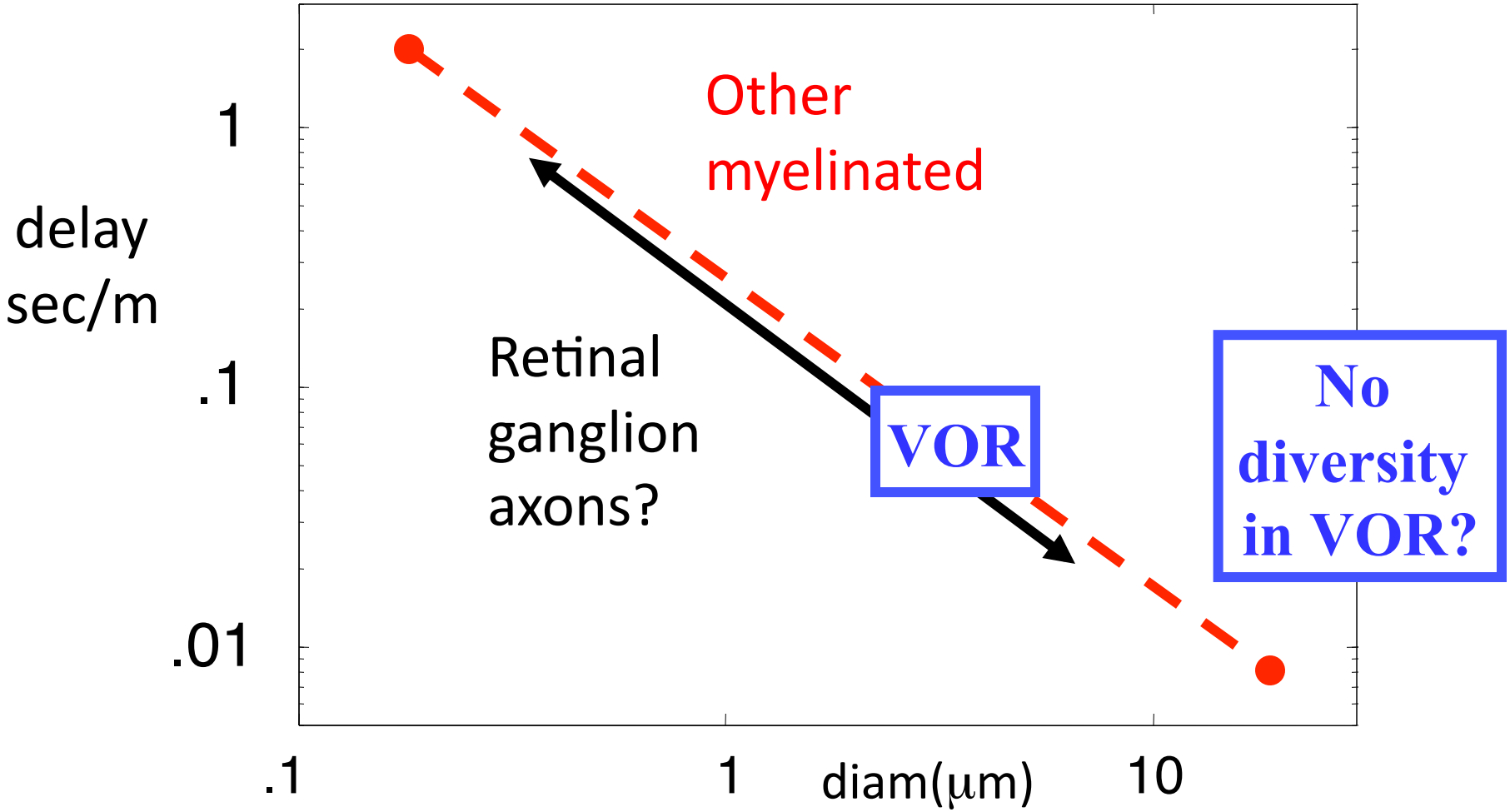


Why such extreme diversity in ***axon*** size and delay?




Slow
Fast
delay
sec/m
1
.1
.01
Axon
size and
speed
C
Aδ
Aγ
Aβ
Aα
.1
1
diam(μm)
10
Small
Large
.01
1
area
100

Why such extreme diversity in ***axon*** size and delay?

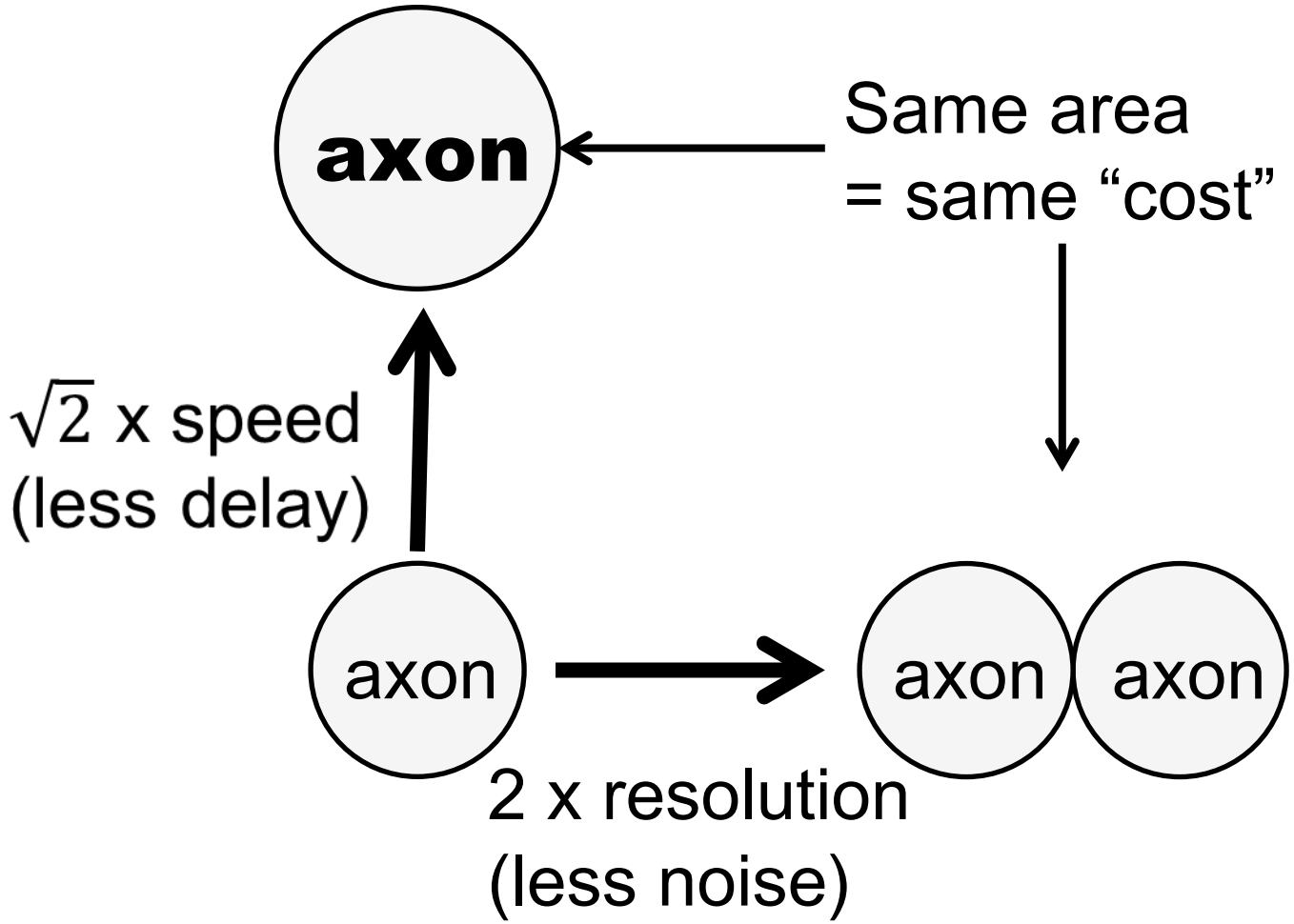


speed costs

.01 **1** **area** **100**

Resolution and bandwidth are cheap

Double the area (and cost)?

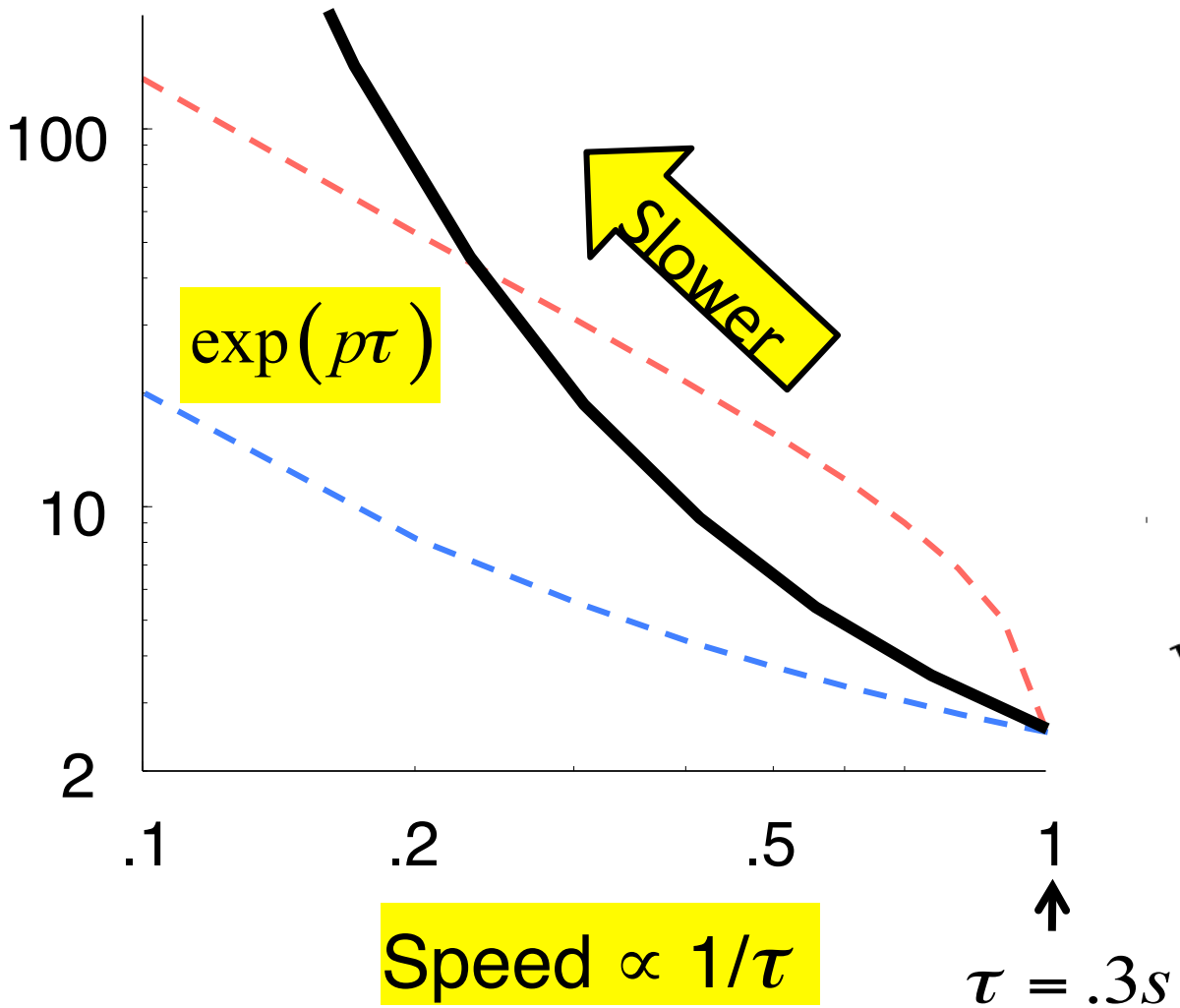


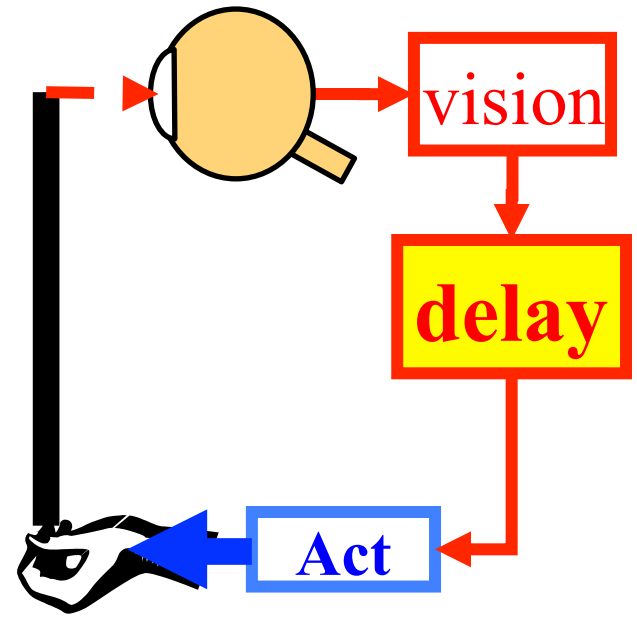
$$delay \propto \frac{1}{speed}$$

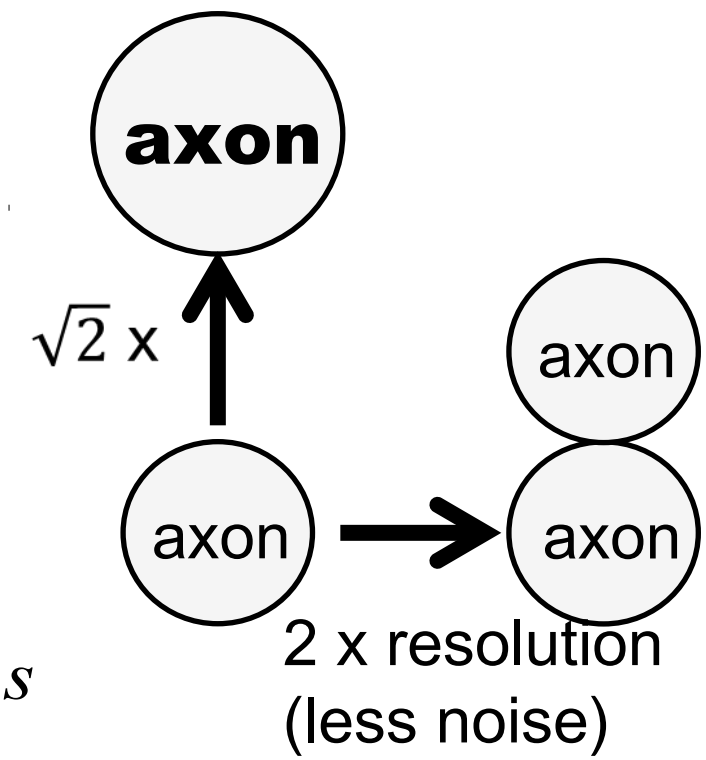
speed costs

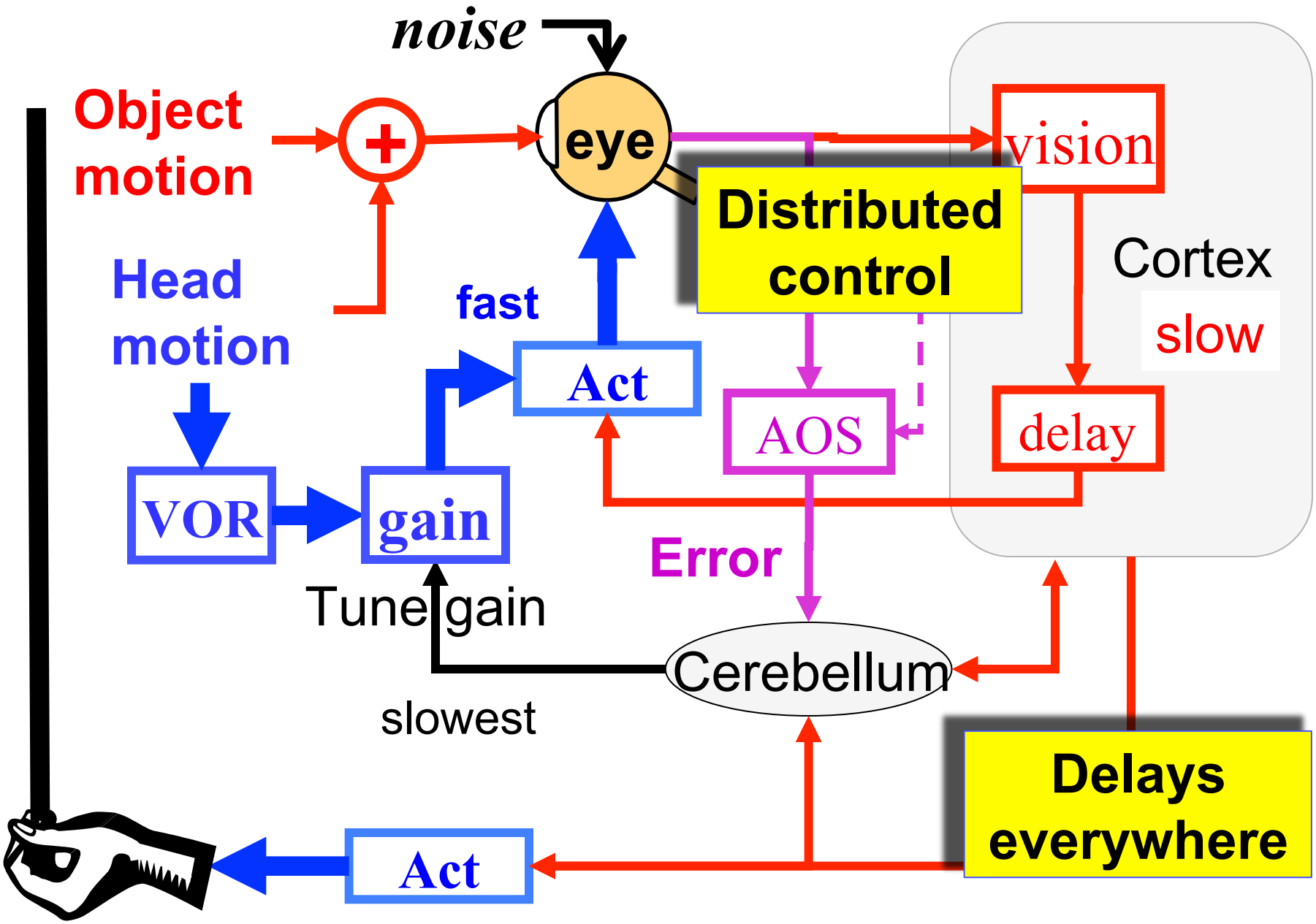
Resolution and bandwidth are cheap

speed doubly expensive but necessary

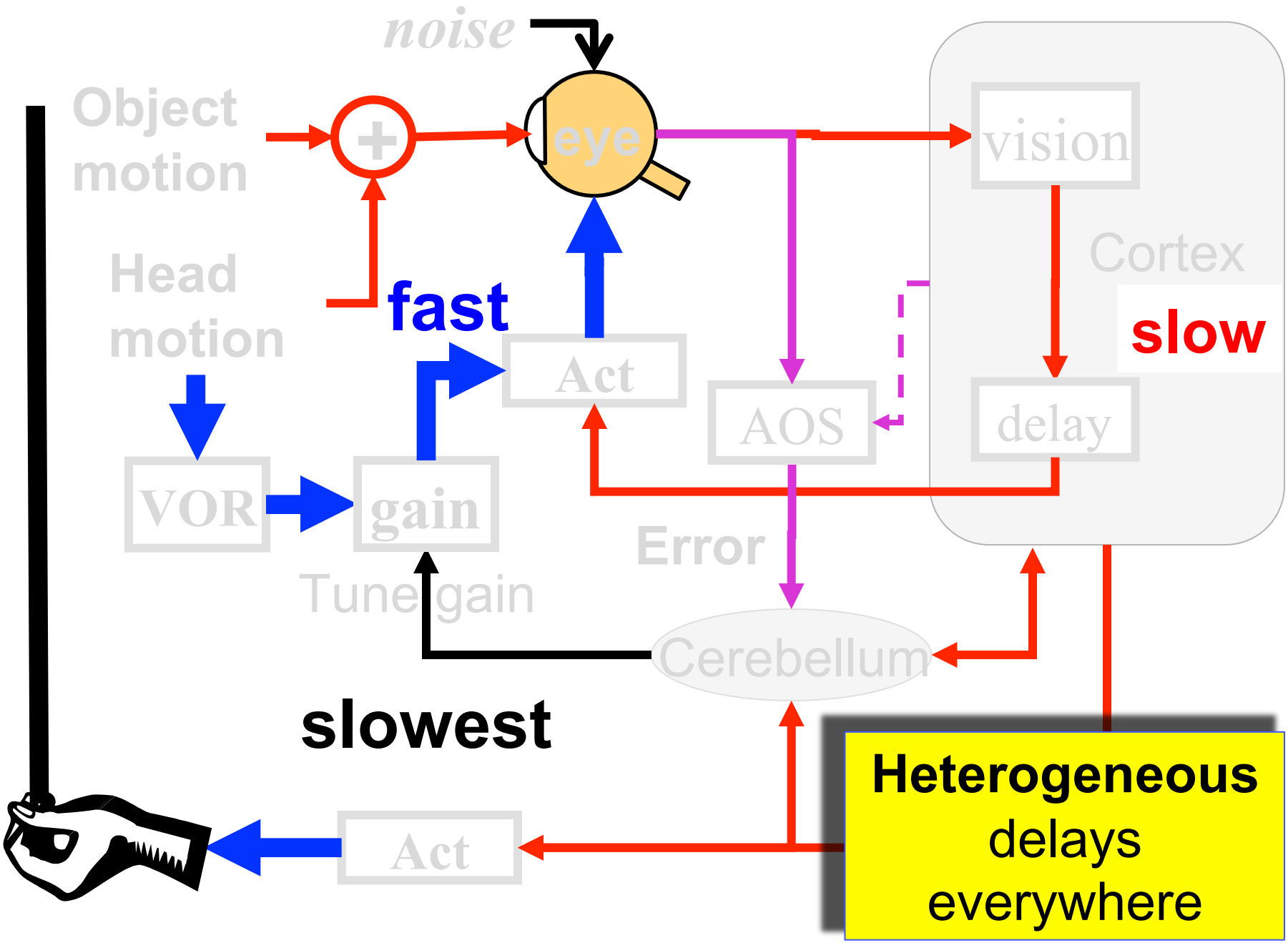






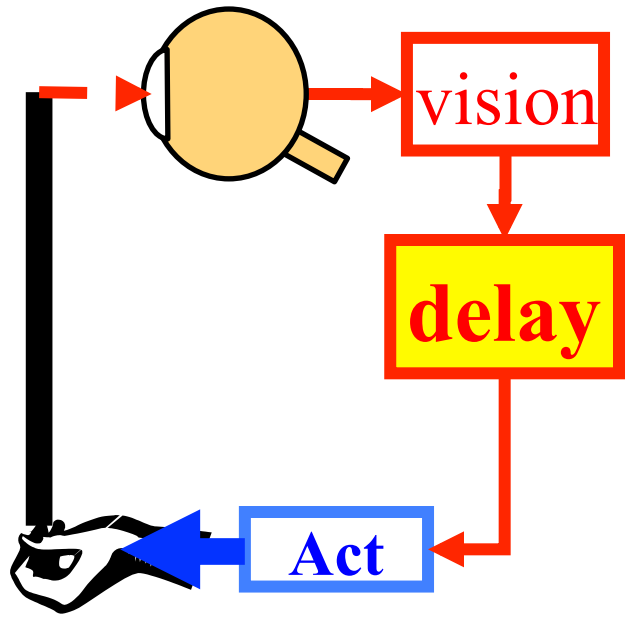


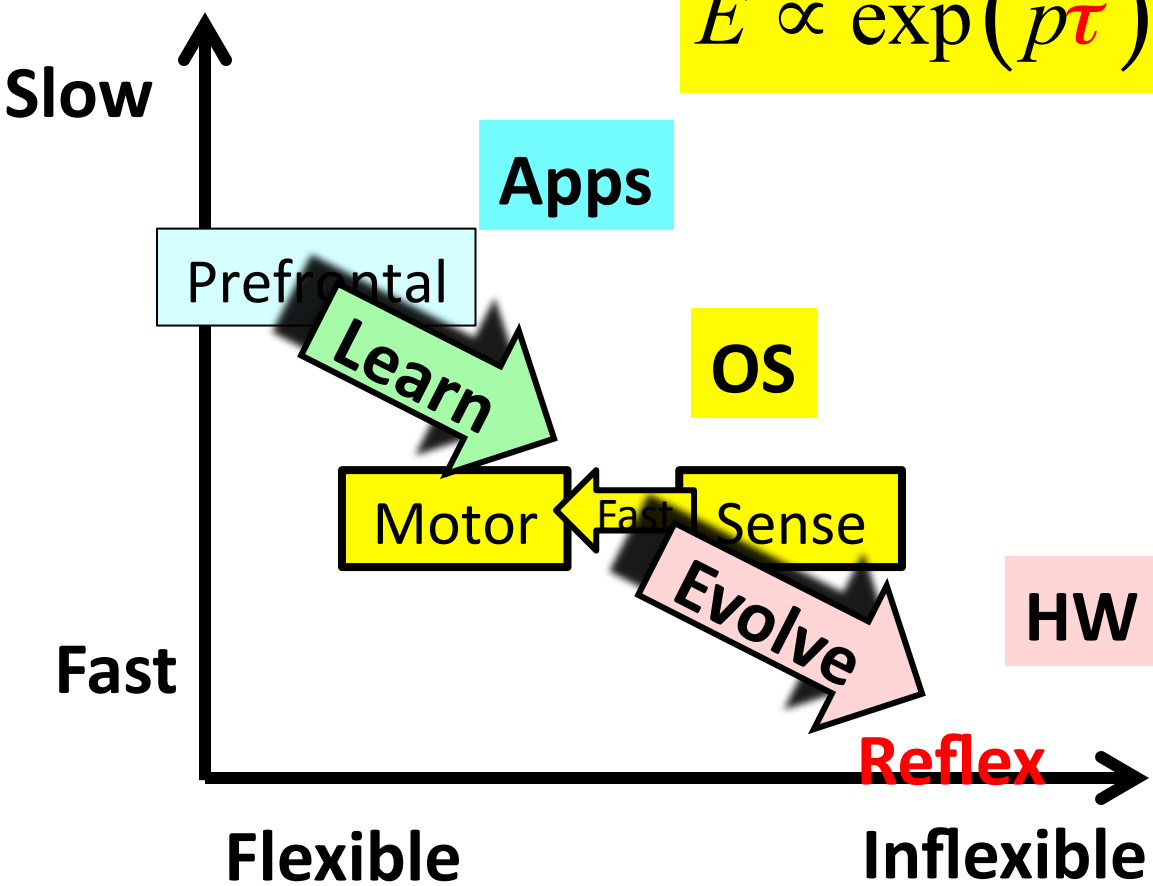
AOS = Accessory Optical system

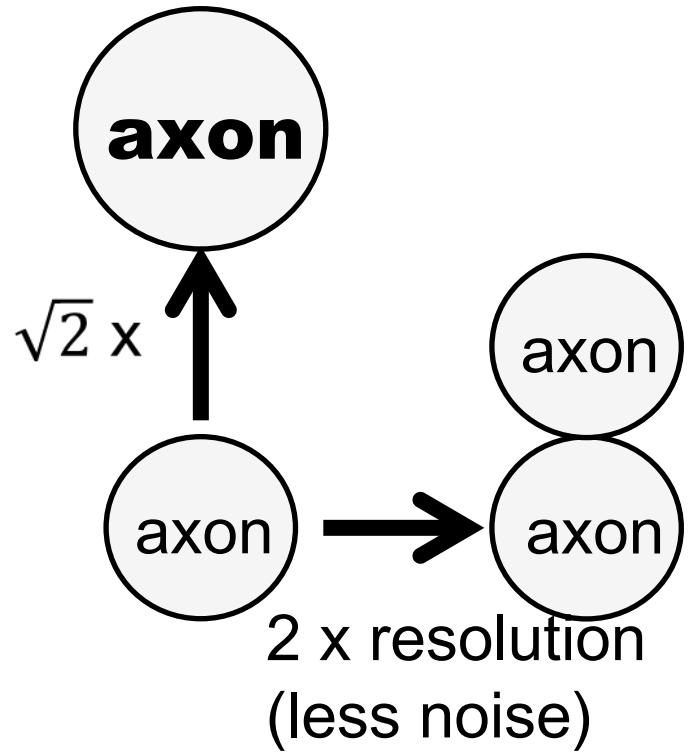

noise
Object motion
eye
vision
Cortex
slow
Head motion
fast
Act
AOS
delay
VOR
gain
Error
Tune gain
Cerebellum
slowest
Act
Heterogeneous delays everywhere

speed doubly expensive but necessary

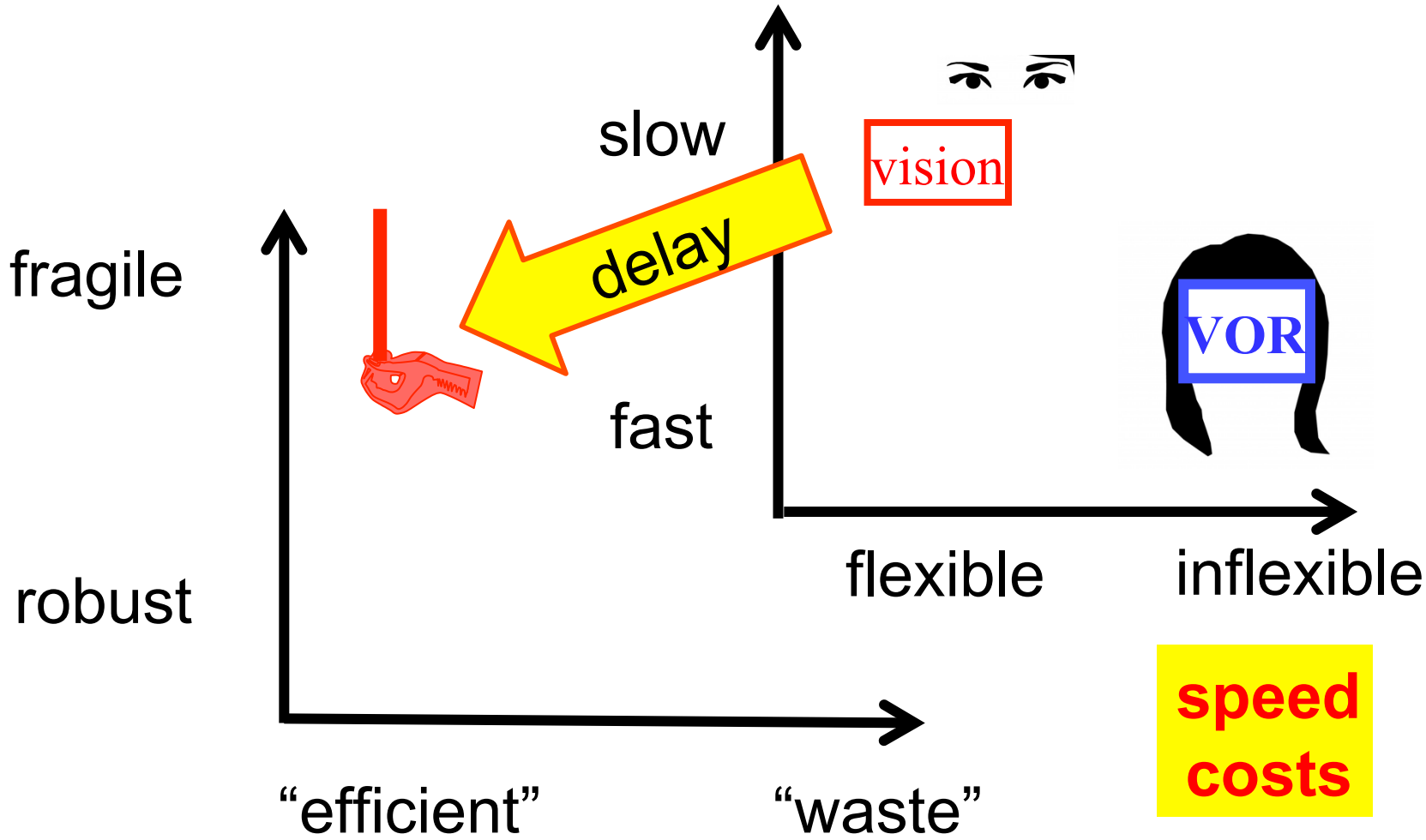
$$E \propto \exp(p\tau)N$$





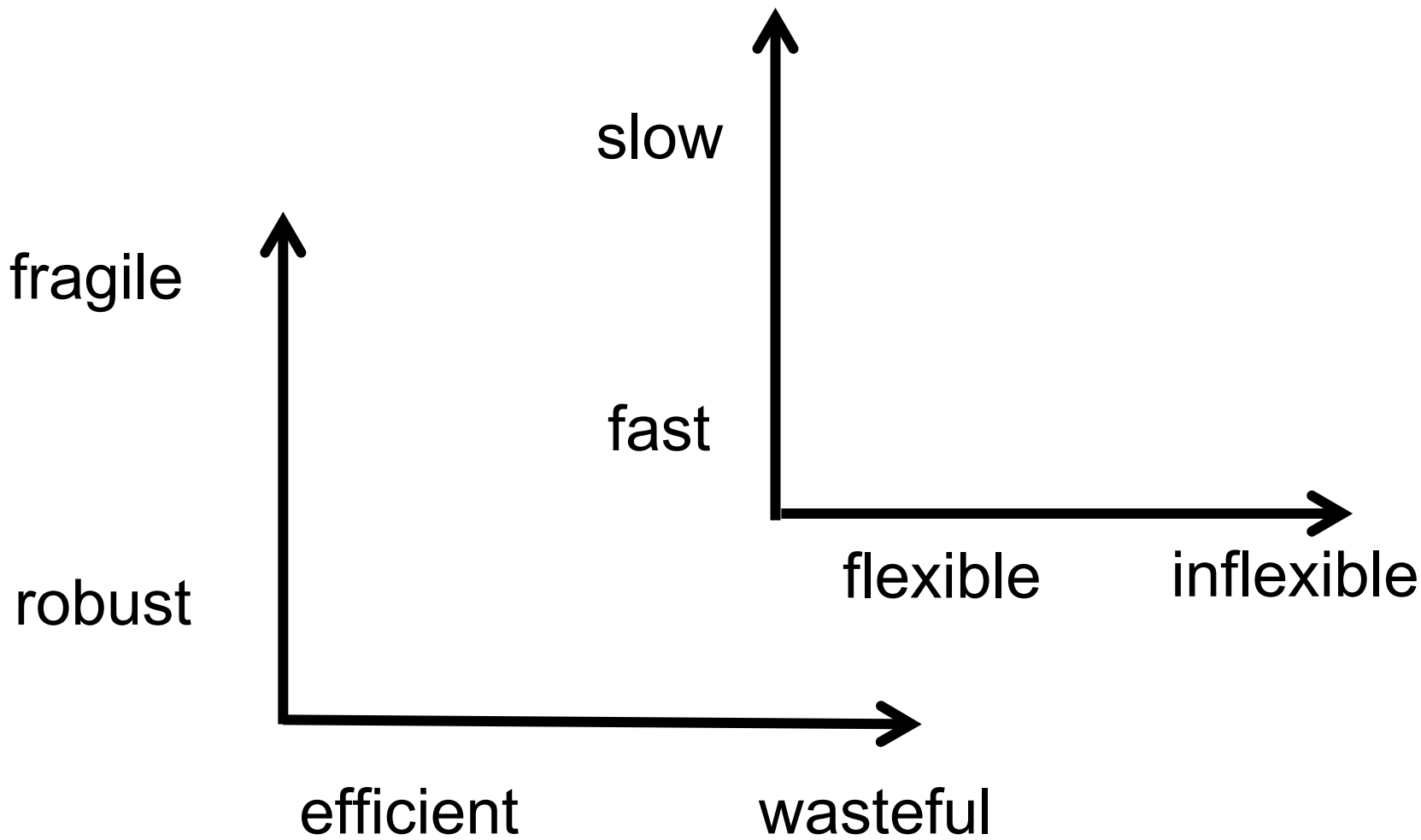


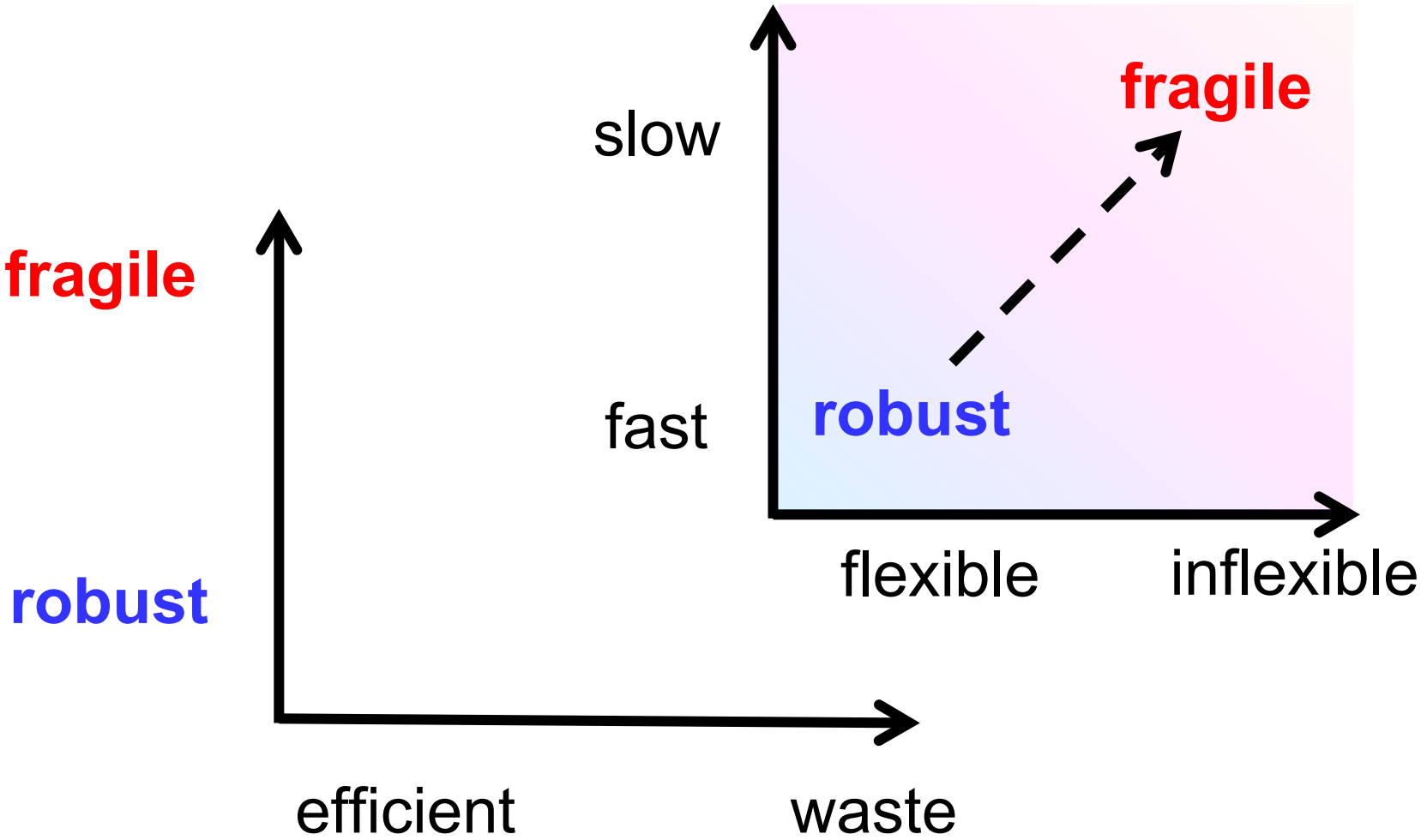
How do these fit together?

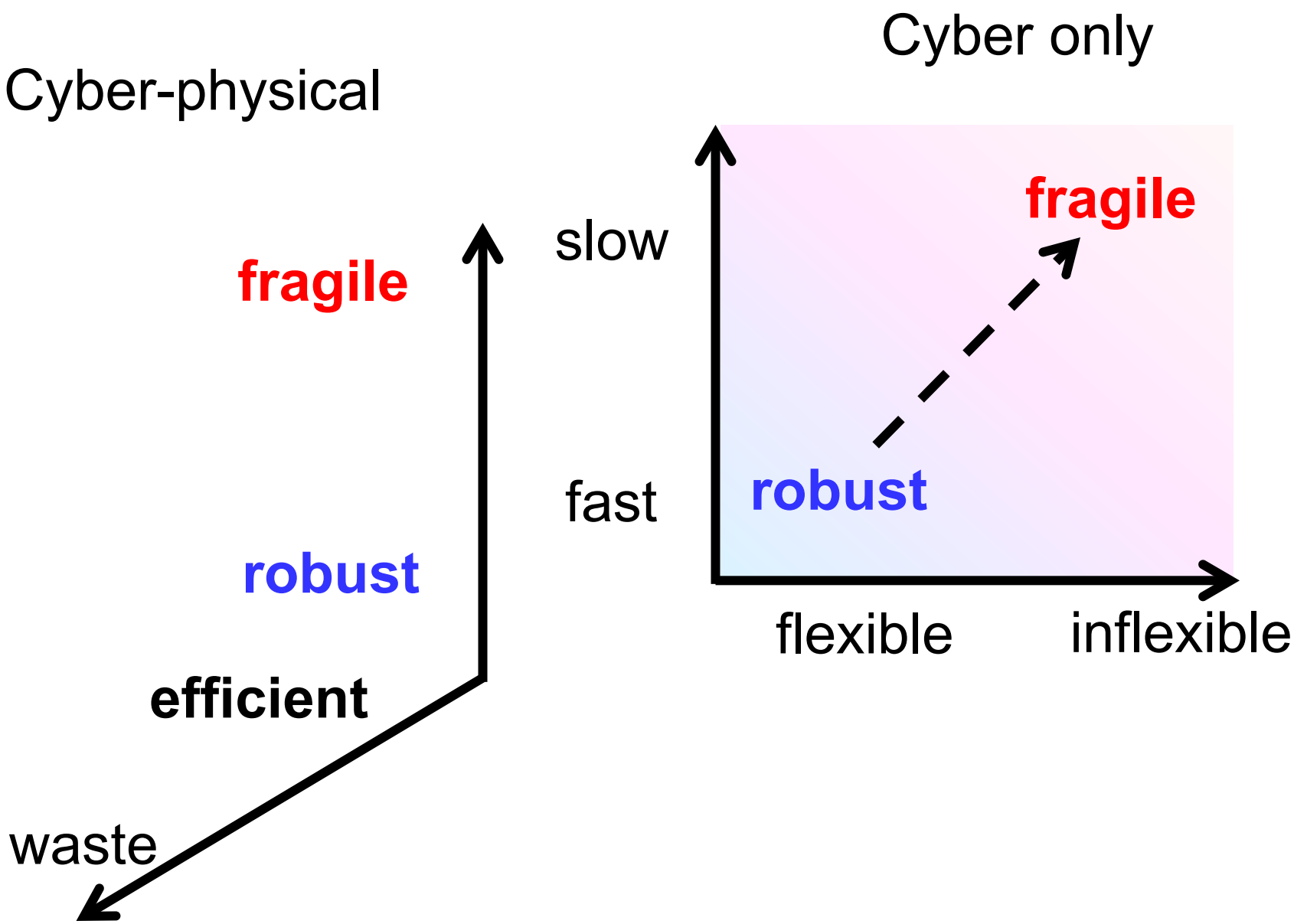


speed costs

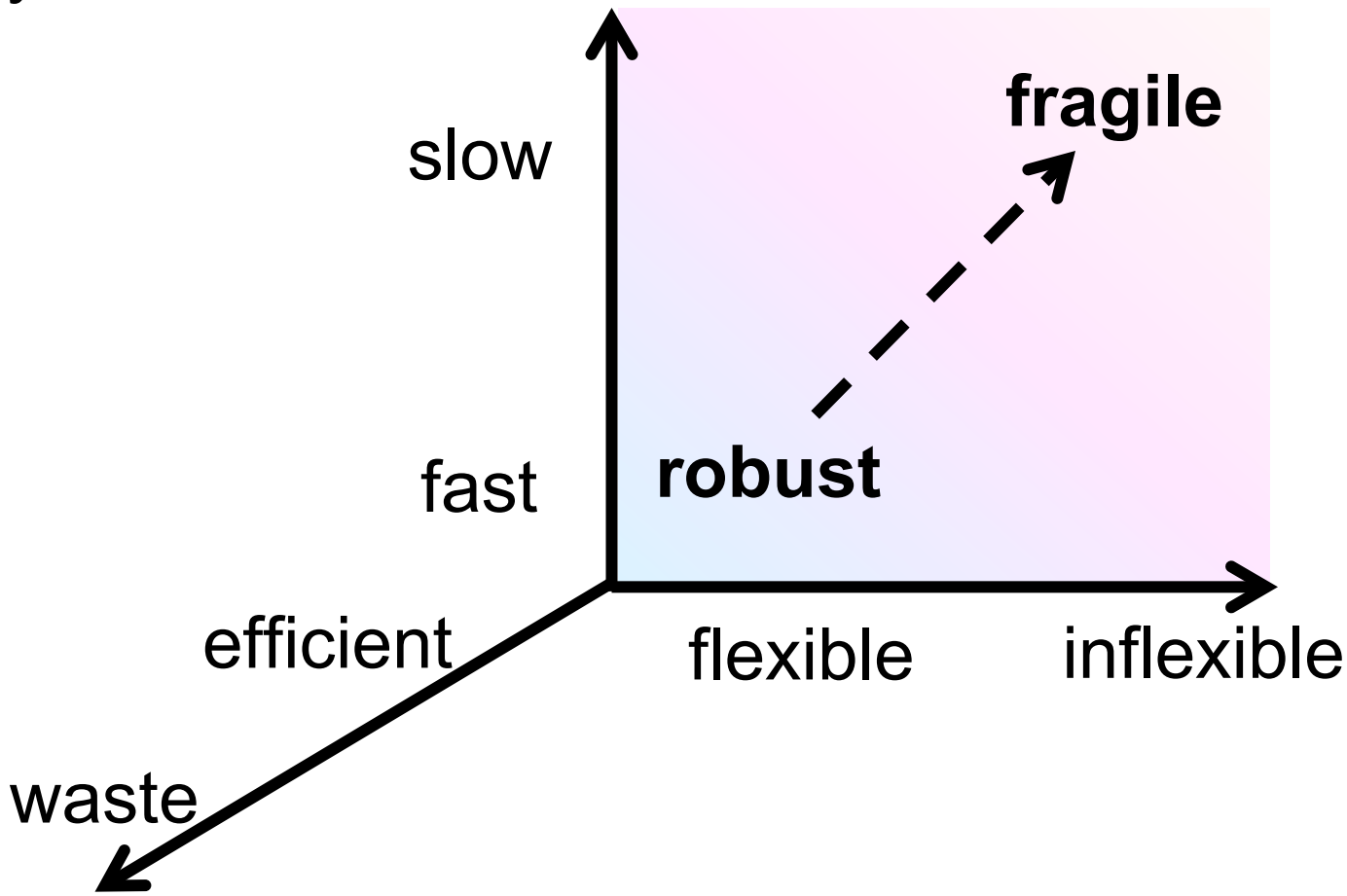
In general?


slow
fast
flexible
inflexible
fragile
robust
efficient
wasteful


fragile
robust
efficient
waste
slow
fast
fragile
robust
flexible
inflexible


Cyber-physical
fragile
robust
efficient
waste
Cyber only
slow
fast
fragile
robust
flexible
inflexible

Cyber-physical



PCA ≈ Principal ***Concept*** Analysis ☺

accessible
accountable
accurate
adaptable
administrable
affordable
auditable
autonomy
available
compatible
composable
configurable
correctness
customizable
debugable
degradable
determinable
demonstrable

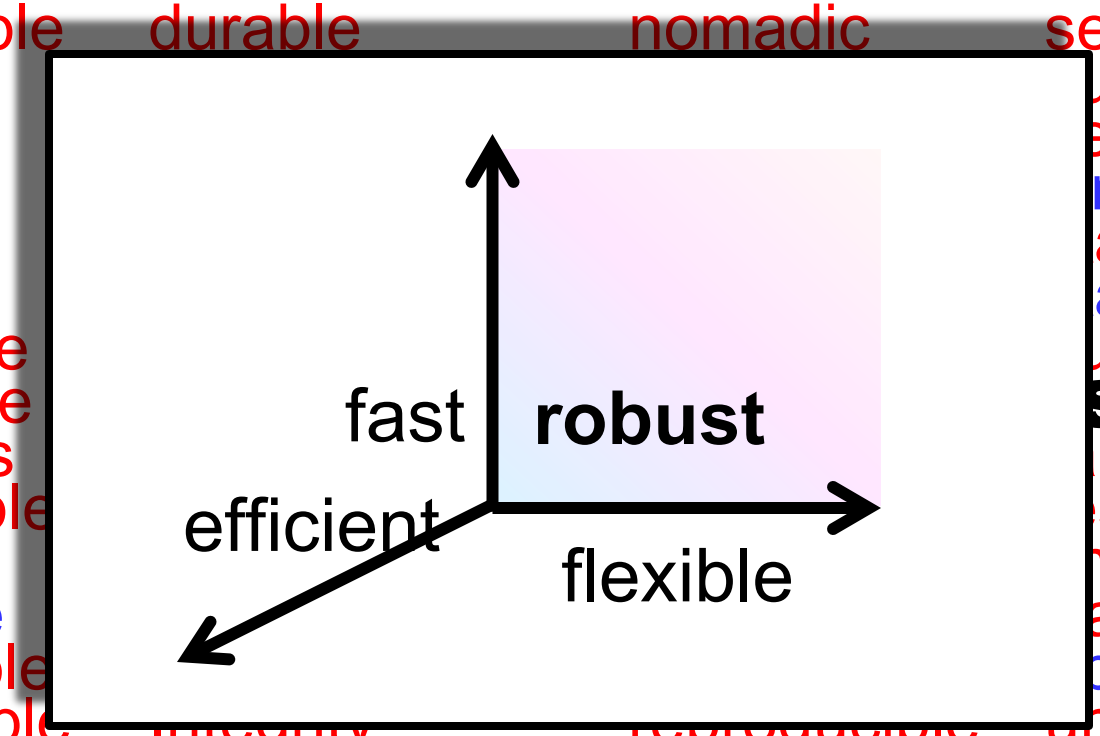
dependable
deployable
discoverable
distributable
durable

interchangeabl
e
interoperable
learnable
maintainable

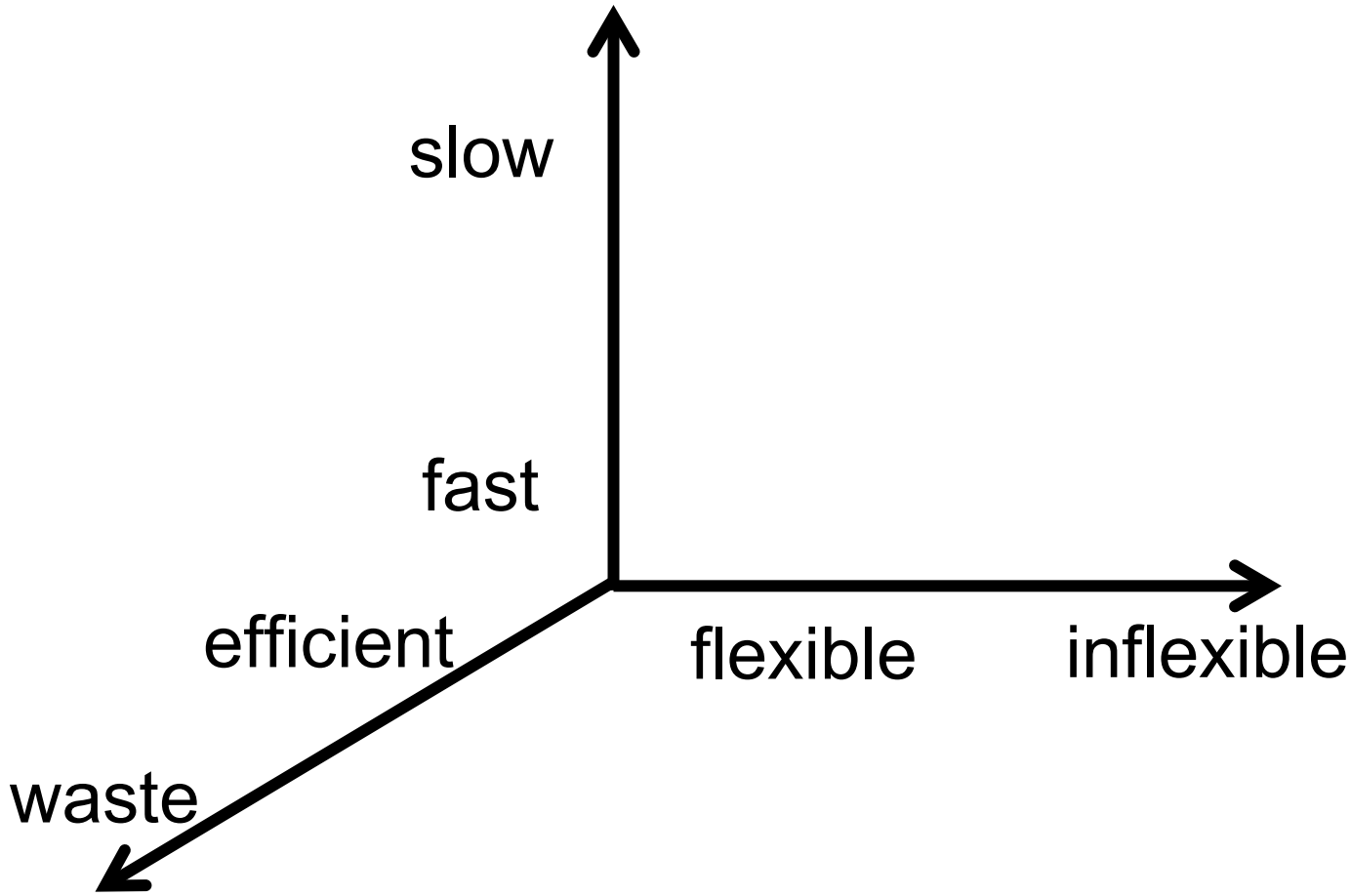
manageable
mobile
modifiable
modular
nomadic

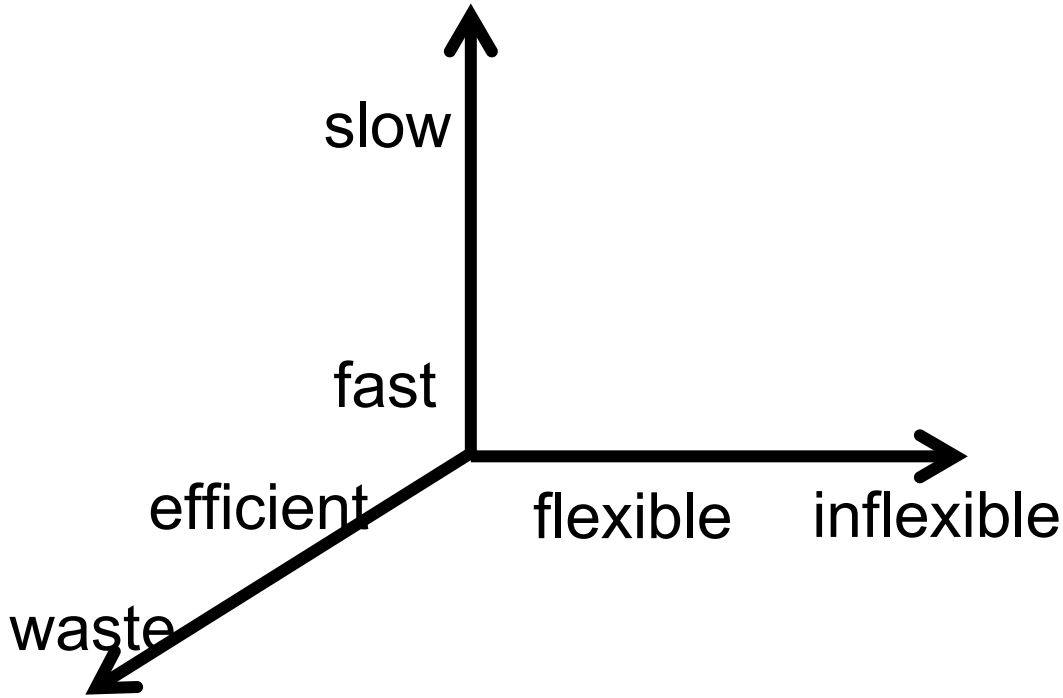
resilient
responsive
reusable

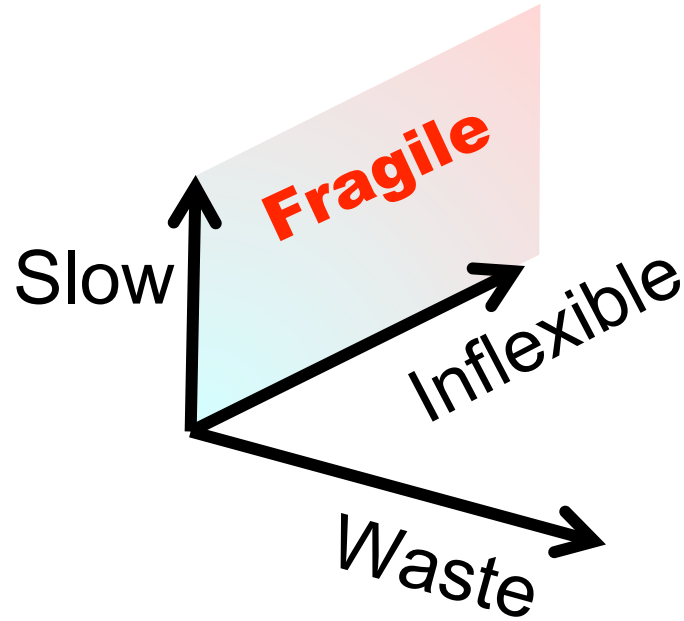
safety
scalable
seamless
self-sustainable
serviceable
upportable
ecurable
mple
able
andards
urvivable
stainable
ilorable
stable
mely
aceable
biquitous
understandable
upgradable
usable

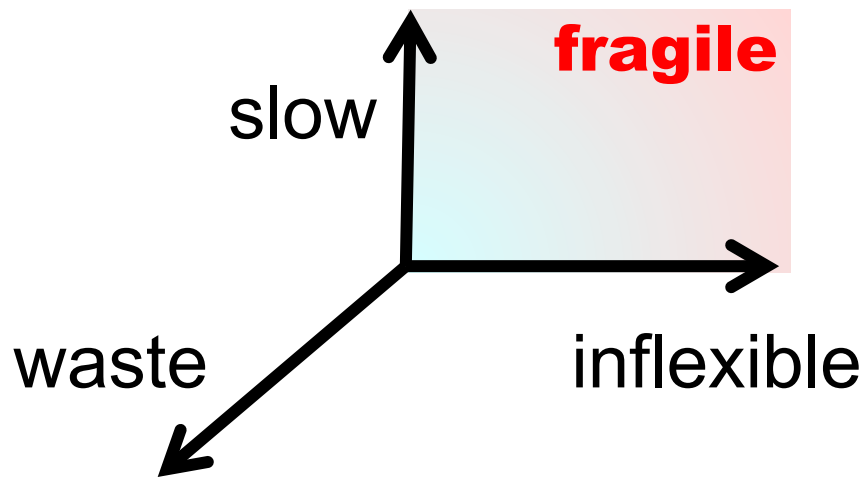


robust


slow
fast
efficient
flexible
inflexible
waste







Same picture

Compute

Gödel

Communicate

Shannon

Turing

Von Neumann

Theory?

Deep, but fragmented, incoherent, incomplete

Nash

Carnot

Boltzmann

Bode

Heisenberg

Einstein

Control, OR

Physics

Priorities

- Functionality (behavior, semantics)
- **Robustness**
  - Uncertain environment and components
  - Fast (sense, decide, act)
  - Flexible (adaptable, evolvable)
- **Efficiency**
  - Energy
  - Other resources (make and maintain)

Compute

Function, delay, robustness *most* important

- Functionality (behavior, semantics)
- **Robustness**
  - –Uncertain environment and components
  - –Fast (sense, decide, act)
  - –Flexible (adaptable, evolvable)
- **Efficiency**
  - –Energy
  - –Other resources (make and maintain)

Control, OR

Co[illegible]cate

Info theory

- ~~Functionality (behavior, semantics)~~
- ~~**Robustness**~~
  - Uncertain environment and components
  - ~~Fast (sense, decide, act)~~
  - ~~Flexible (adaptable, evolvable)~~
- **Efficiency**
  - Energy
  - Other resources (make and maintain)

Physics

Co[illegible]cate

Info theory

- Functionality (behavior, semantics)
- **Robustness**
  - –Uncertain environment and [illegible]nts
  - –Fast (sense, decis[illegible]
  - –Flexi[illegible], evolvable)

Noise, average, asymptotic

- **Efficiency**
  - –Energy
  - –Other resources (make and maintain)

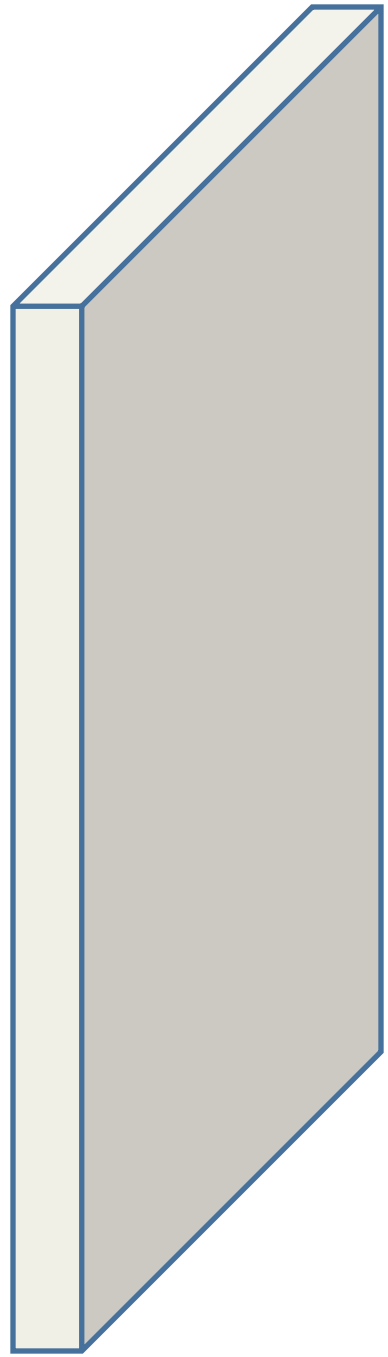
Physics

Compute

Info theory

Function, delay, robustness *most* important

Function, delay, robustness *least* important



Control, OR

Physics

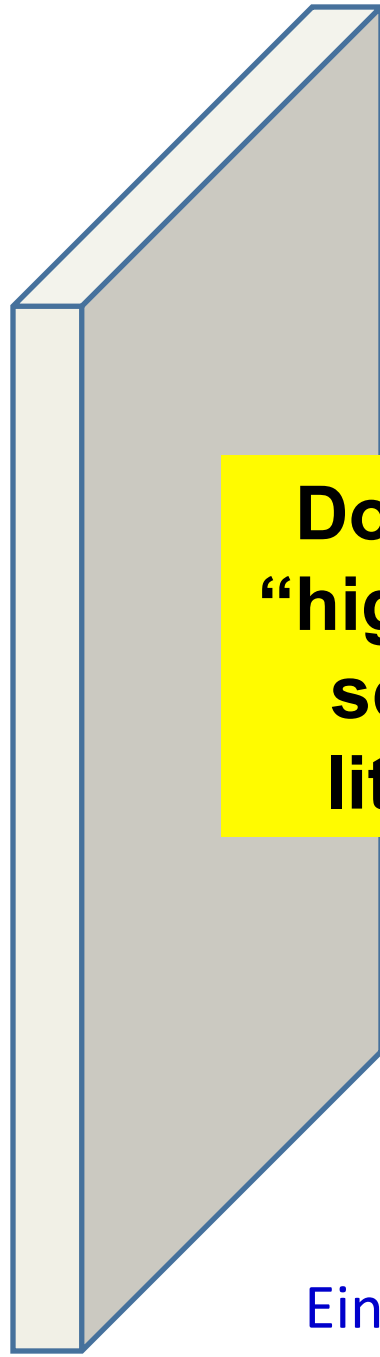
Compute

Turing

Function, delay, robustness *most* important

Bode

Control, OR



Dominates "high impact science" literature

Info theory

Shannon

Function, delay, robustness *least* important

Carnot

Boltzmann

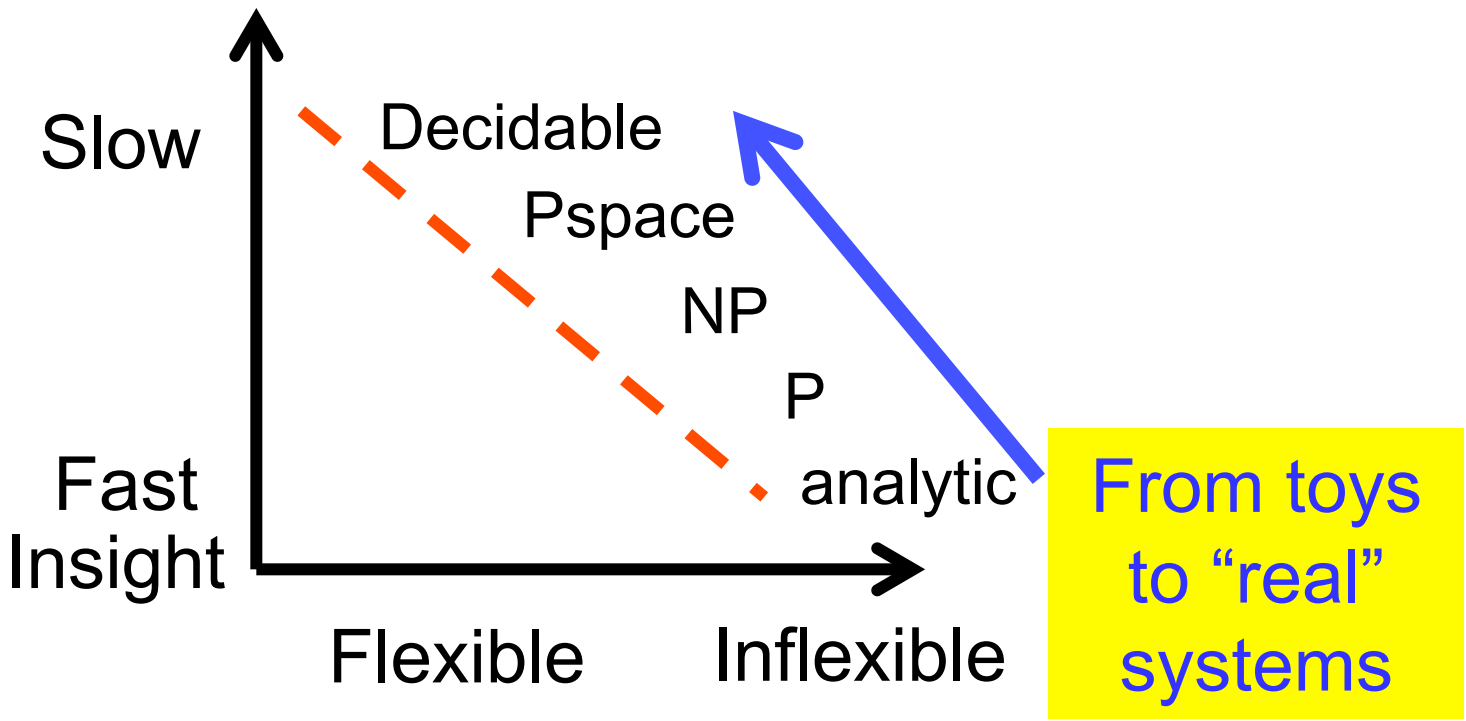
Heisenberg

Einstein

Physics

Compute

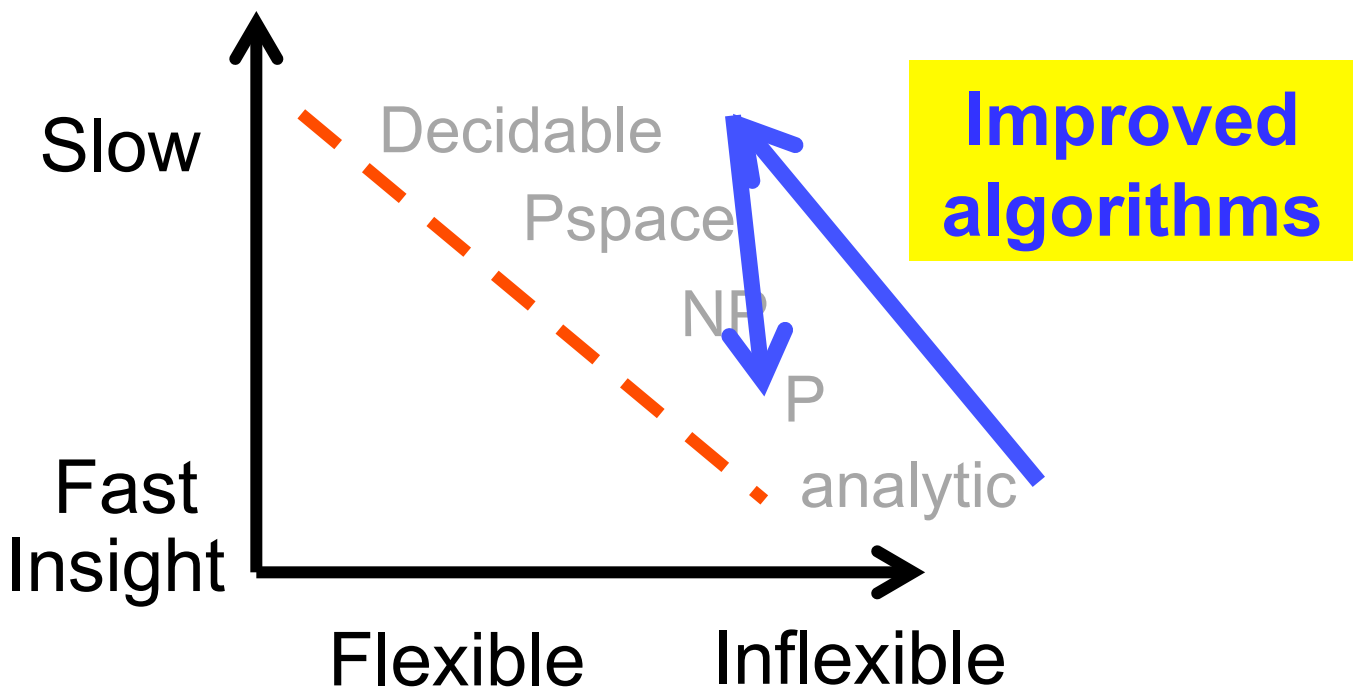
Research progress



Control, OR

Compute

Research progress



Control, OR

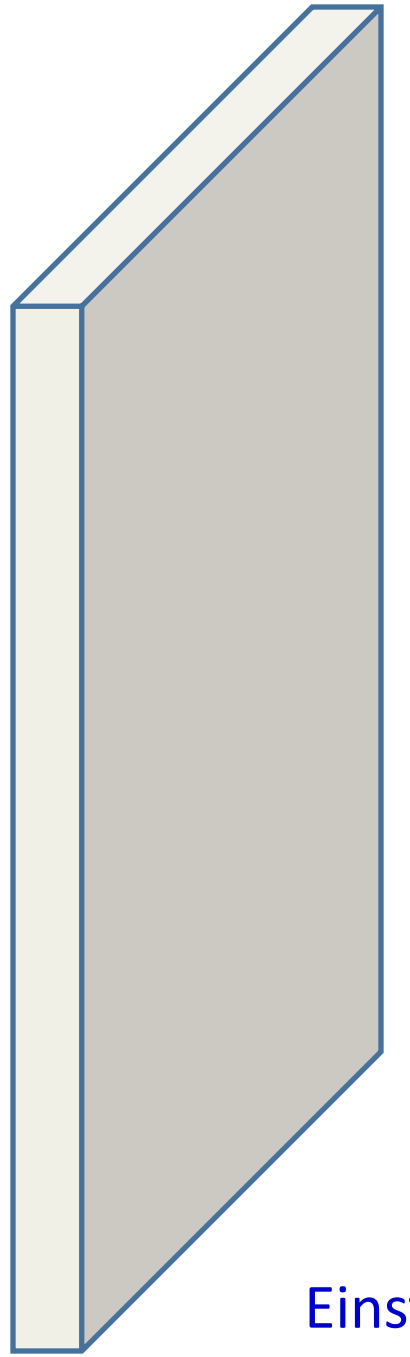
Compute

Turing

Function, delay, robustness *most* important

Bode

Control, OR



Info theory

Shannon

Function, delay, robustness *least* important

Carnot

Boltzmann

Heisenberg

Physics

Einstein

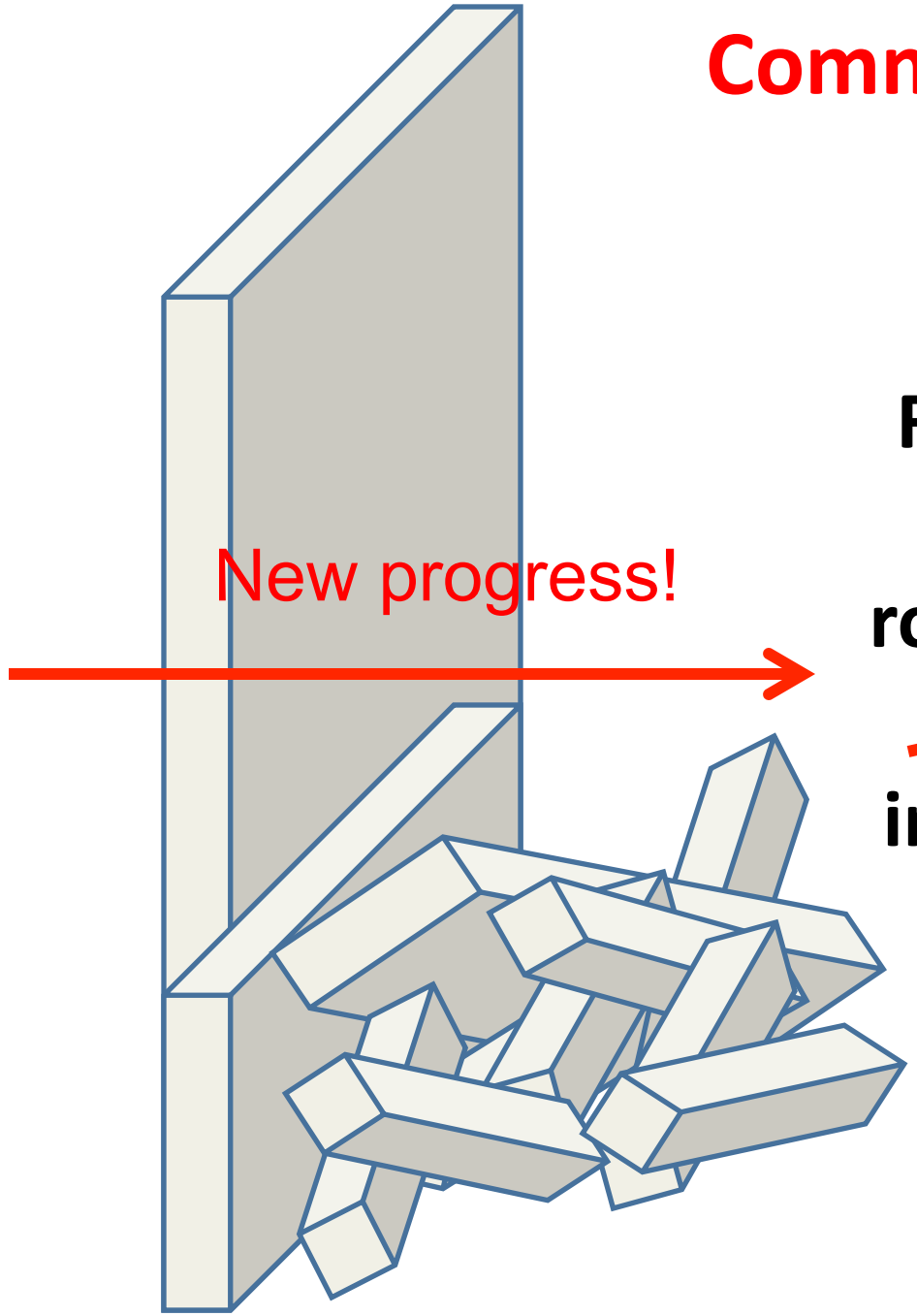
Compute

Turing

Function, delay, robustness *most* important

Bode

Control, OR



Communicate

Shannon

Function, delay, robustness ~~*least*~~ important

Physics

Compute

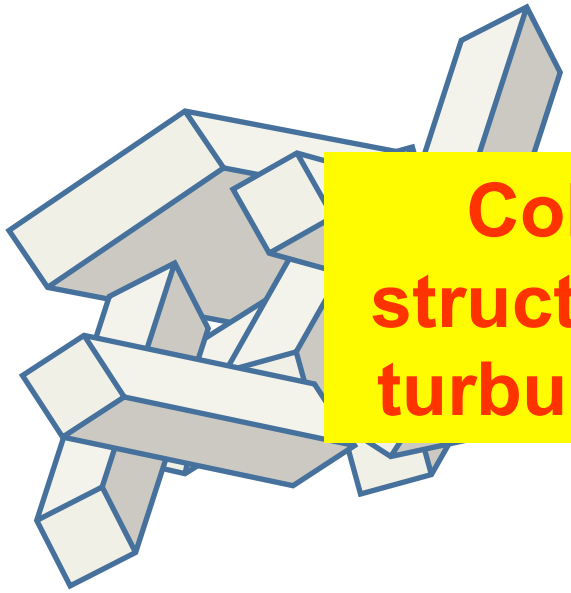
Turing

New progress!

Function, delay, robustness

~~*least*~~

important



Coherent structures and turbulent drag

Physics

Bode

Control, OR

Physics of Fluids (2011)

Amplification and nonlinear mechanisms in plane Couette flow

Dennice F. Gayme,[1] Beverley J. McKeon,[1] Bassam Bamieh,[2] Antonis Papachristodoulou,[3] and John C. Doyle[3]

Shear flow turbulence

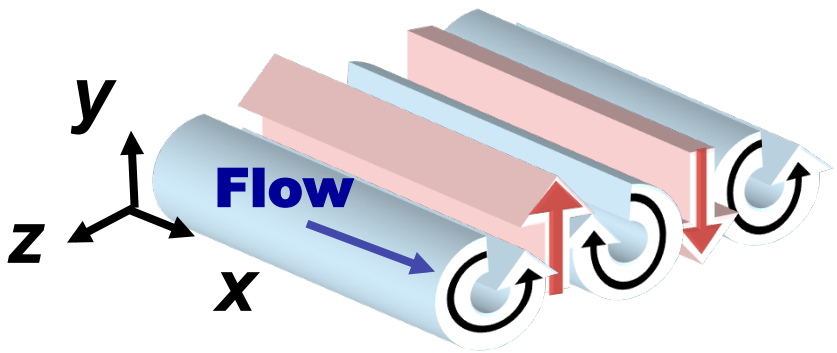
- Exhaustively studied
  - Extensive experiments and ***big*** data
  - Detailed models and ***big*** simulations
  - Great! But all just deepen the mystery
- Perfectly illustrates robust/fragile
- Without which? Bewilderment.

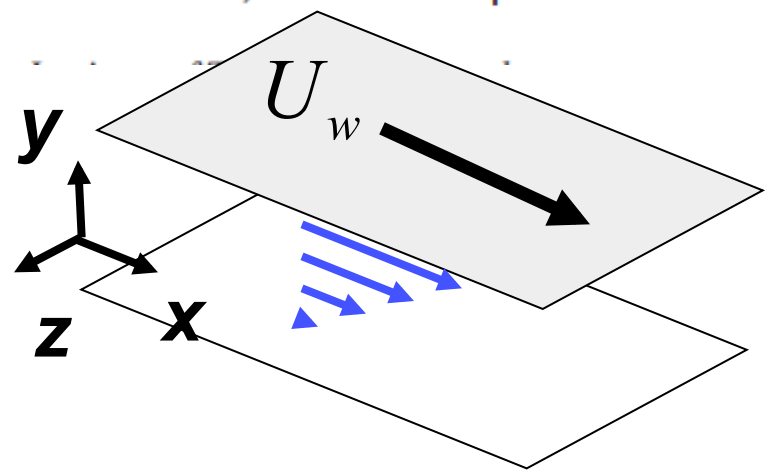
Physics of Fluids (2011)

PHYSICS OF FLUIDS **23**, 065108 (2011)

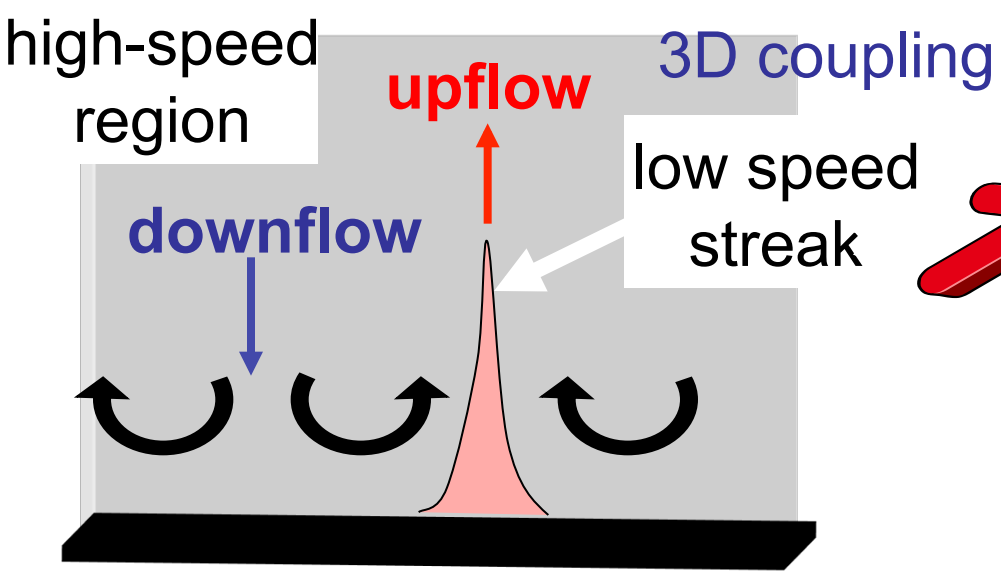
Amplification and nonlinear mechanisms in plane Couette flow

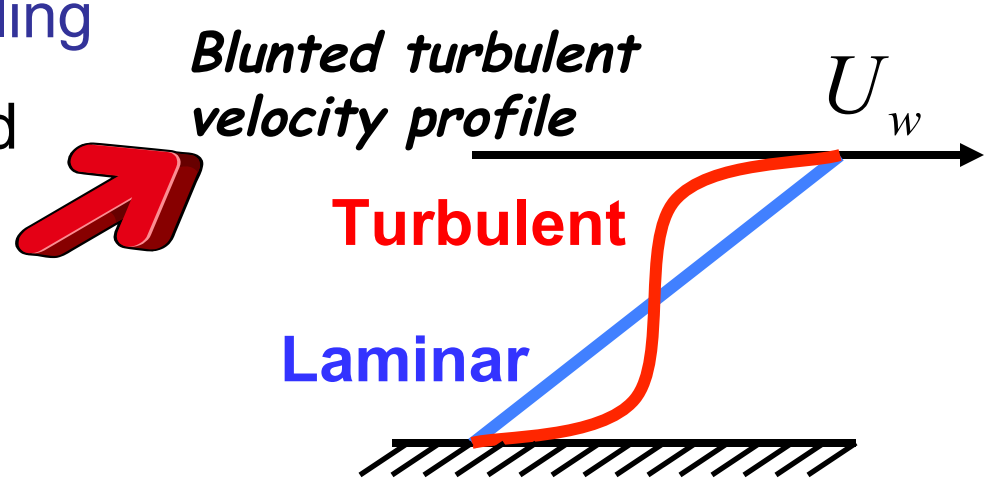
Dennice F. Gayme,[1] Beverley J. McKeon,[1] Bassam Bamieh,[2] Antonis Papachristodoulou,[3] and John C. Doyle[3]



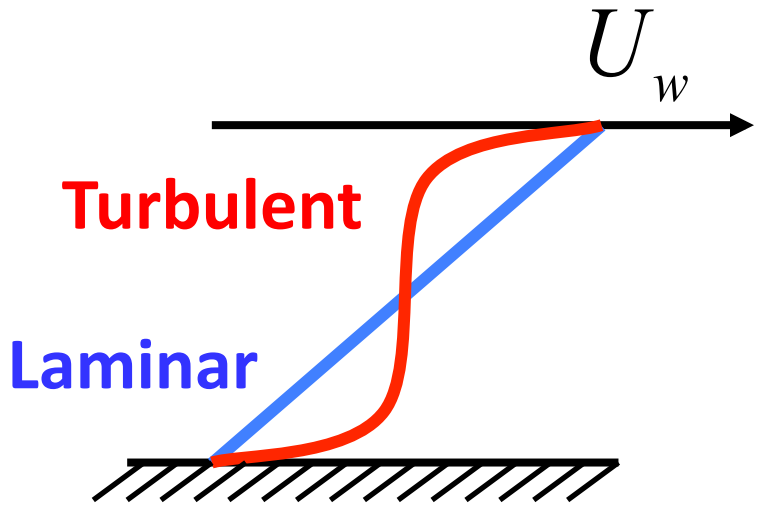


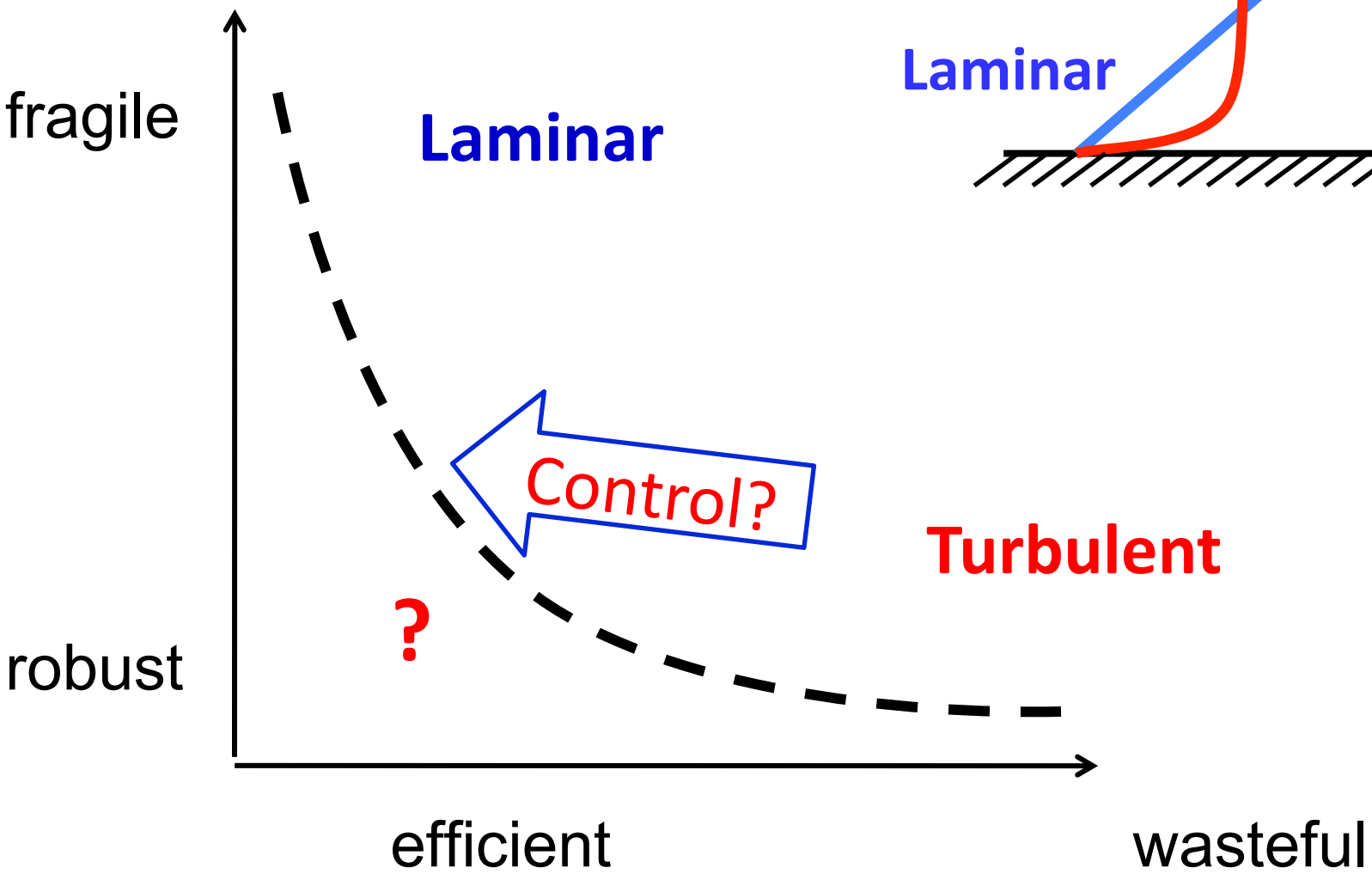
Coherent structures and turbulent drag






Fundamentals!


U_w
Turbulent
Laminar


fragile
robust
Laminar
Control?
Turbulent
?
efficient
wasteful

Compute

Turing

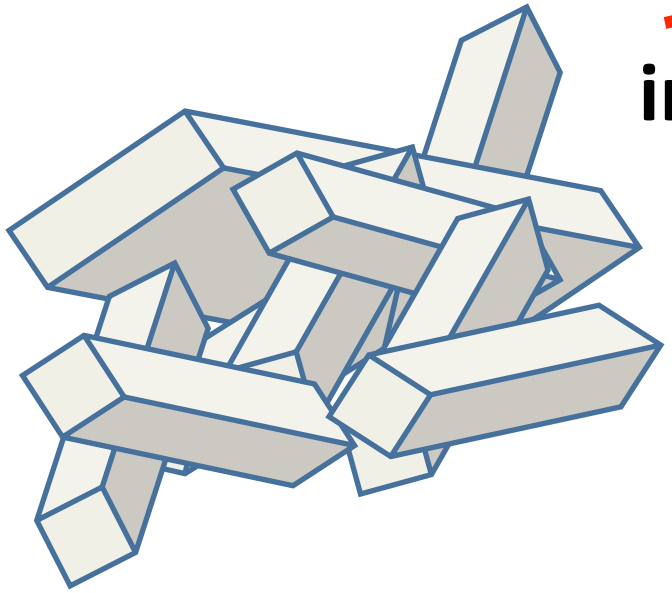
Communications for control, computing, biology

New progress!

Function, delay, robustness

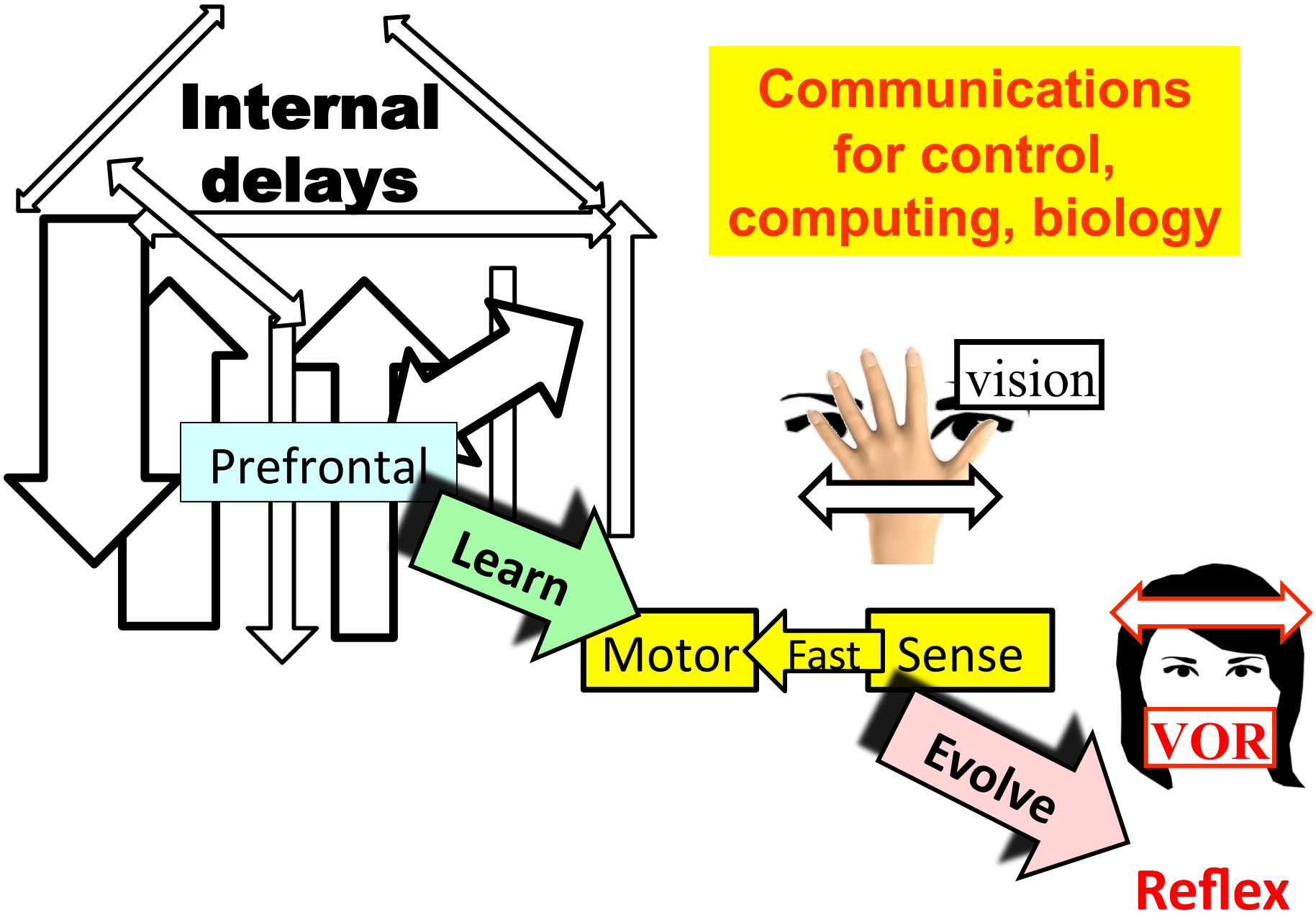
~~*least*~~

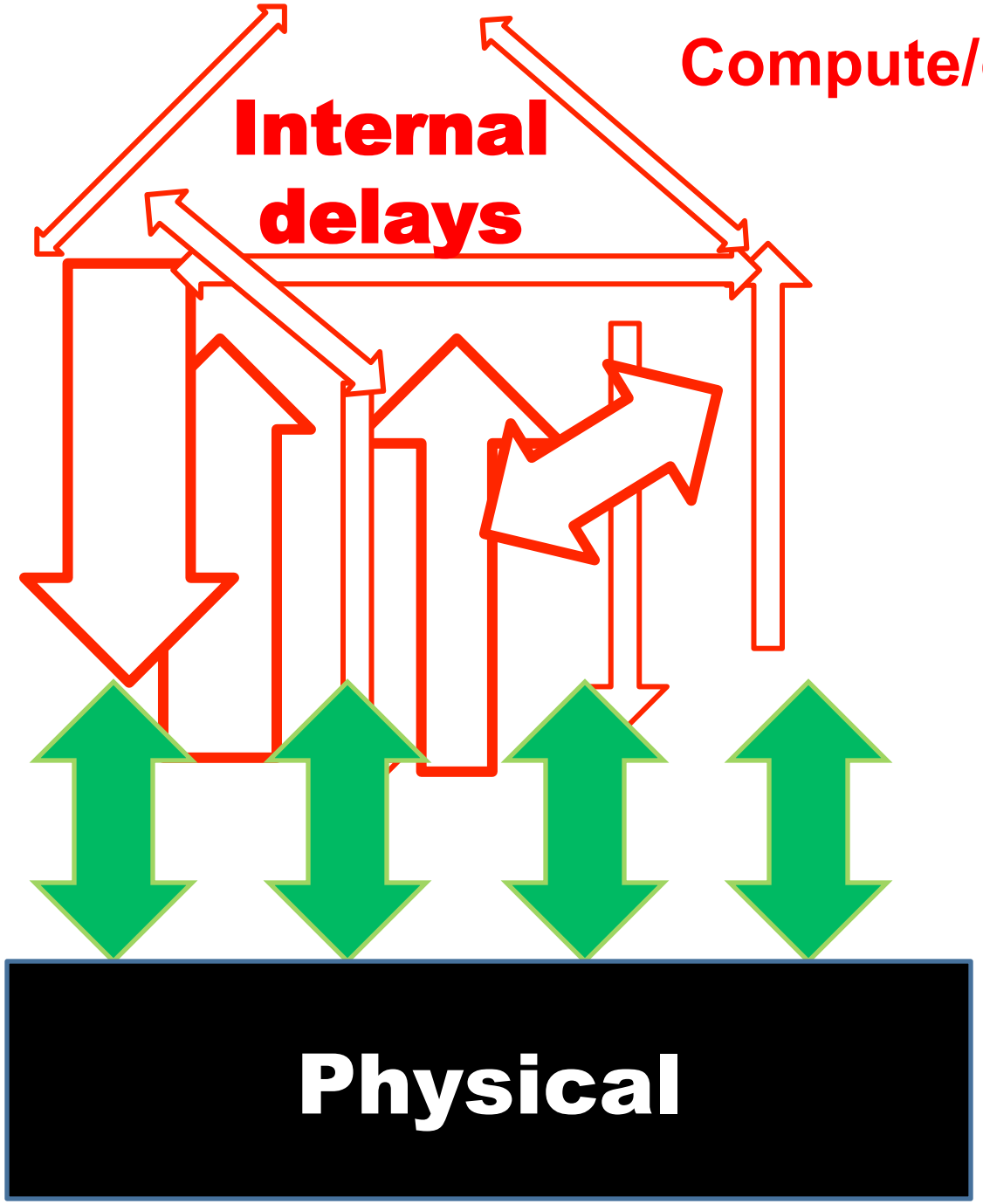
important



Bode

Control, OR


Internal delays
Communications for control, computing, biology
Prefrontal
Learn
vision
Motor
Fast
Sense
Evolve
VOR
Reflex



Compute/communicate

New theory: Distributed control with delays *everywhere*.

Sense/Act

Compute

Comms for Comp/Cntrl/Bio

Info Thry

Optimization

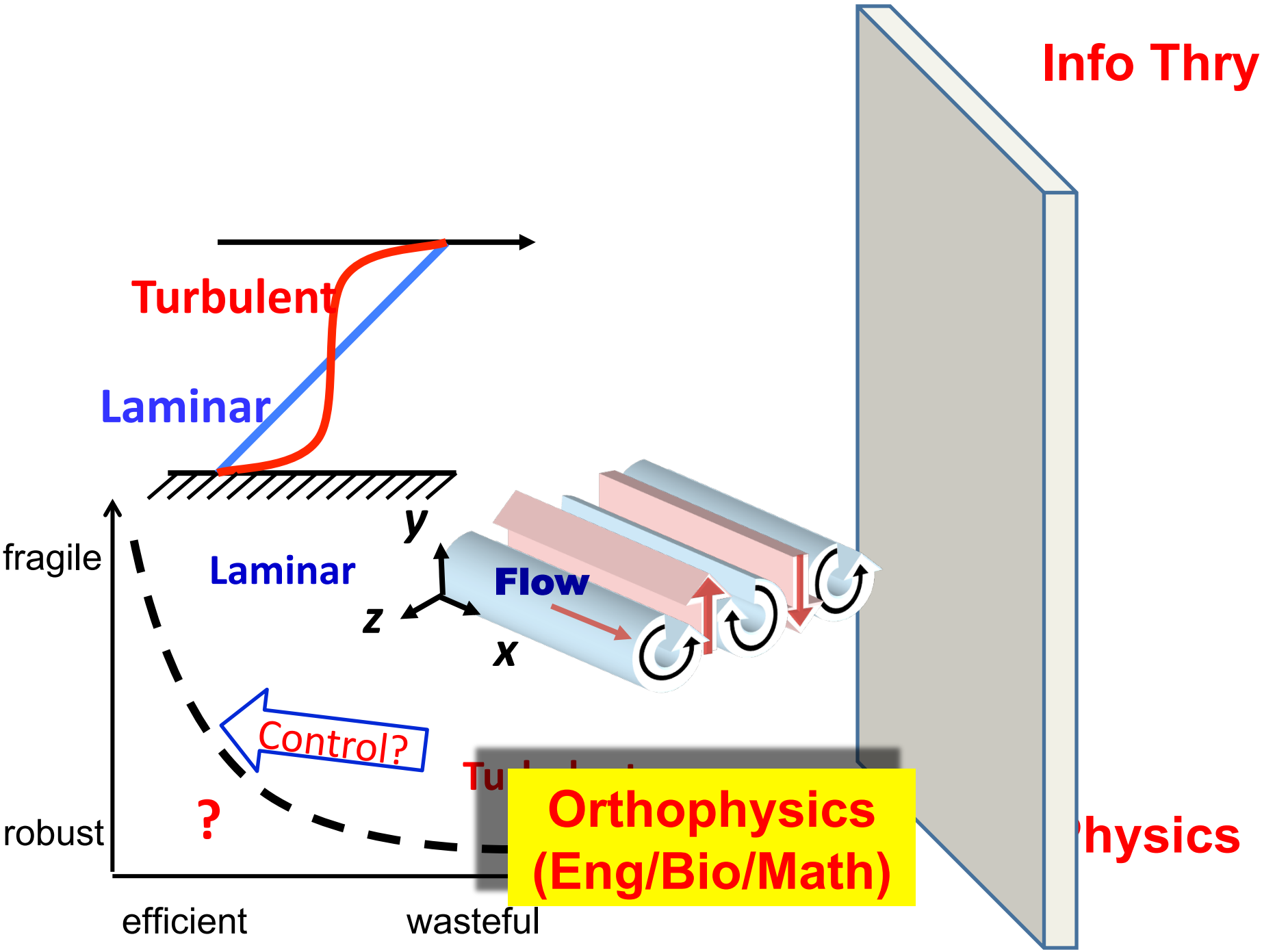
Statistics

Theory

Control, OR

Orthophysics (Eng/Bio/Math)

Physics


Info Thry
Turbulent
Laminar
fragile
Laminar
y
z
x
Flow
Control?
?
robust
efficient
wasteful
Orthophysics
(Eng/Bio/Math)
hysics

Doyle, Csete, *Proc Nat Acad Sci USA*, JULY 25 2011

Architecture, constraints, and behavior

John C. Doyle[a,1] and Marie Csete[b,1]

[a]Control and Dynamical Systems, California Institute of Technology, Pasadena, CA 91125; and [b]Department of Anesthesiology, University of California, San Diego, CA 92103

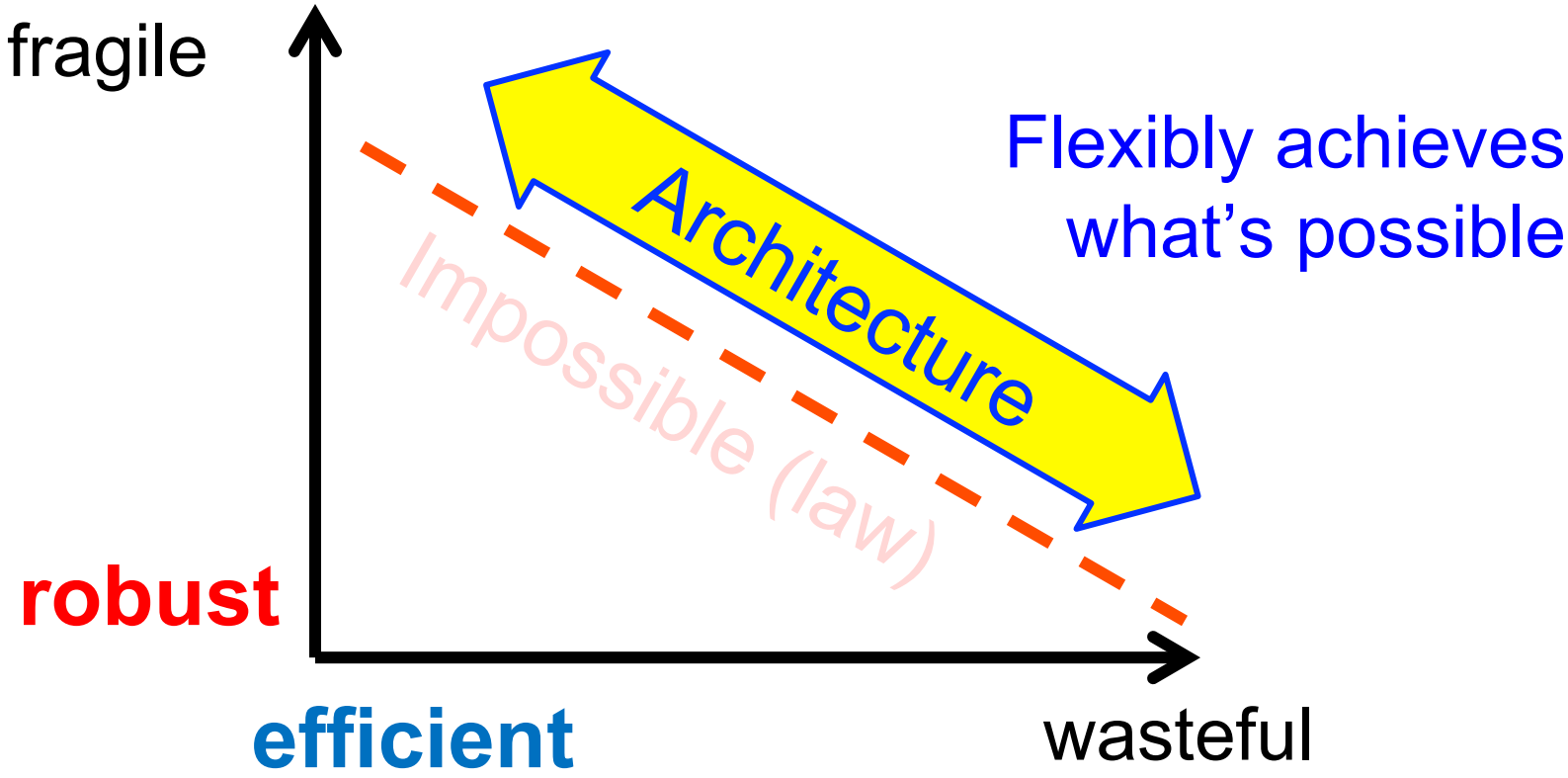
Edited by Donald W. Pfaff, The Rockefeller University, New York, NY, and approved June 10, 2011 (received for review March 3, 2011)

This paper aims to bridge progress in neuroscience involving sophisticated quantitative analysis of behavior, including the use of robust control, with other relevant conceptual and theoretical frameworks from systems engineering, systems biology, and mathematics. Familiar and accessible case studies are used to illustrate concepts of robustness, organization, and architecture (modularity and protocols) that are central to understanding complex networks. These essential organizational features are hidden during normal function of a system but are fundamental for understanding the nature, design, and function of complex biologic and technologic systems.

evolved for sensorimotor control and retain much of that evolved architecture, then the apparent distinctions between perceptual, cognitive, and motor processes may be another form of illusion (9), reinforcing the claim that robust control and adaptive feedback (7, 11) rather than more conventional serial signal processing might be more useful in interpreting neurophysiology data (9). This view also seems broadly consistent with the arguments from grounded cognition that modal simulations, bodily states, and situated action underlie not only motor control but cognition in general (12), including language (13). Furthermore, the myriad constraints involved in the evolution of circuit

For more info
Most accessible
No math
References

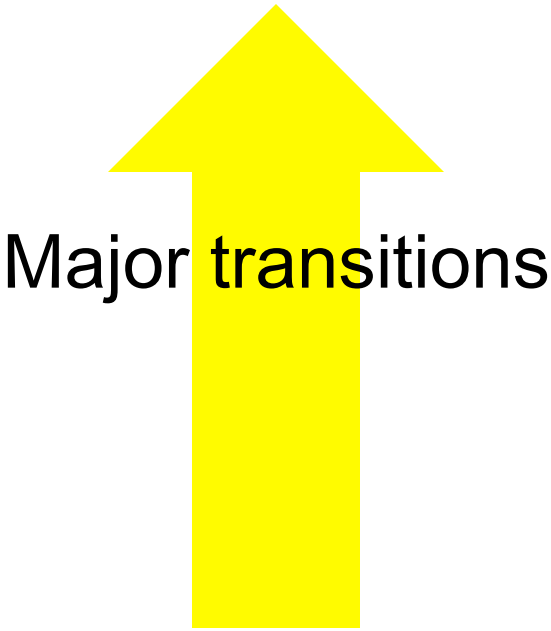
Universal laws and architectures

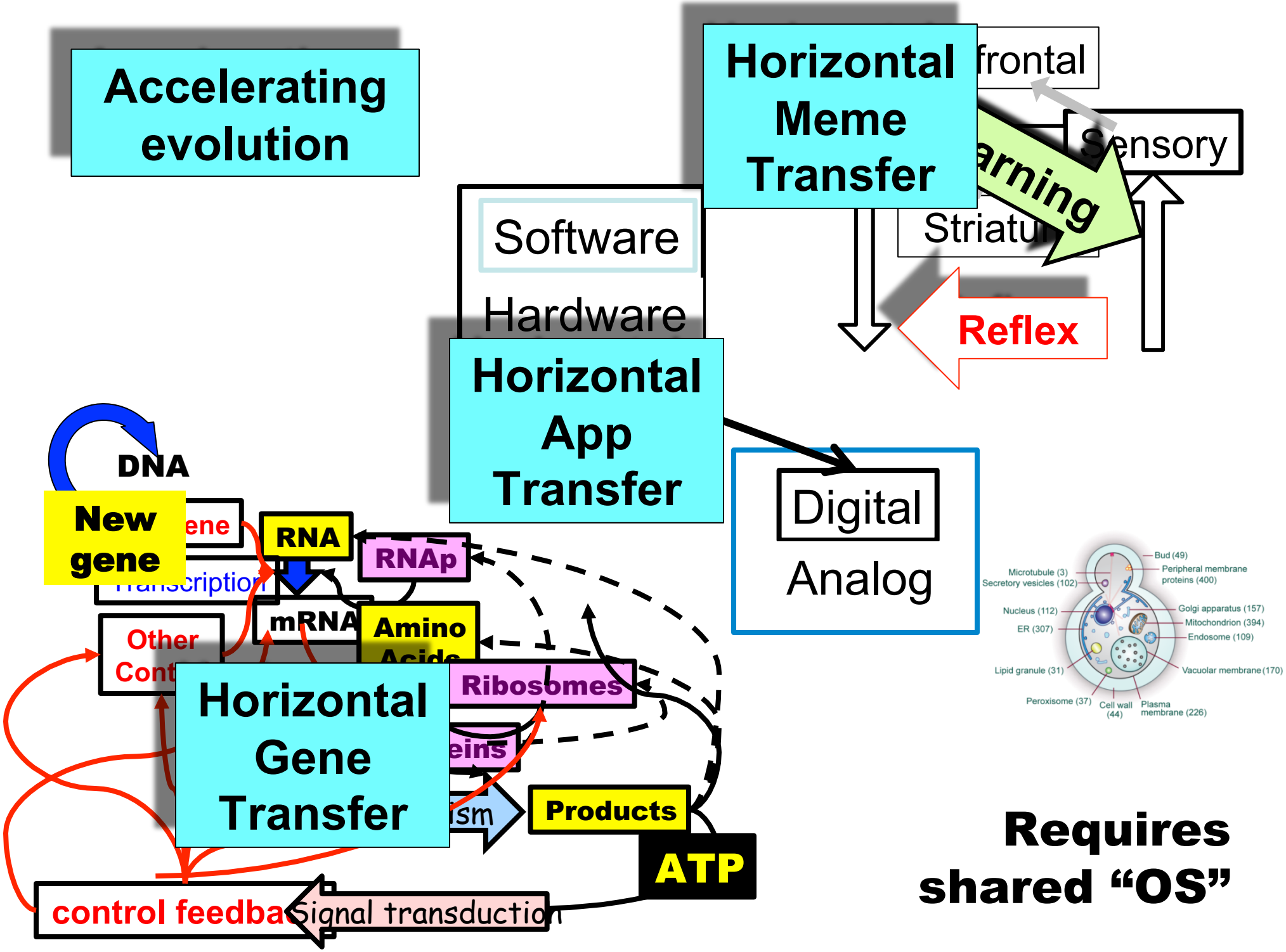


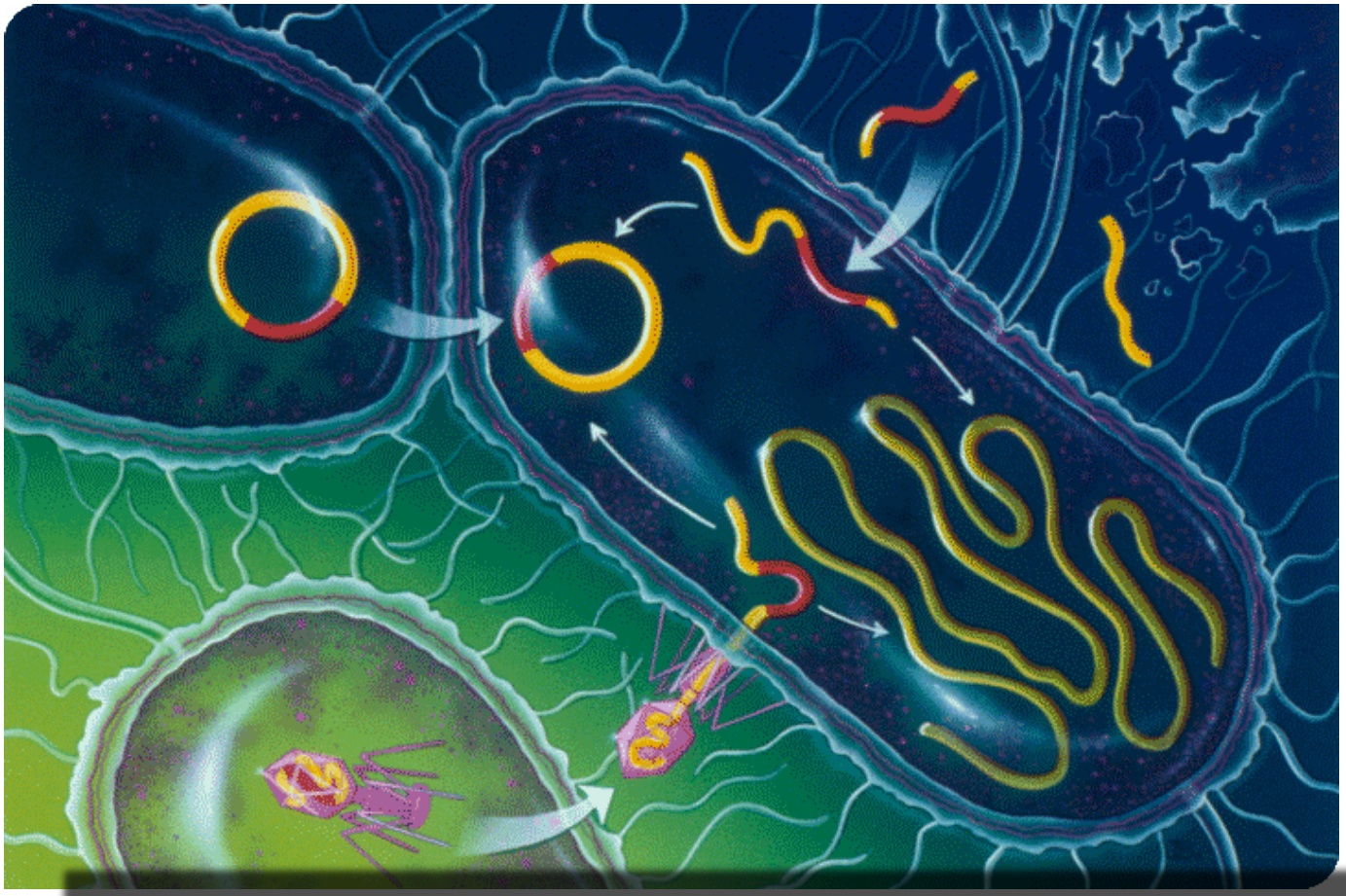
Efficiency/instability/layers/feedback

Evolvability?

- Sustainable infrastructure? (e.g. smartgrids)
- Money/finance/lobbyists/etc
- Industrialization
- Society/agriculture/weapons/etc
- Bipedalism
- Maternal care
- Warm blood
- Flight
- Mitochondria
- Oxygen
- Translation (ribosomes)
- Glycolysis (2011 Science)



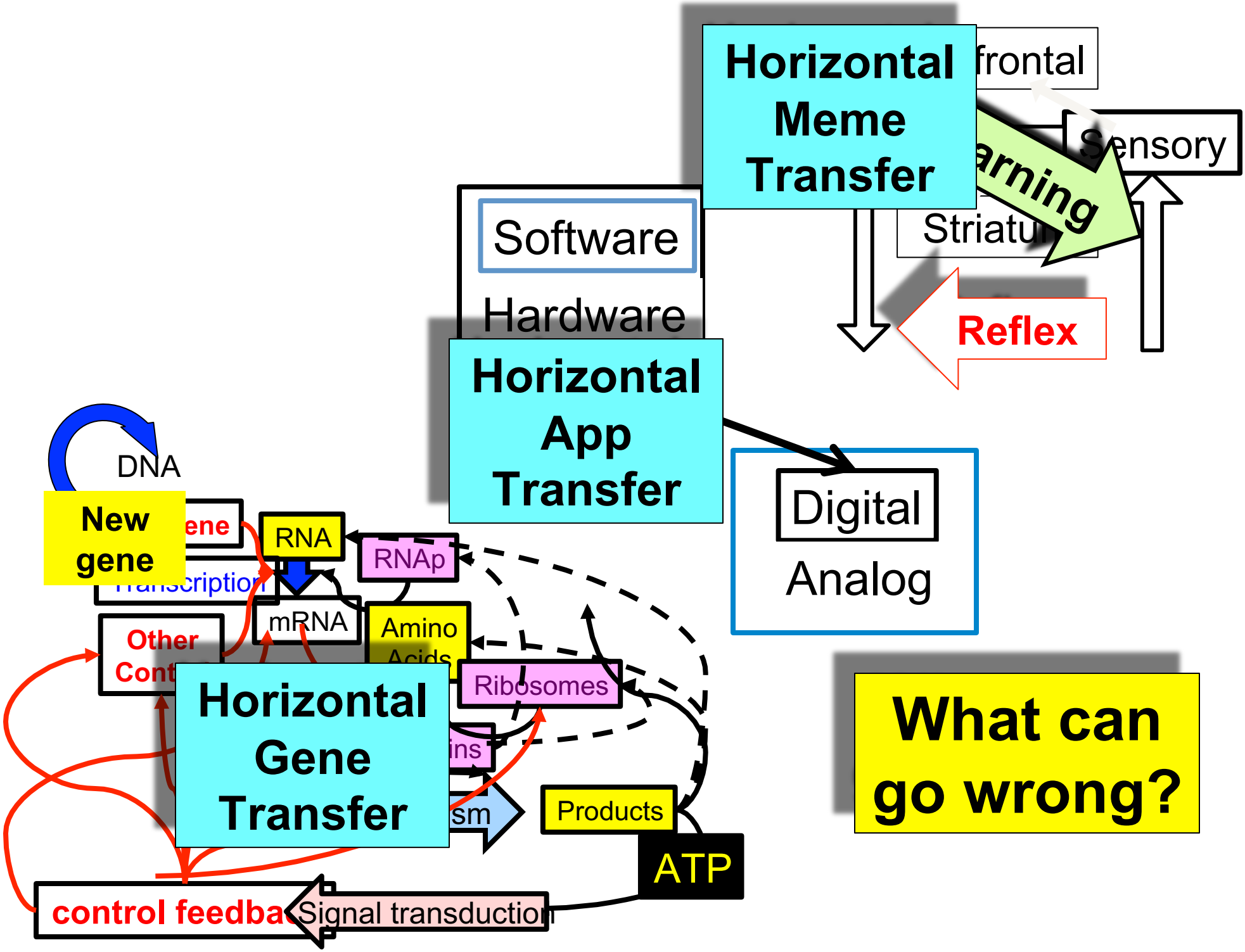

Accelerating evolution
Horizontal Meme Transfer
frontal
Sensory
arning
Striatu
Software
Hardware
Reflex
Horizontal App Transfer
Digital
Analog
DNA
New gene
ene
RNA
RNAp
Transcription
mRNA
Amino Acids
Other Cont
Ribosomes
eins
Horizontal Gene Transfer
sm
Products
ATP
control feedba
Signal transduction
Bud (49)
Microtubule (3)
Peripheral membrane proteins (400)
Secretory vesicles (102)
Nucleus (112)
Golgi apparatus (157)
Mitochondrion (394)
ER (307)
Endosome (109)
Lipid granule (31)
Vacuolar membrane (170)
Peroxisome (37)
Cell wall (44)
Plasma membrane (226)
Requires shared "OS"

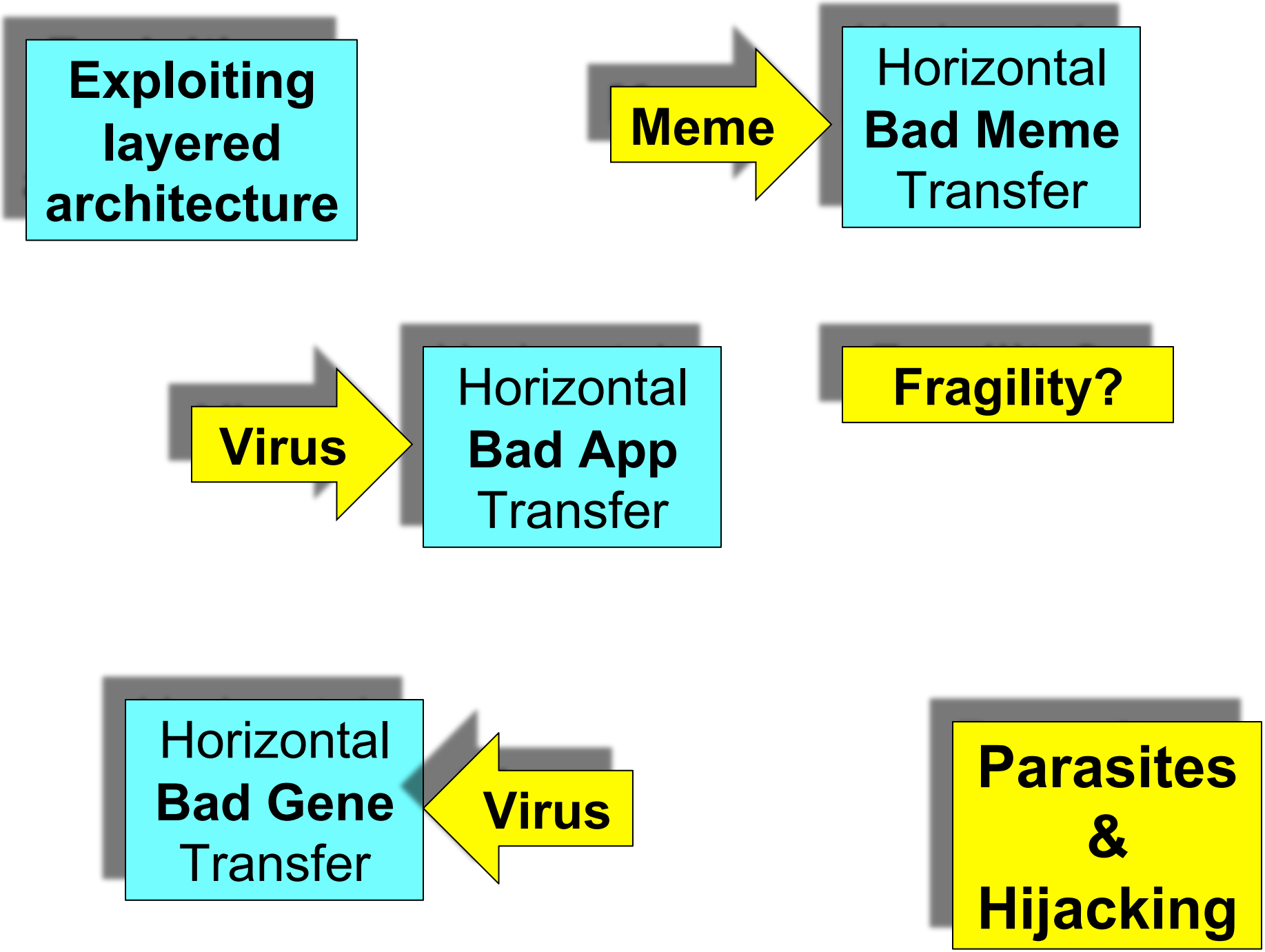


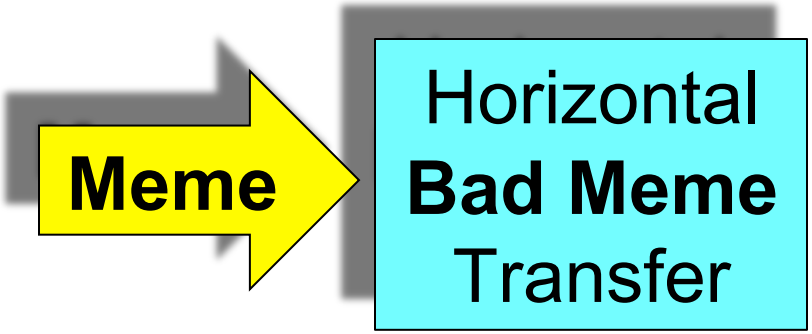
Horizontal Gene Transfer

Sequence ~100 E Coli (*not* chosen randomly)

- ~ 4K genes per cell
- ~20K *different* genes in total (pangenome)
- ~ 1K universally shared genes
- ~ 300 essential (minimal) genes

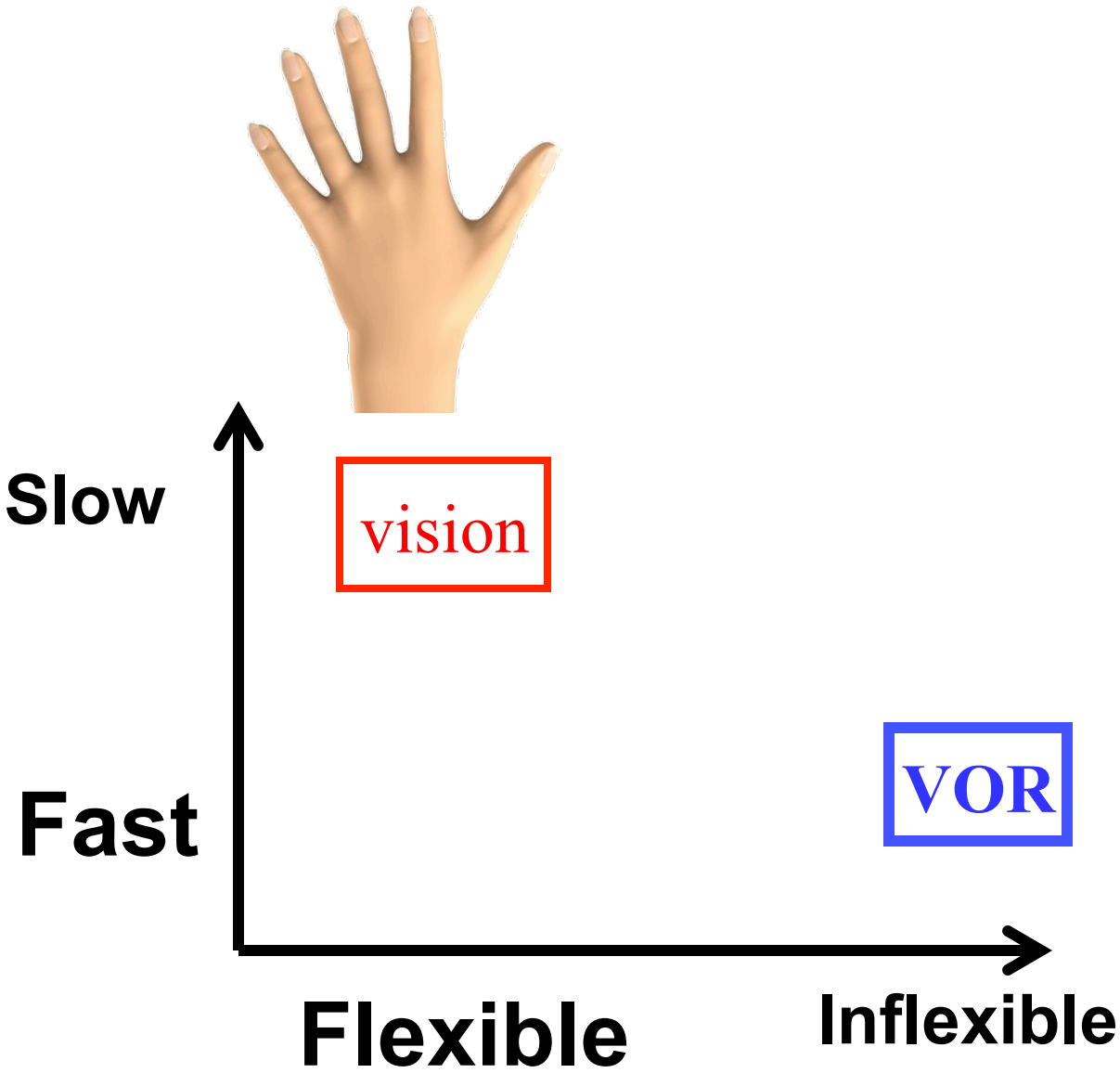

Horizontal Meme Transfer
frontal
Sensory
arning
Striatu
Software
Hardware
Reflex
Horizontal App Transfer
Digital
Analog
DNA
New gene
ene
RNA
RNAp
Transcription
mRNA
Amino Acids
Other Cont
Ribosomes
Horizontal Gene Transfer
ins
sm
Products
ATP
control feedba
Signal transduction
What can go wrong?

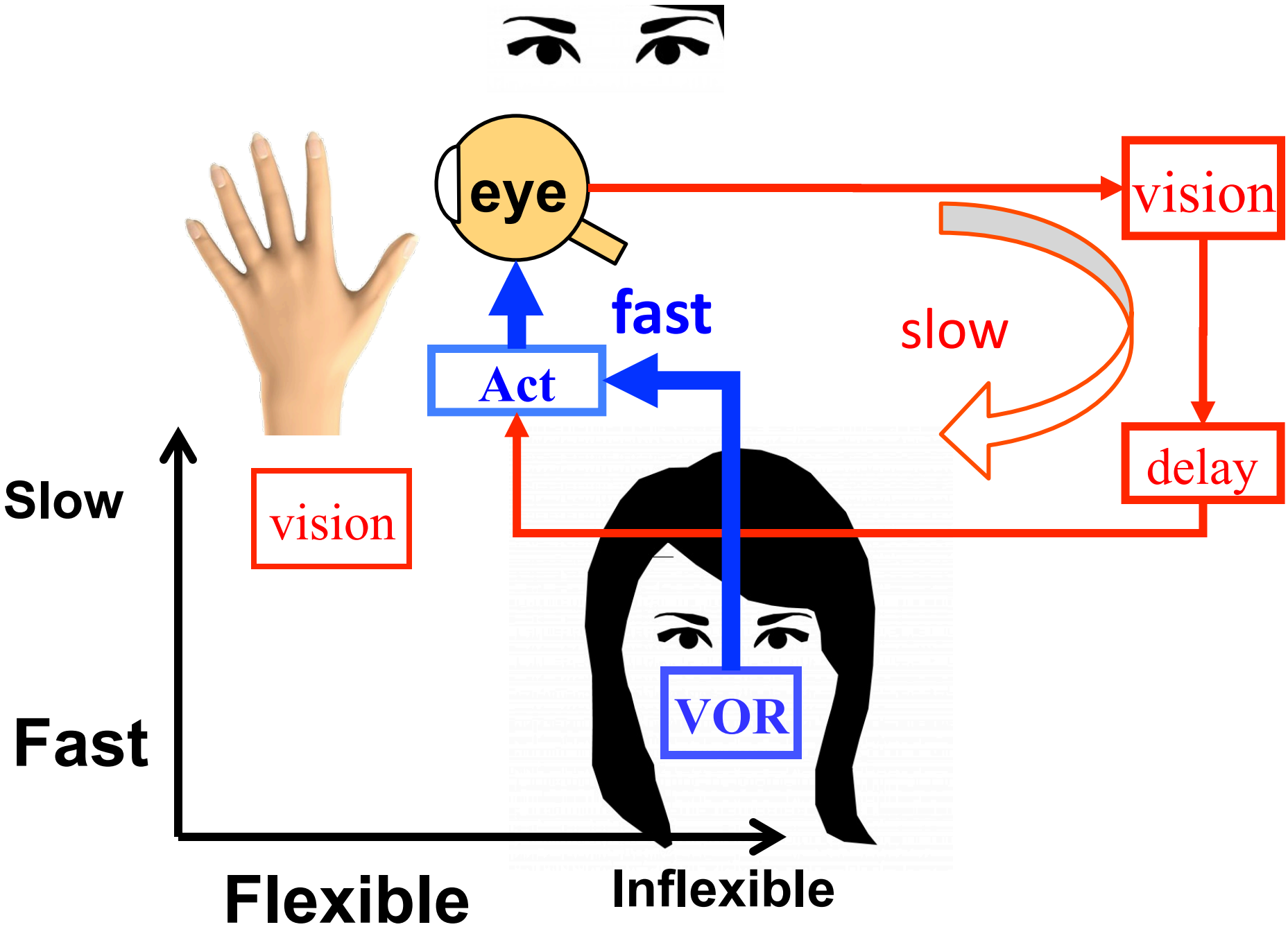

Exploiting layered architecture
Meme
Horizontal Bad Meme Transfer
Virus
Horizontal Bad App Transfer
Fragility?
Horizontal Bad Gene Transfer
Virus
Parasites & Hijacking

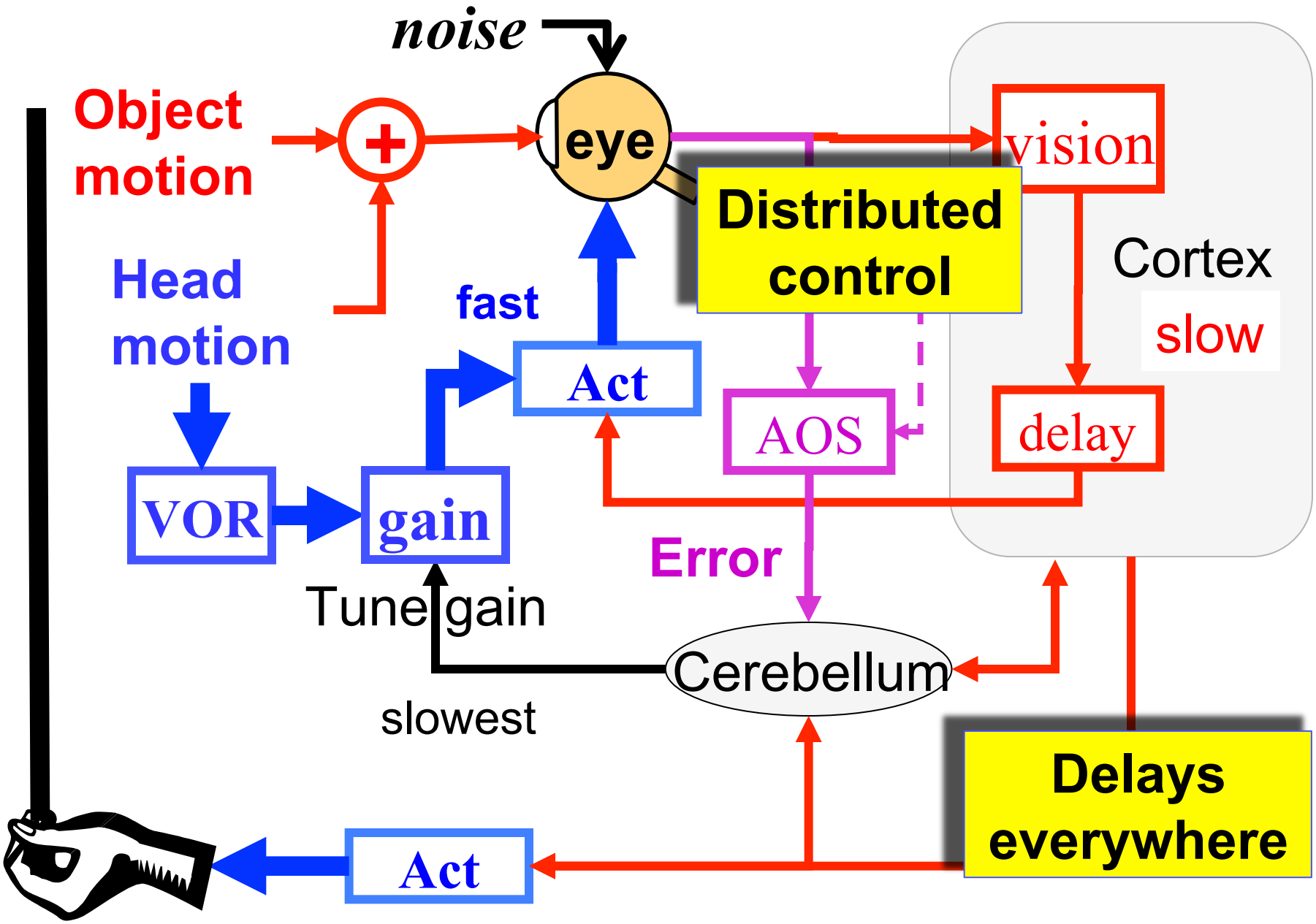


Many human beliefs are:

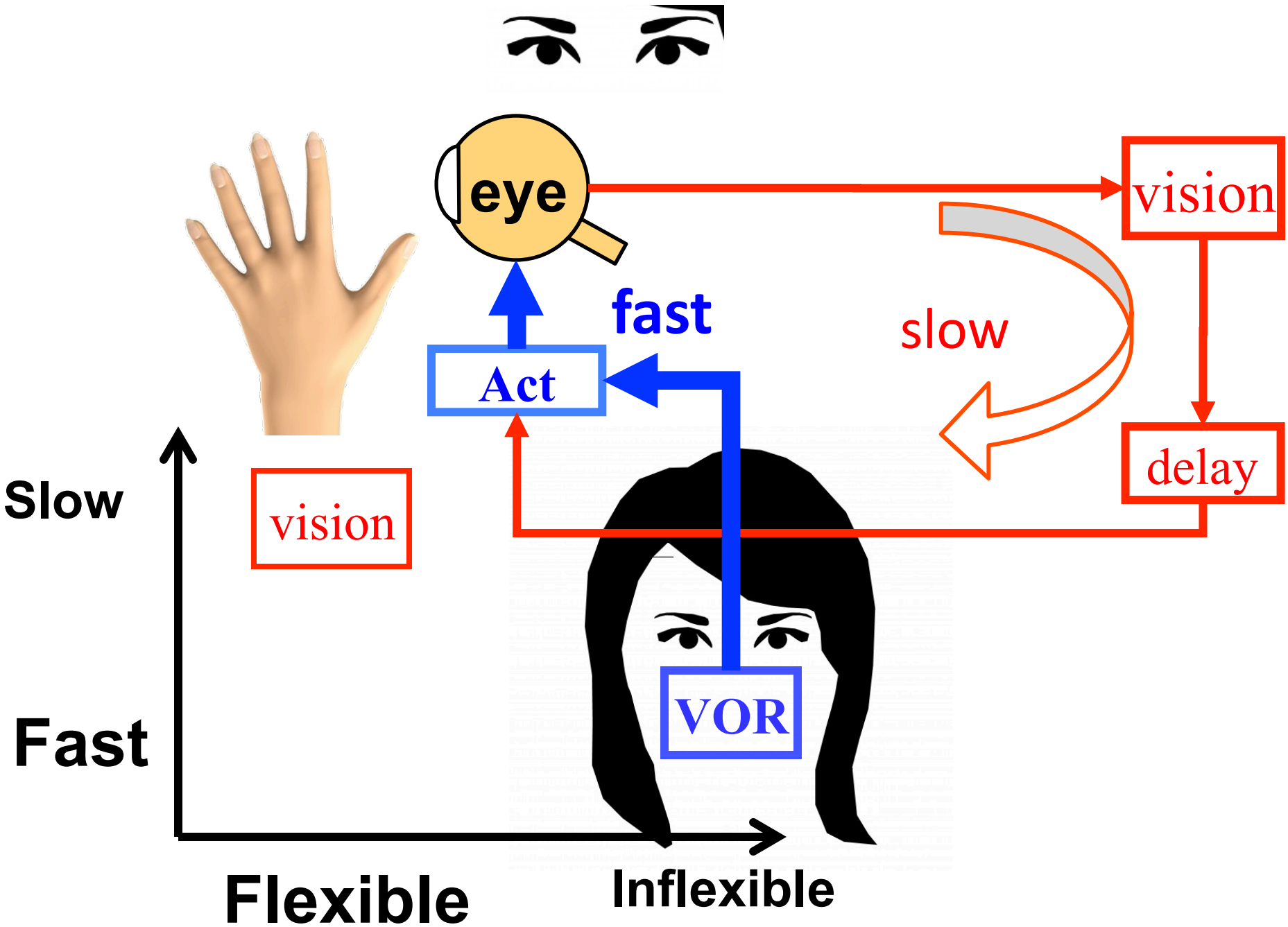
- False
- Unhealthy

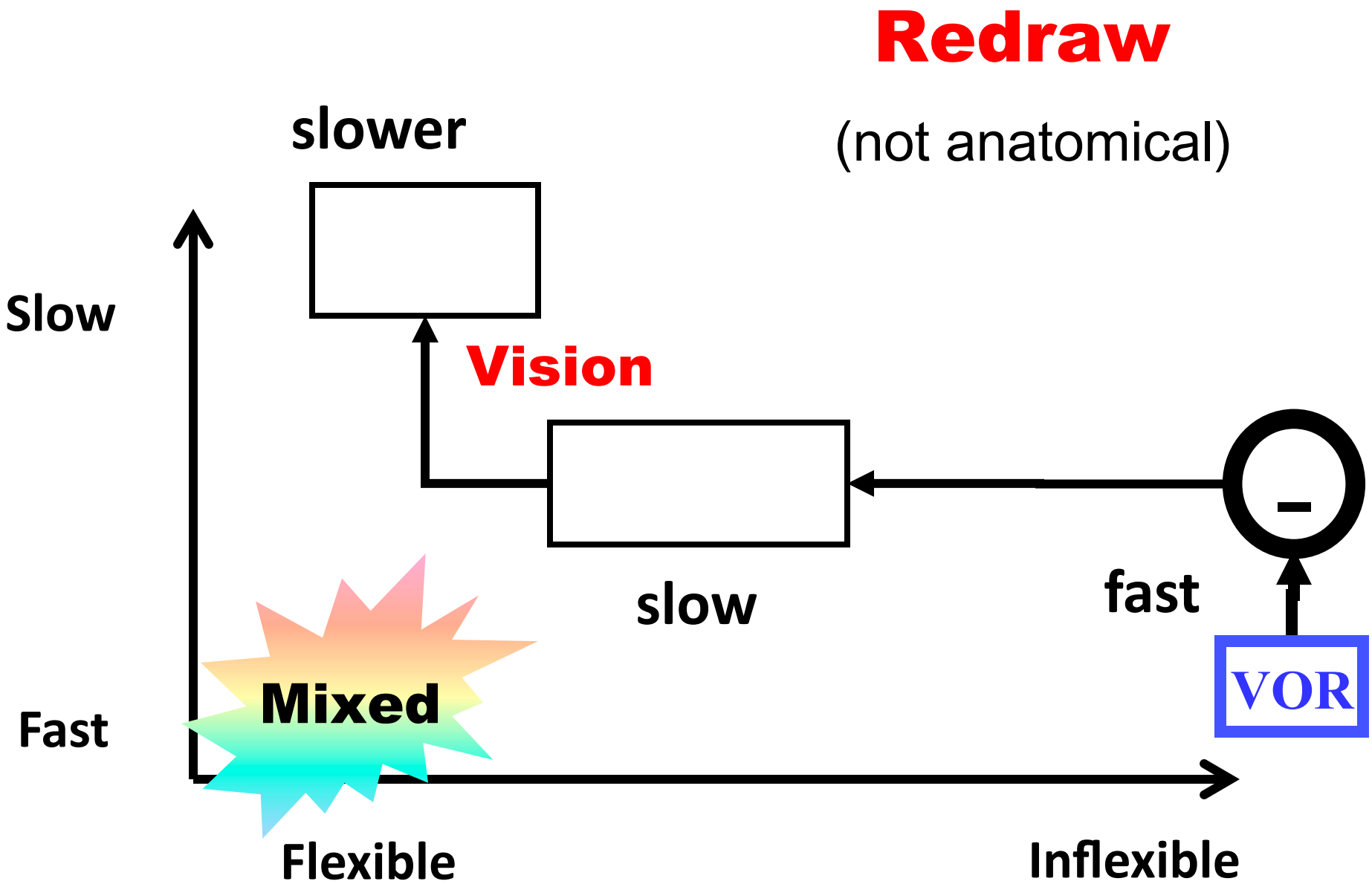

Slow
Fast
vision
VOR
Flexible
Inflexible

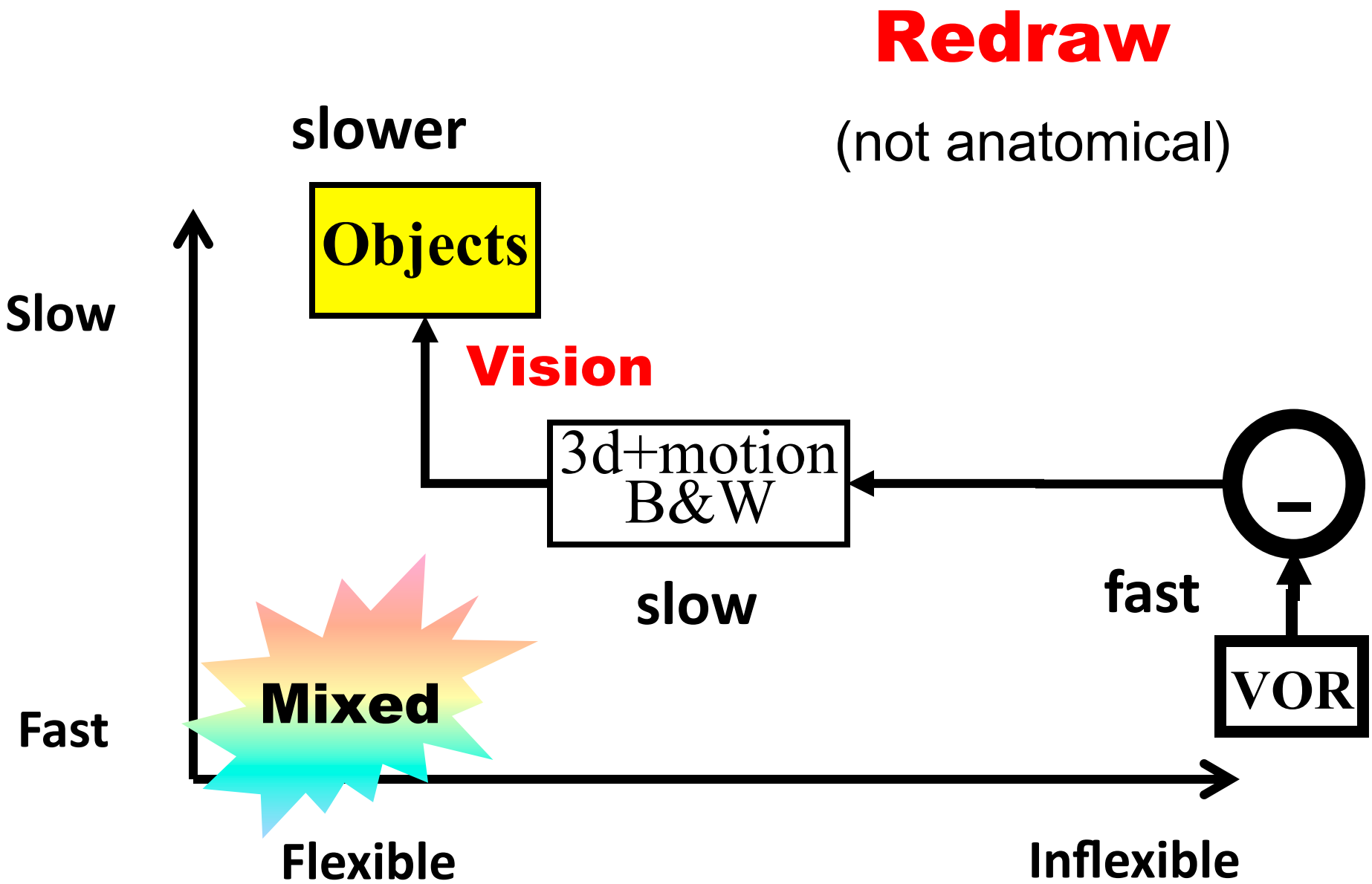

eye
vision
fast
slow
Act
delay
vision
Slow
Fast
VOR
Flexible
Inflexible

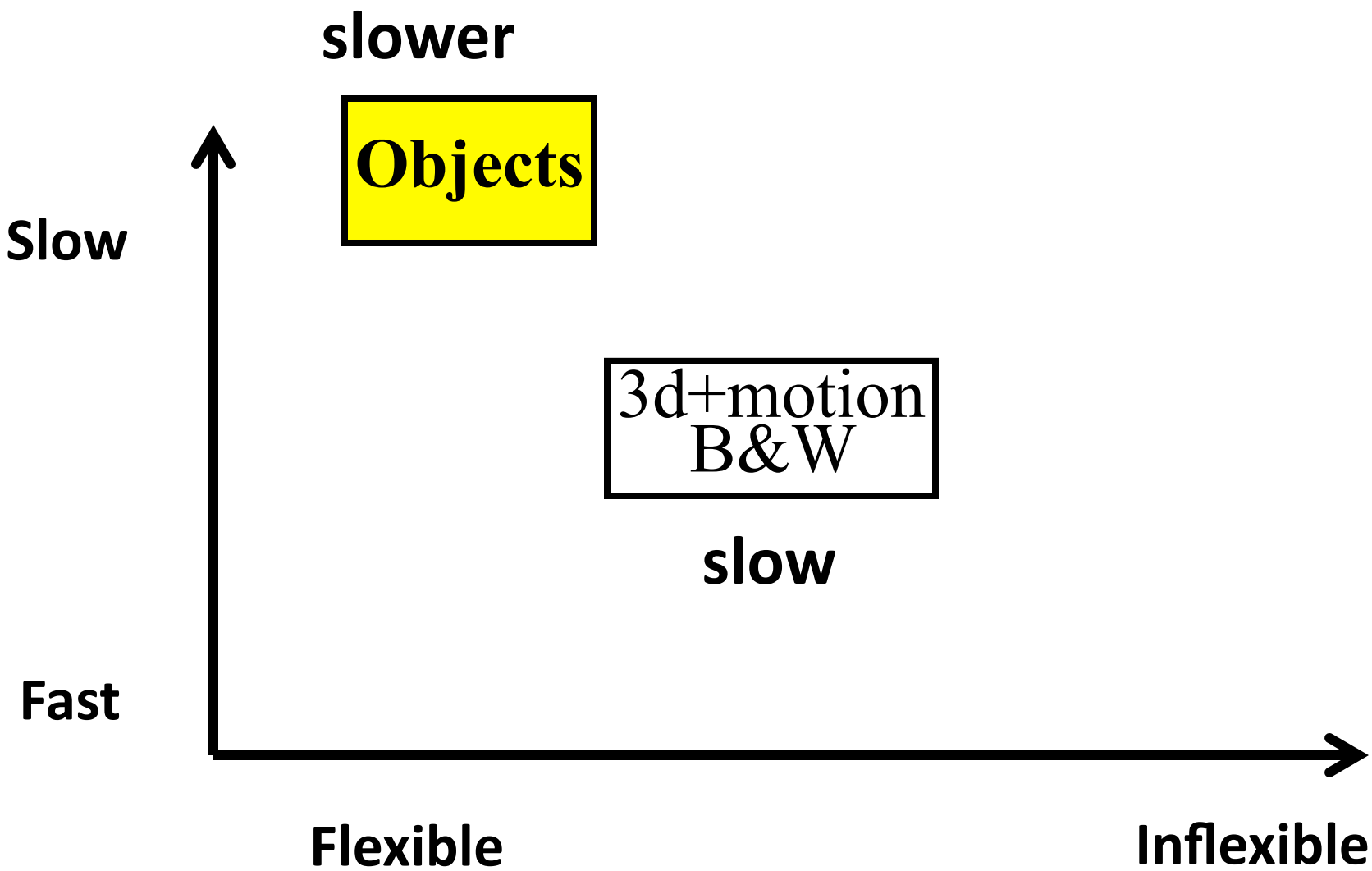


AOS = Accessory Optical system

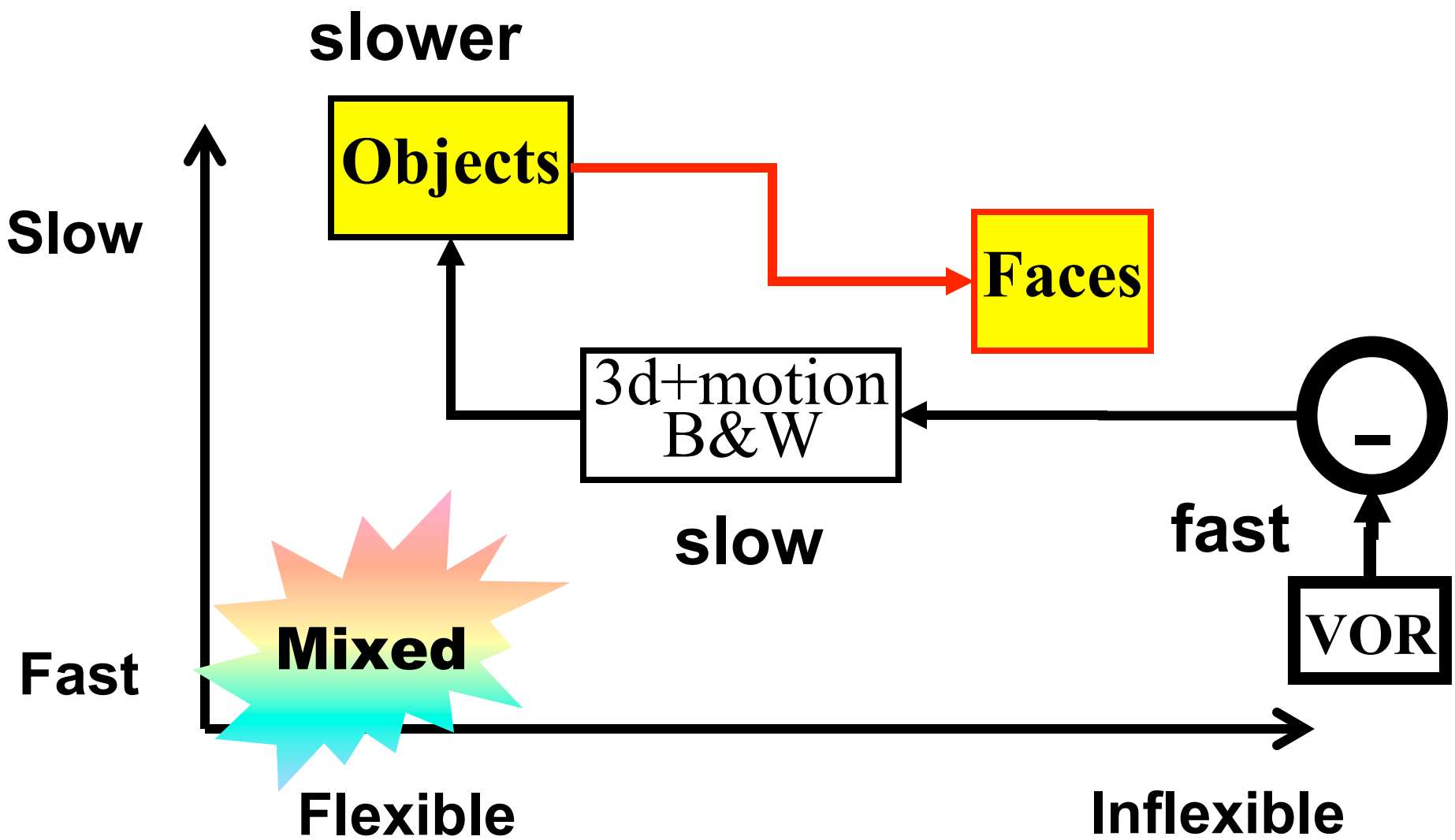

eye
vision
fast
slow
Act
delay
vision
Slow
Fast
VOR
Flexible
Inflexible


Redraw
(not anatomical)
slower
Slow
Vision
slow
fast
VOR
Mixed
Fast
Flexible
Inflexible


Redraw
(not anatomical)
slower
Objects
Slow
Vision
3d+motion
B&W
slow
fast
VOR
Mixed
Fast
Flexible
Inflexible


slower
Objects
Slow
3d+motion
B&W
slow
Fast
Flexible
Inflexible

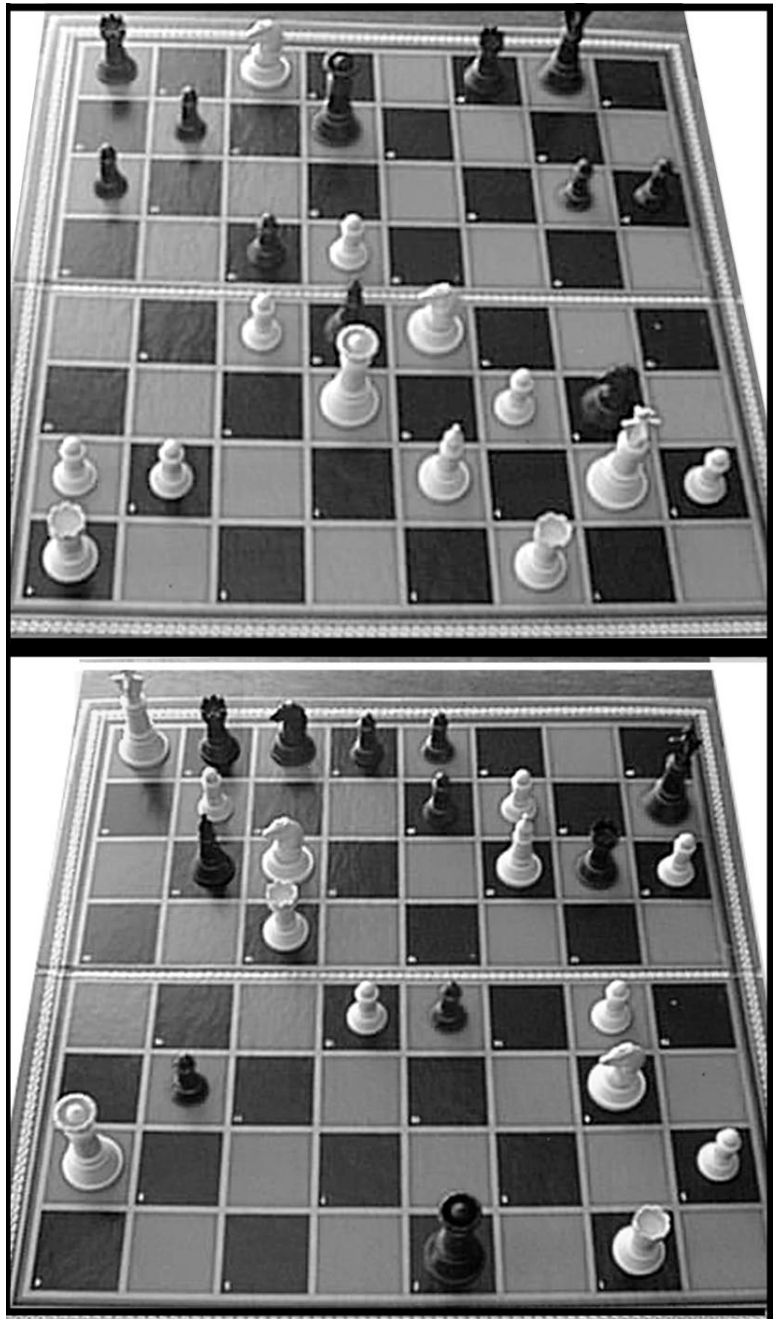
Not sure how to draw this…



Chess experts

- can reconstruct entire chessboard with < ~ 5s inspection
- can recognize 1e5 distinct patterns
- can play multiple games blindfolded and simultaneous
- are no better on random boards

(Simon and Gilmartin, de Groot)

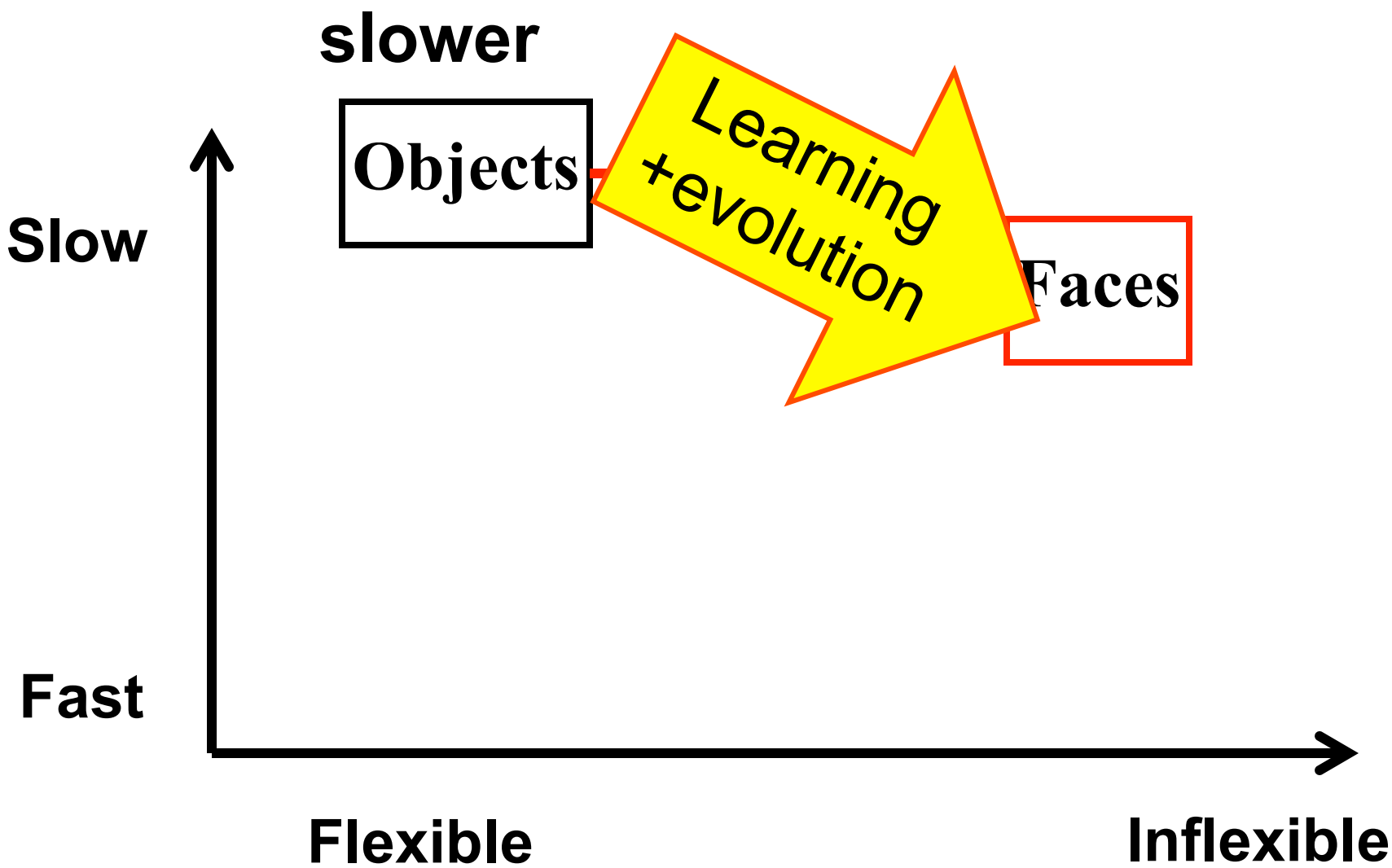


www.psywww.com/intropsych/ch07_cognition/expertise_and_domain_specific_knowledge.html

Specific brain lesions can cause “blindness” to

- Faces
- Fruit or Animals or Tools or ??
- Left side of body
- Movement
- Nonmovement
- ???

Not sure how to draw this…



Specialized Face Learning Is Associated with Individual Recognition in Paper Wasps

Science
AAAS

Michael J. Sheehan* and Elizabeth A. Tibbetts

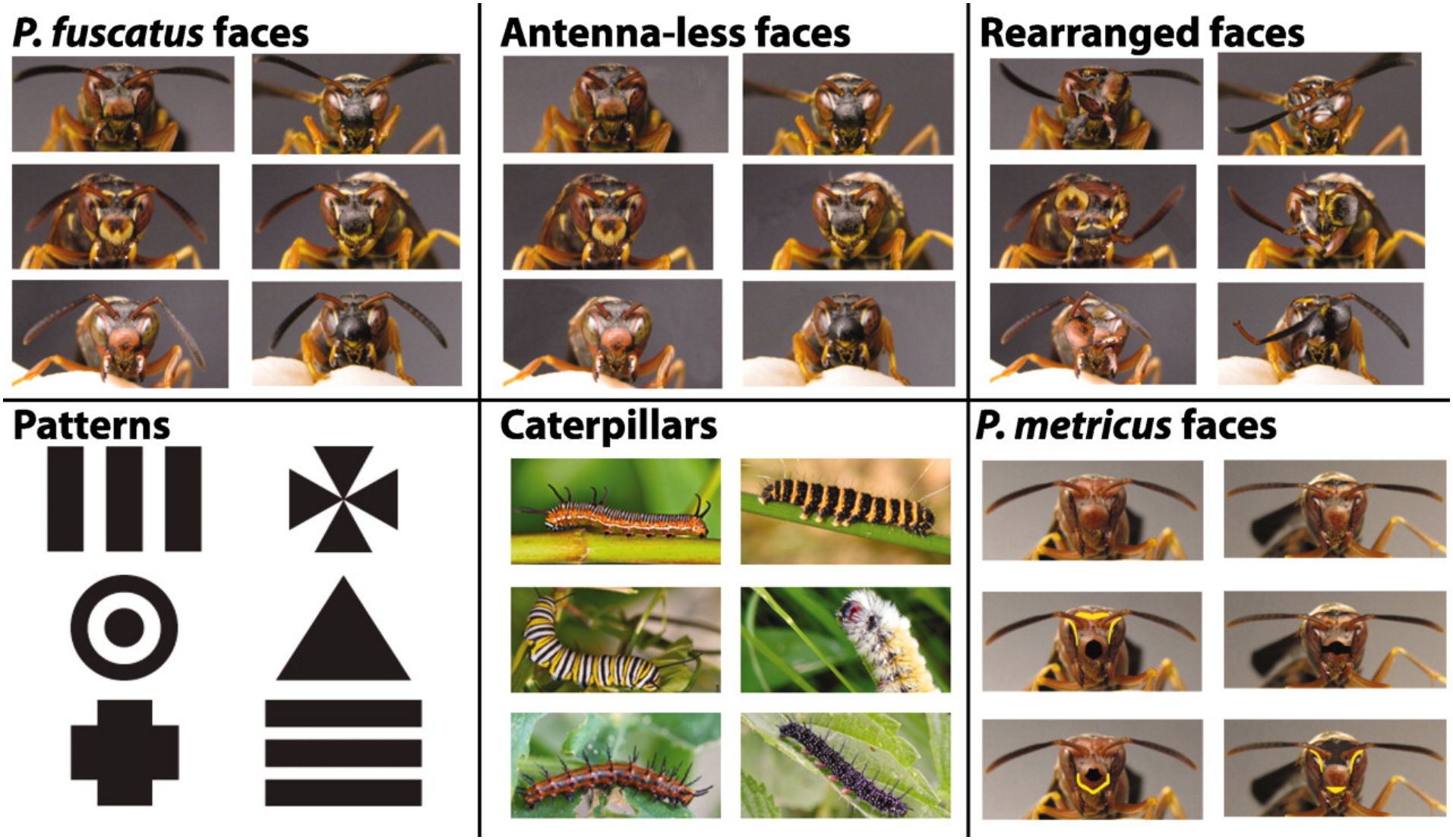
We demonstrate that the evolution of facial recognition in wasps is associated with specialized face-learning abilities. *Polistes fuscatus* can differentiate among normal wasp face images more rapidly and accurately than nonface images or manipulated faces. A close relative lacking facial recognition, *Polistes metricus*, however, lacks specialized face learning. Similar specializations for face learning are found in primates and other mammals, although *P. fuscatus* represents an independent evolution of specialization. Convergence toward face specialization in distant taxa as well as divergence among closely related taxa with different recognition behavior suggests that specialized cognition is surprisingly labile and may be adaptively shaped by species-specific selective pressures such as face recognition.

When needed, even wasps can do it.

2 DECEMBER 2011 VOL 334 **SCIENCE** www.sciencemag.org

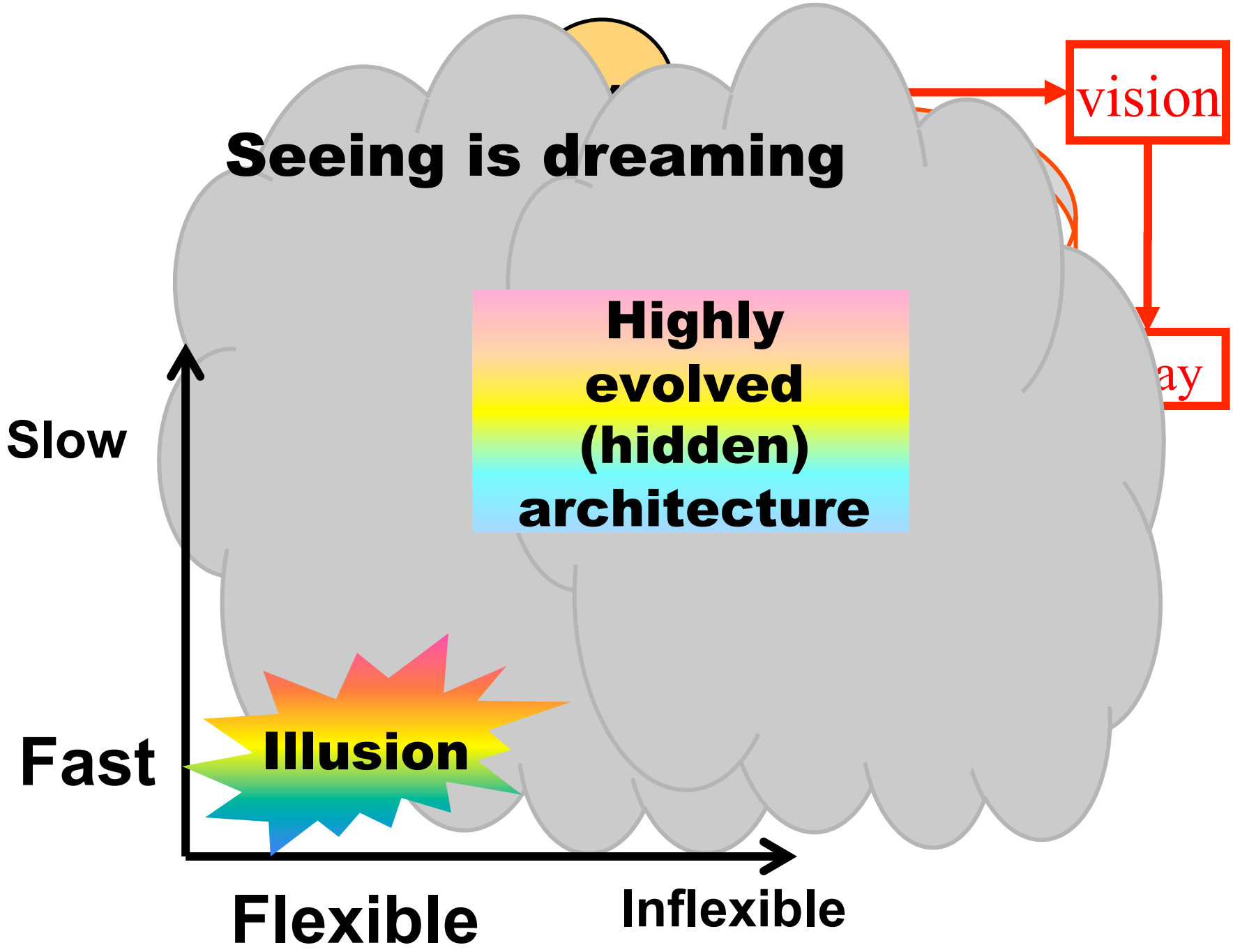
- *Polistes fuscatus* can differentiate among normal wasp face images more rapidly and accurately than nonface images or manipulated faces.
- *Polistes metricus* is a close relative lacking facial recognition and specialized face learning.
- Similar specializations for face learning are found in primates and other mammals, although *P. fuscatus* represents an independent evolution of specialization.
- Convergence toward face specialization in distant taxa as well as divergence among closely related taxa with different recognition behavior suggests that specialized cognition is surprisingly labile and may be adaptively shaped by species-specific selective pressures such as face recognition.

Fig. 1 Images used for training wasps.

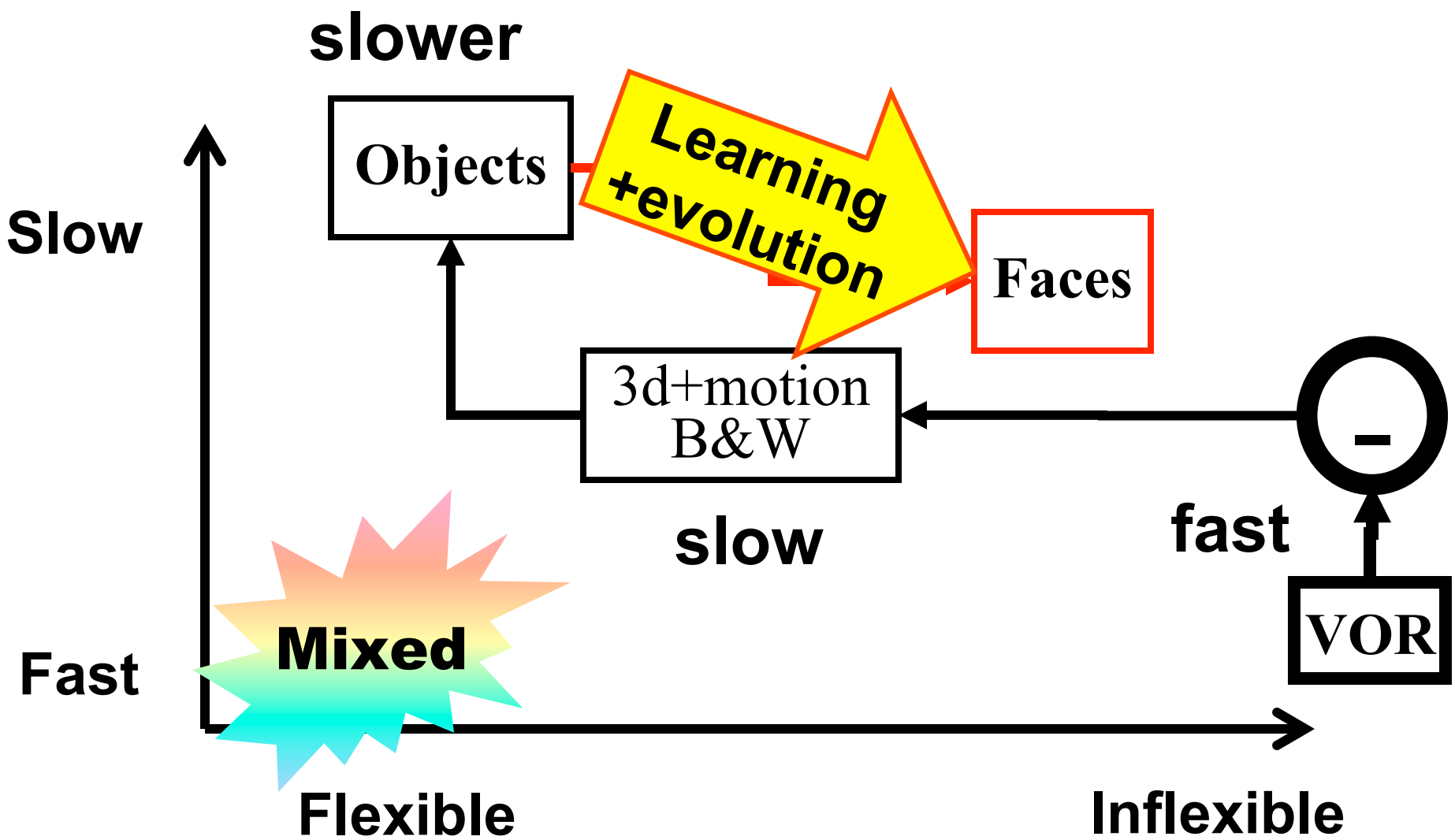


M J Sheehan, E A Tibbetts Science 2011;334:1272-1275

Published by AAAS


Seeing is dreaming
vision
ay
Highly evolved (hidden) architecture
Slow
Fast
Illusion
Flexible
Inflexible

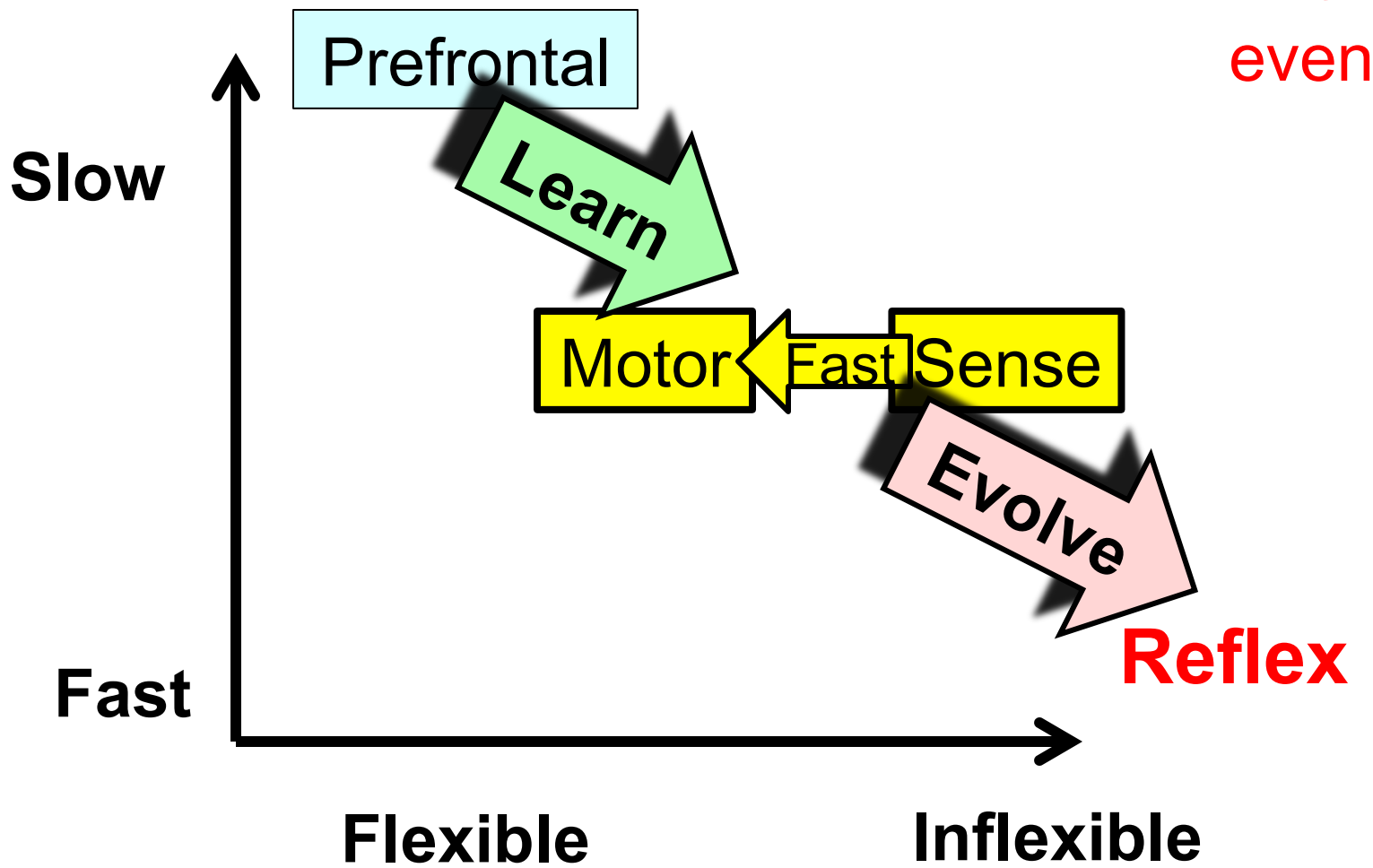
Not sure how to draw this…

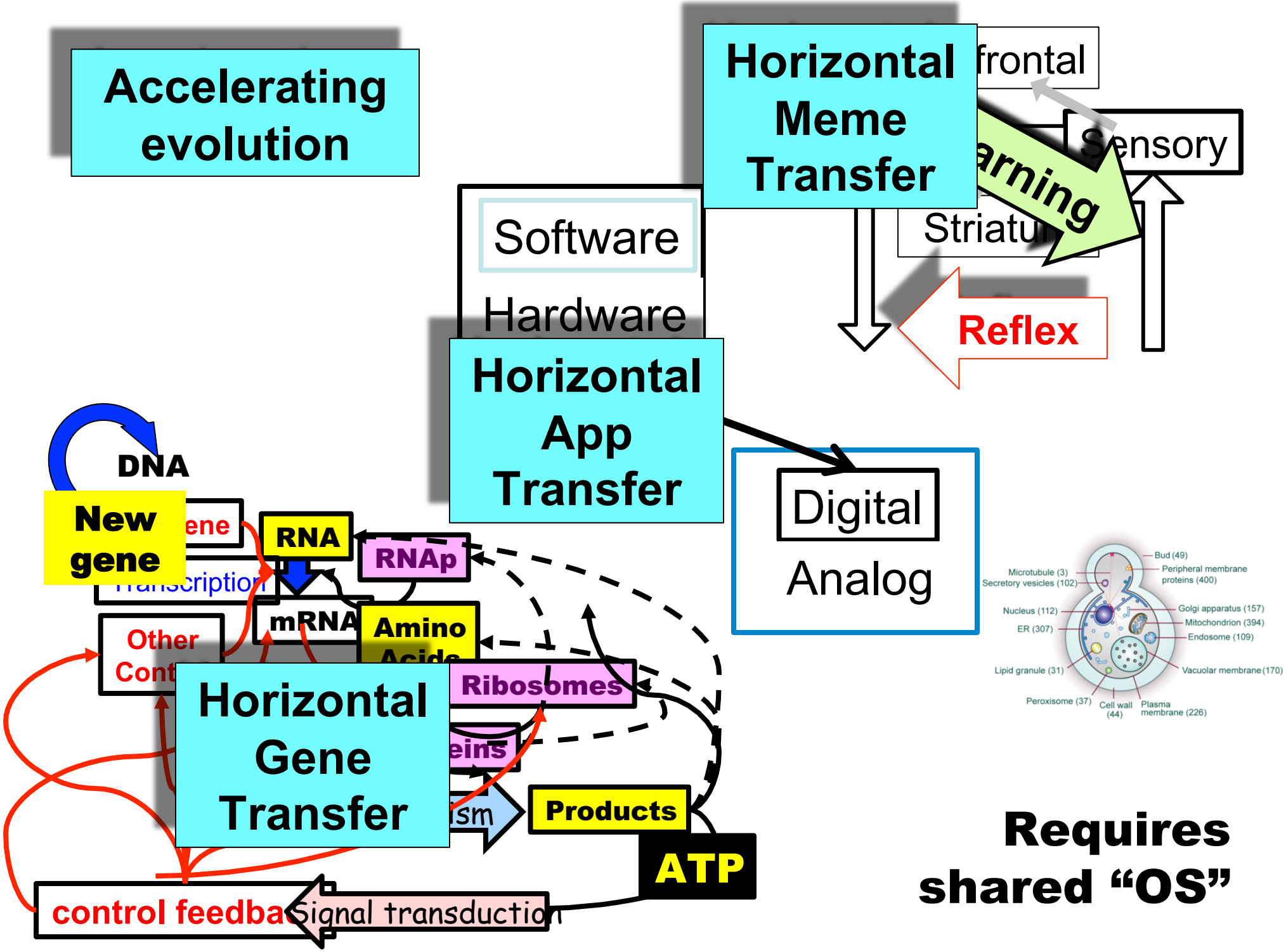


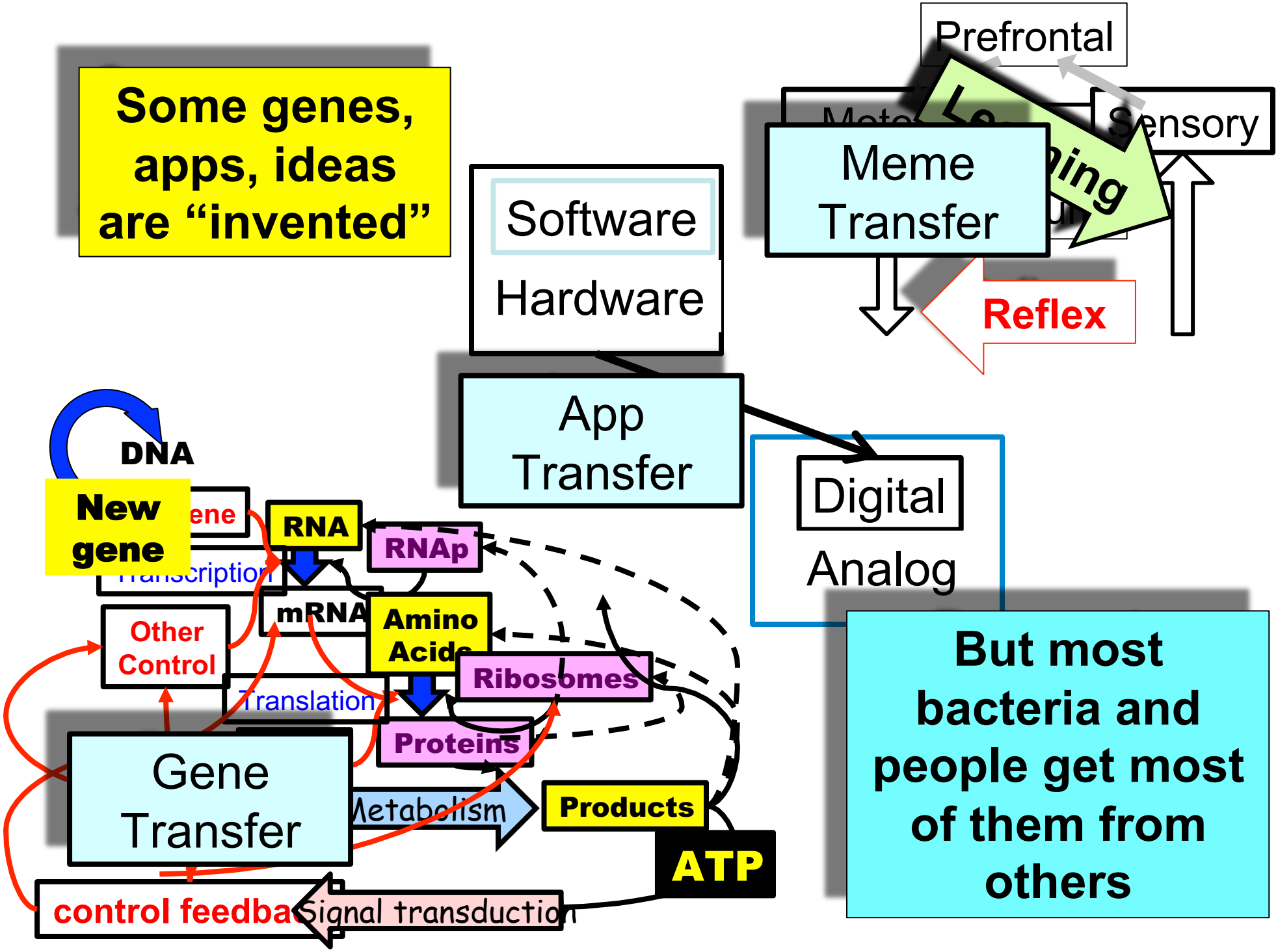
Universal tradeoffs?

Learning can be ***very*** slow.

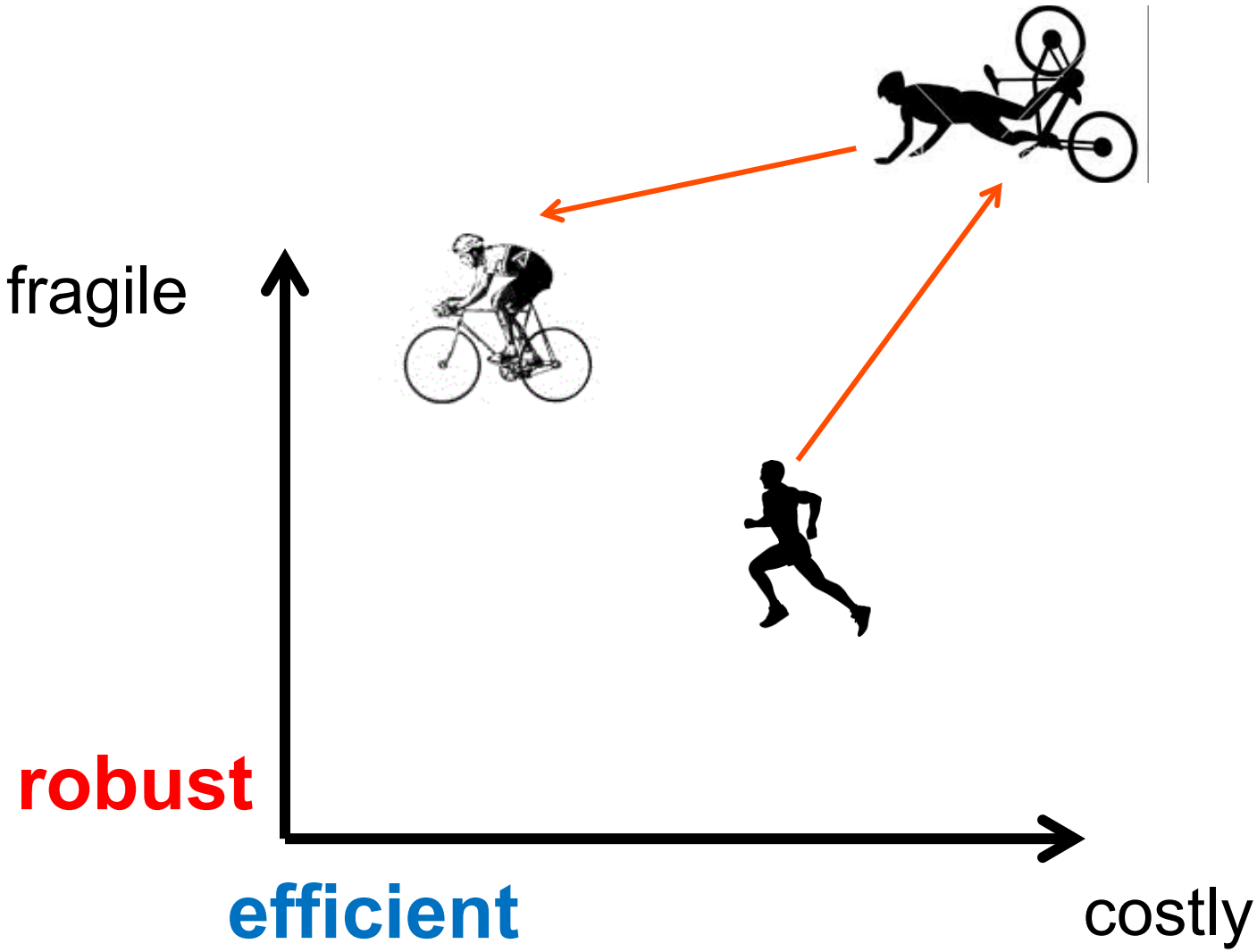
Evolution is even slower.




Accelerating evolution
Horizontal Meme Transfer
frontal
Sensory
arning
Striatu
Software
Hardware
Reflex
Horizontal App Transfer
Digital
Analog
DNA
New gene
ene
RNA
RNAp
Transcription
mRNA
Amino Acids
Other Cont
Ribosomes
eins
Horizontal Gene Transfer
sm
Products
ATP
control feedba
Signal transduction
Bud (49)
Microtubule (3)
Peripheral membrane proteins (400)
Secretory vesicles (102)
Nucleus (112)
Golgi apparatus (157)
Mitochondrion (394)
ER (307)
Endosome (109)
Lipid granule (31)
Vacuolar membrane (170)
Peroxisome (37)
Cell wall (44)
Plasma membrane (226)
Requires shared "OS"


Some genes, apps, ideas are "invented"
Prefrontal
Sensory
Meme Transfer
Reflex
Software
Hardware
App Transfer
Digital
Analog
But most bacteria and people get most of them from others
DNA
New gene
RNA
RNAp
mRNA
Amino Acids
Ribosomes
Other Control
Translation
Proteins
Gene Transfer
Metabolism
Products
ATP
control feedback
Signal transduction

Learning

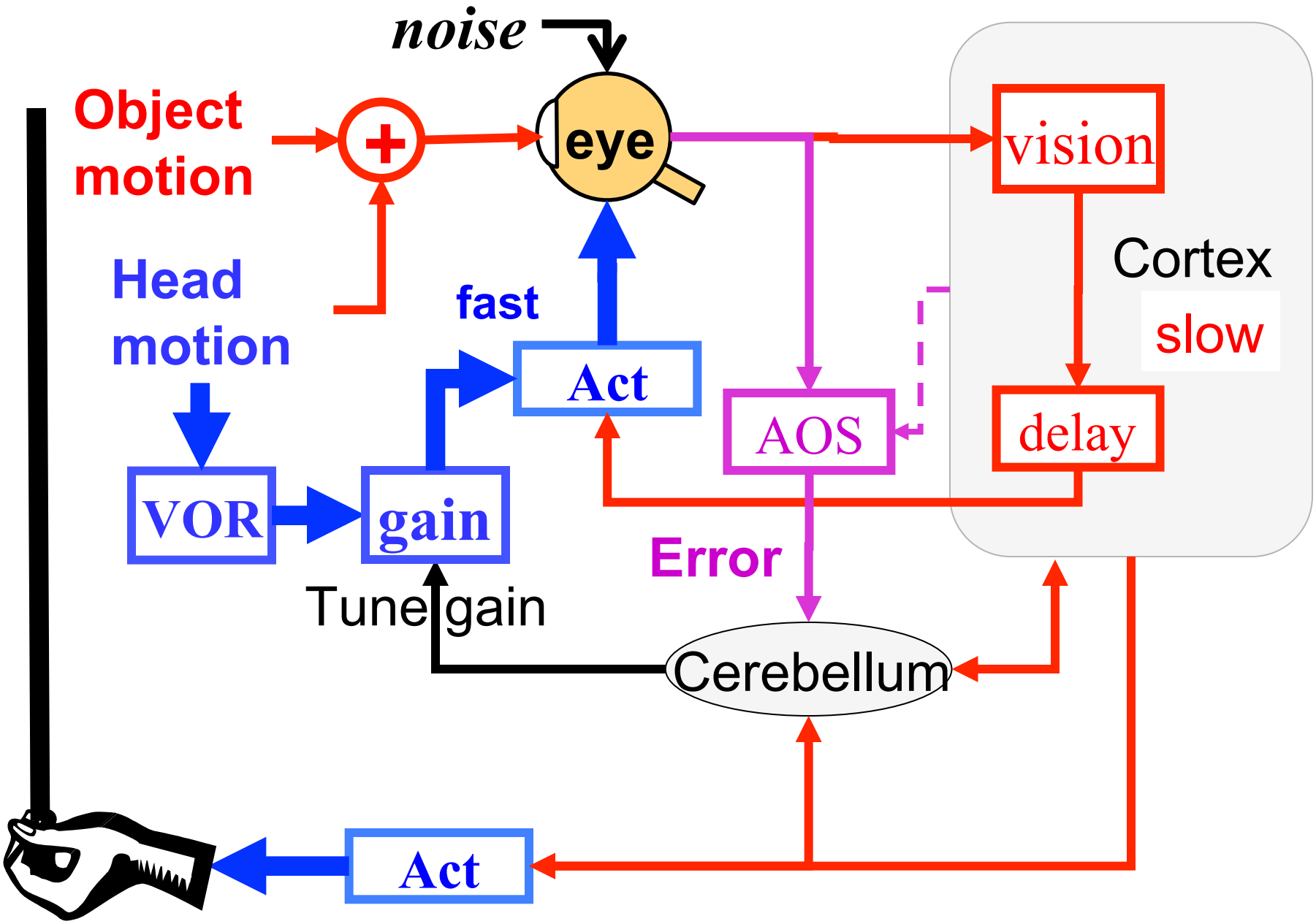


Learning

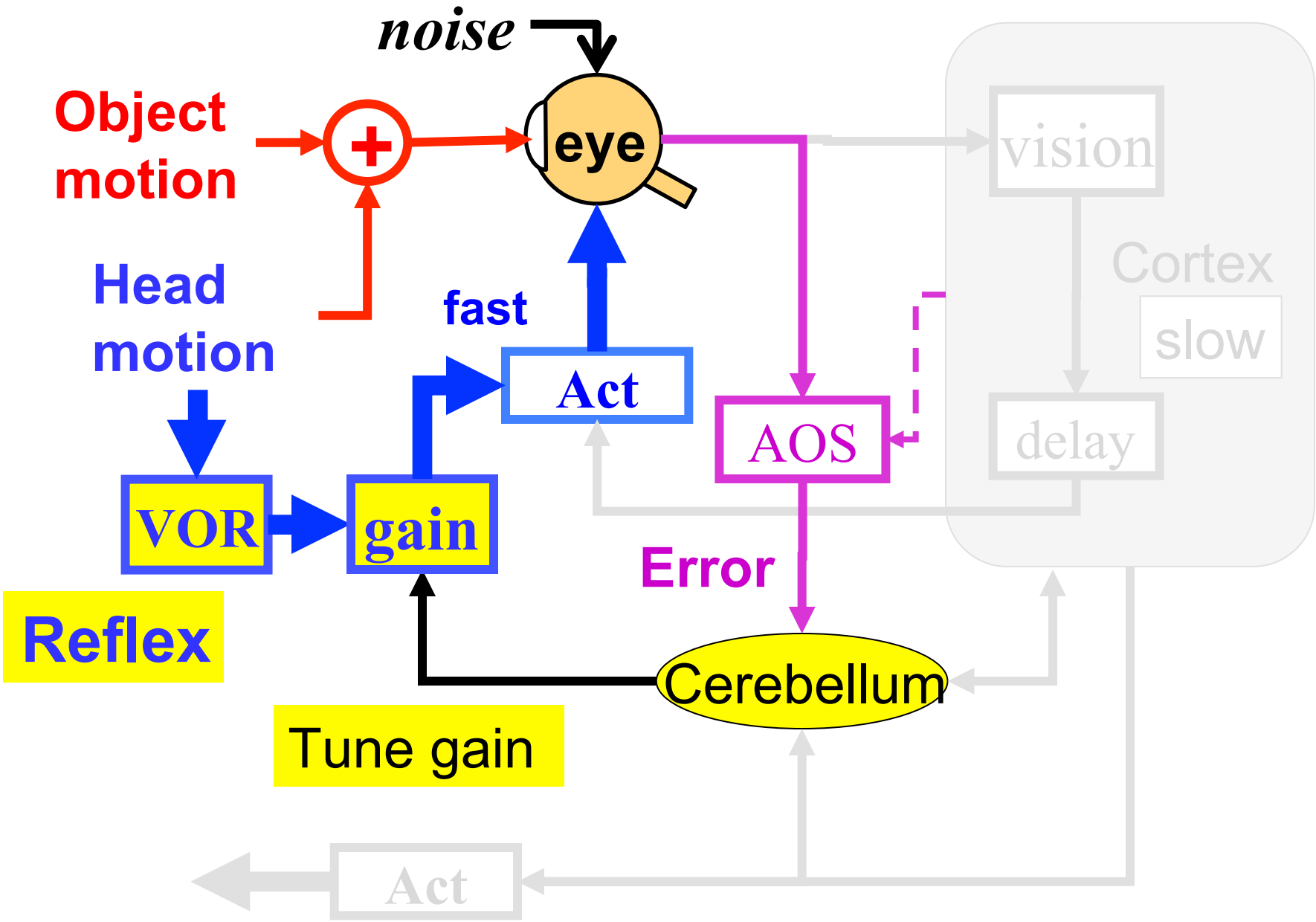
bike

walk

crawl

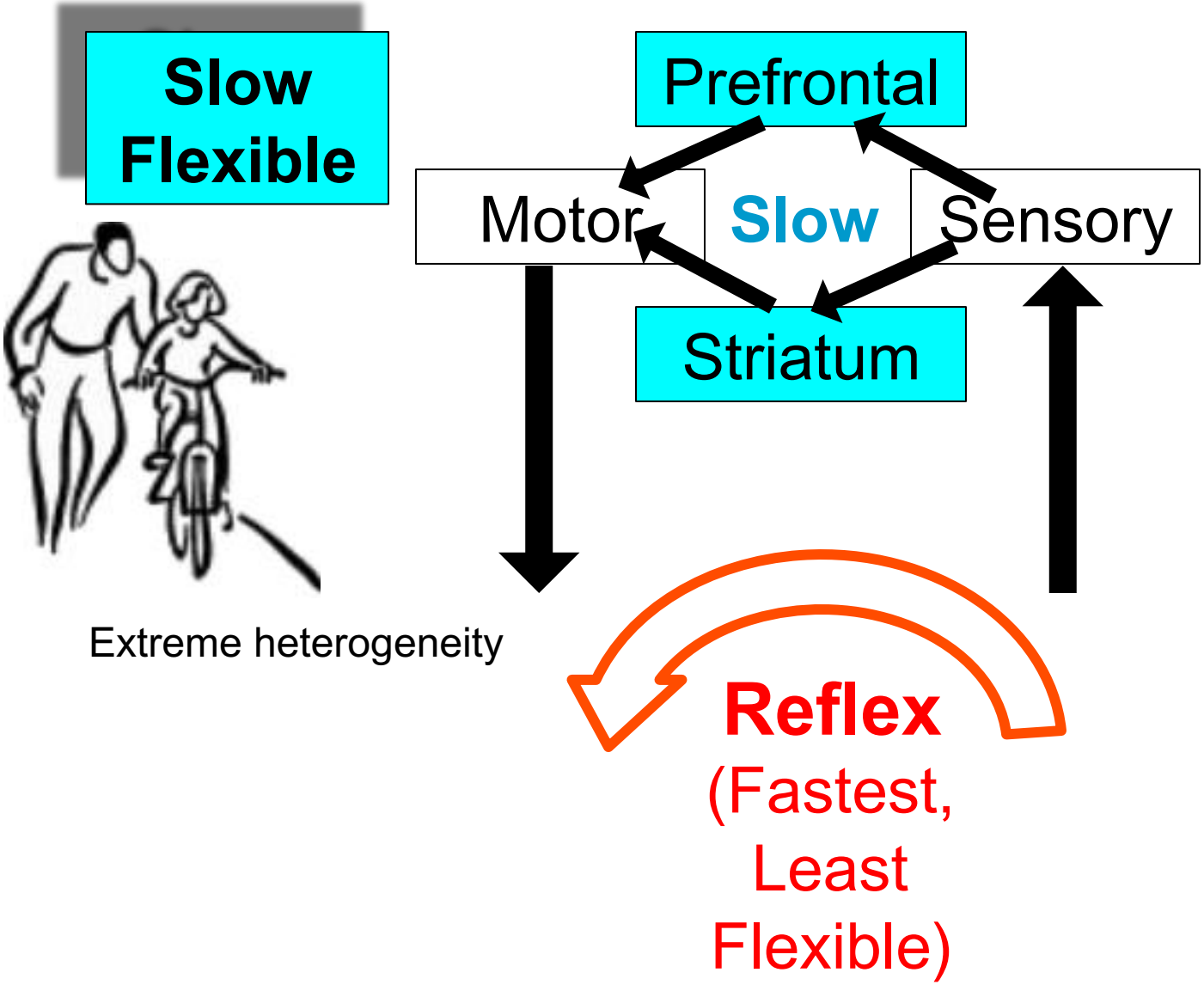


AOS = Accessory Optical system



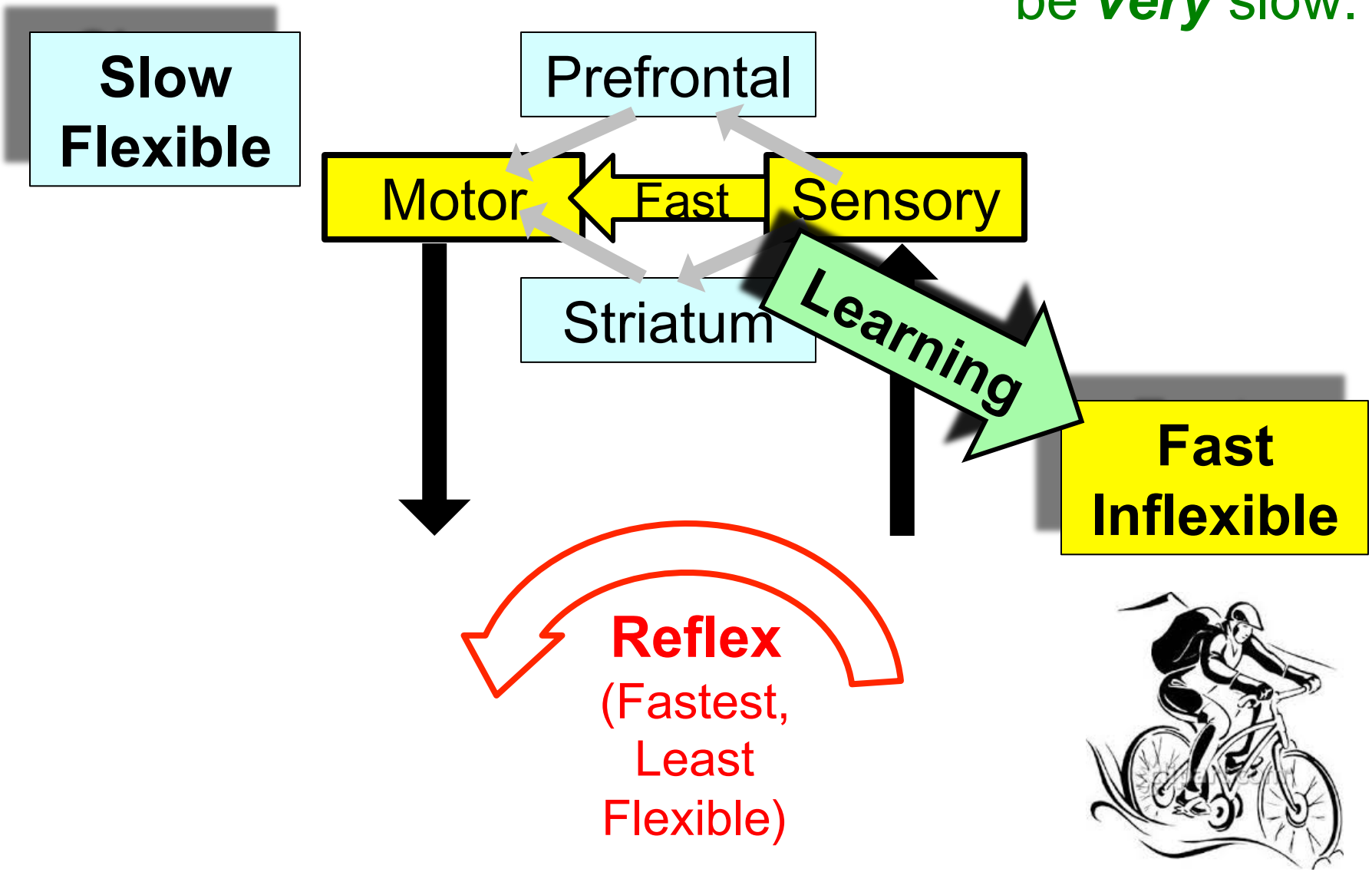
AOS = Accessory Optical system

Learning

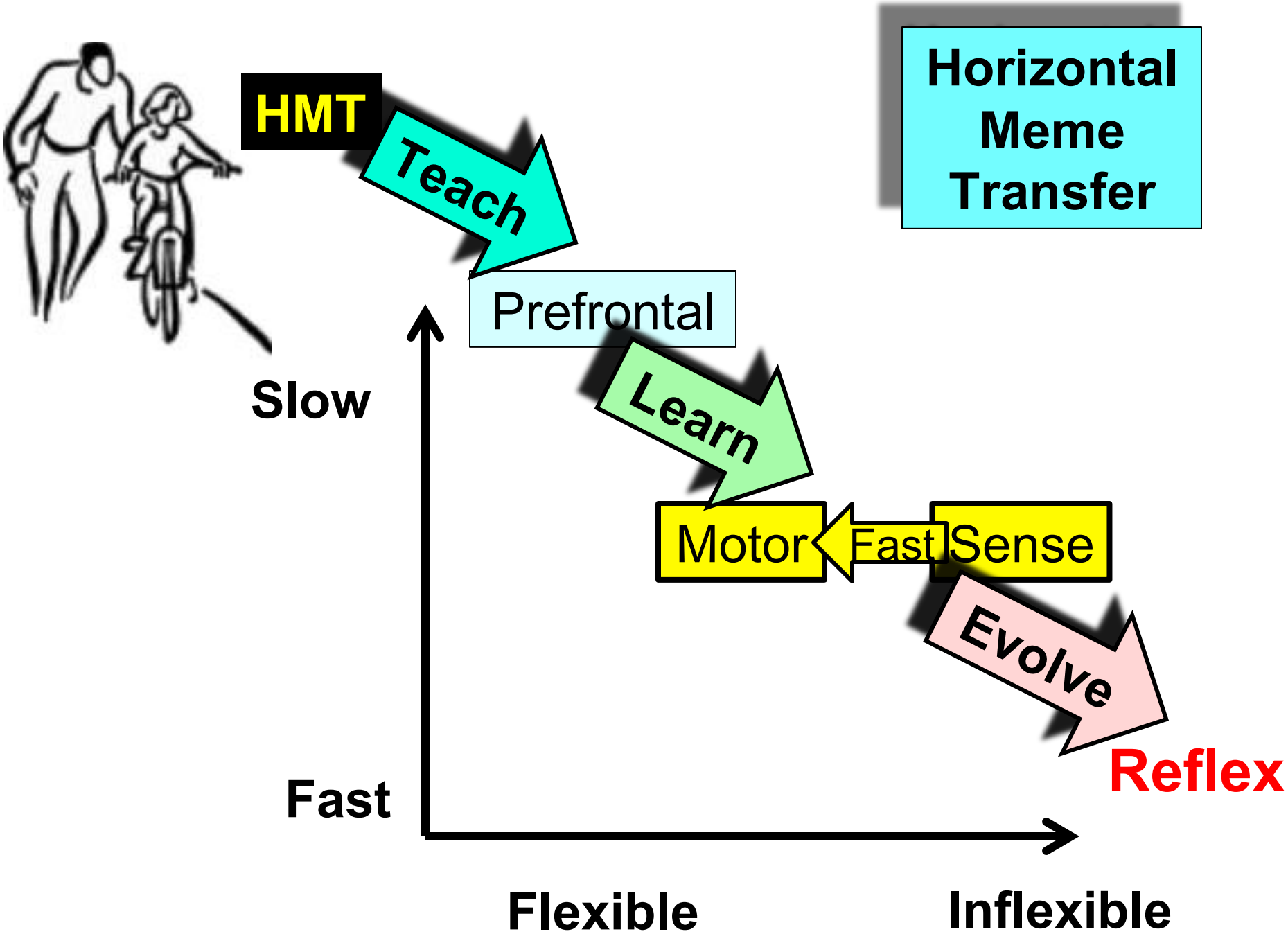


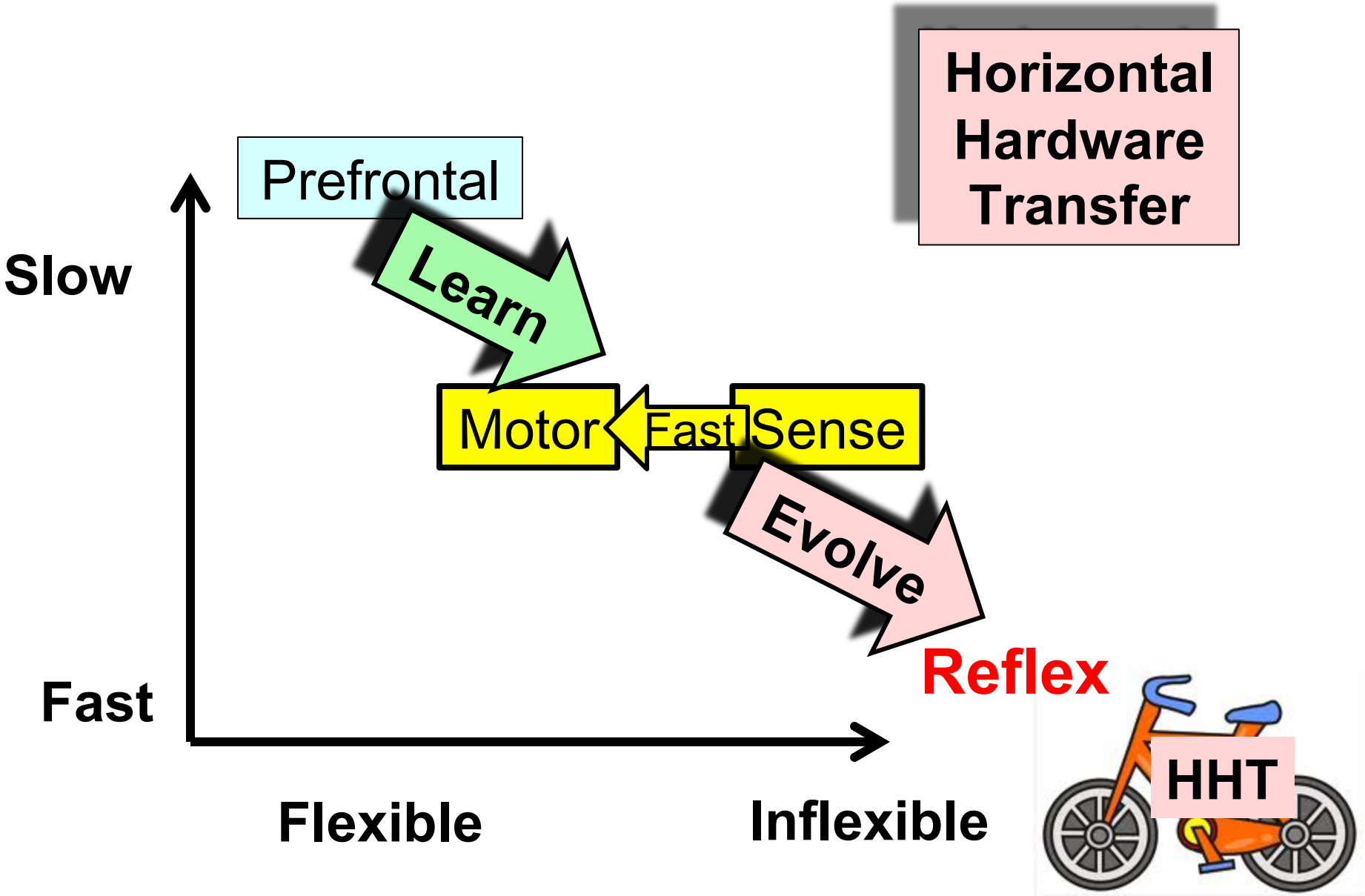
Ashby & Crossley

Learning can be ***very*** slow.



Ashby & Crossley


Horizontal
Meme
Transfer
HMT
Teach
Prefrontal
Learn
Motor
Fast
Sense
Evolve
Reflex
Slow
Fast
Flexible
Inflexible


Horizontal Hardware Transfer
Prefrontal
Learn
Slow
Motor
Fast
Sense
Evolve
Reflex
Fast
HHT
Flexible
Inflexible

HMT

Apps

Prefrontal

Slow

Learn

OS

Motor

Fast

Sense

HW

Evolve

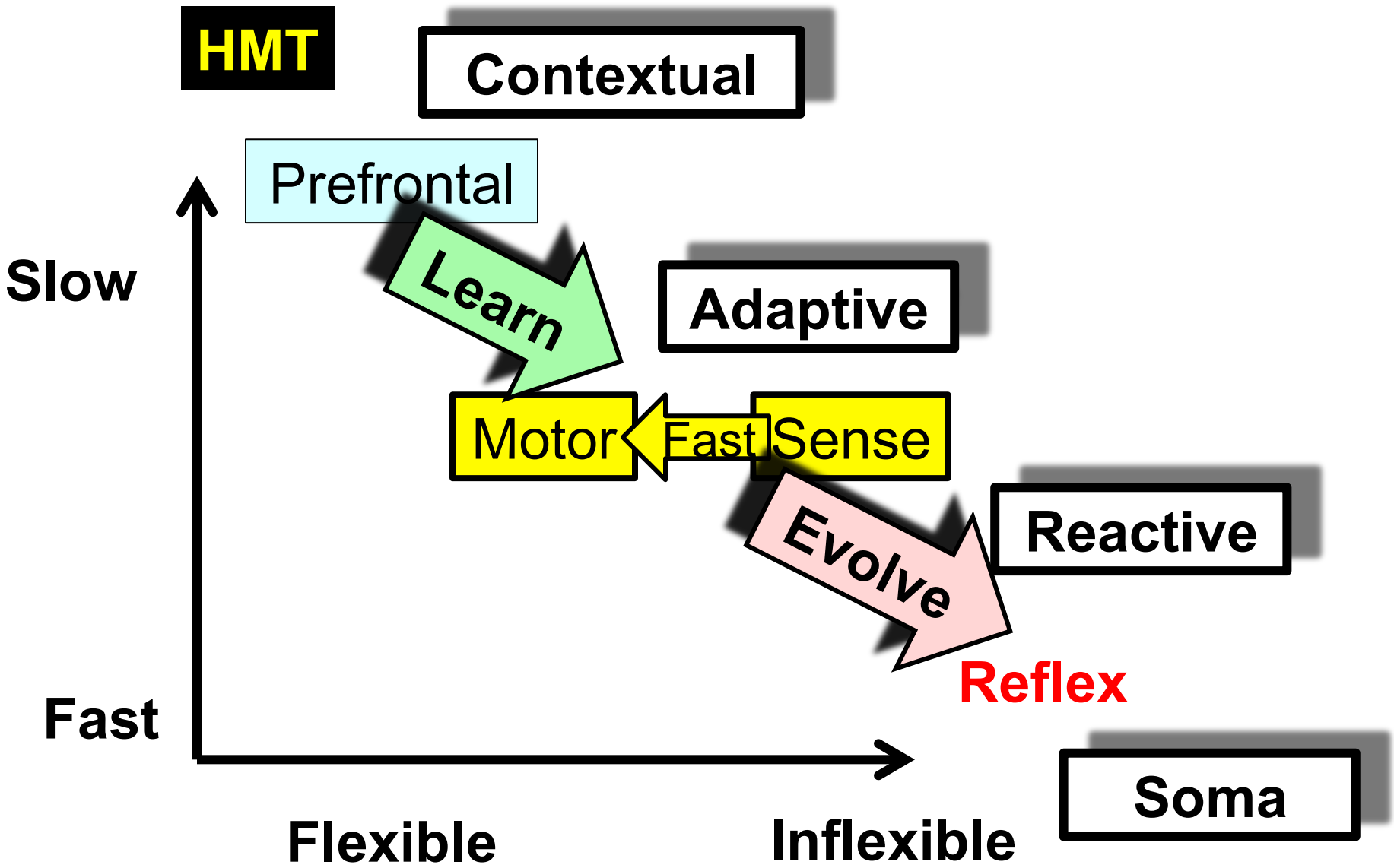
Reflex

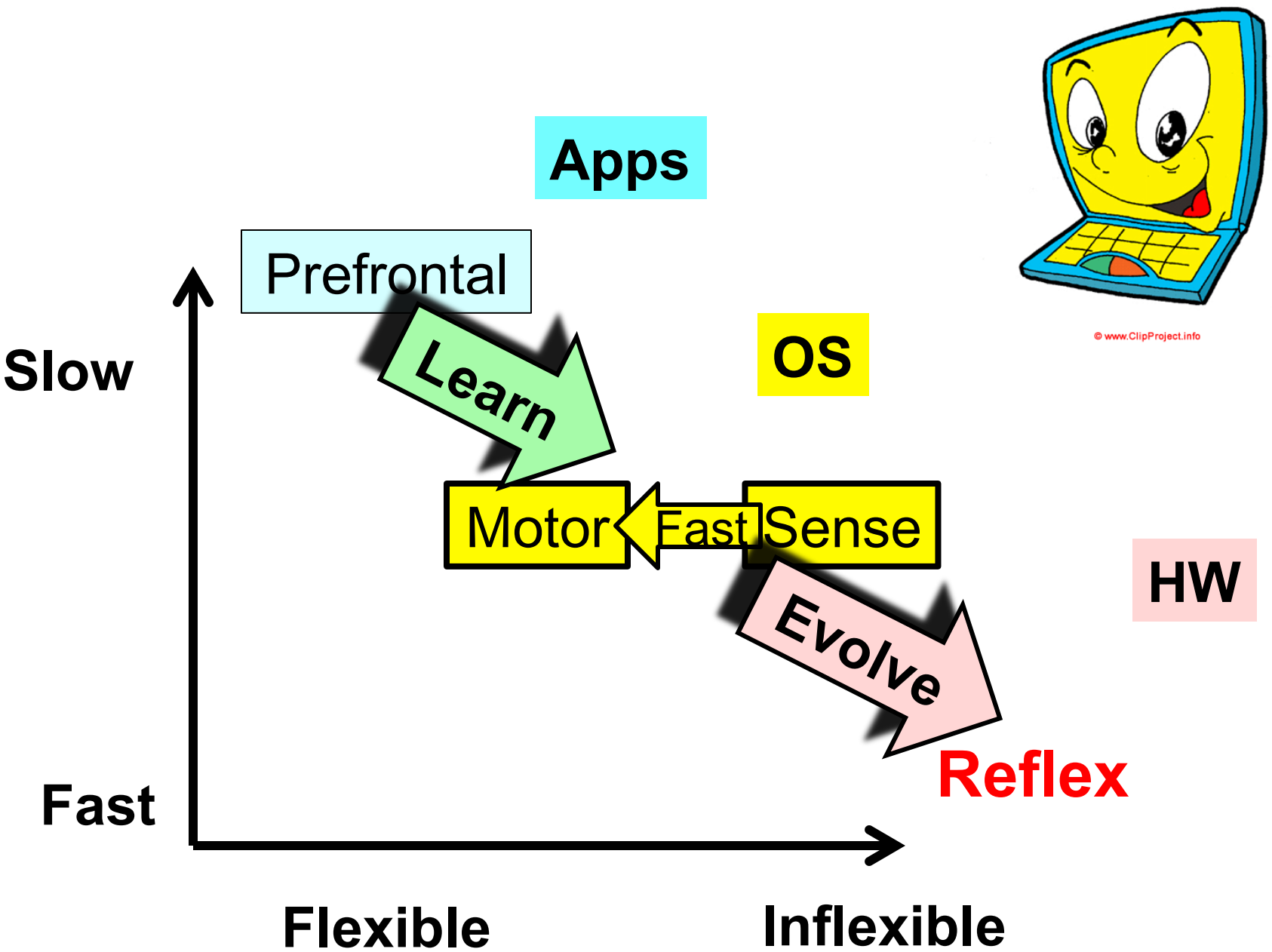
Fast

HHT

Flexible

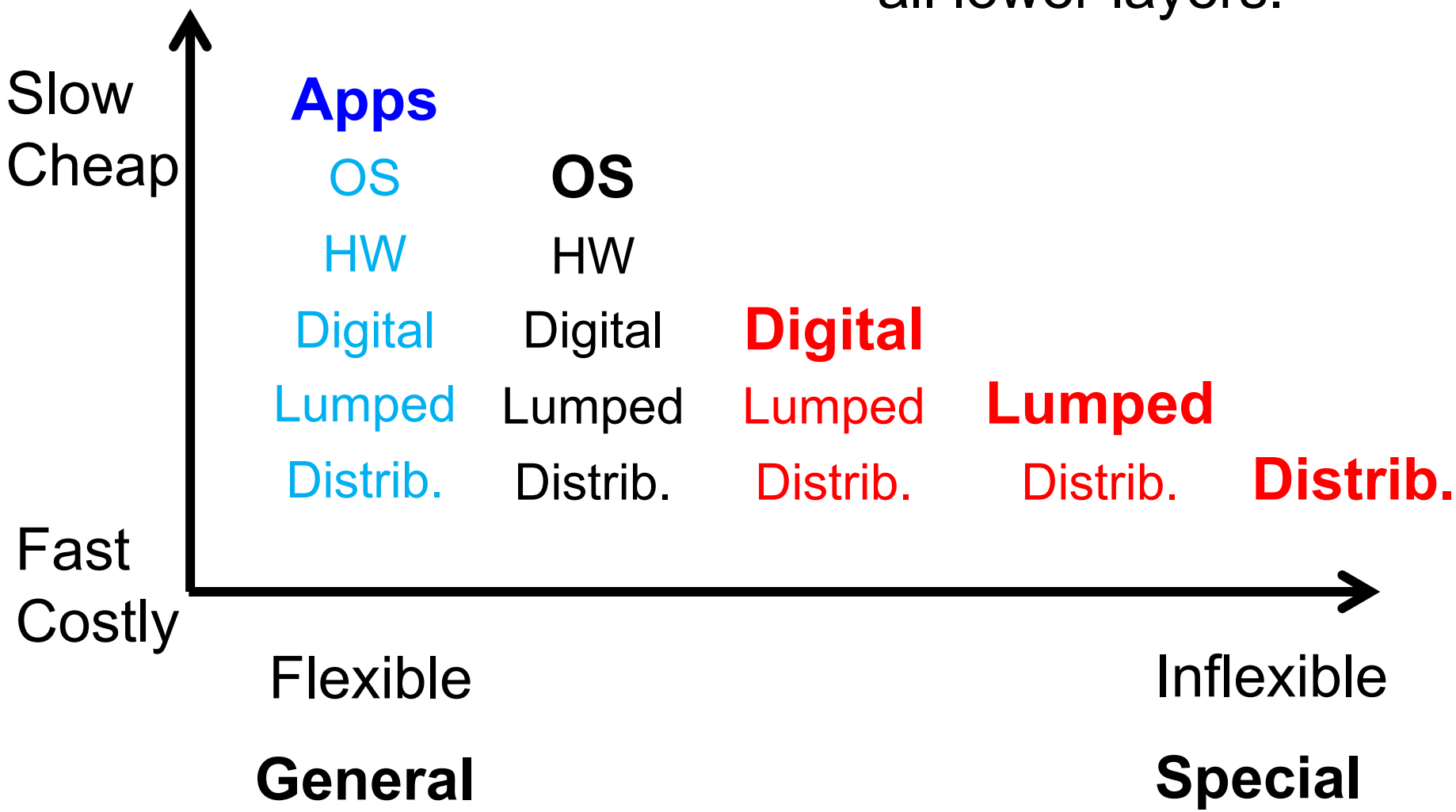
Inflexible


HMT
Contextual
Prefrontal
Slow
Learn
Adaptive
Motor
Fast
Sense
Evolve
Reactive
Reflex
Fast
Soma
Flexible
Inflexible

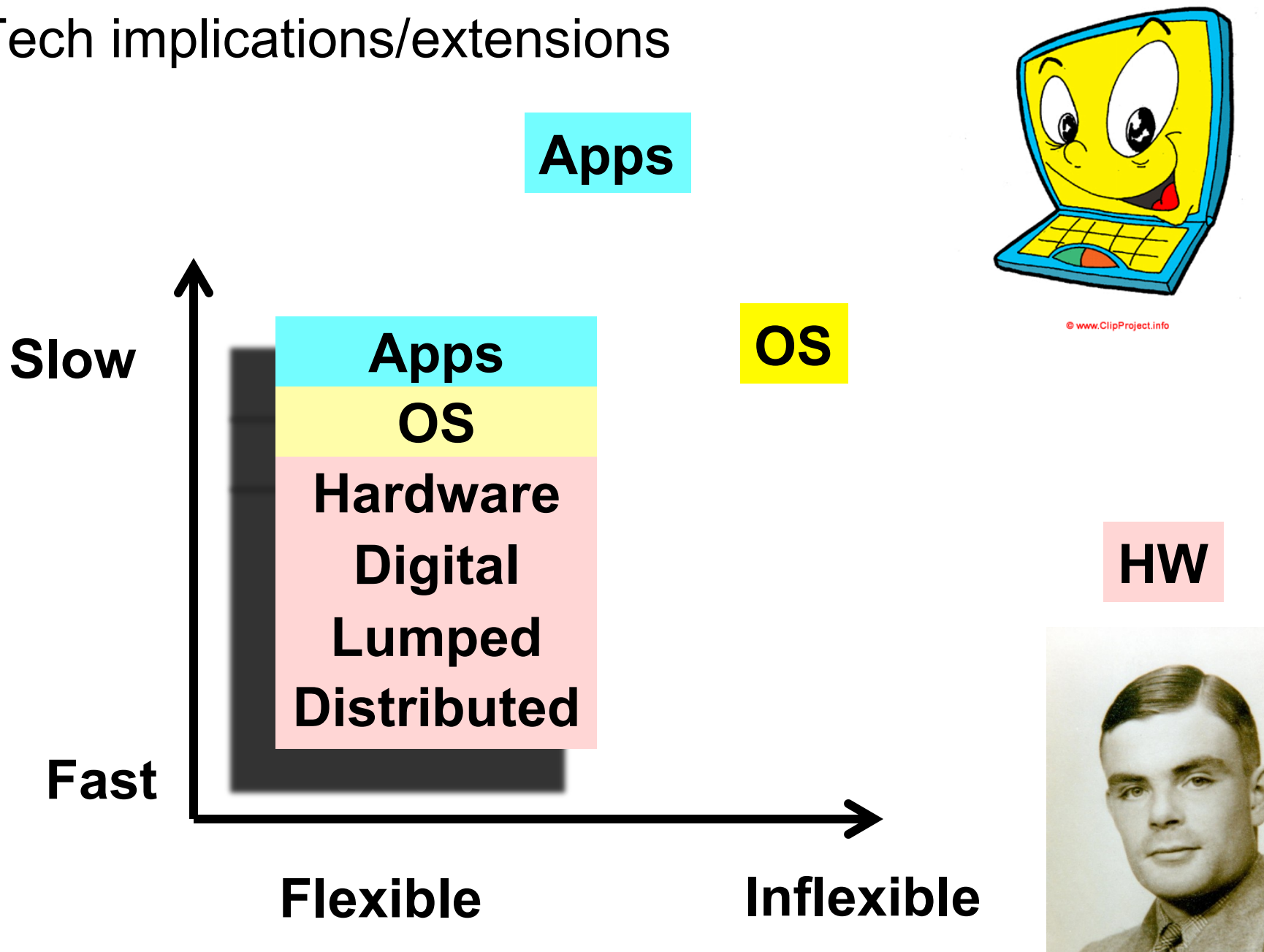

Apps
Prefrontal
Slow
Learn
OS
Motor
Fast
Sense
HW
Evolve
Reflex
Fast
Flexible
Inflexible
© www.ClipProject.info

Layered Architecture

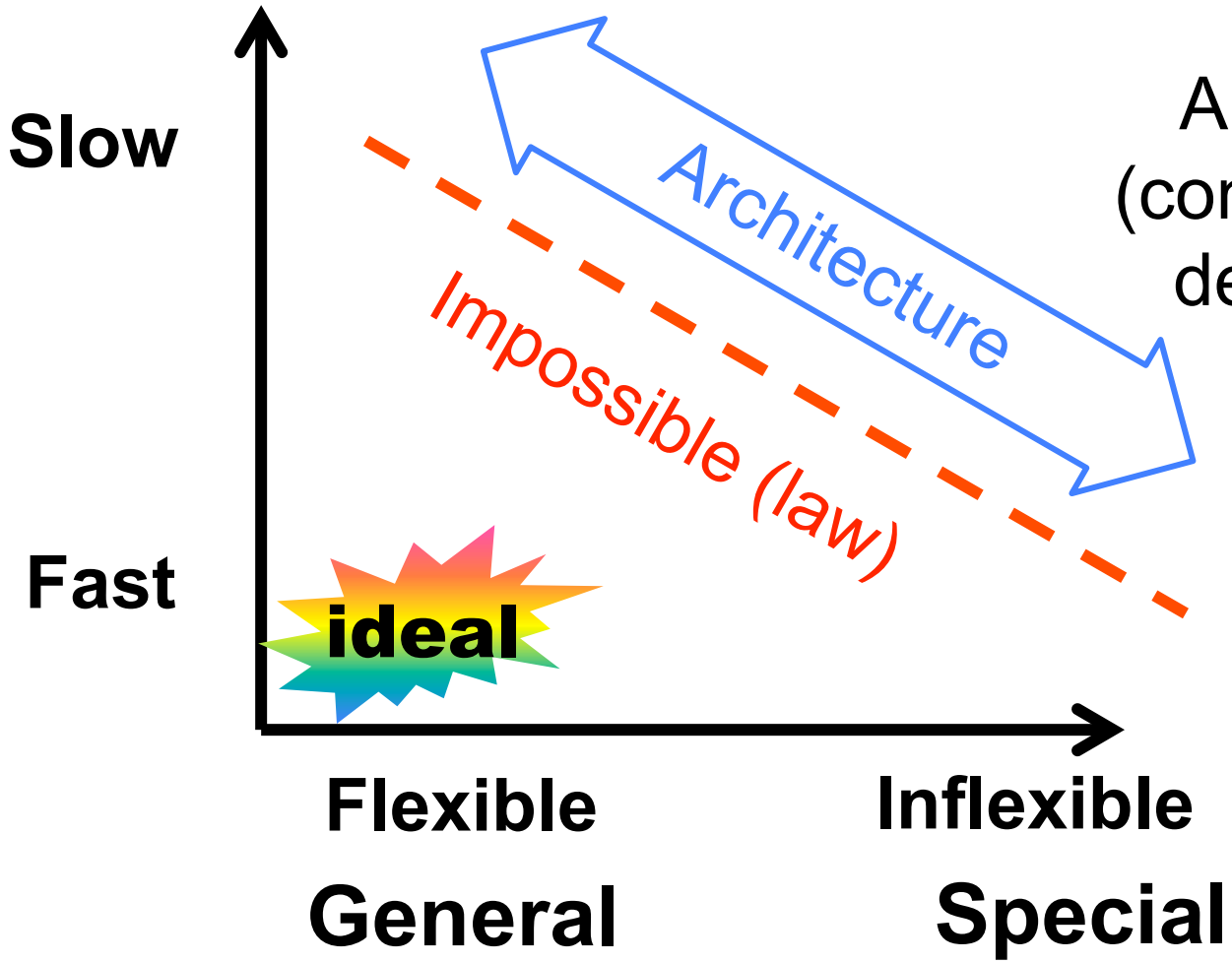
Any layer needs all lower layers.



Tech implications/extensions

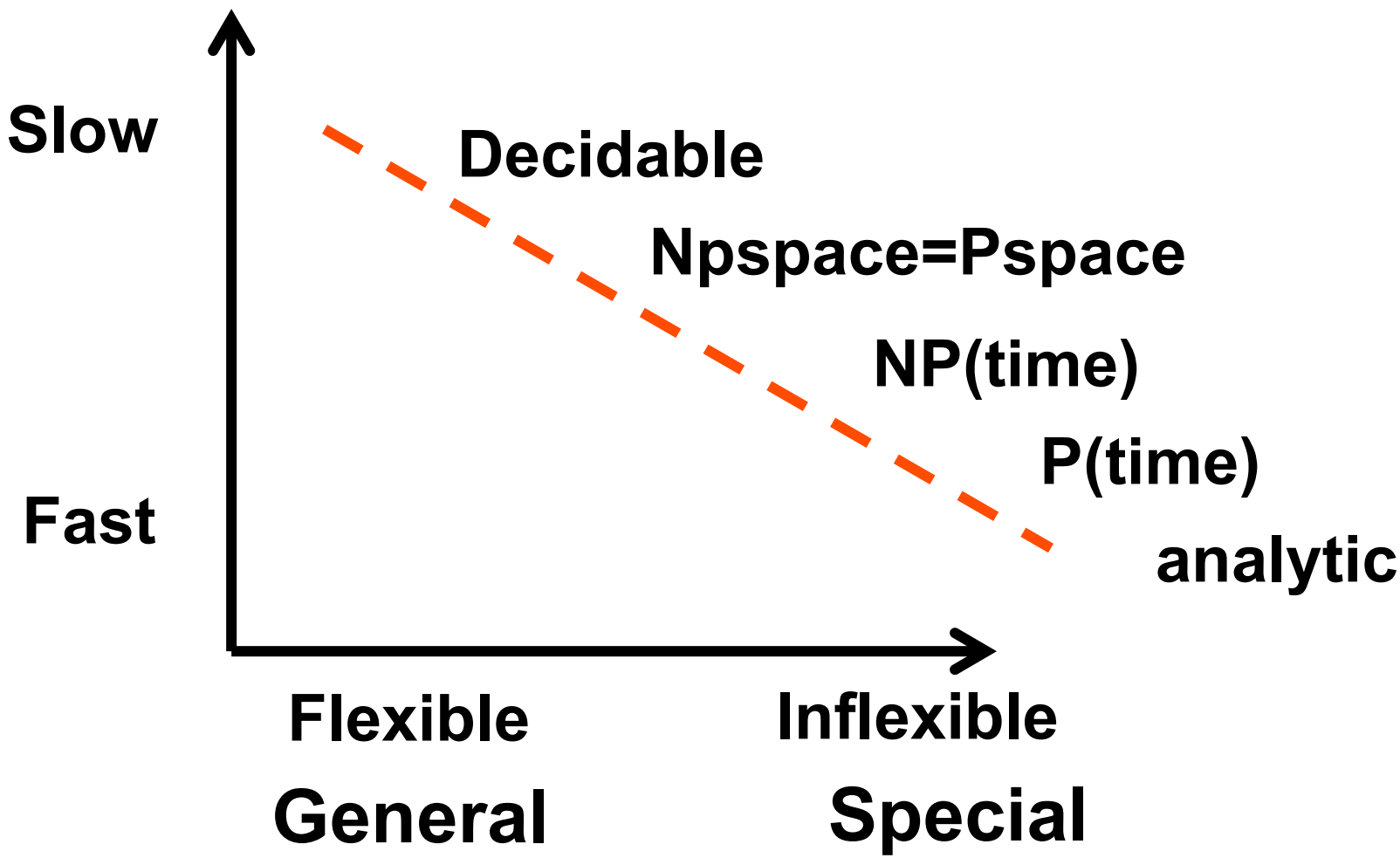


Universal laws and architectures (Turing)

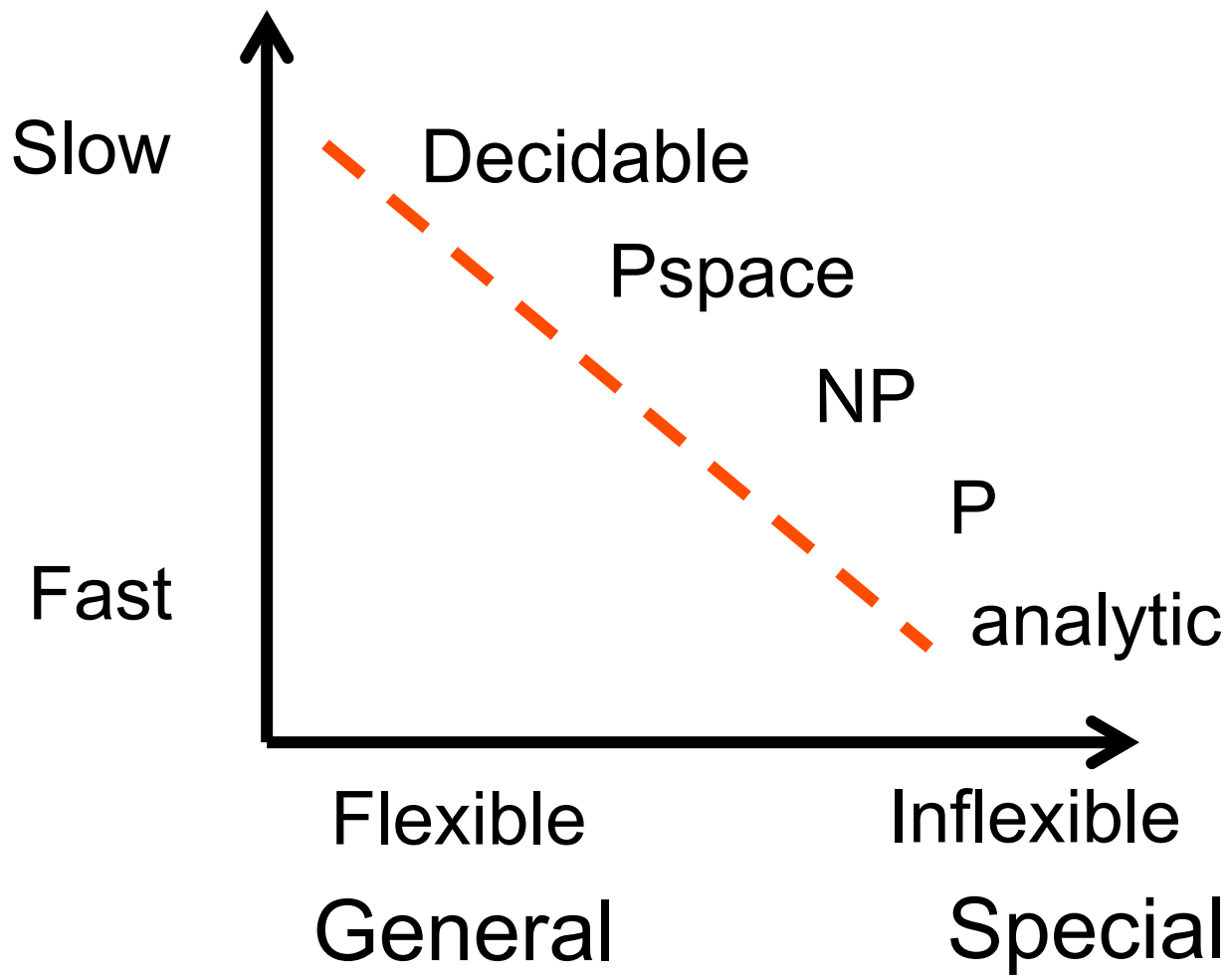


Architecture (constraints that deconstrain)

Computation
(on and off-line)



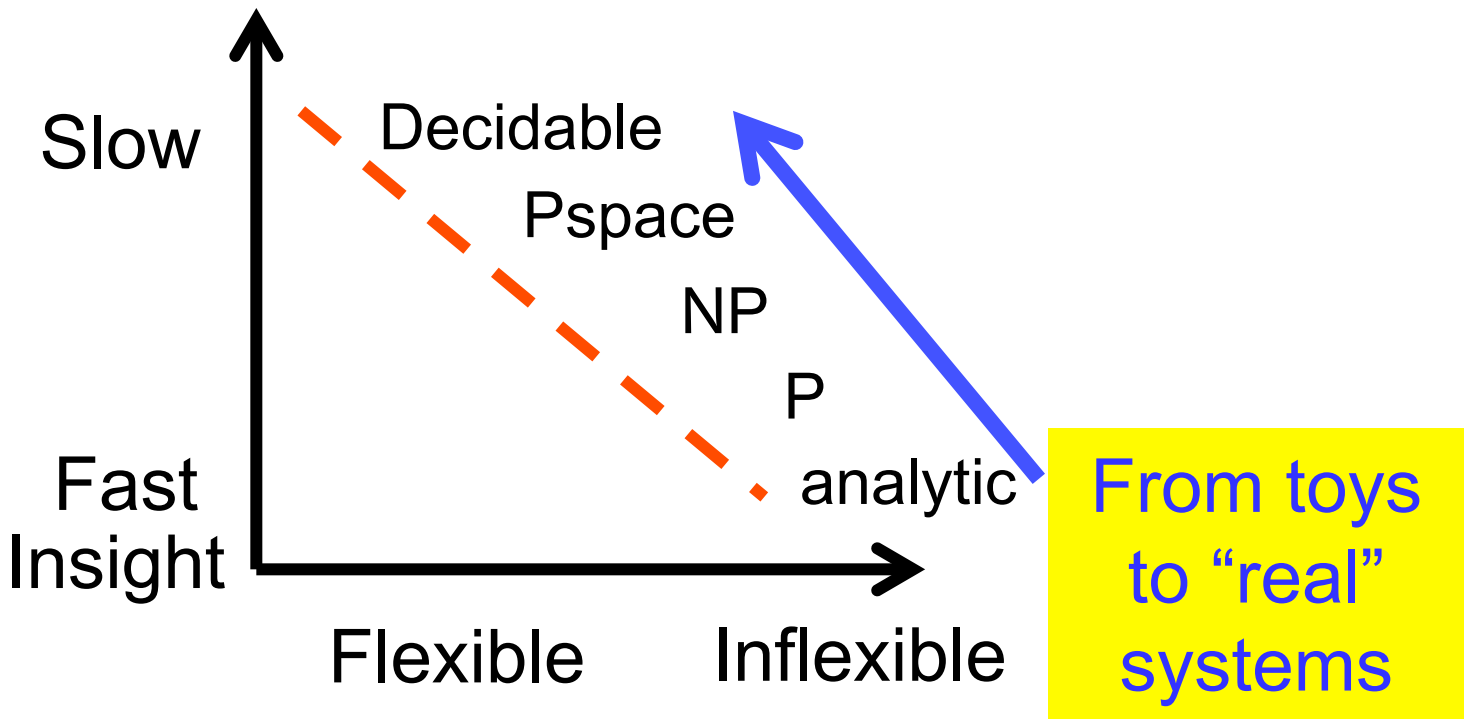
Computation
(on and off-line)



Insight
Accessible
Verifiable

Compute

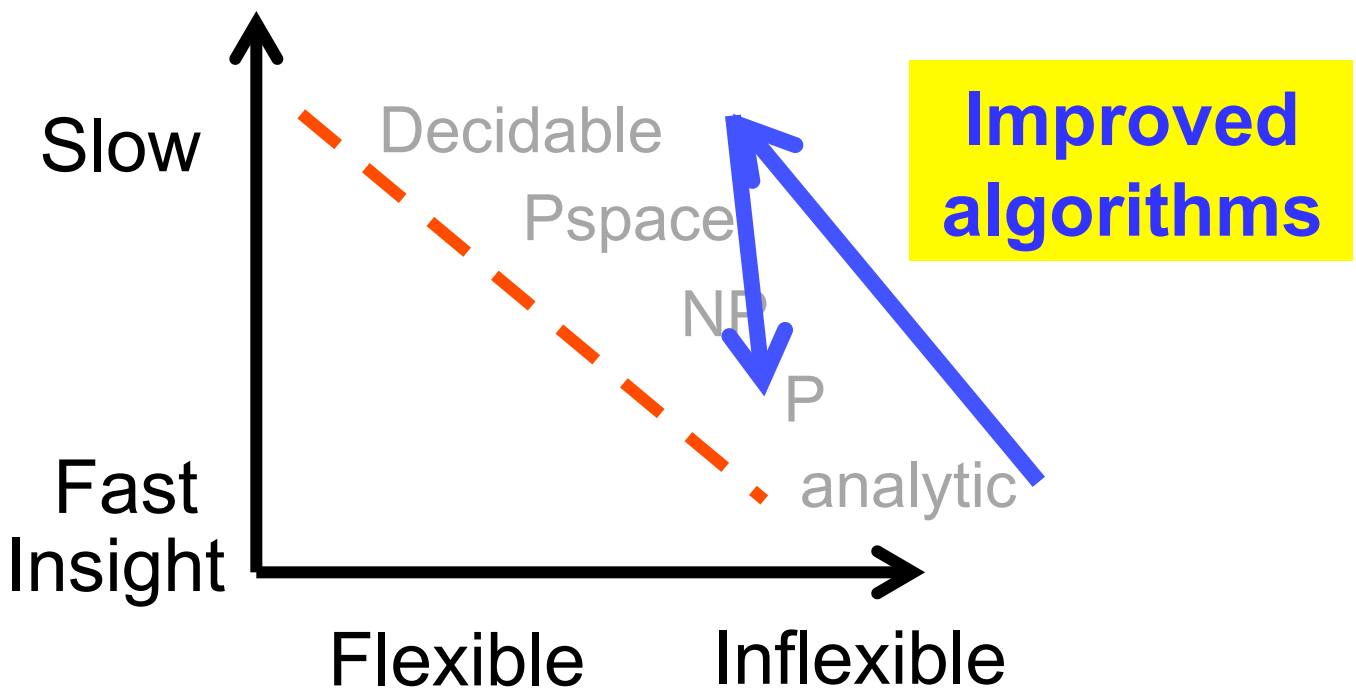
Research progress



Control, OR

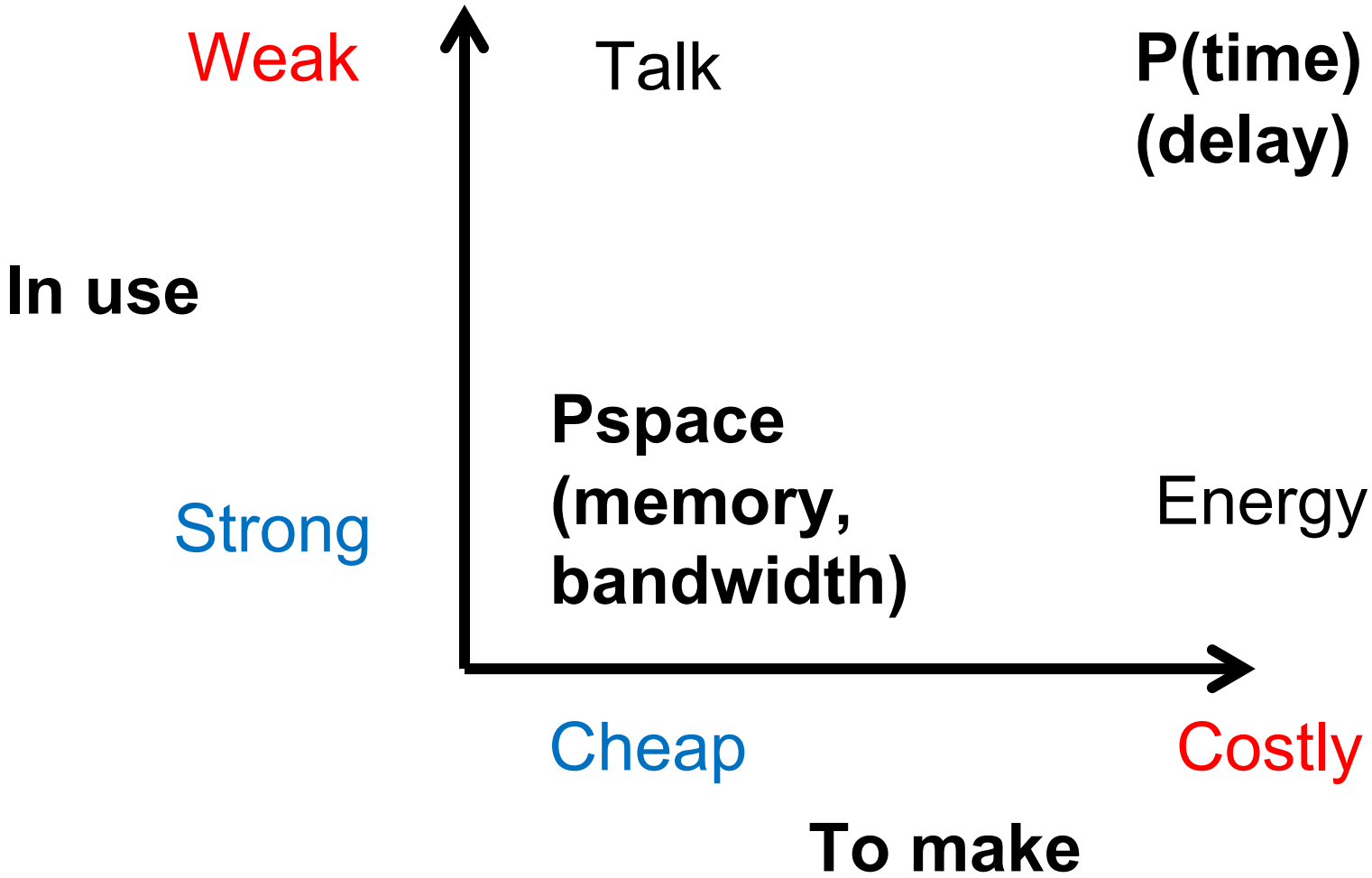
Compute

Research progress



Control, OR

Resource cost vs effectiveness



$??

~~$50~~

1 TB < ~~$100~~

In use

Pspace
(memory,
bandwidth)

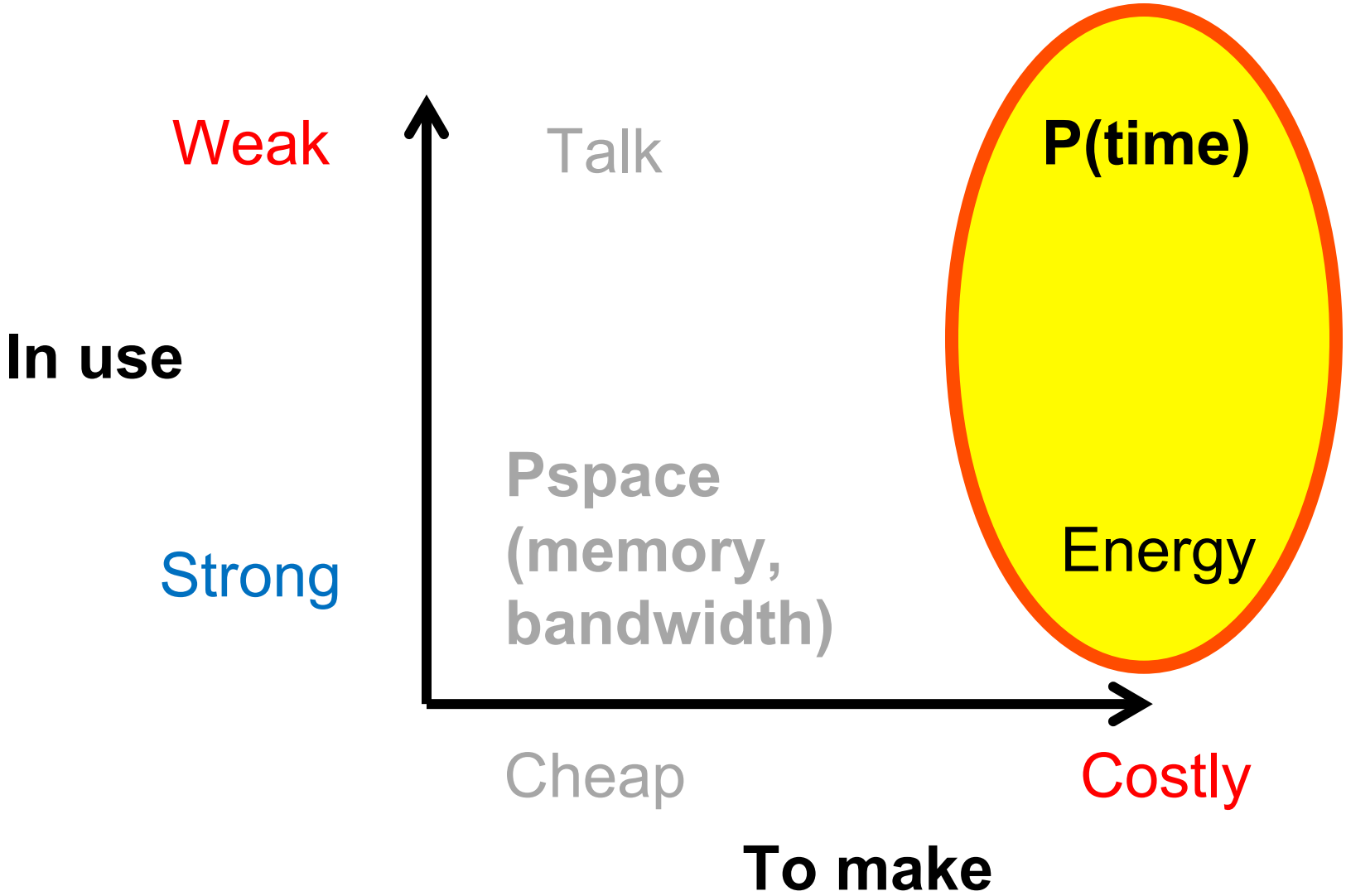
1 TB = 1e12B

Strong

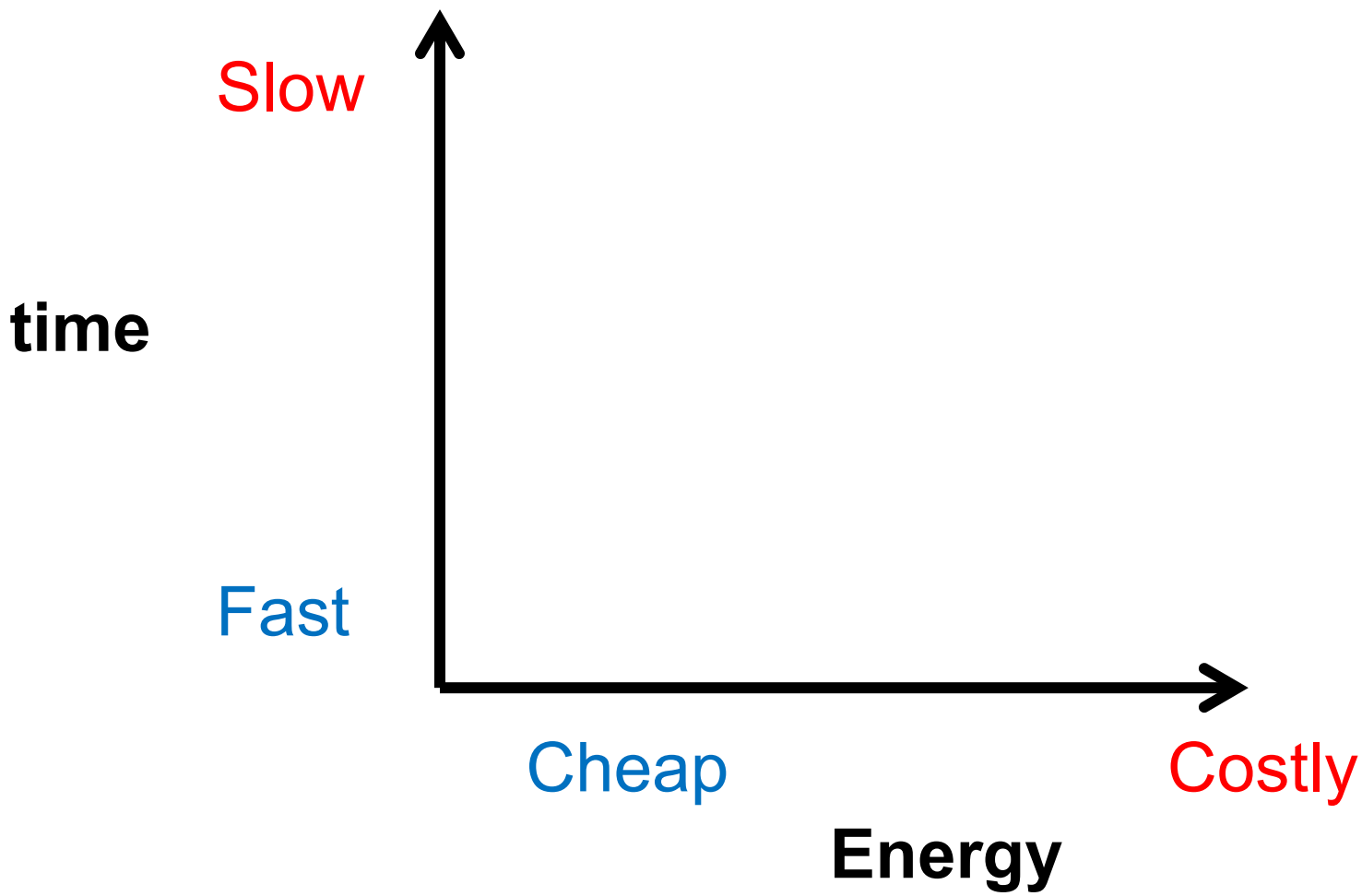
Cheap

To make

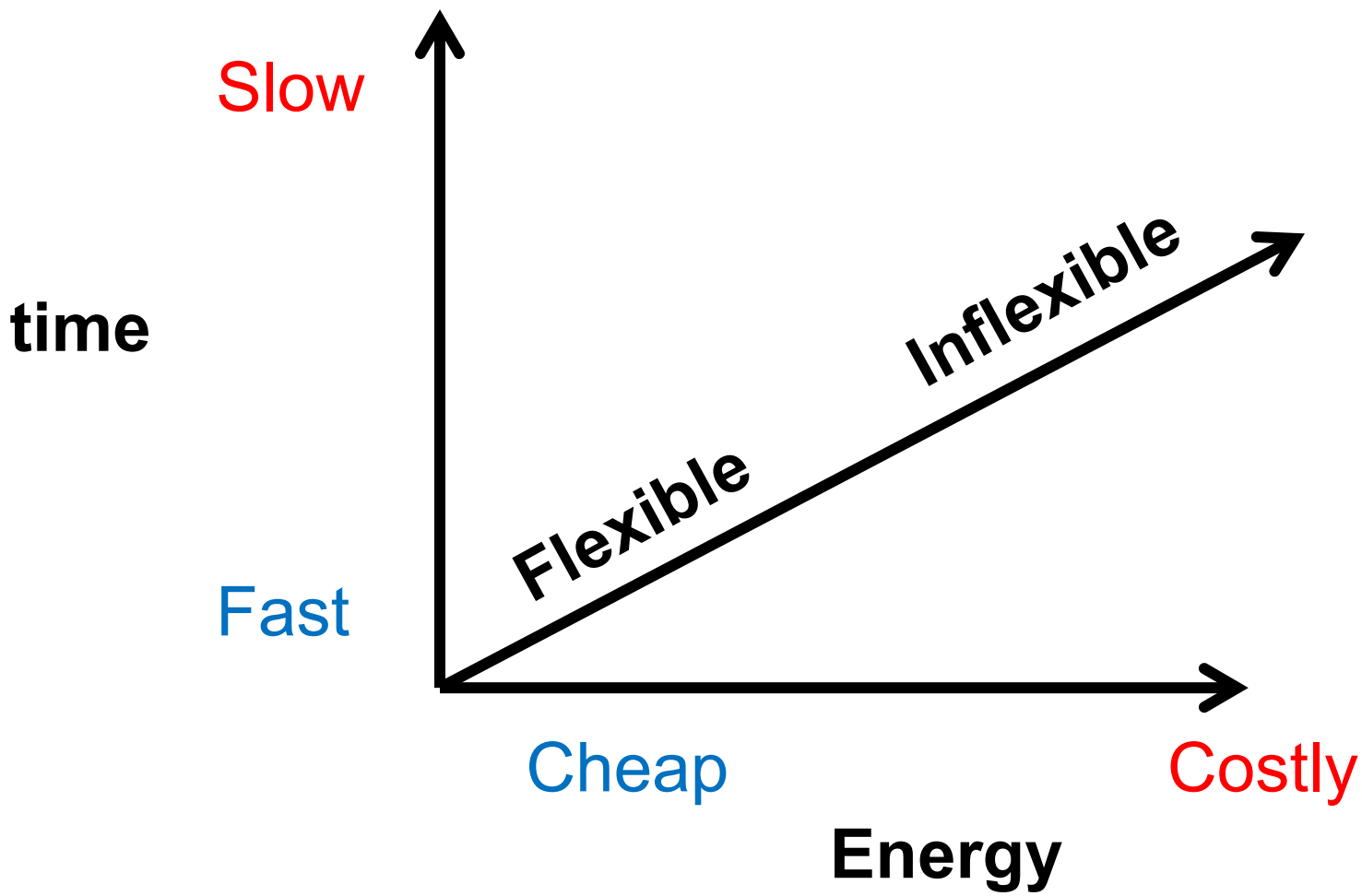
What dominates tradeoffs



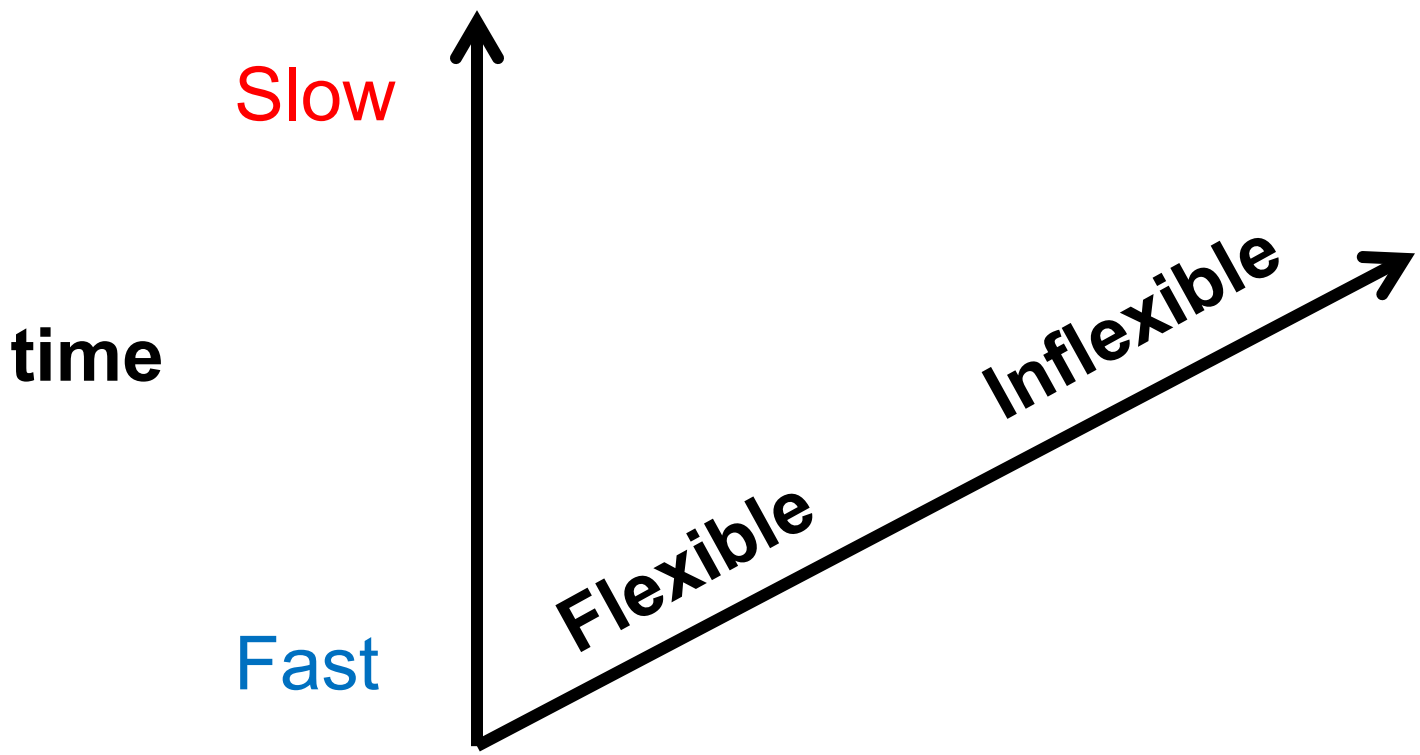
What dominates tradeoffs



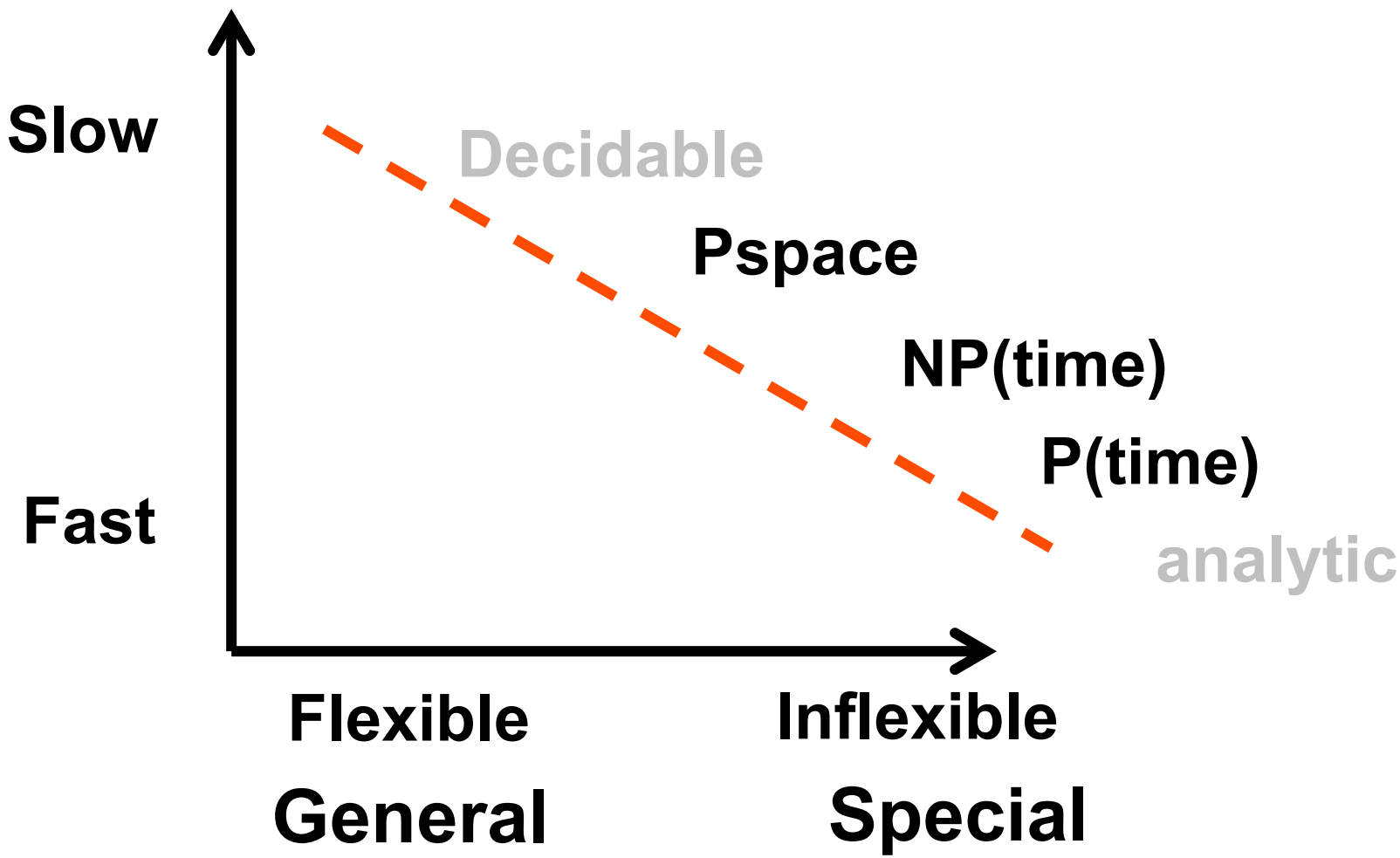
What dominates tradeoffs



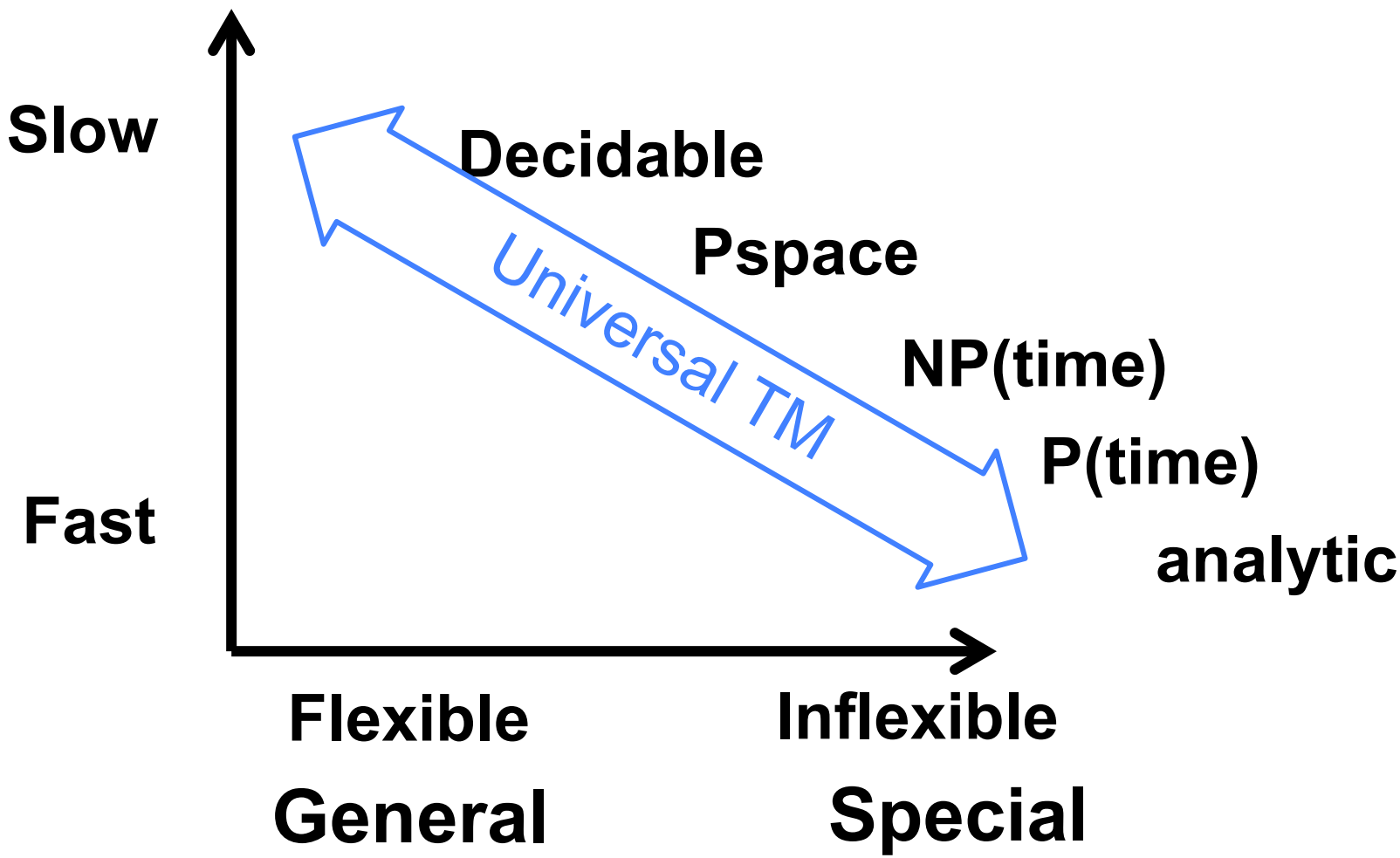
What dominates tradeoffs

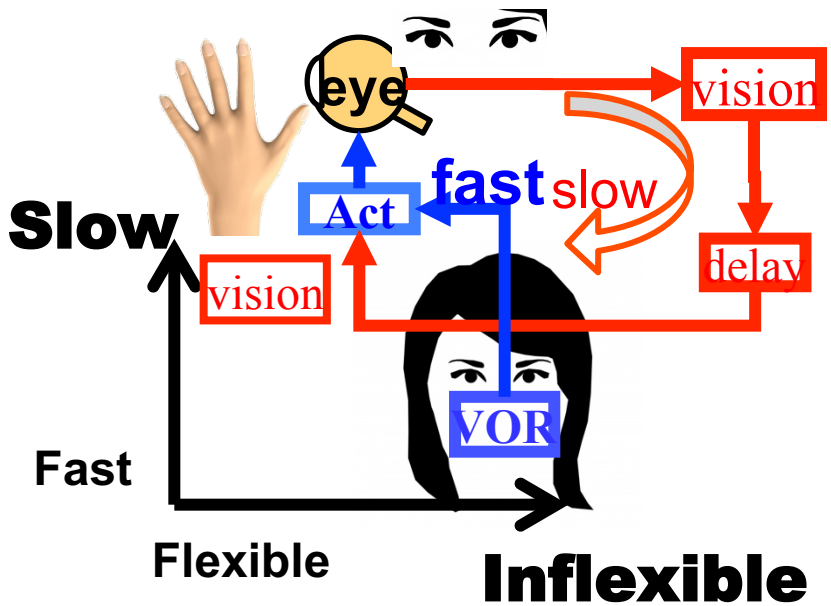


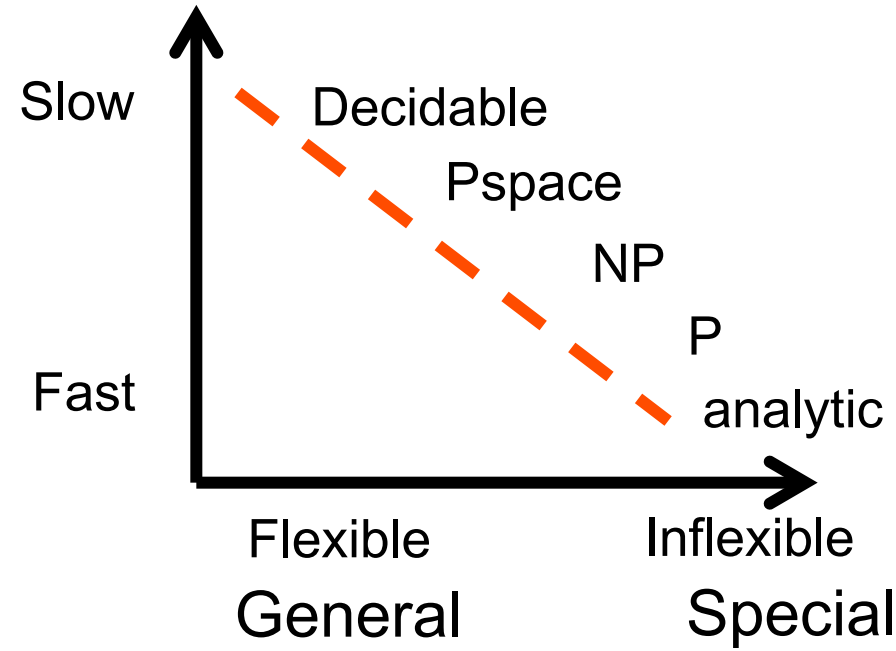
Computation
(on and off-line)

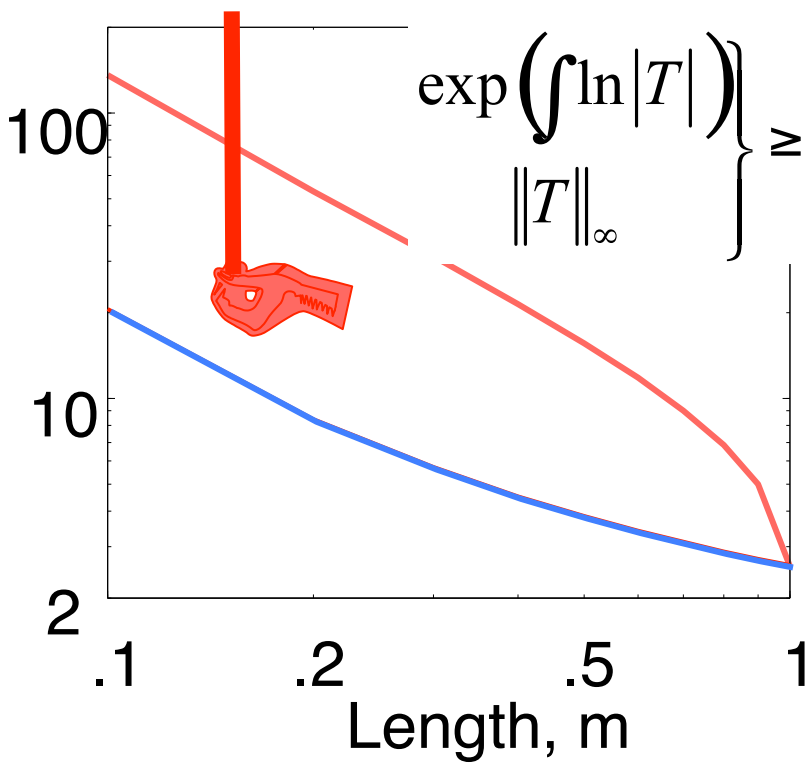


Universal architecture

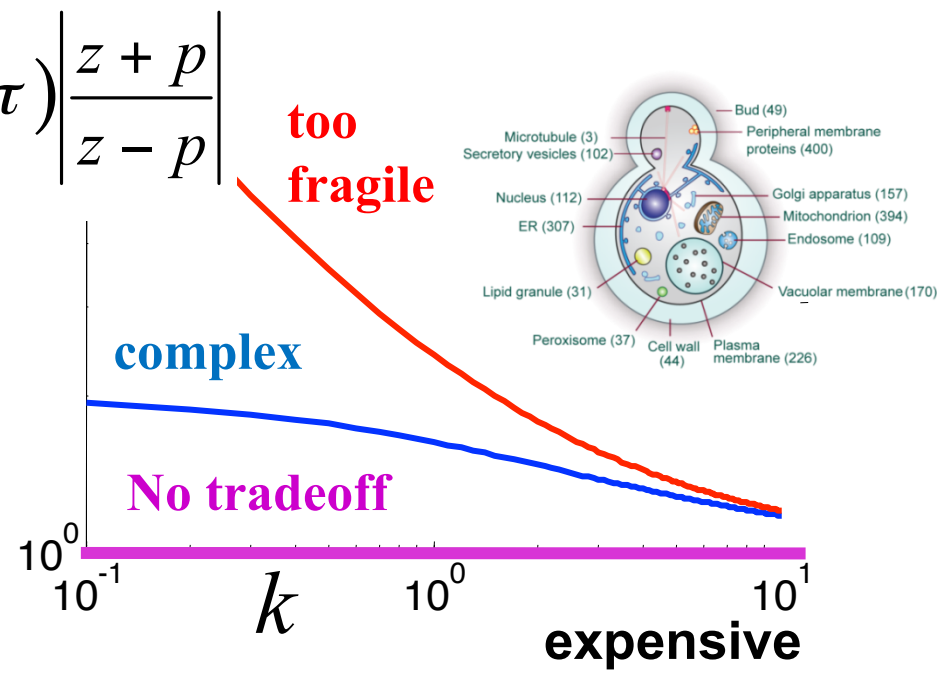








$$\left.\begin{matrix}\exp\left(\int \ln|T|\right) \\ \|T\|_\infty\end{matrix}\right\} \geq \exp(p\tau)\left|\frac{z+p}{z-p}\right|$$



Accelerating evolution

Horizontal Meme Transfer

frontal

Sensory

arning

Striatum

Software

Hardware

Reflex

Horizontal App Transfer

Digital

Analog

DNA

New gene

ene

Transcription

RNA

RNAp

mRNA

Amino Acids

Other Cont

Ribosomes

eins

ism

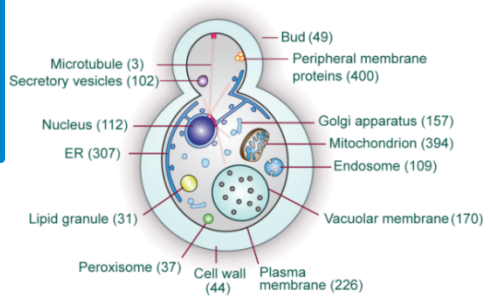
Products

ATP

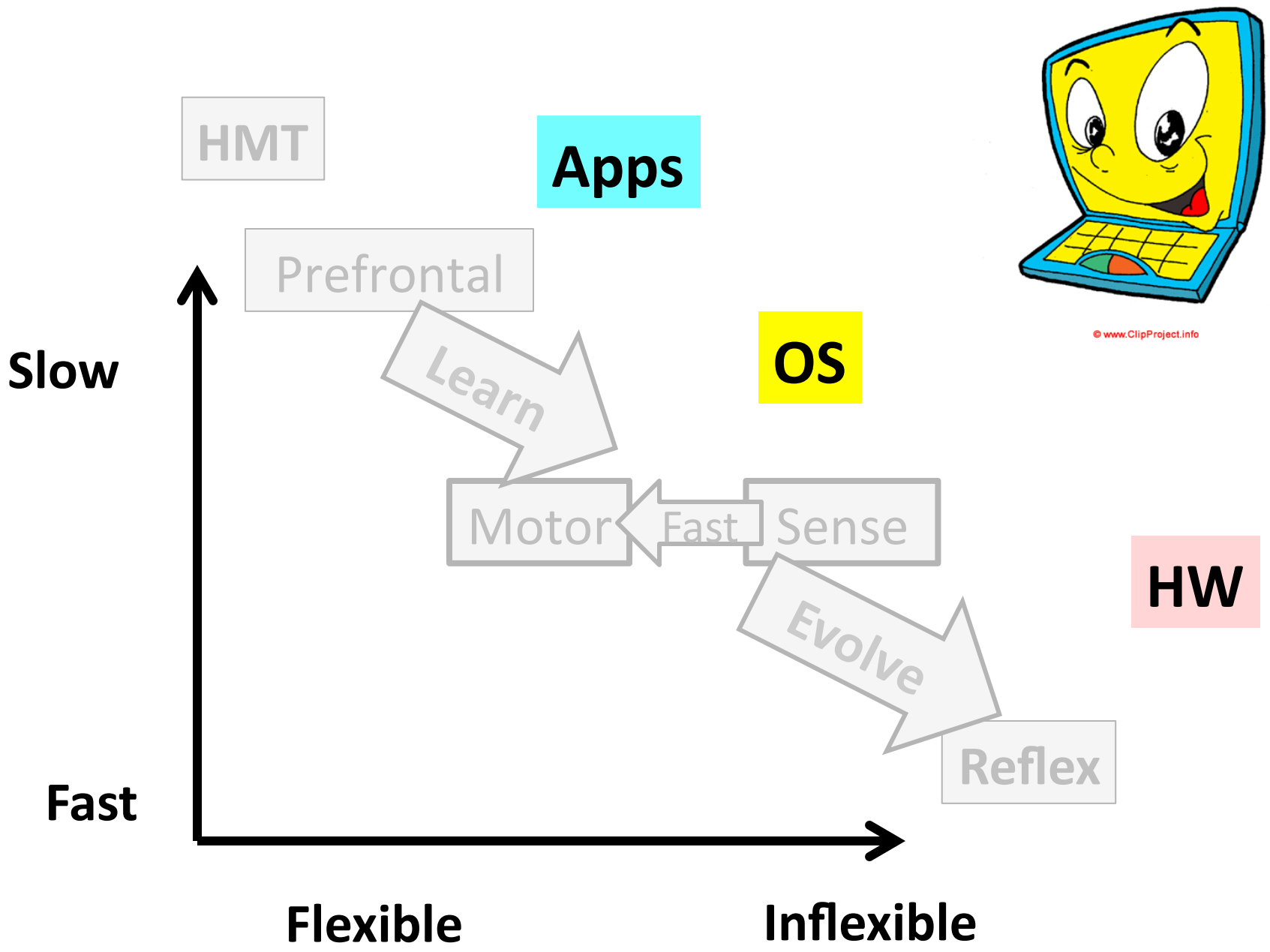
Horizontal Gene Transfer

control feedbac

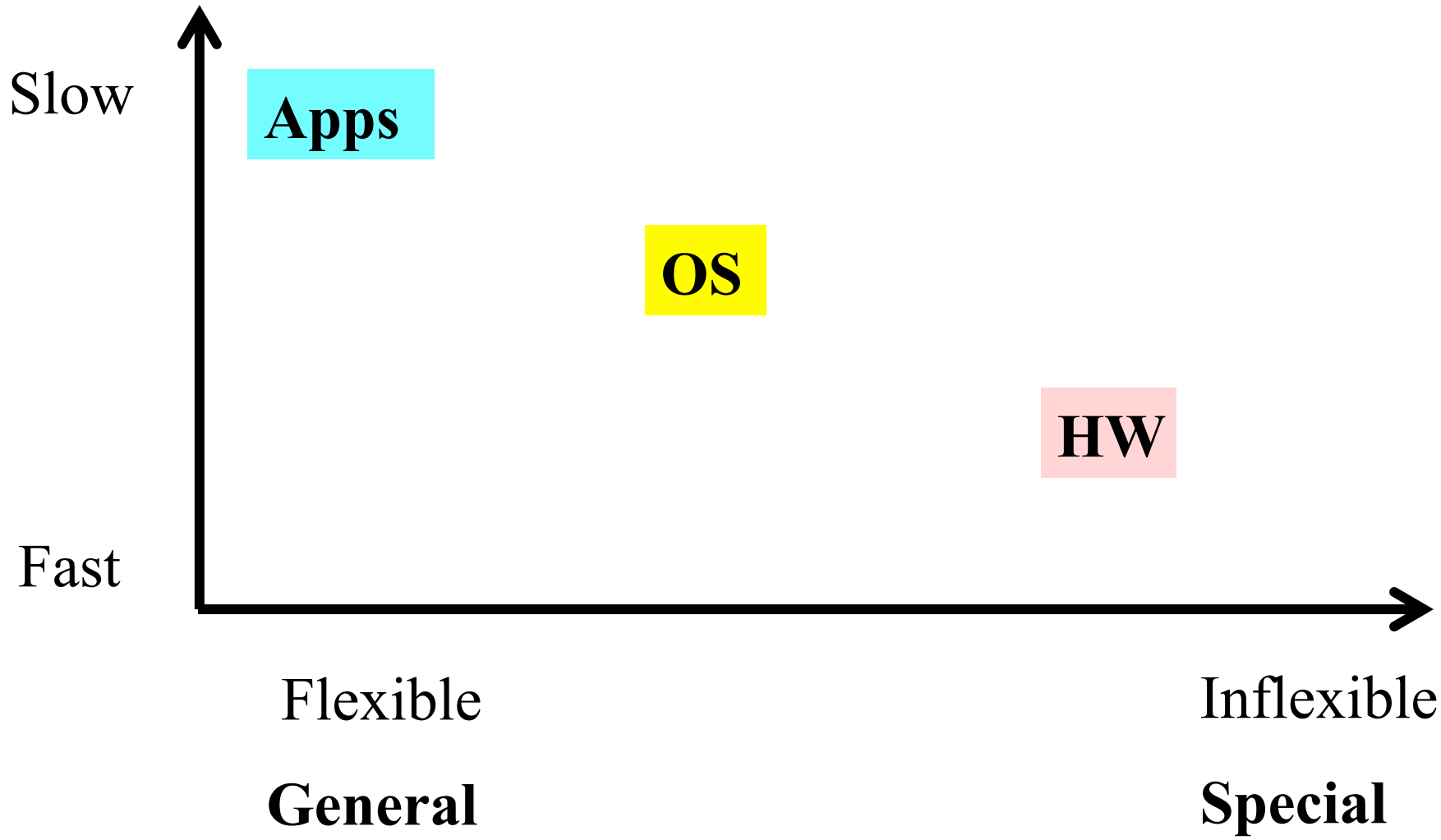
Signal transduction



Requires shared "OS"

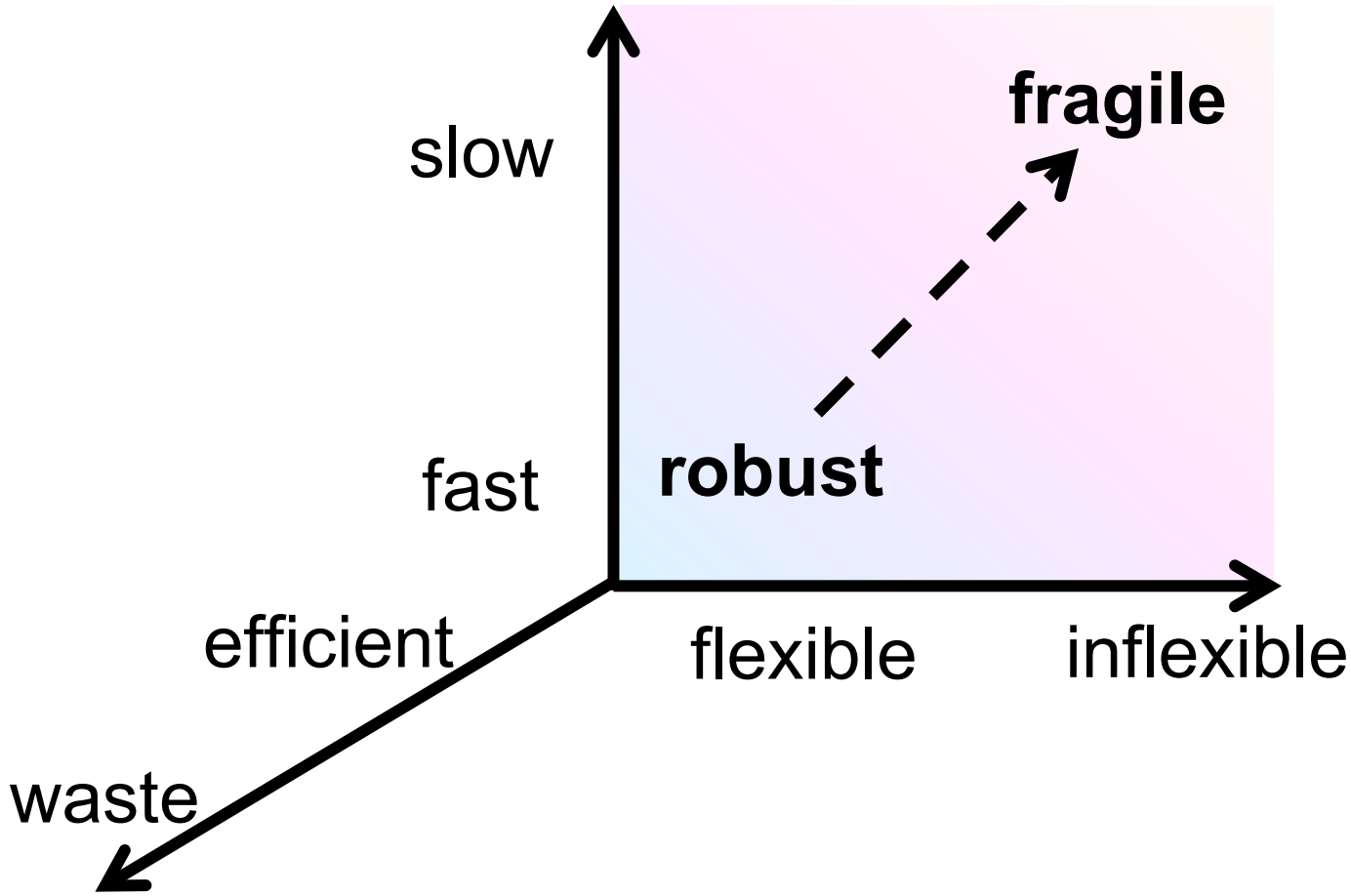

HMT
Apps
Prefrontal
Slow
Learn
OS
Motor
Fast
Sense
HW
Evolve
Reflex
Fast
Flexible
Inflexible
© www.ClipProject.info

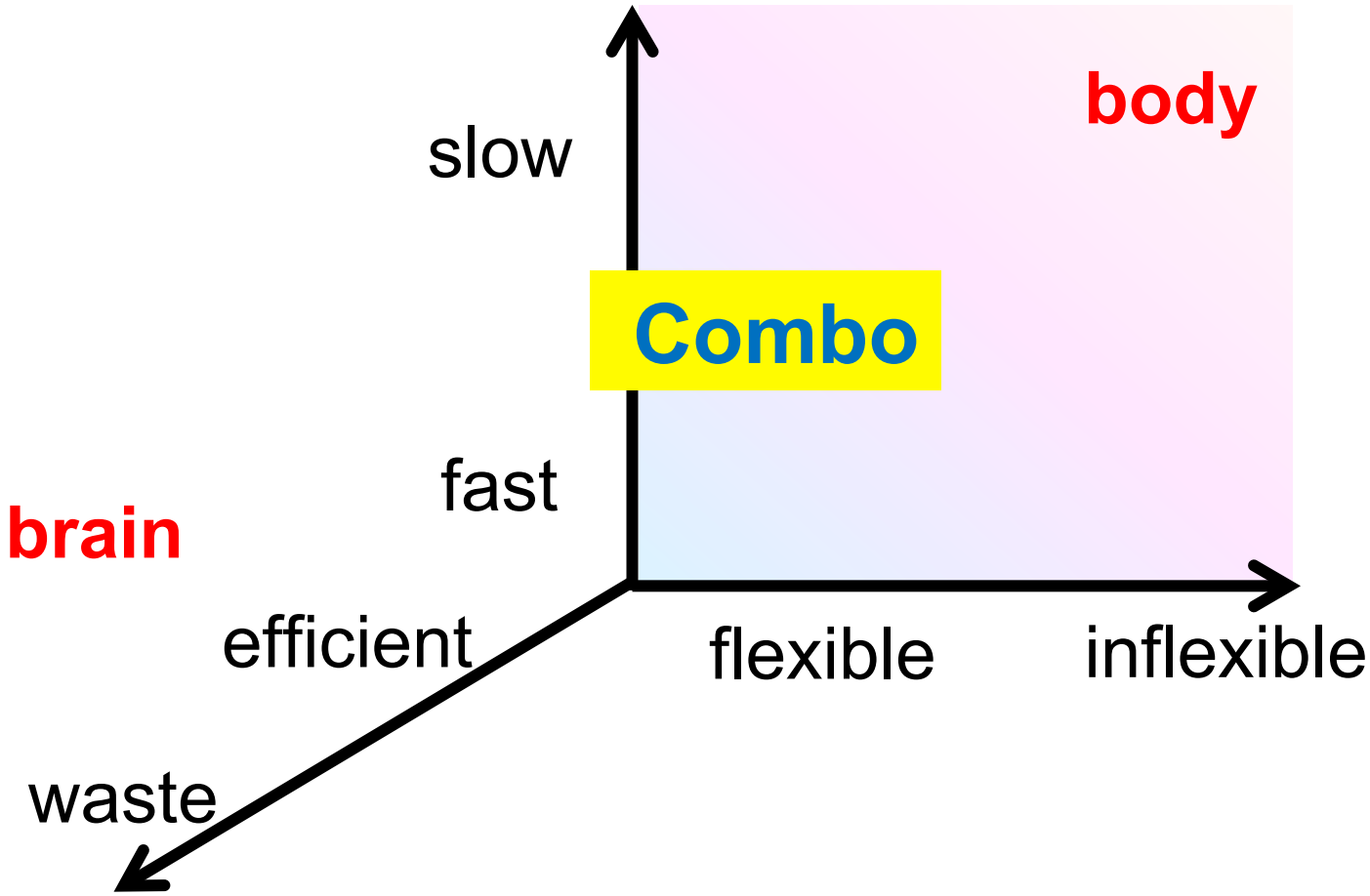
Exploiting layered architecture

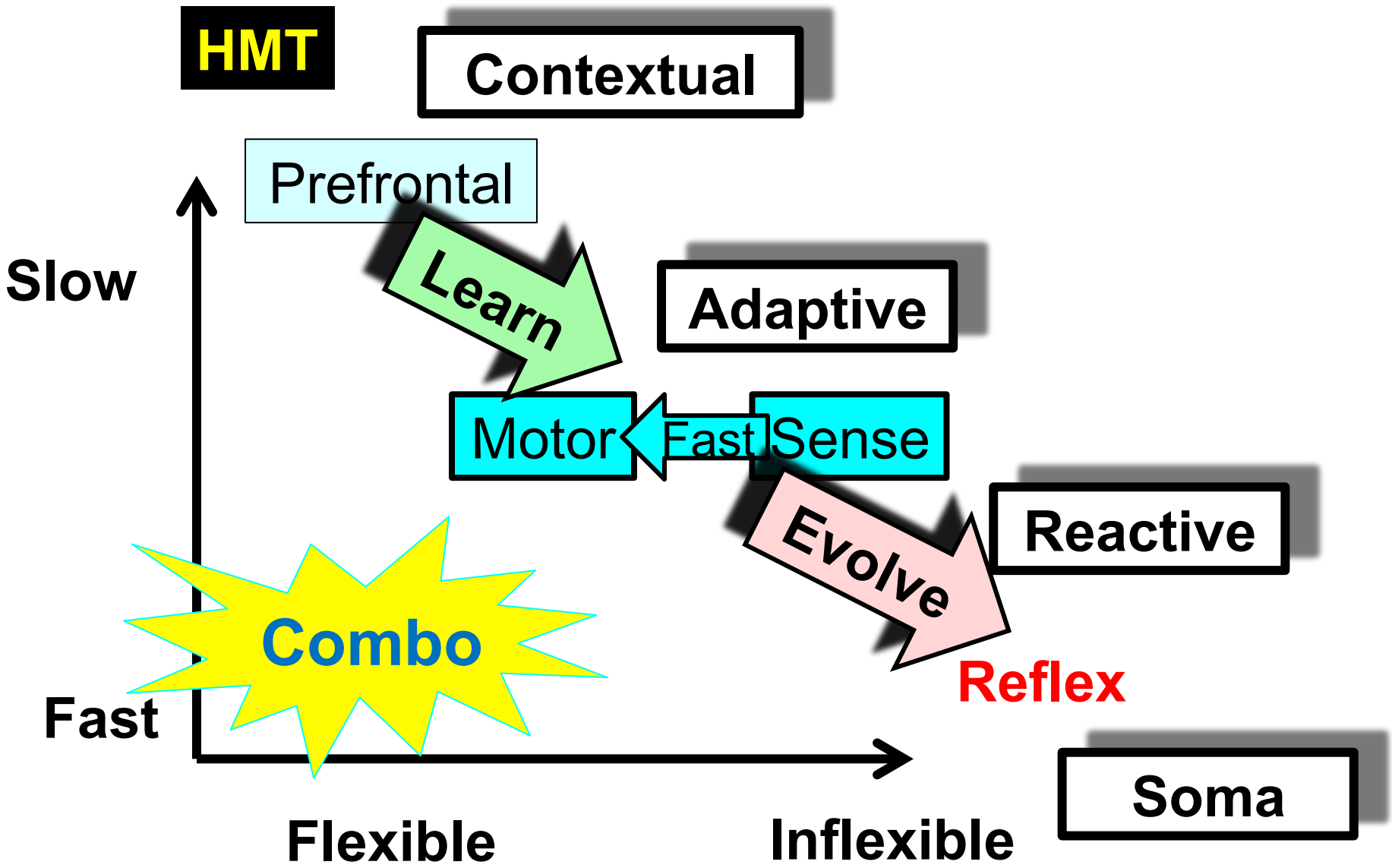


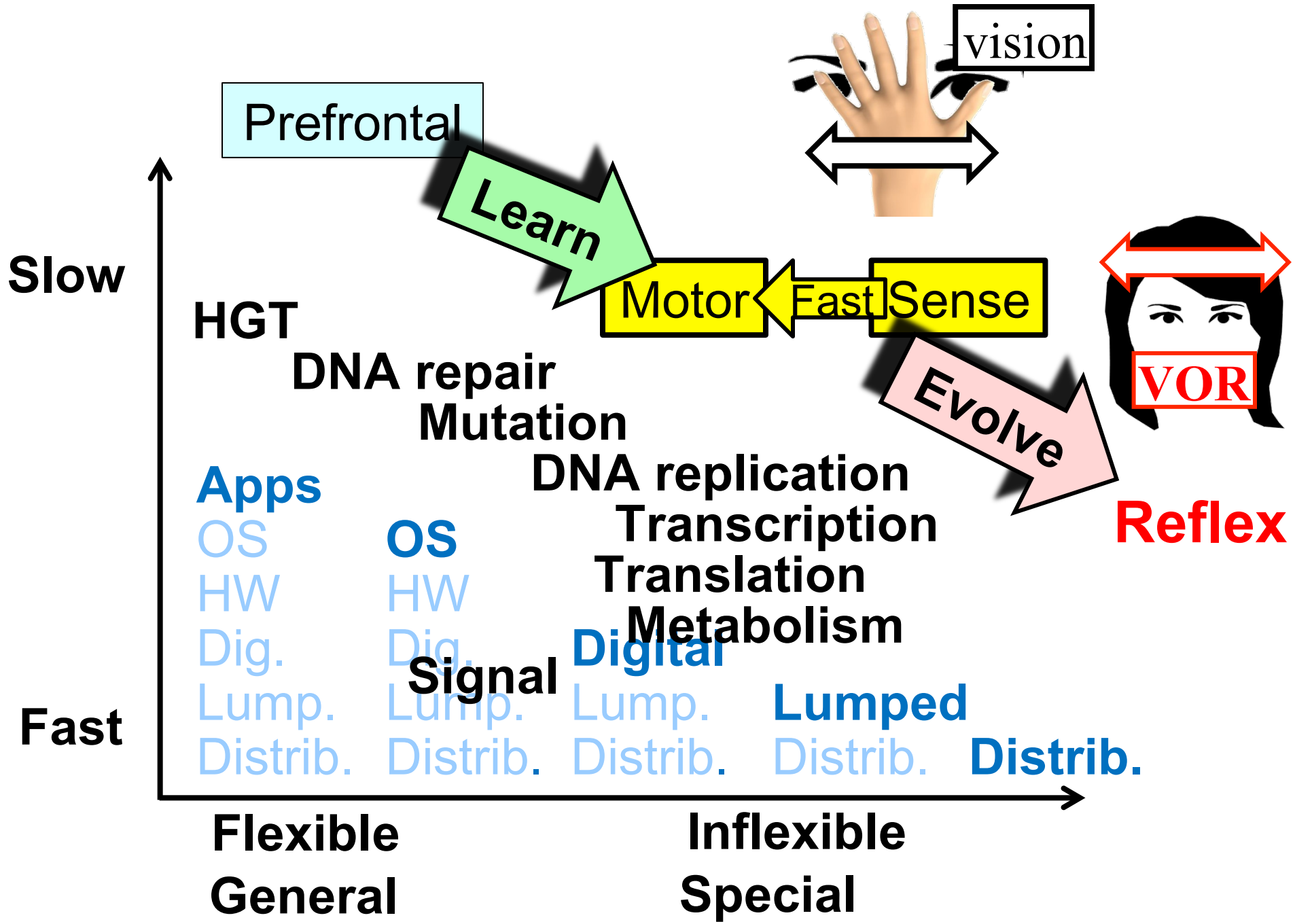
Core protocols

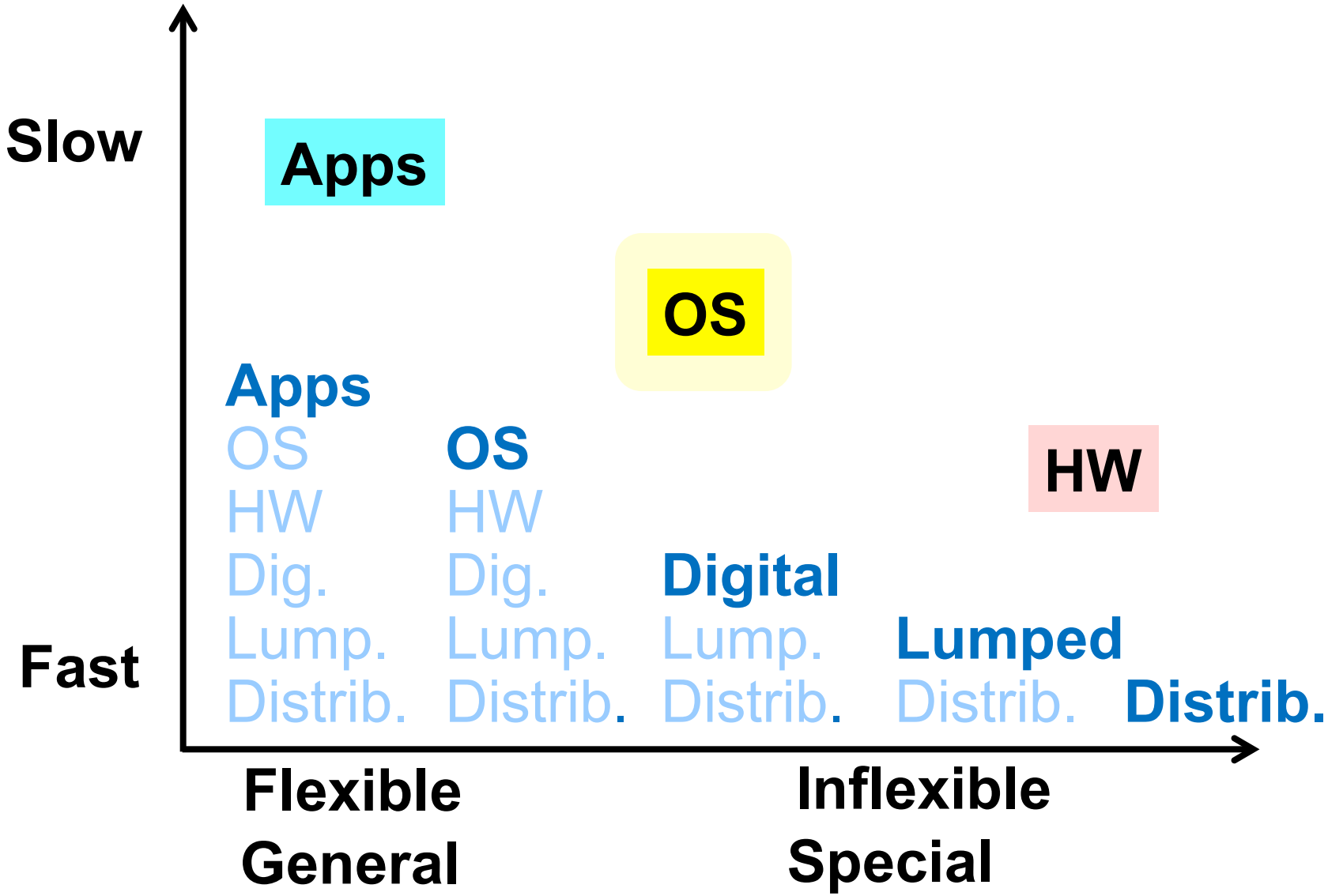
- OS seems to confuse
- Replace with “core protocols”?
- Examples different than OS or translation:
  - Core metabolism
  - 2 component signal transduction
- Highly conserved/constrained core (knot)
- Highly diverse/deconstrained edges

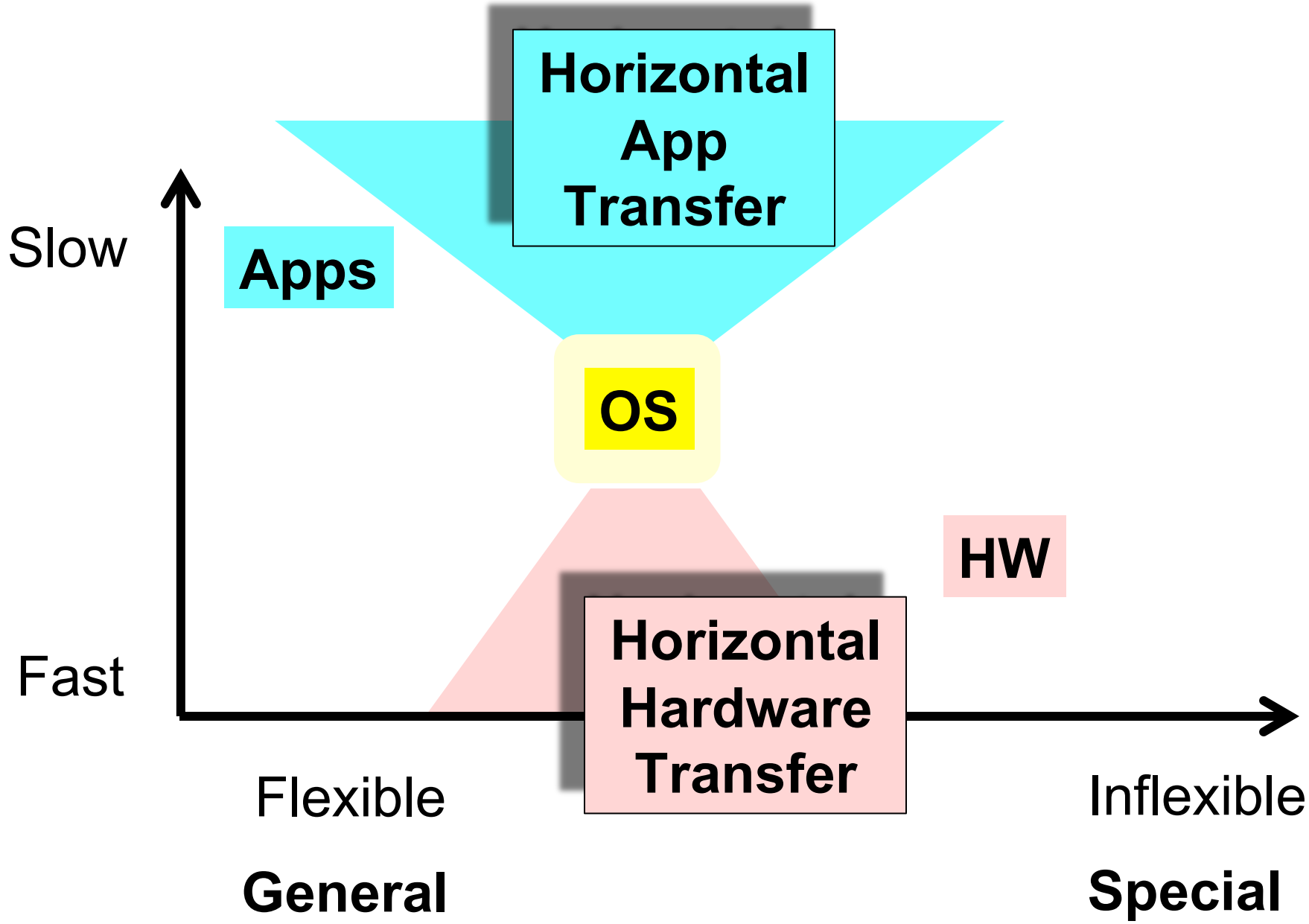

slow
fast
fragile
robust
efficient
waste
flexible
inflexible

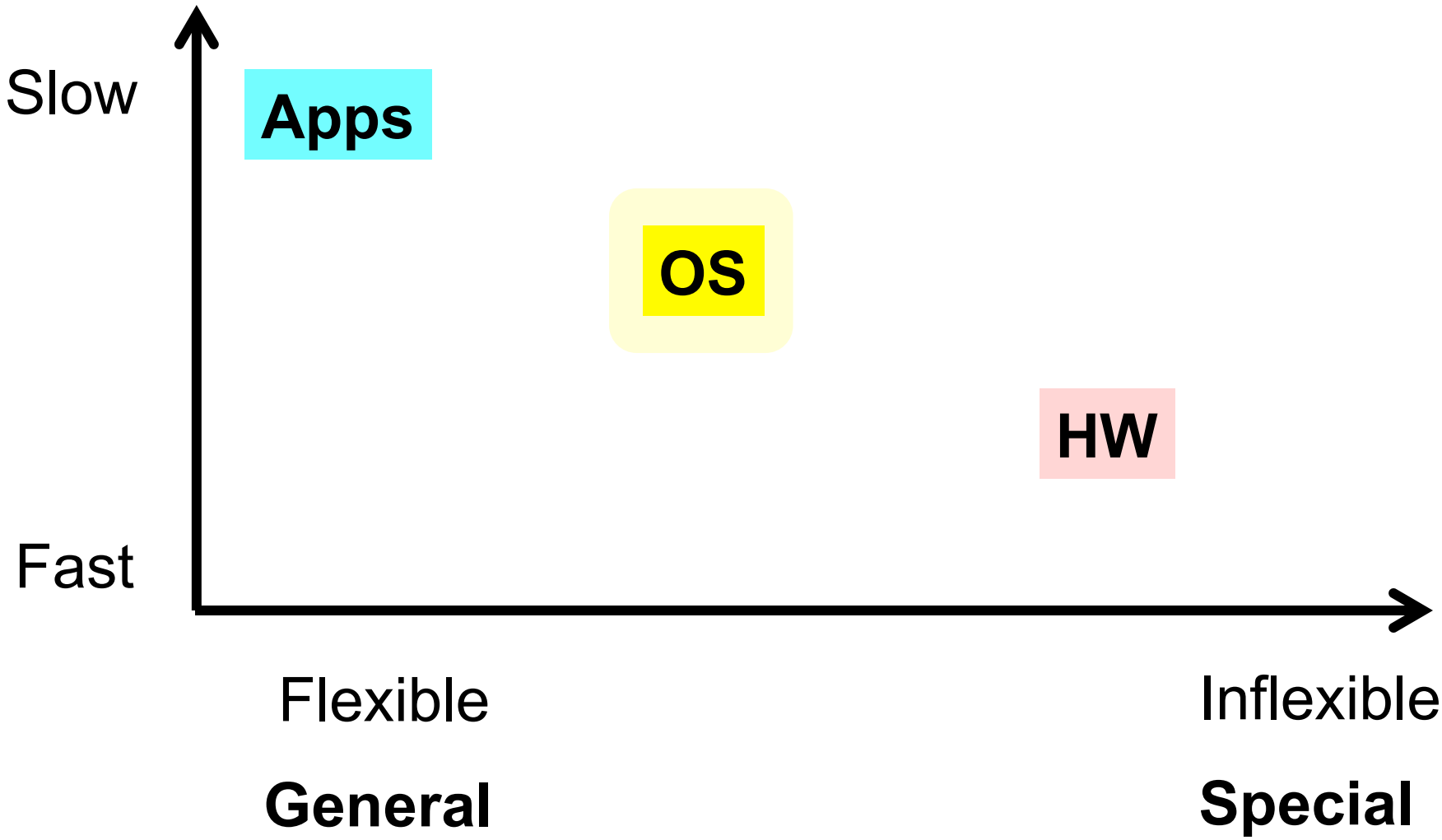

body
slow
Combo
fast
brain
efficient
flexible
inflexible
waste

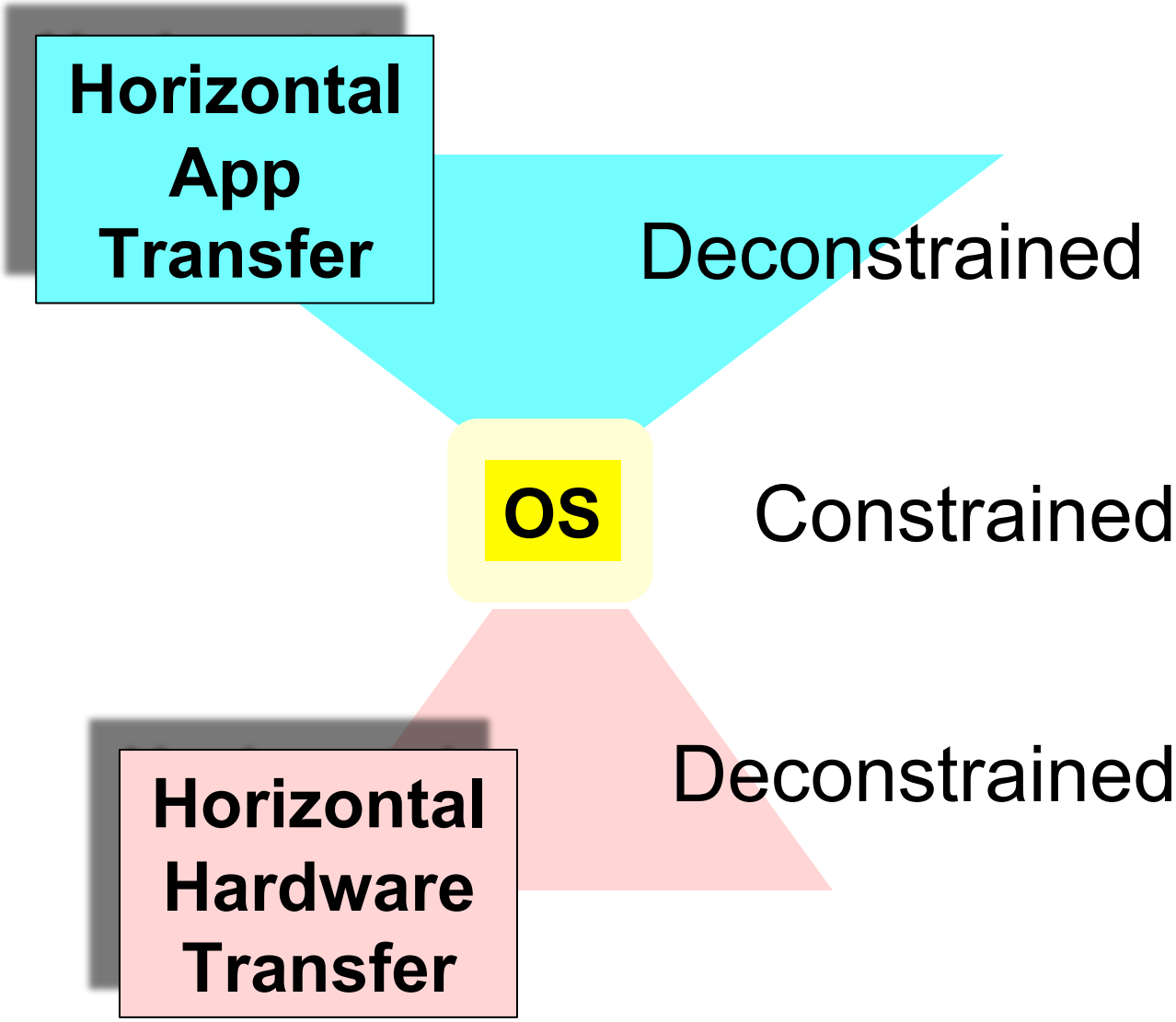

HMT
Contextual
Prefrontal
Slow
Learn
Adaptive
Motor
Fast
Sense
Evolve
Reactive
Combo
Reflex
Fast
Soma
Flexible
Inflexible

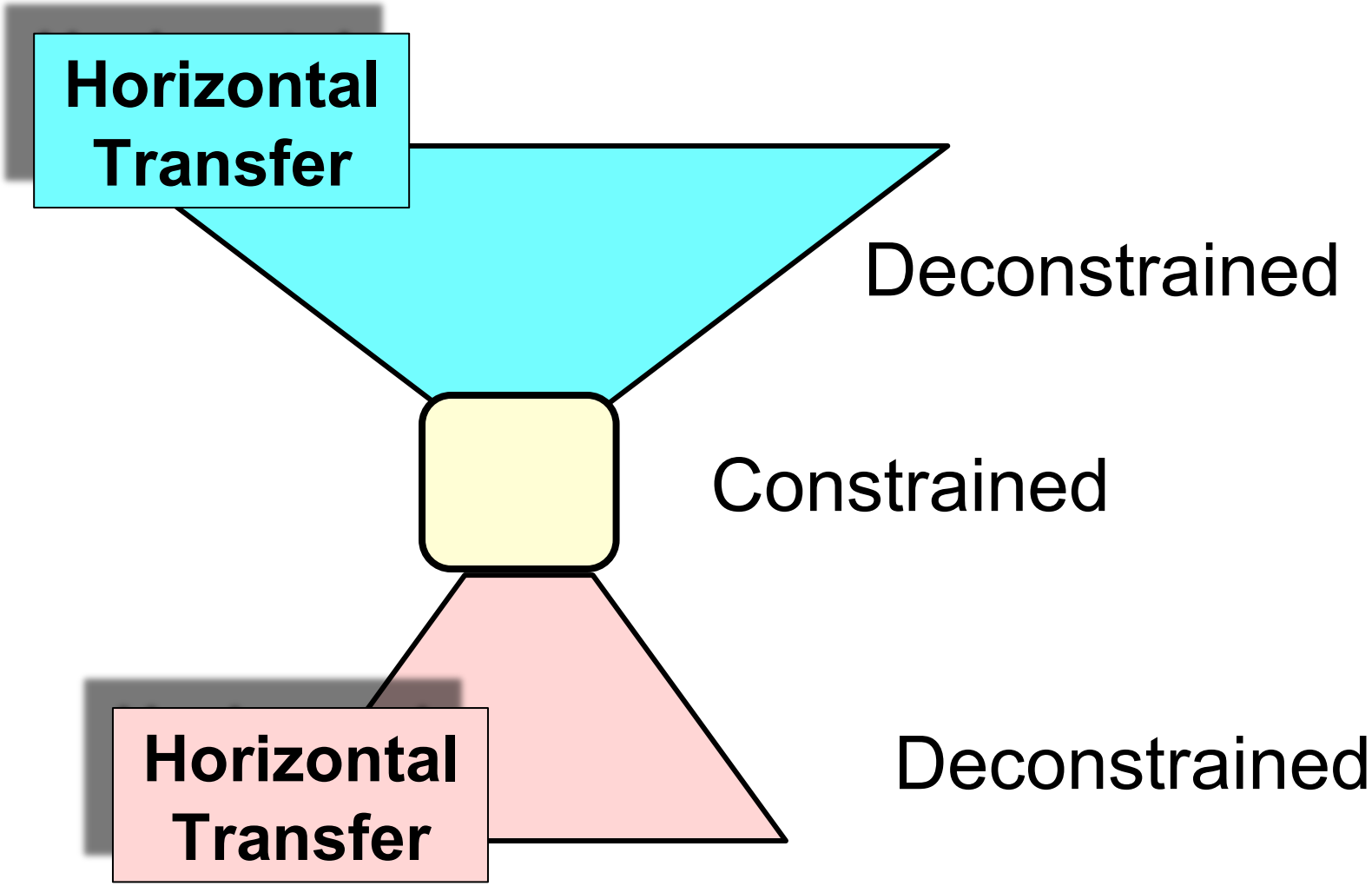

vision
Prefrontal
Learn
Motor
Fast
Sense
VOR
Evolve
Reflex
Slow
HGT
DNA repair
Mutation
DNA replication
Transcription
Translation
Metabolism
Apps
OS
HW
Dig.
Lump.
Distrib.
OS
HW
Dig.
Lump.
Distrib.
Signal
Digital
Lump.
Distrib.
Lumped
Distrib.
Distrib.
Fast
Flexible
General
Inflexible
Special

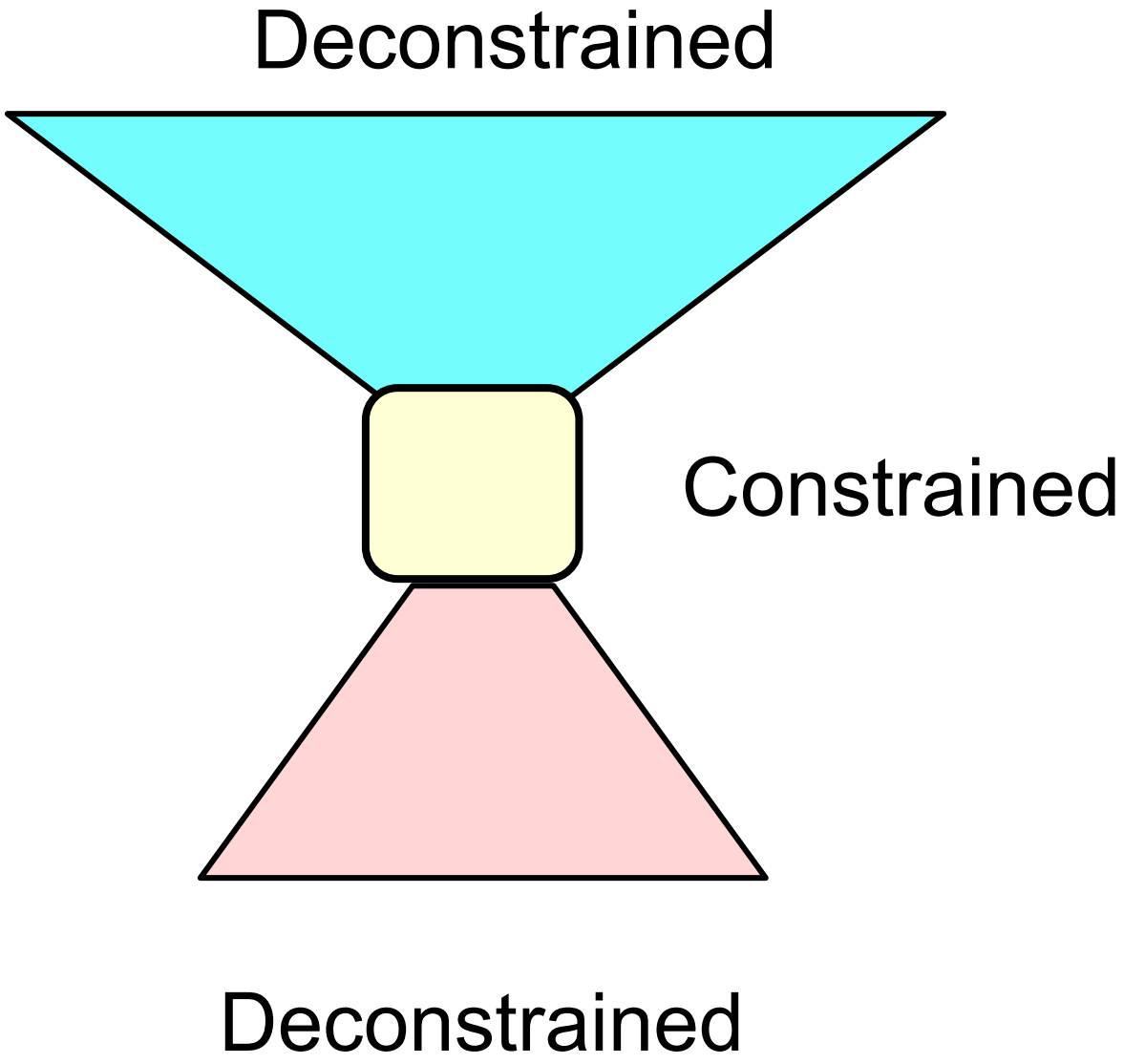

Slow
Fast
Apps
OS
Apps
OS
HW
Dig.
Lump.
Distrib.
OS
HW
Dig.
Lump.
Distrib.
Digital
Lump.
Distrib.
Lumped
Distrib.
HW
Distrib.
Flexible
General
Inflexible
Special


Horizontal
App
Transfer
Slow
Apps
OS
HW
Fast
Horizontal
Hardware
Transfer
Flexible
Inflexible
General
Special

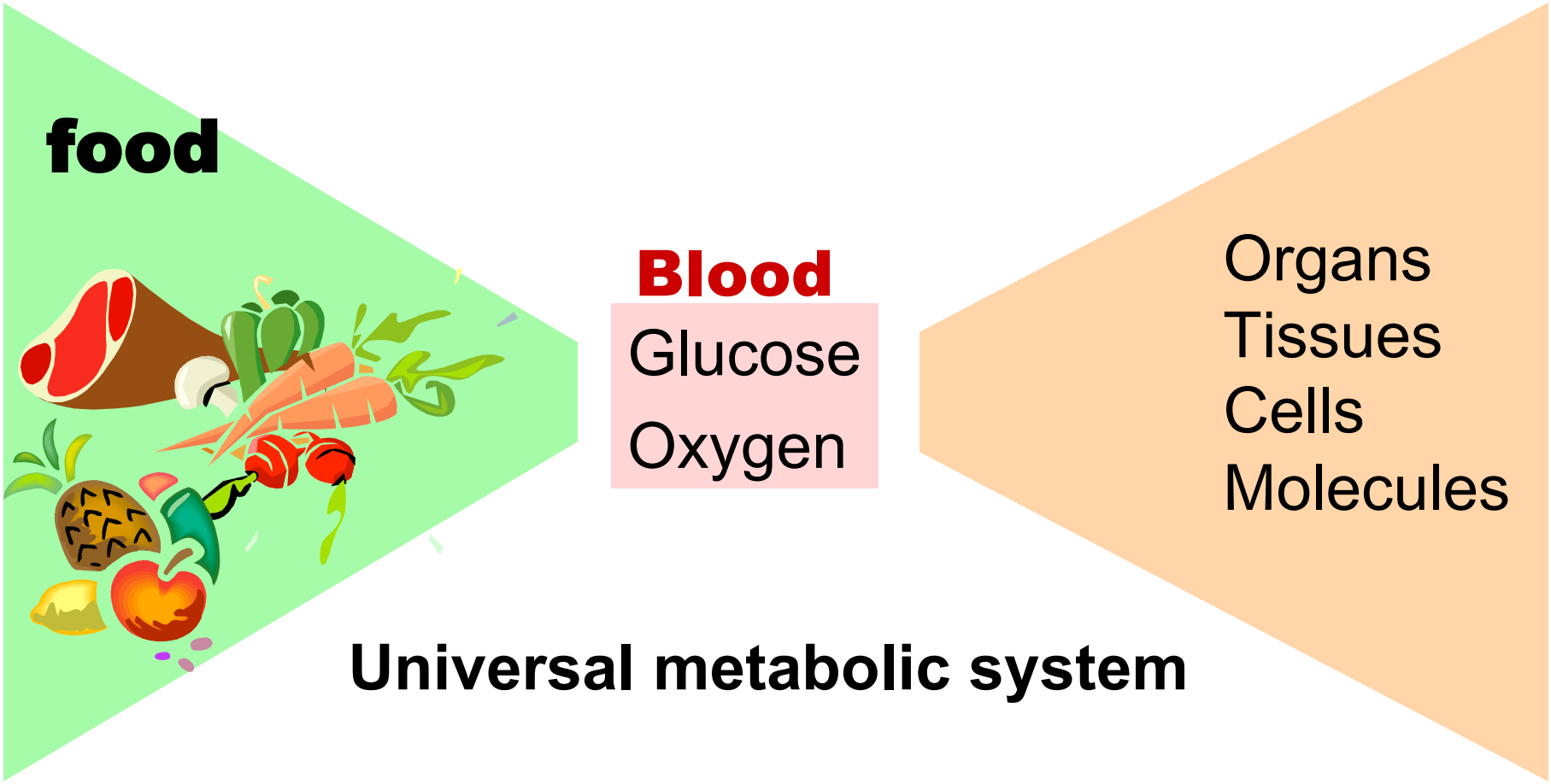

Slow
Apps
OS
HW
Fast
Flexible
Inflexible
General
Special


Horizontal App Transfer
Deconstrained
OS
Constrained
Deconstrained
Horizontal Hardware Transfer


Horizontal Transfer
Deconstrained
Constrained
Horizontal Transfer
Deconstrained


Deconstrained
Constrained
Deconstrained

Efficient
Robust
Evolvable



Universal metabolic system

Efficient
Robust
Evolvable

Deconstrained

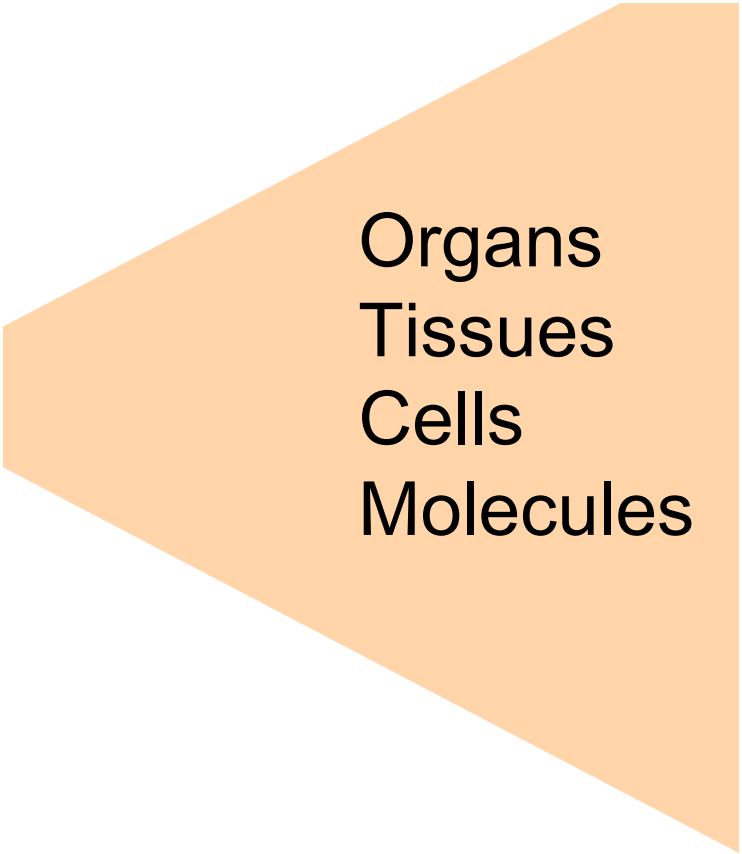
Constrained

Blood

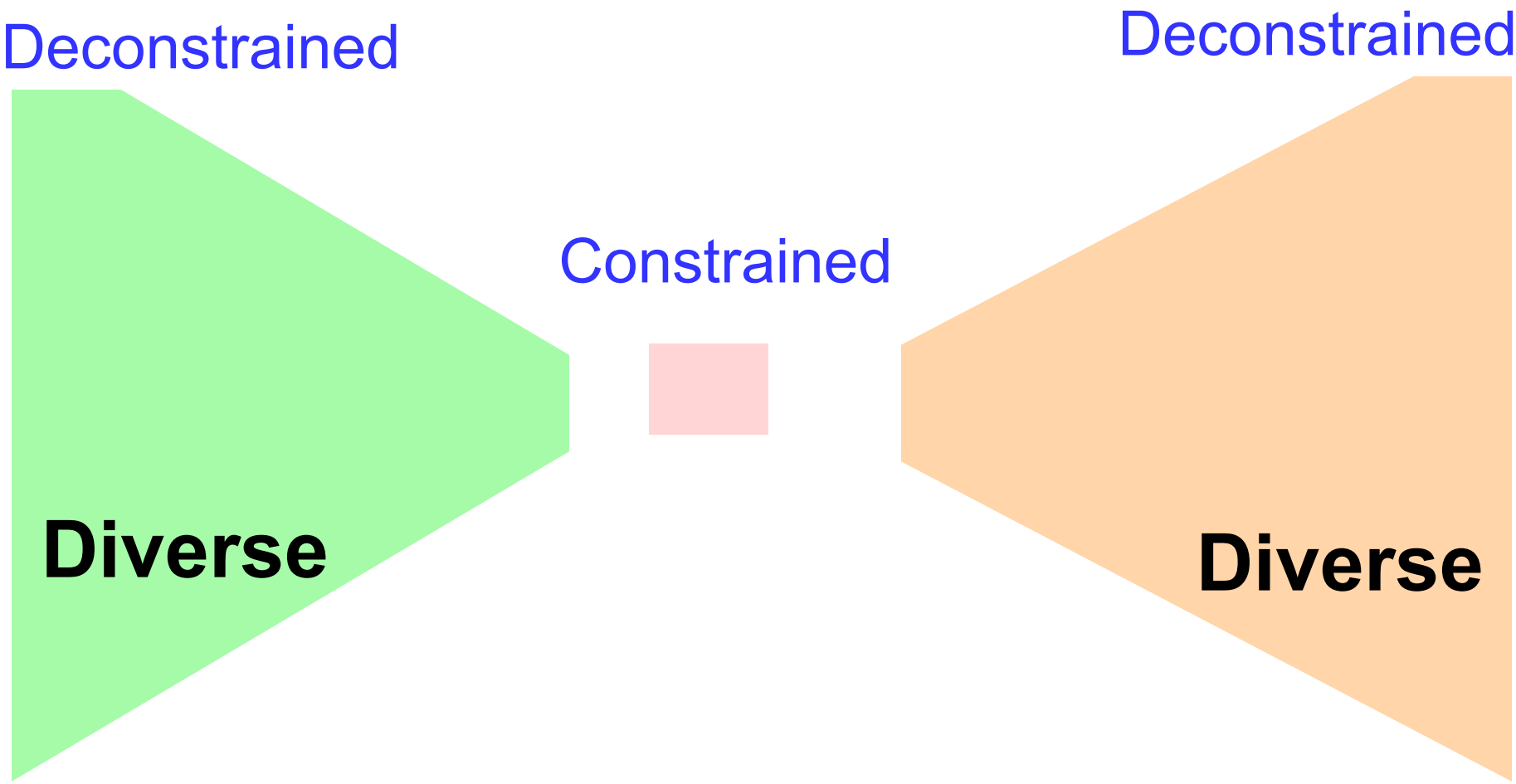
Glucose

Oxygen

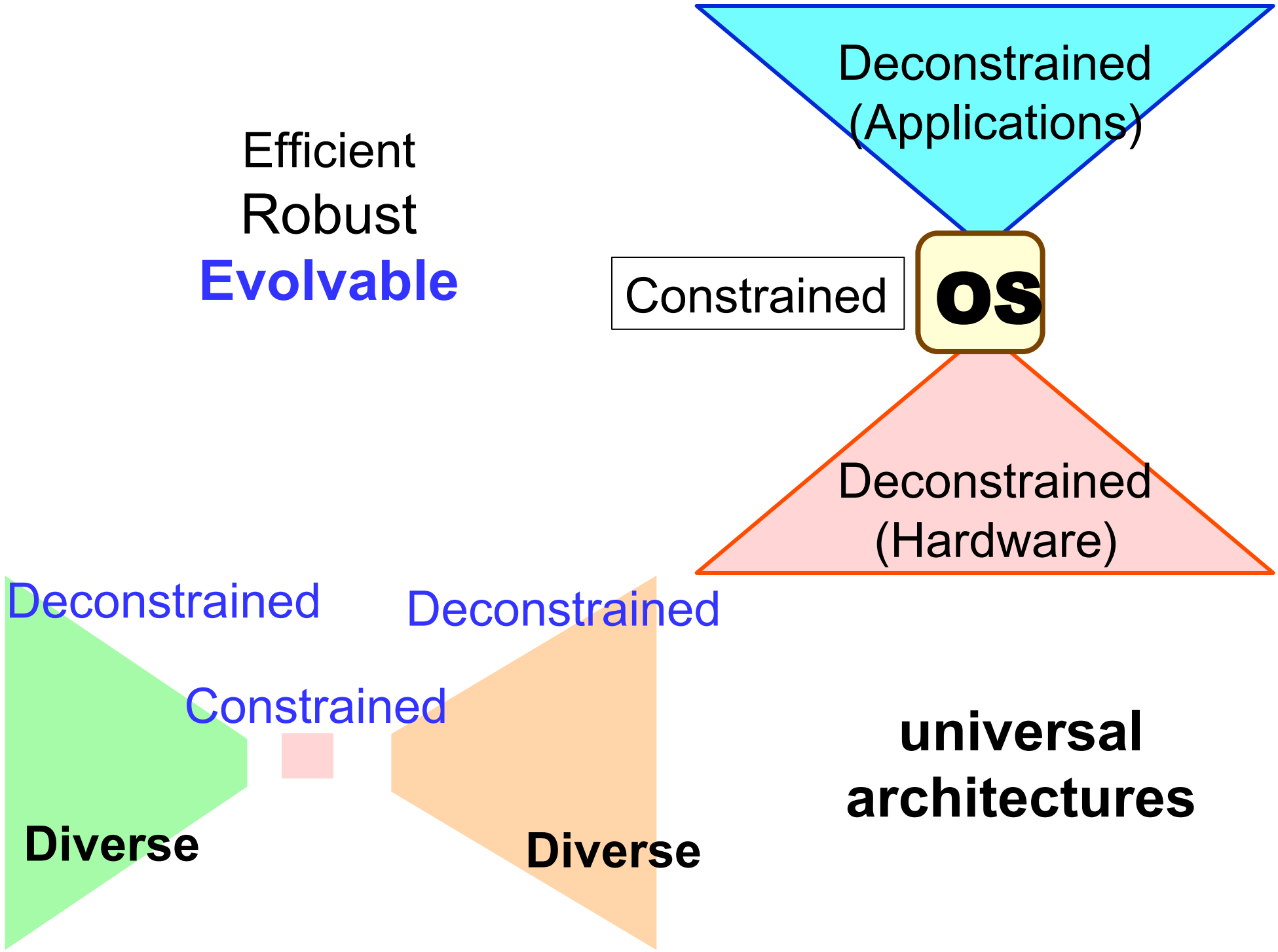
Deconstrained



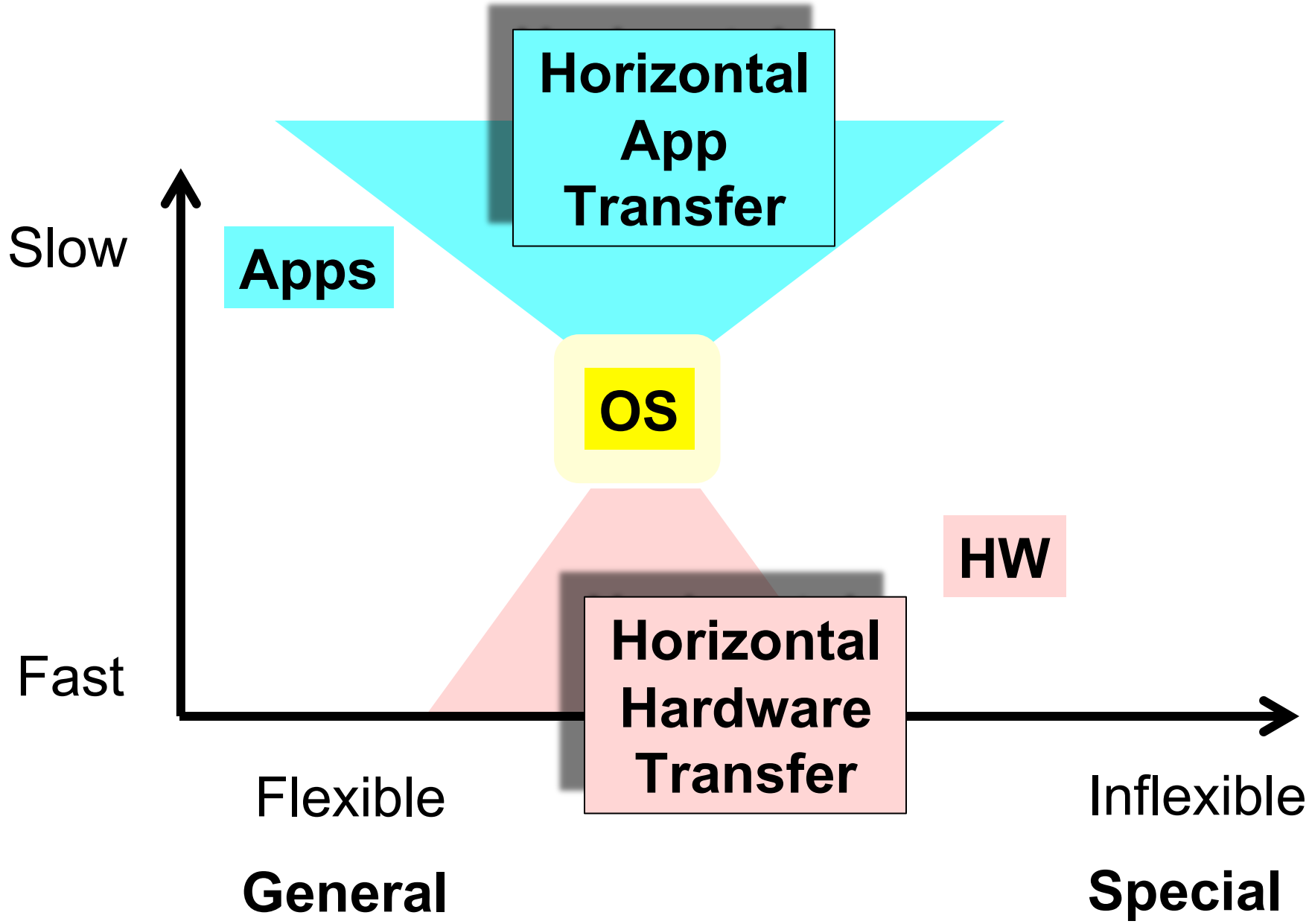
Efficient
Robust
Evolvable



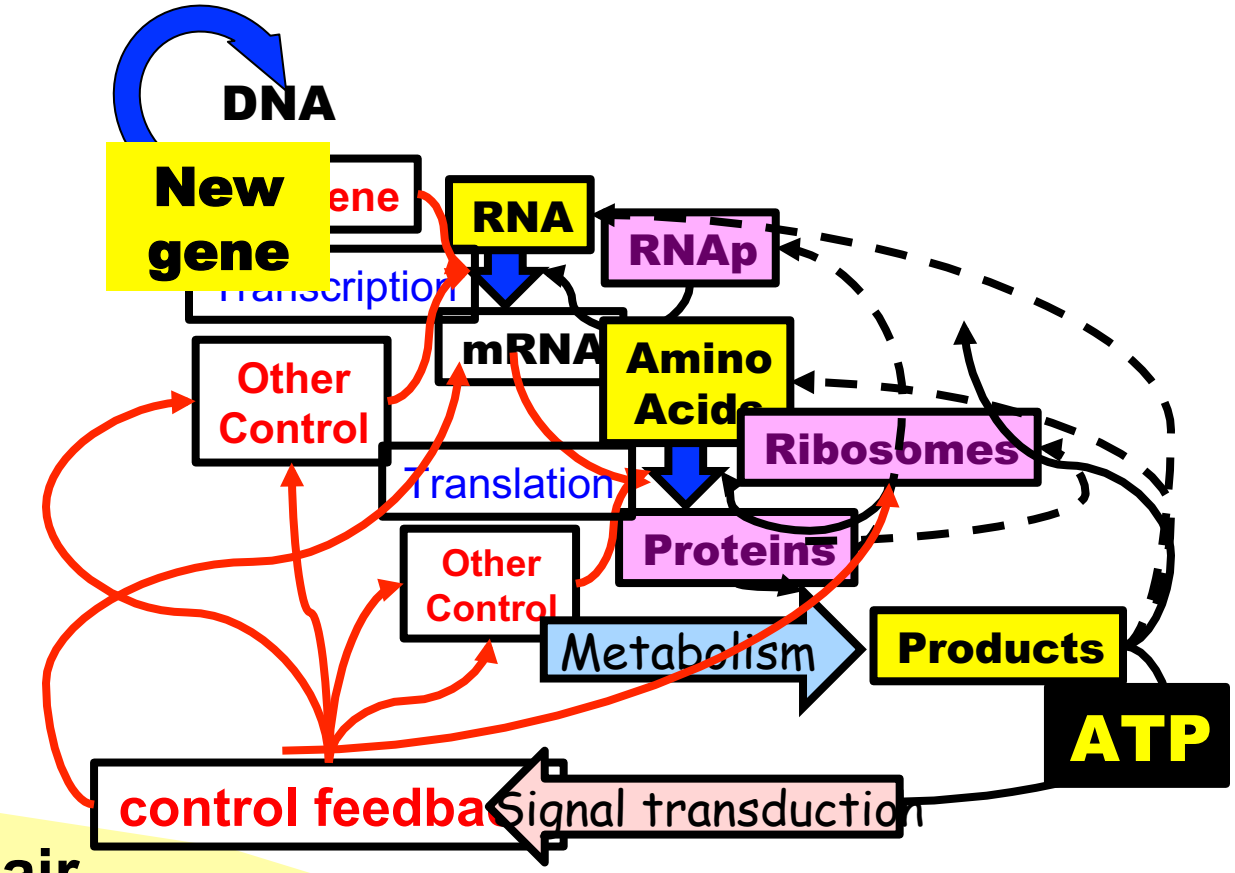
Efficient
Robust
Evolvable

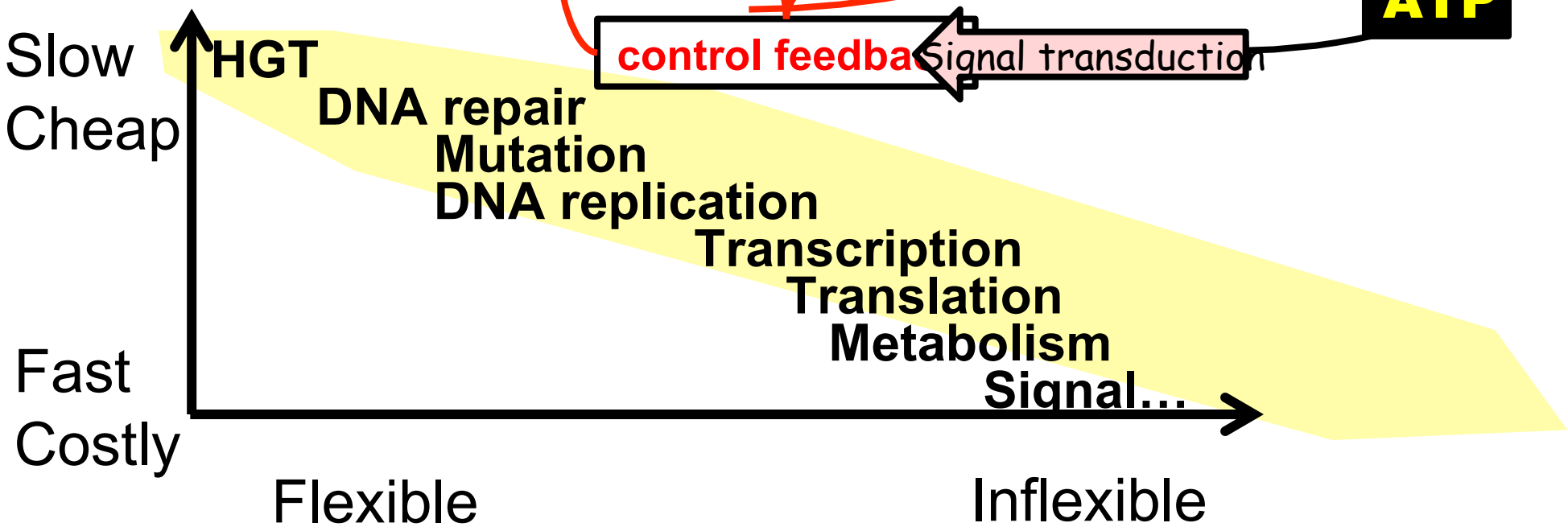


universal architectures

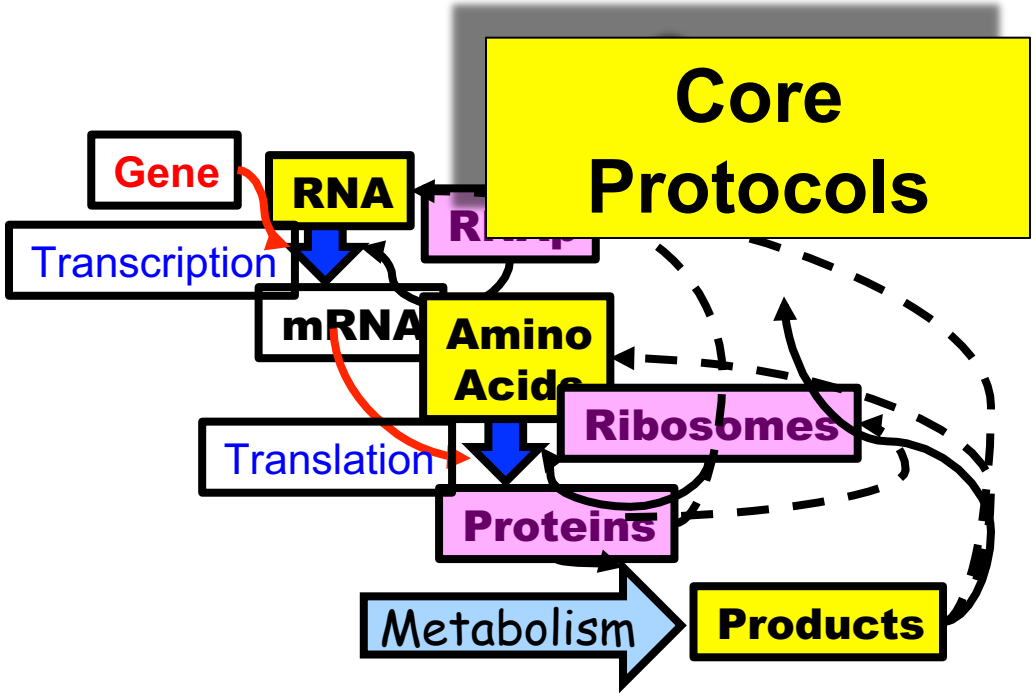

Horizontal
App
Transfer
Slow
Apps
OS
HW
Fast
Horizontal
Hardware
Transfer
Flexible
Inflexible
General
Special

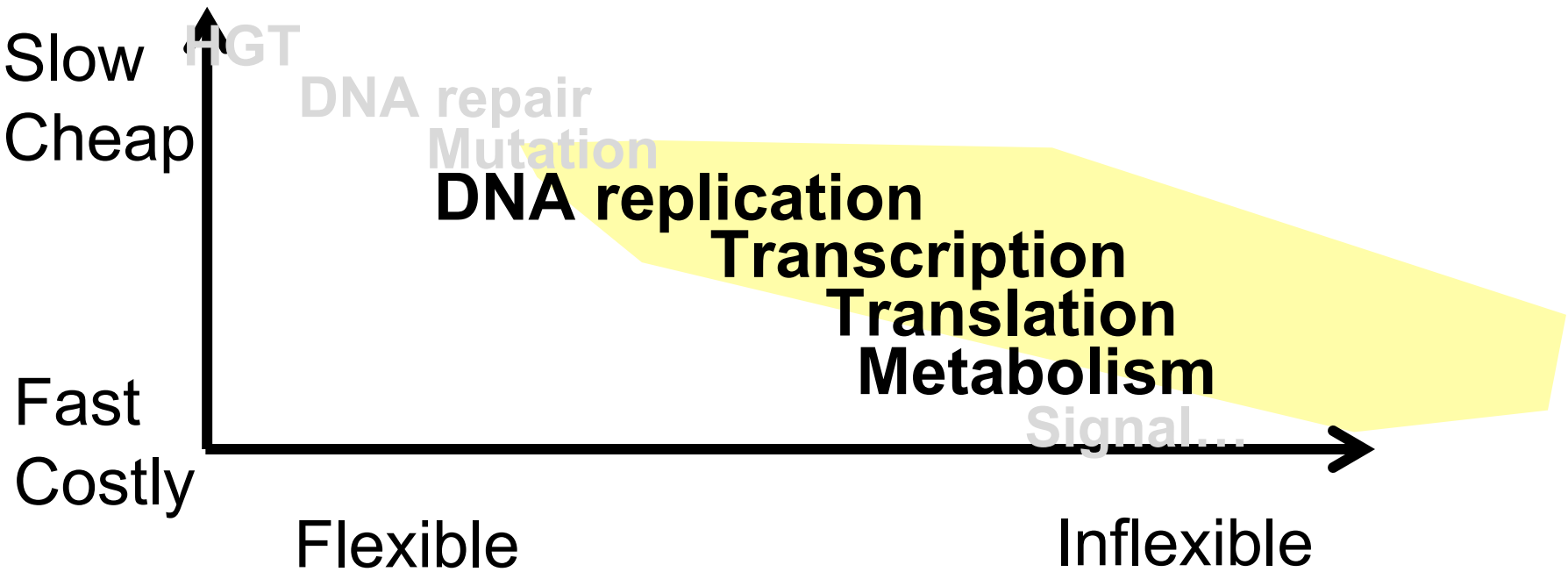
Layered Architecture

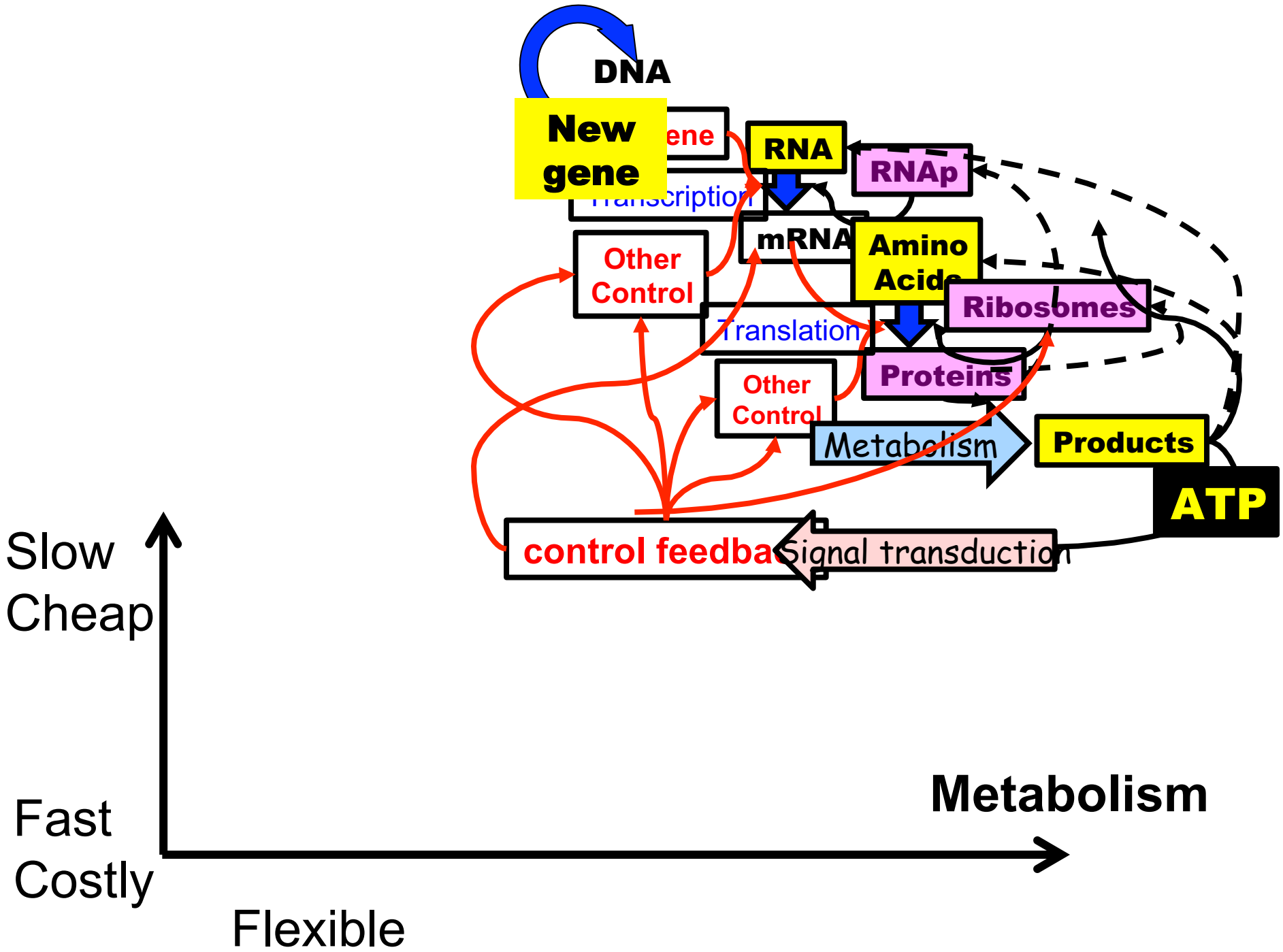


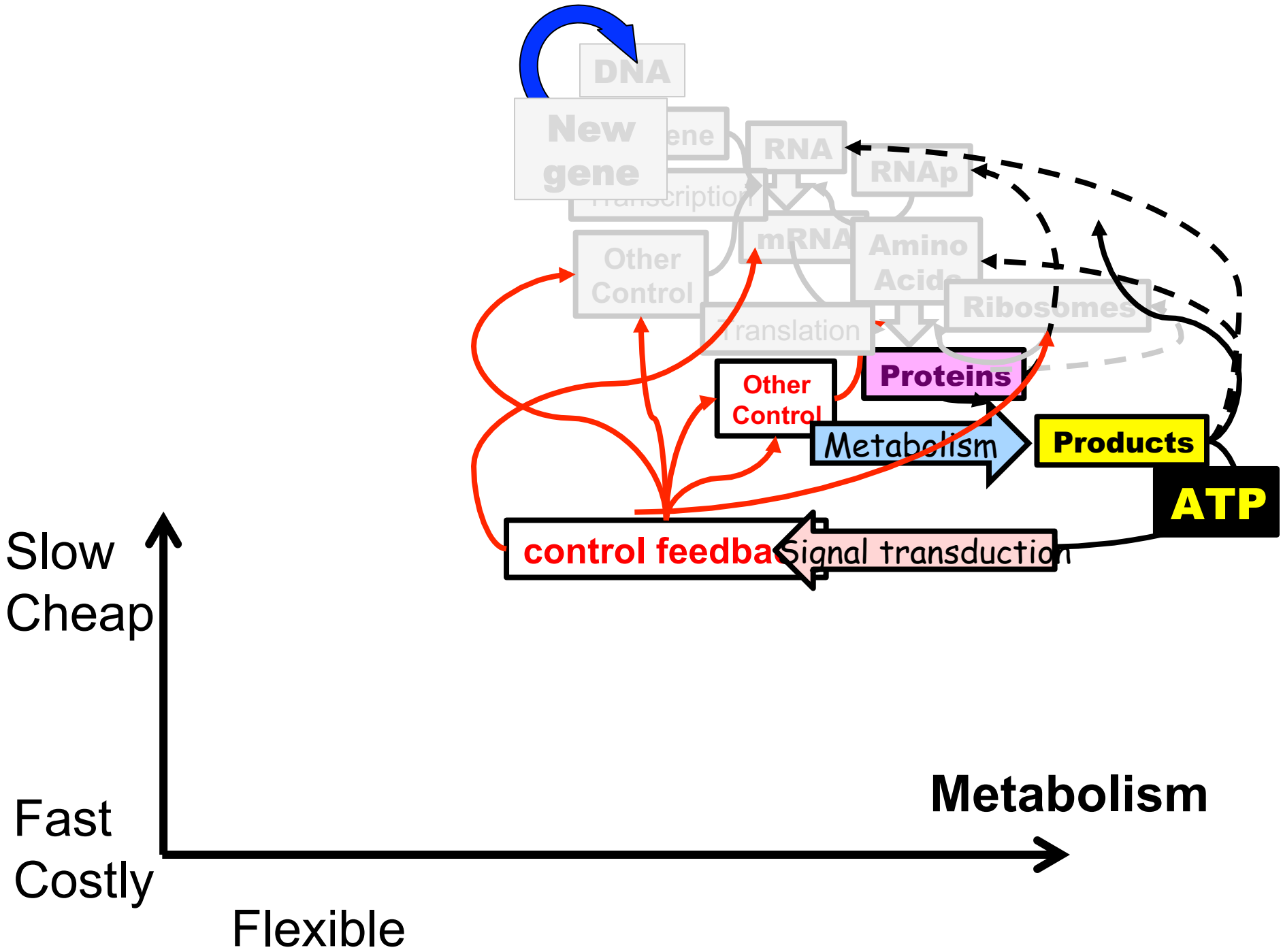


Layered Architecture






DNA
New gene
ene
RNA
RNAp
Transcription
mRNA
Amino Acids
Other Control
Ribosomes
Translation
Proteins
Other Control
Metabolism
Products
ATP
control feedba
Signal transduction
Slow
Cheap
Fast
Costly
Flexible
Metabolism


DNA
New gene
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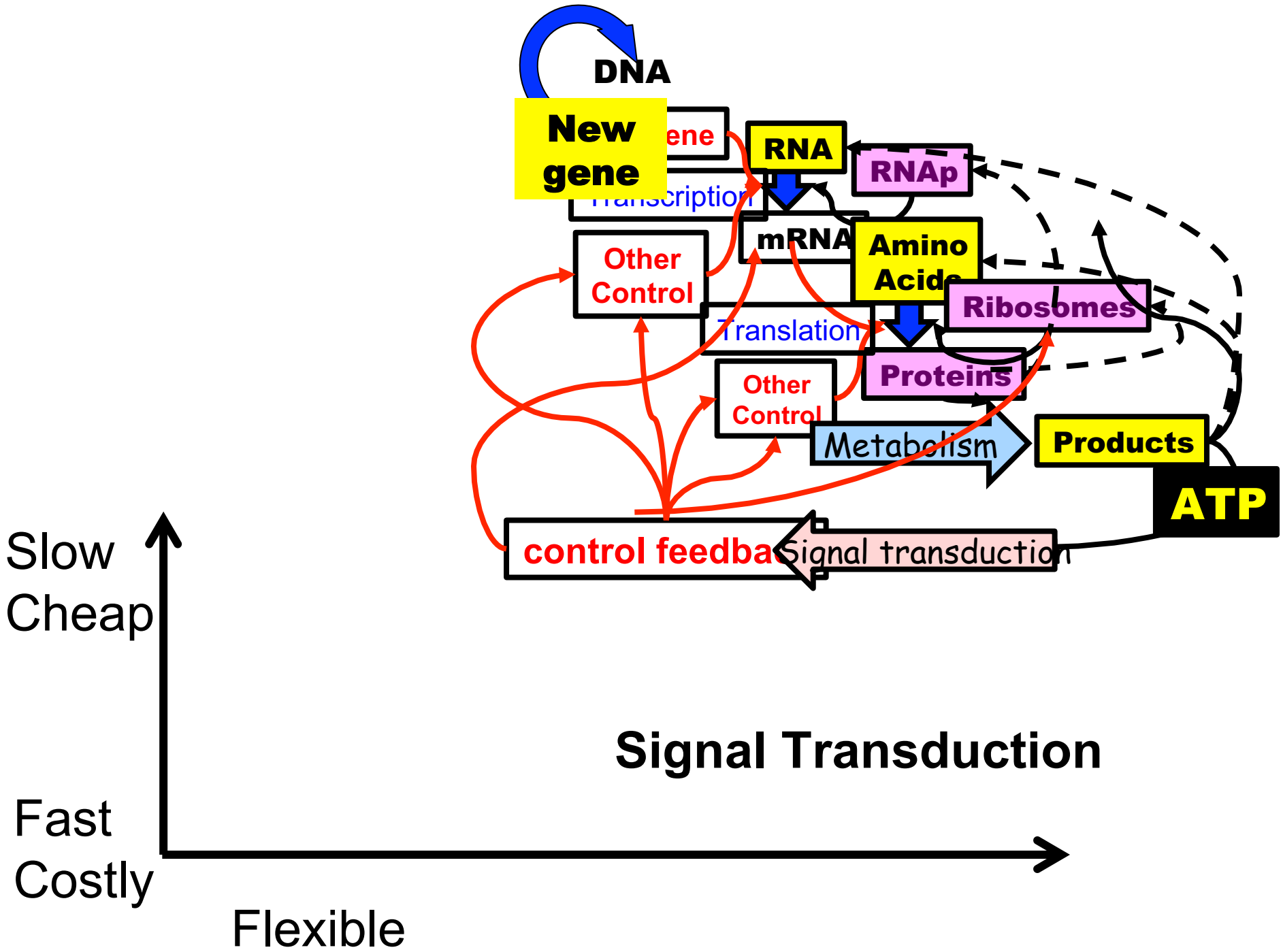
RNA
RNAp
Transcription
mRNA
Amino Acids
Other Control
Ribosomes
Translation
Proteins
Other Control
Metabolism
Products
ATP
control feedba
Signal transduction
Slow
Cheap
Fast
Costly
Flexible
Metabolism


DNA
New gene
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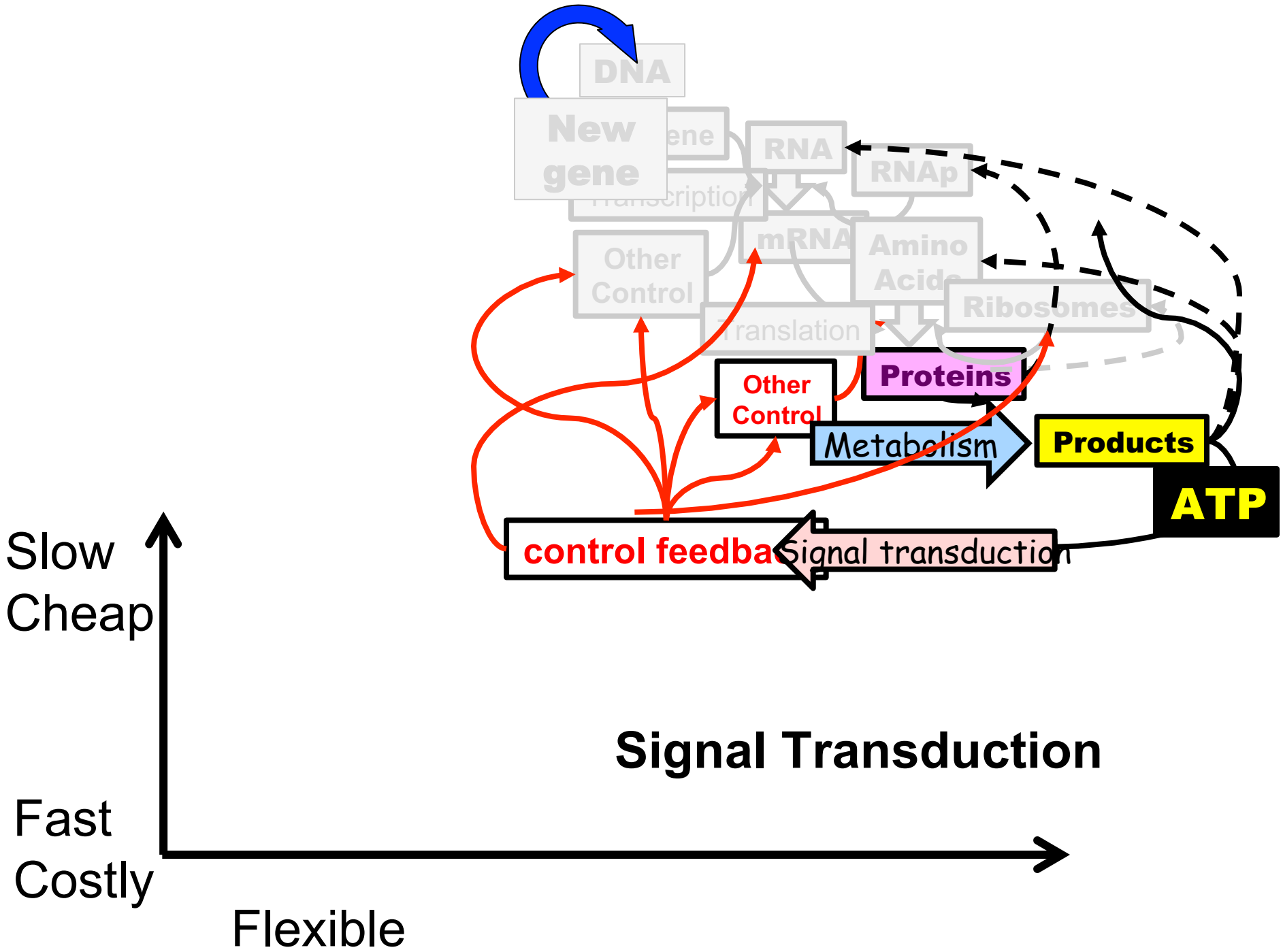
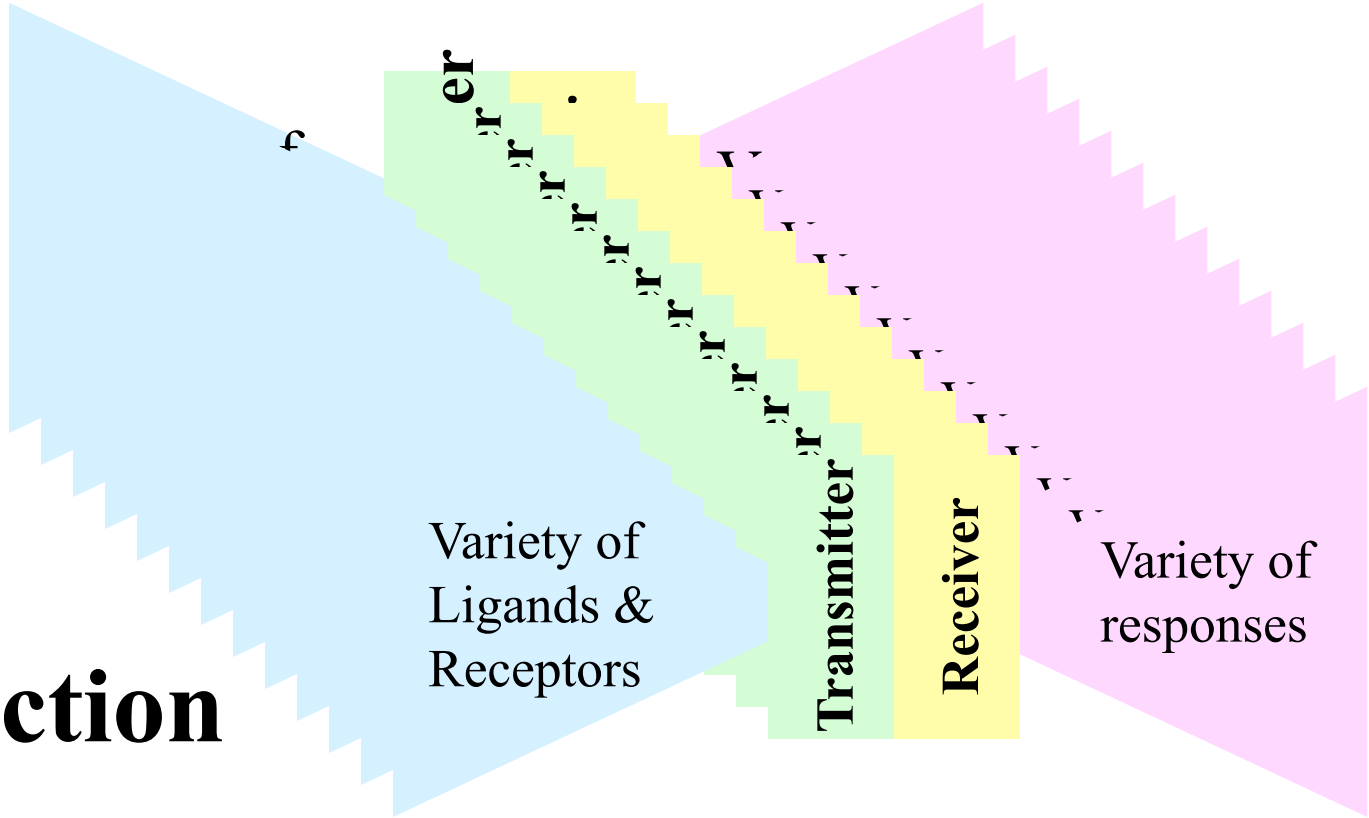
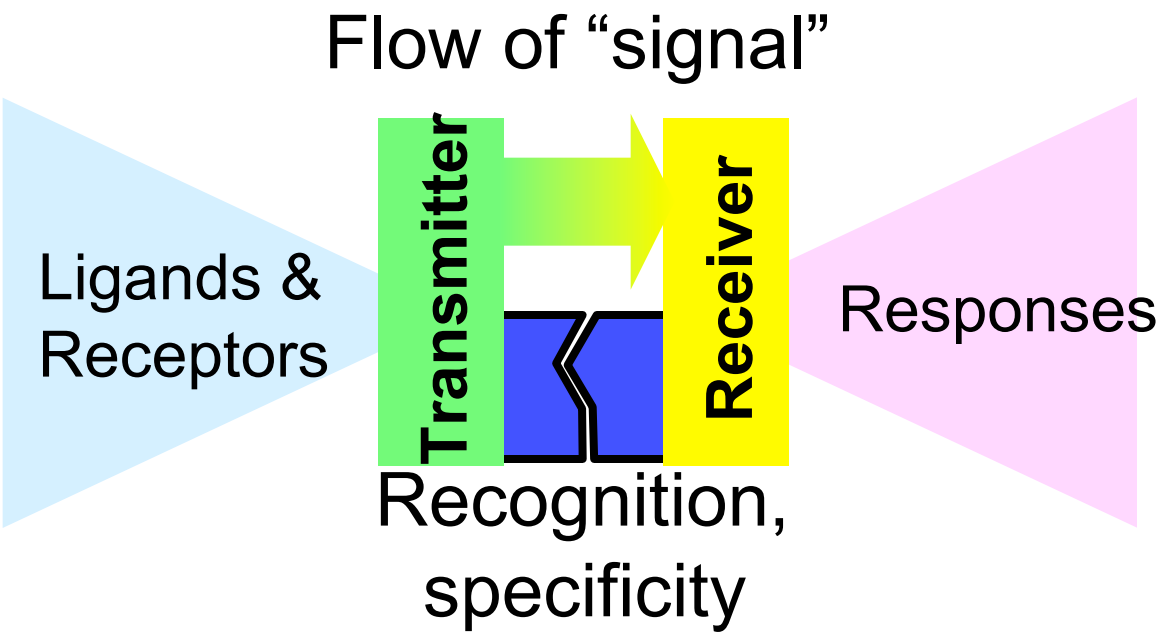
RNA
RNAp
Transcription
mRNA
Amino Acids
Other Control
Ribosomes
Translation
Proteins
Other Control
Metabolism
Products
ATP
control feedba
Signal transduction
Slow
Cheap
Signal Transduction
Fast
Costly
Flexible


DNA
New gene
ene
RNA
RNAp
Transcription
mRNA
Amino Acids
Other Control
Ribosomes
Translation
Proteins
Other Control
Metabolism
Products
ATP
control feedba
Signal transduction
Slow
Cheap
Signal Transduction
Fast
Costly
Flexible

- ≈50 such “two component” systems in *E. Coli*
- All use the same protocol
  - Histidine autokinase transmitter
  - Aspartyl phospho-acceptor receiver
- Huge variety of receptors and responses
- Also multistage (phosphorelay) versions

Signal transduction



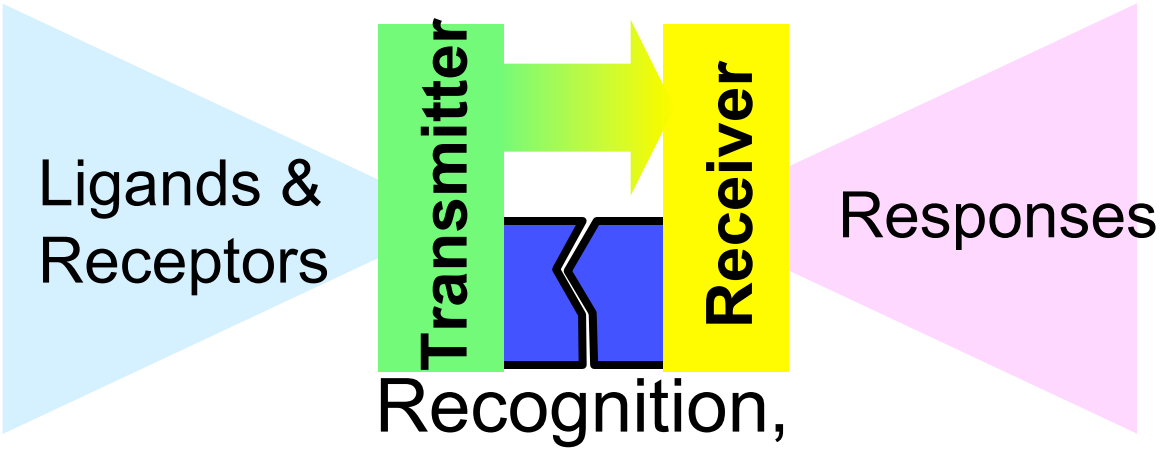


Shared protocols

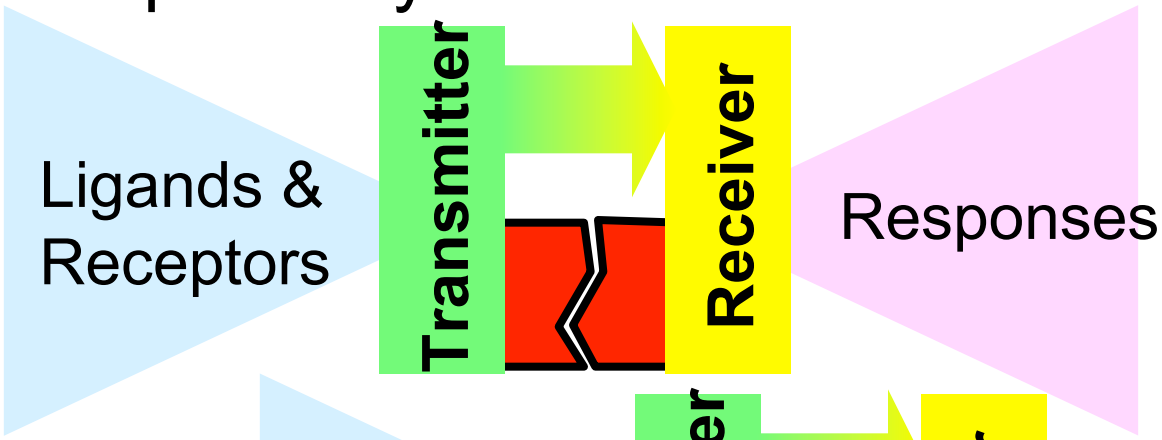
- “Name resolution” within signal transduction
- Transmitter must locate “cognate” receiver and avoid non-cognate receivers
- Global search by rapid, local diffusion
- Limited to very small volumes

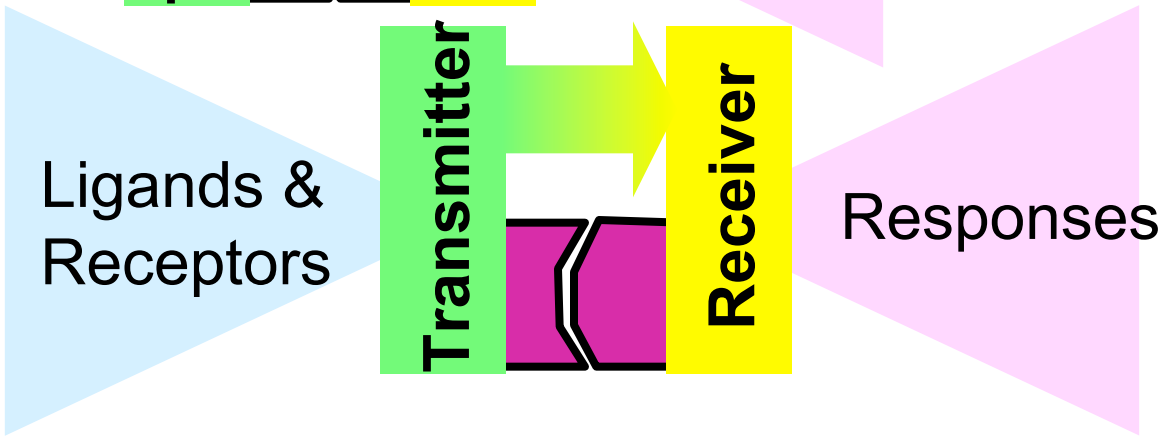
Flow of “signal”

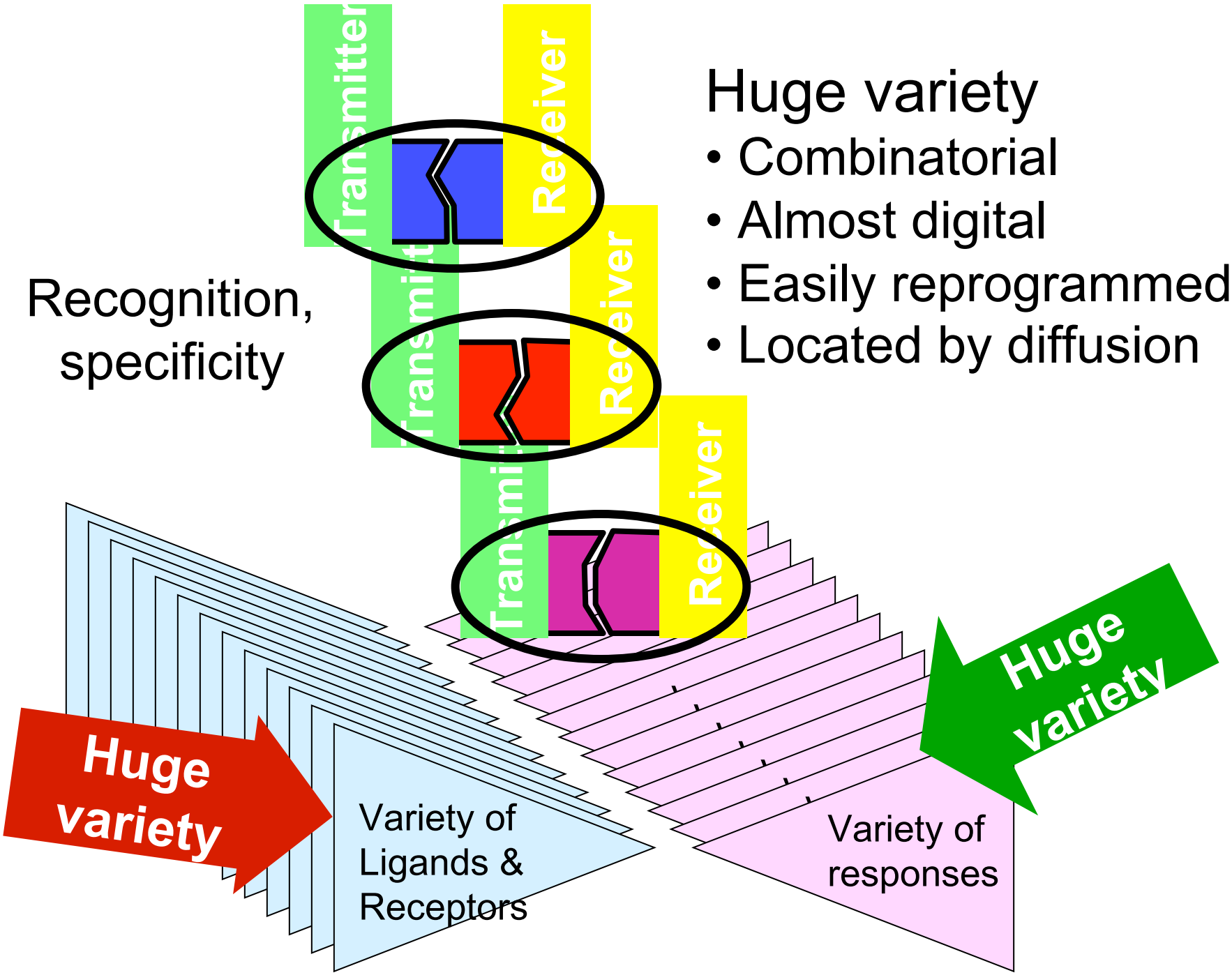
Shared protocols



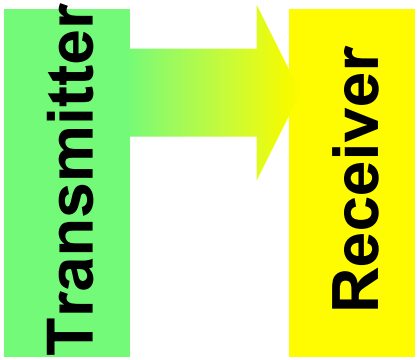
Recognition, specificity





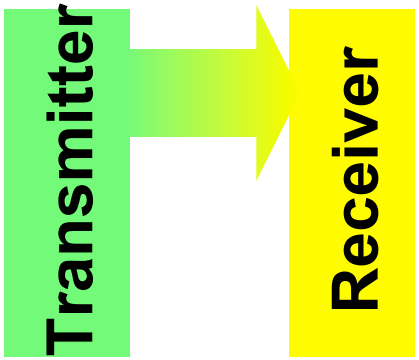

Transmitter
Receiver
Transmitter
Receiver
Transmitter
Receiver
Recognition, specificity
Huge variety
• Combinatorial
• Almost digital
• Easily reprogrammed
• Located by diffusion
Huge variety
Variety of Ligands & Receptors
Huge variety
Variety of responses

Flow of “signal”

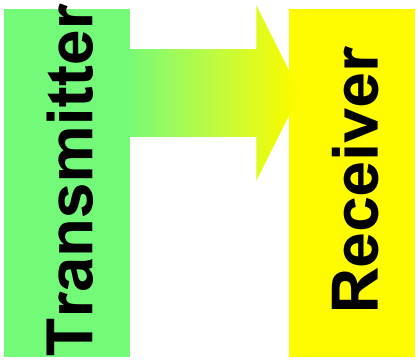


Limited variety

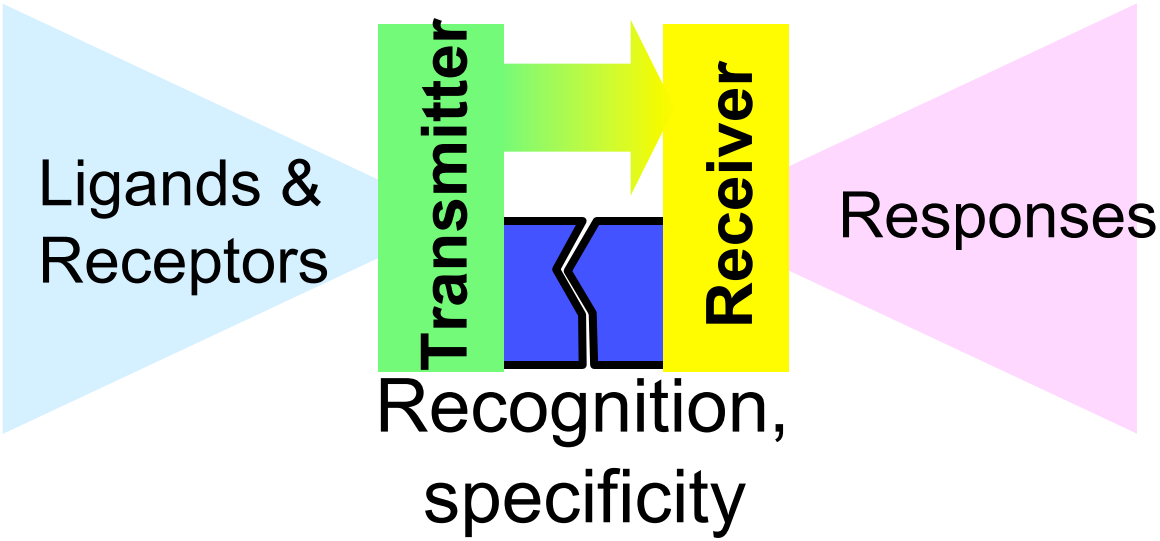
- Fast, analog (via #)
- Hard to change



Reusable in
different pathways



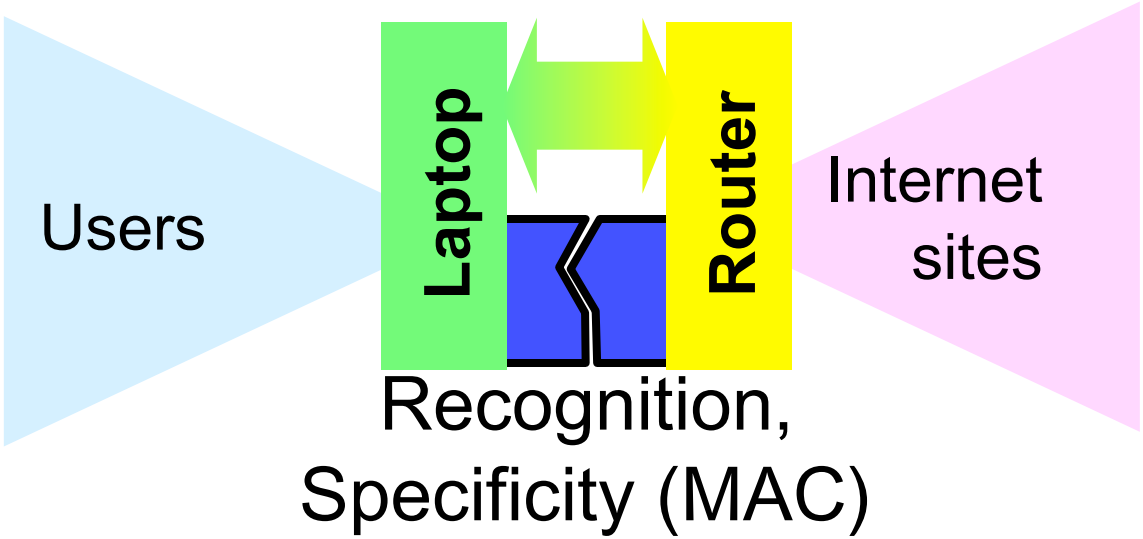
Flow of “signal”



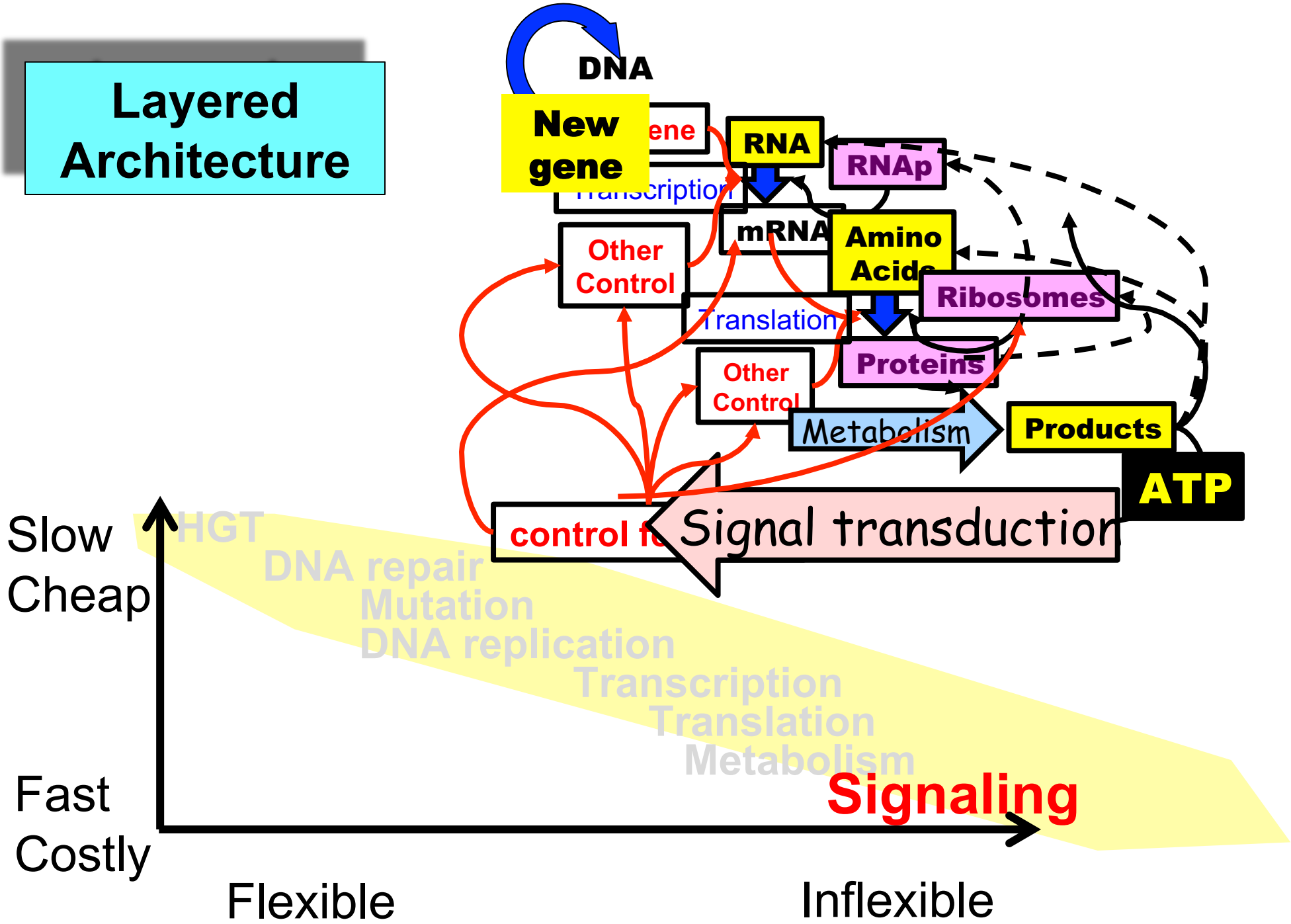
Shared protocols

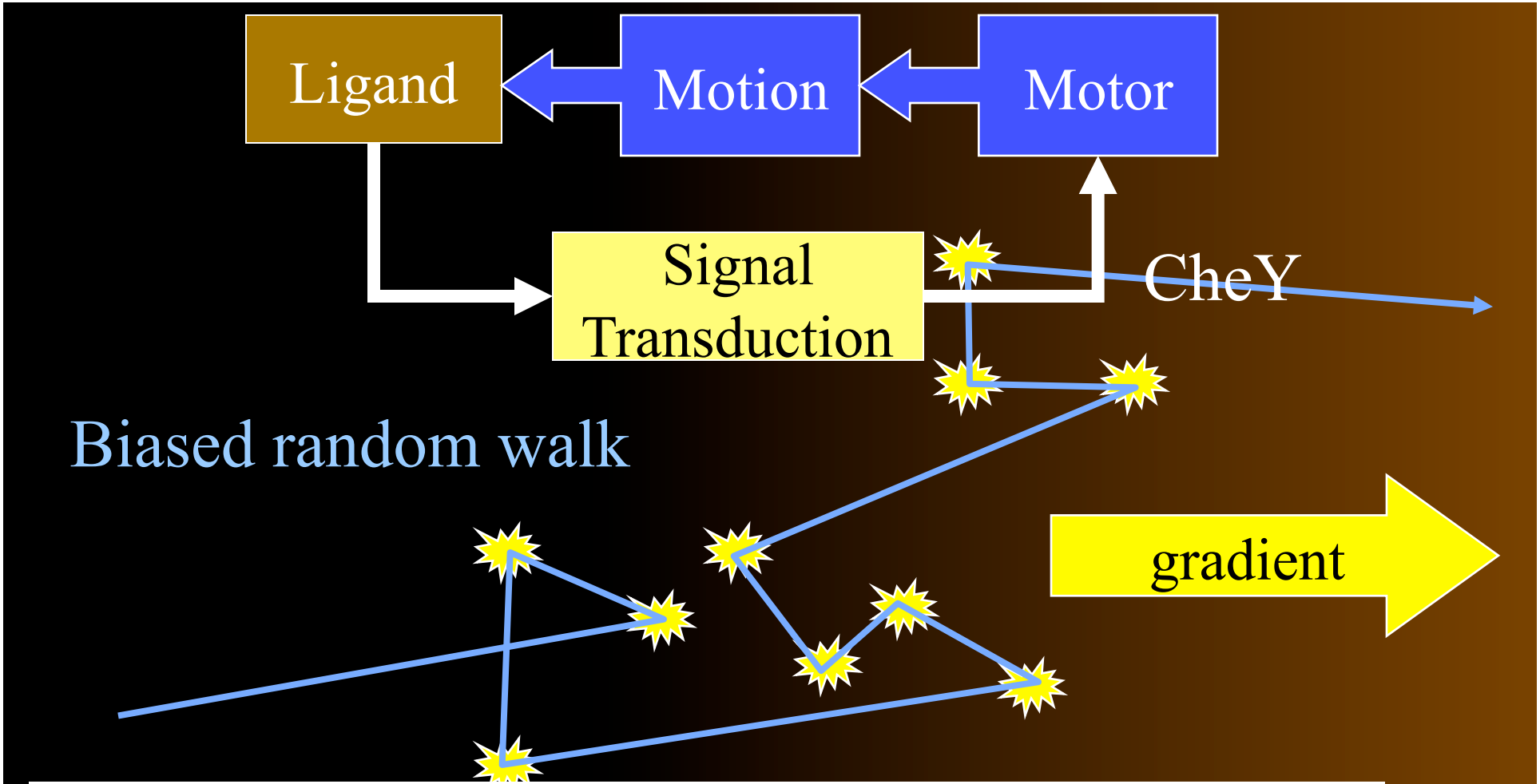
Note: Any wireless system and the Internet to which it is connected work the same way.

Flow of packets



Layered Architecture





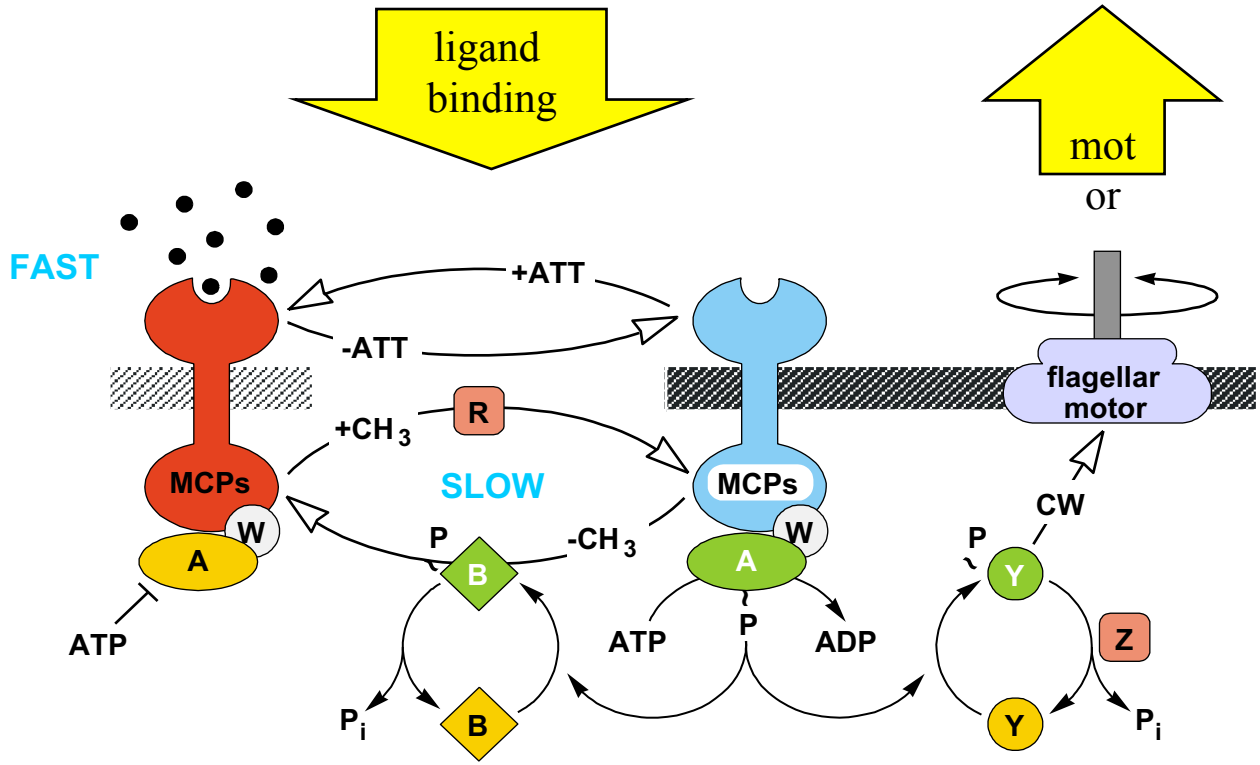
Robust perfect adaptation in bacterial chemotaxis through integral feedback control

Tau-Mu Yi*†, Yun Huang†‡, Melvin I. Simon*§, and John Doyle‡

PNAS | April 25, 2000 | vol. 97 | no. 9 | 4649–4653

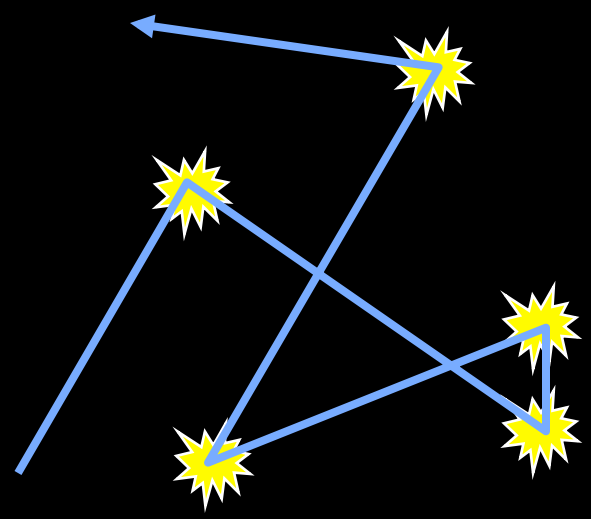
More necessity and robustness

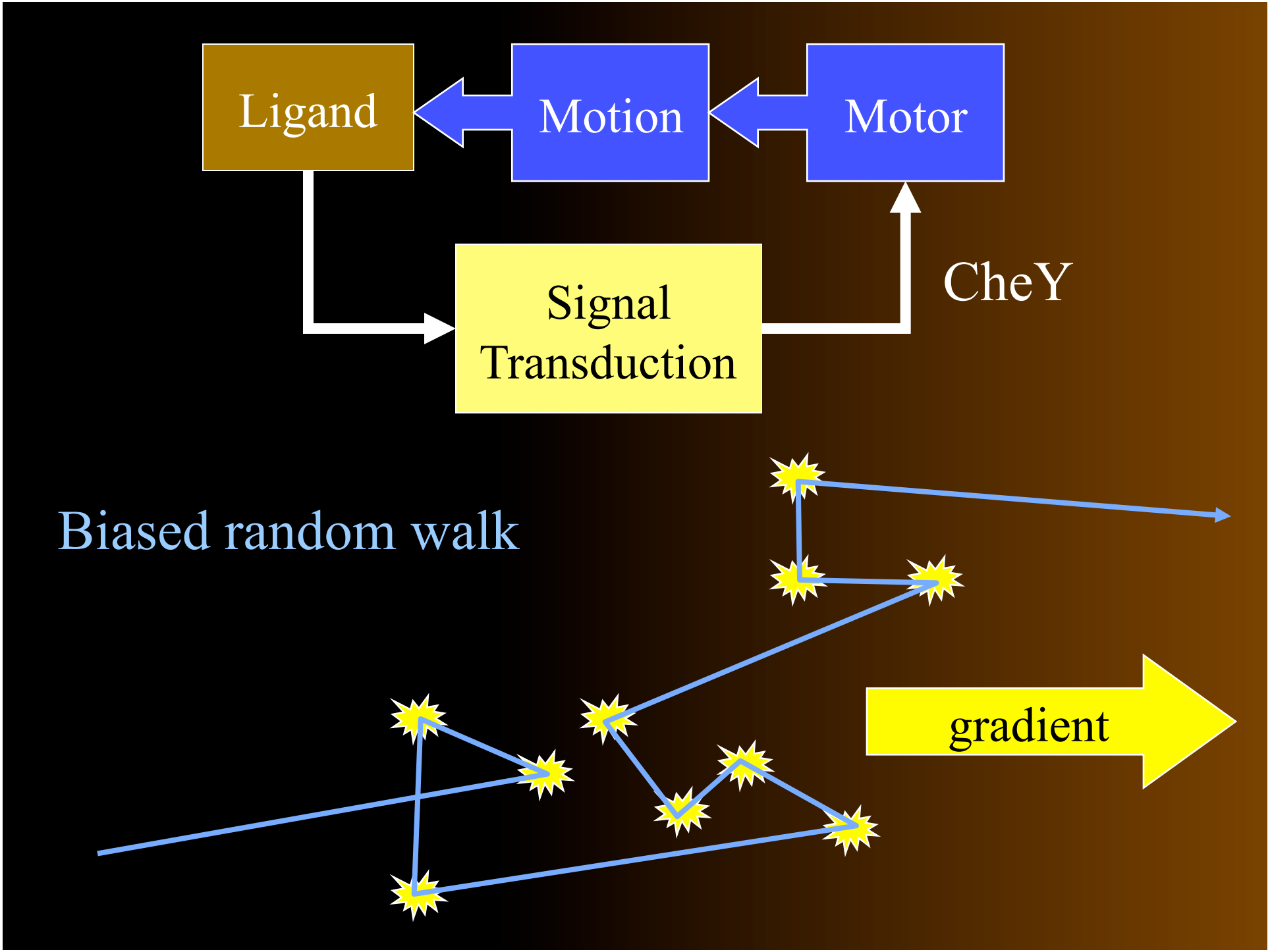
- Integral feedback and signal transduction (bacterial chemotaxis, G protein) (Yi, Huang, Simon)
- Example of "exploratory process"

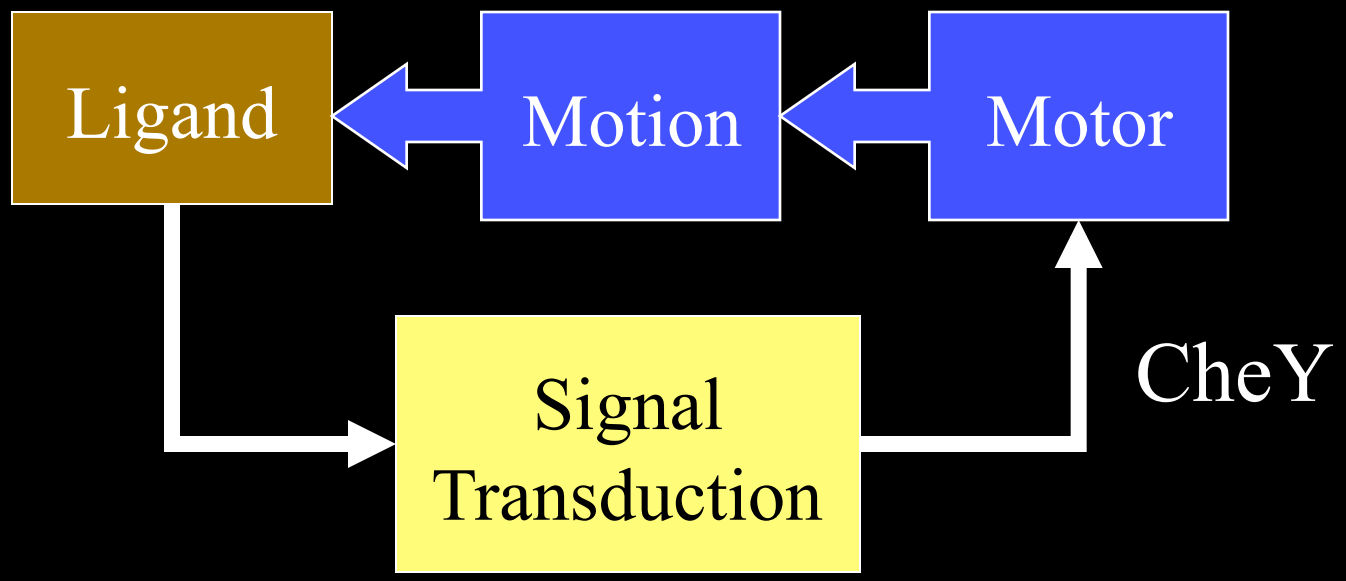


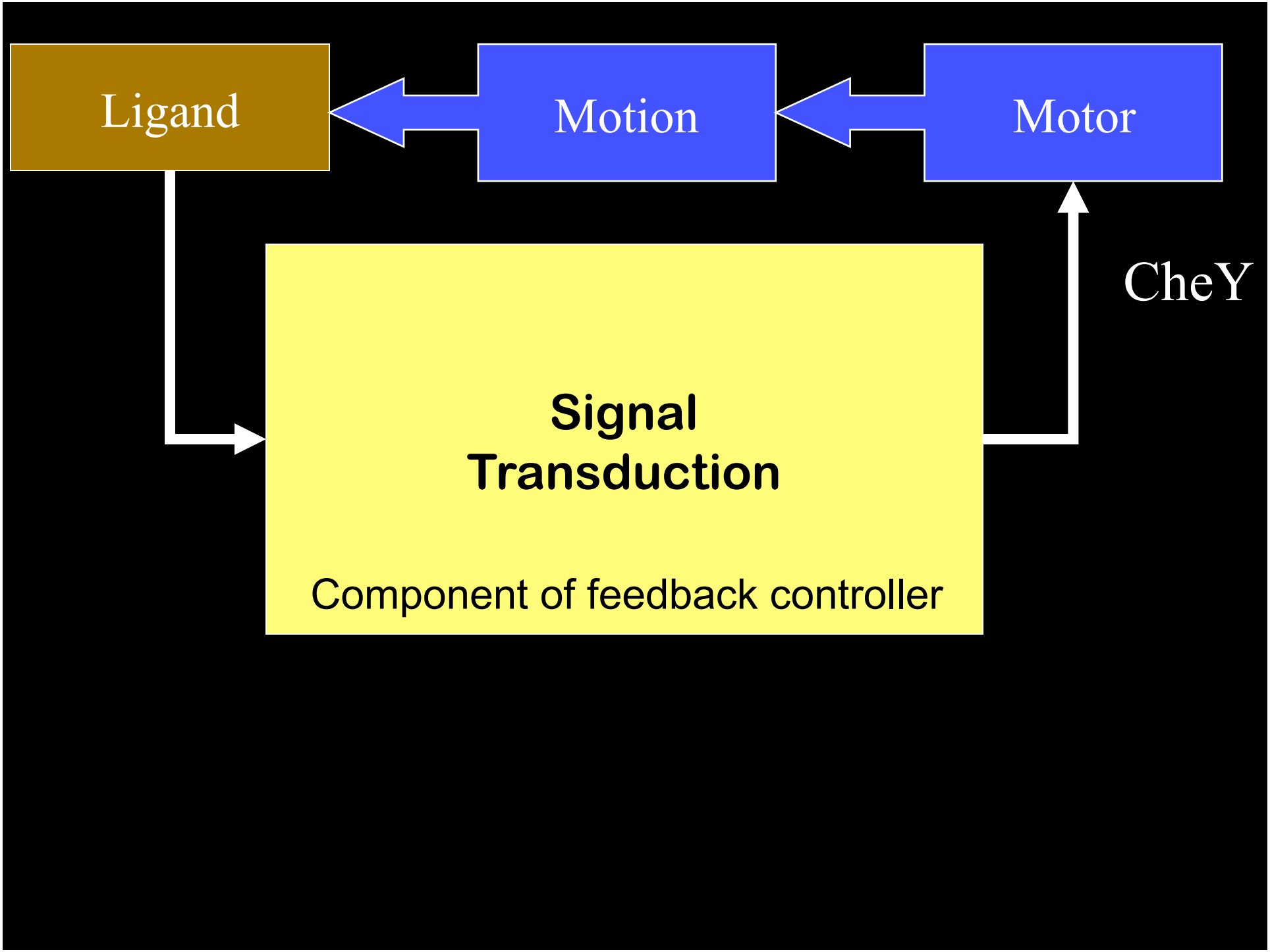
Bacterial chemotaxis

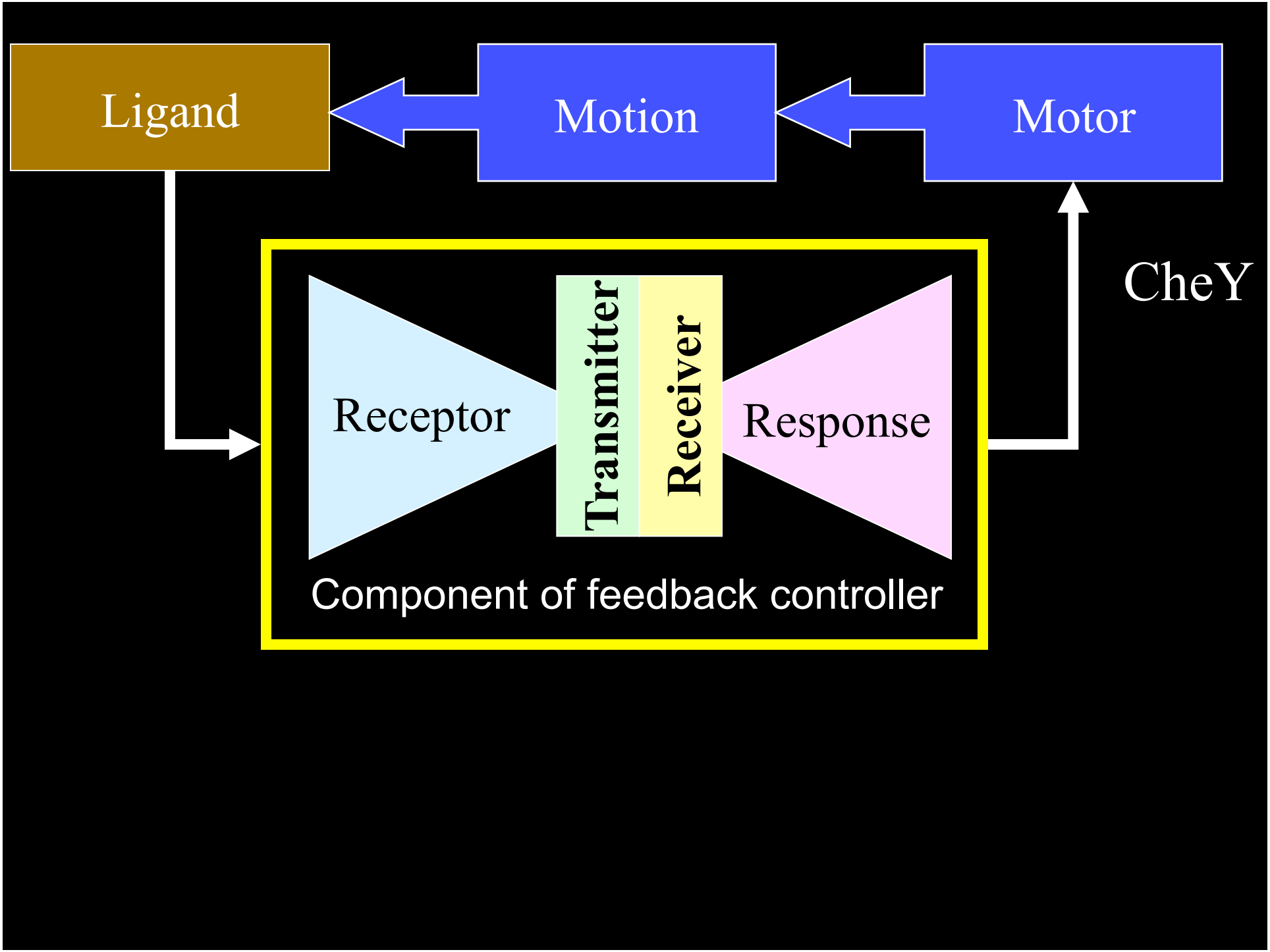
Random walk

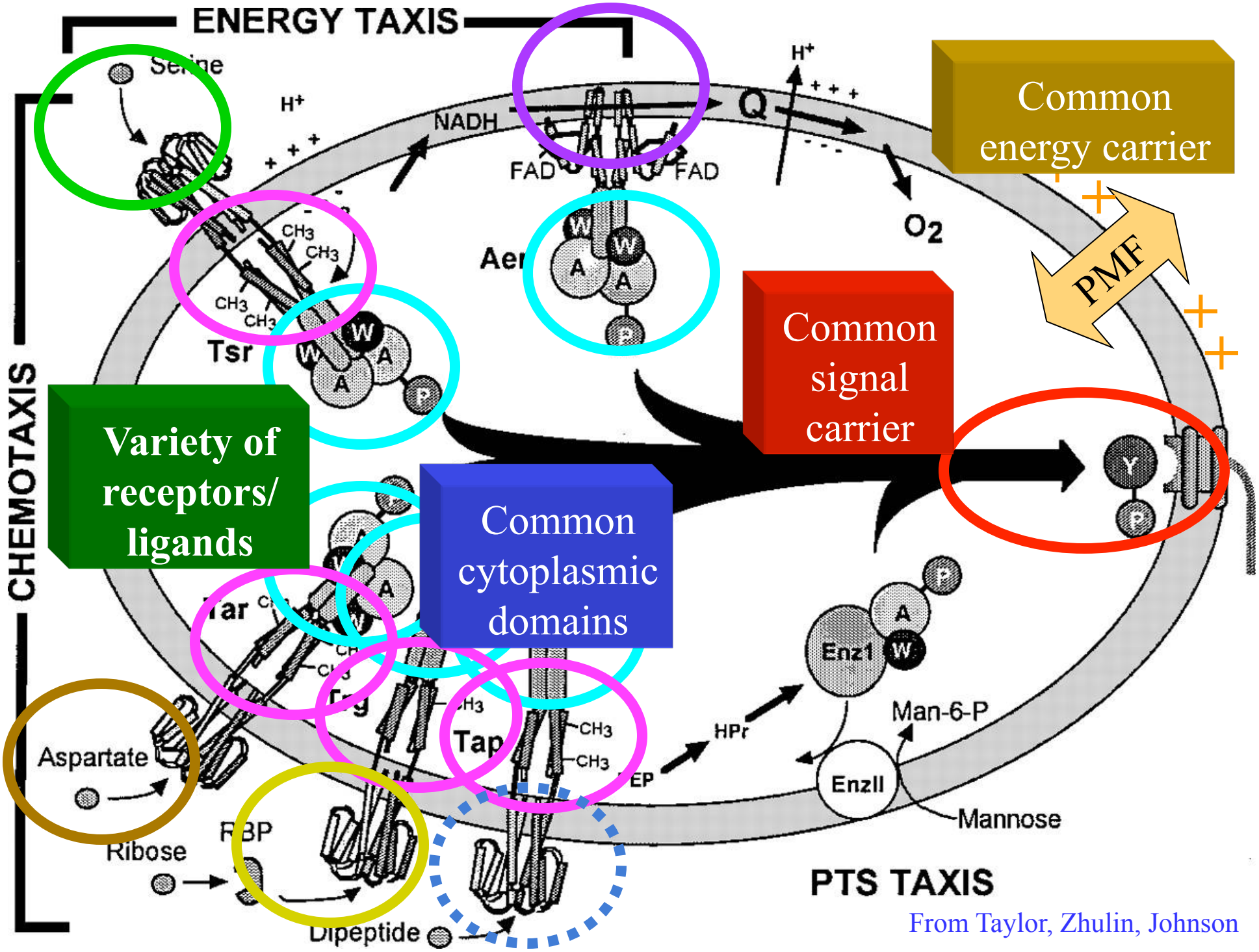



Ligand
Motion
Motor
Signal Transduction
CheY
Biased random walk
gradient

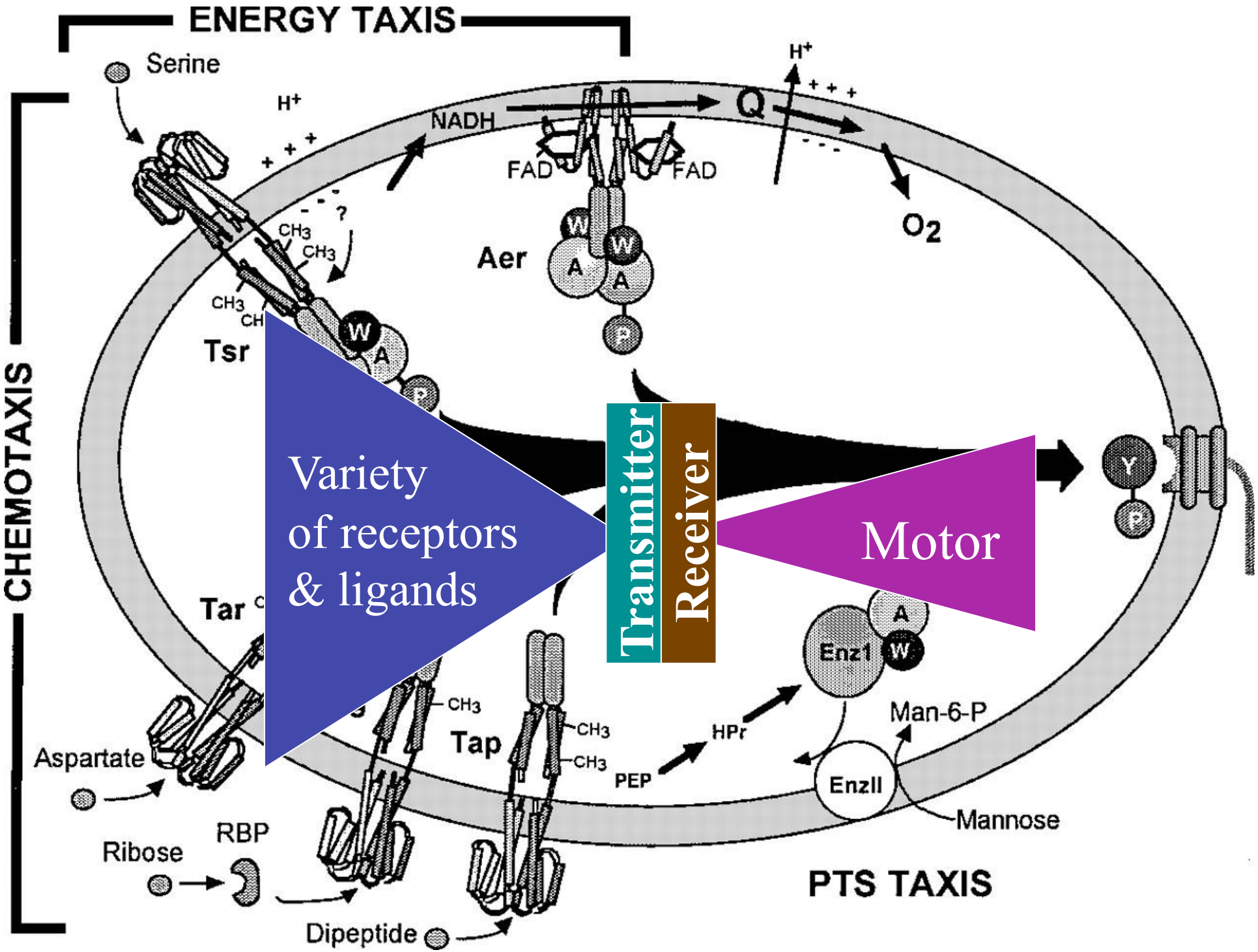

Ligand
Motion
Motor
Signal
Transduction
CheY

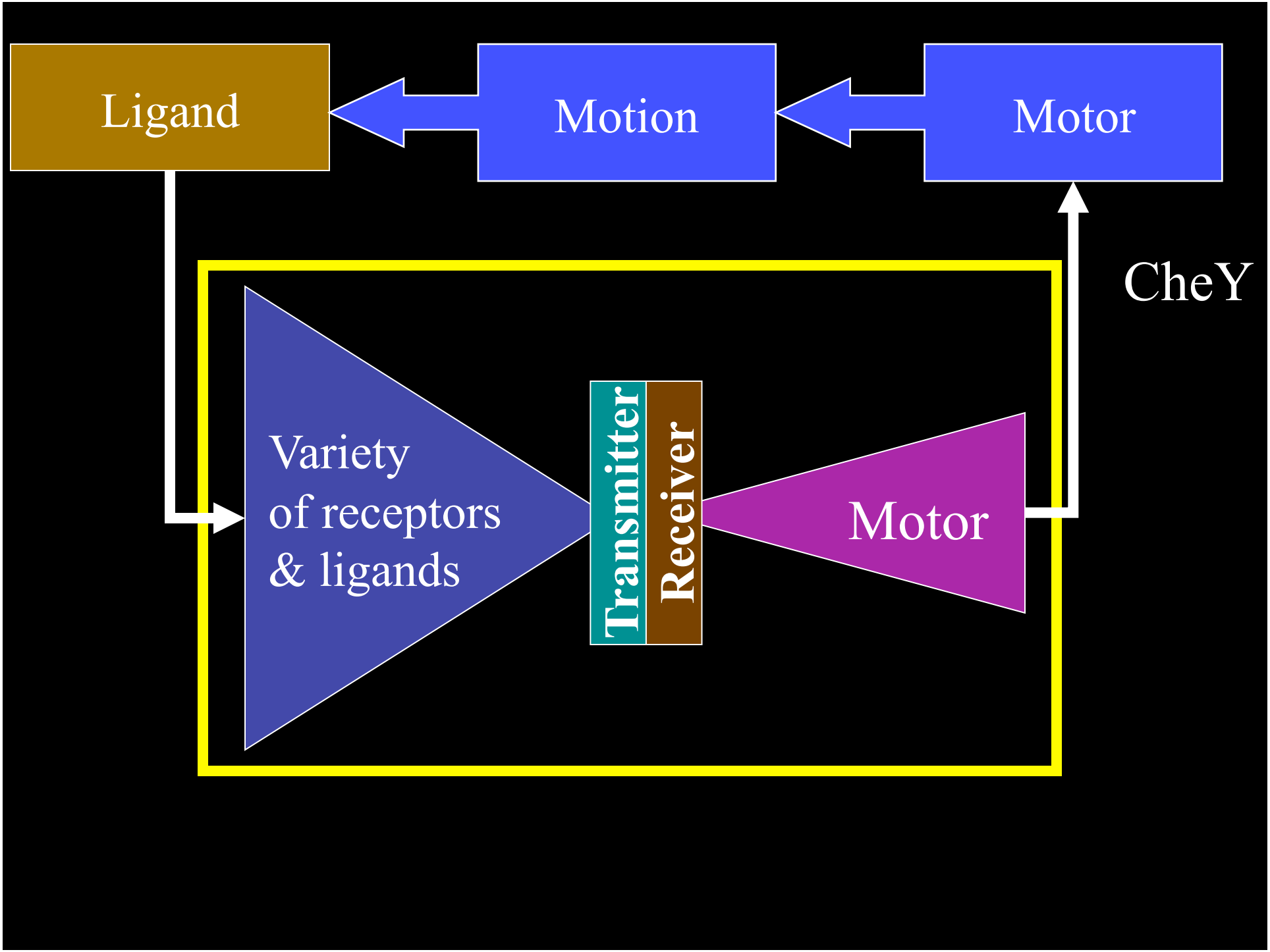

Ligand
Motion
Motor
CheY
Signal
Transduction
Component of feedback controller

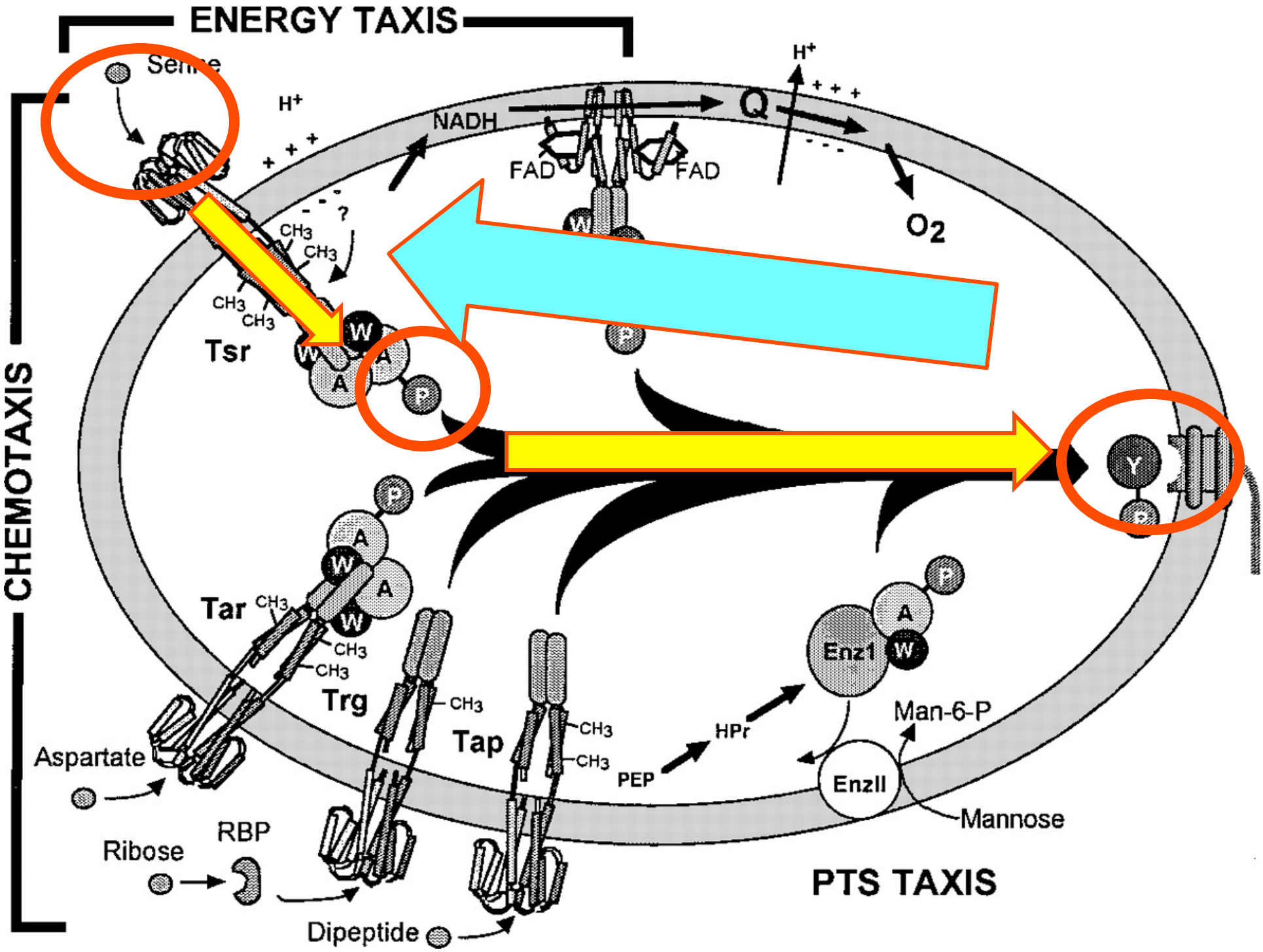

Ligand
Motion
Motor
CheY
Receptor
Transmitter
Receiver
Response
Component of feedback controller

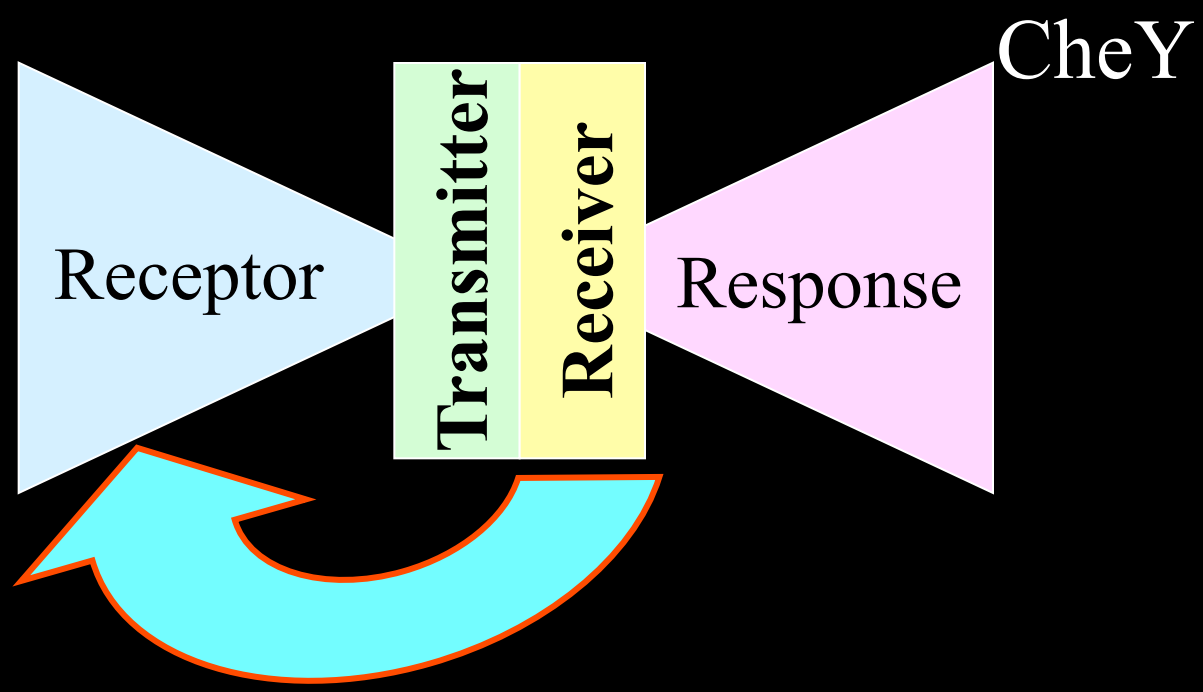


From Taylor, Zhulin, Johnson

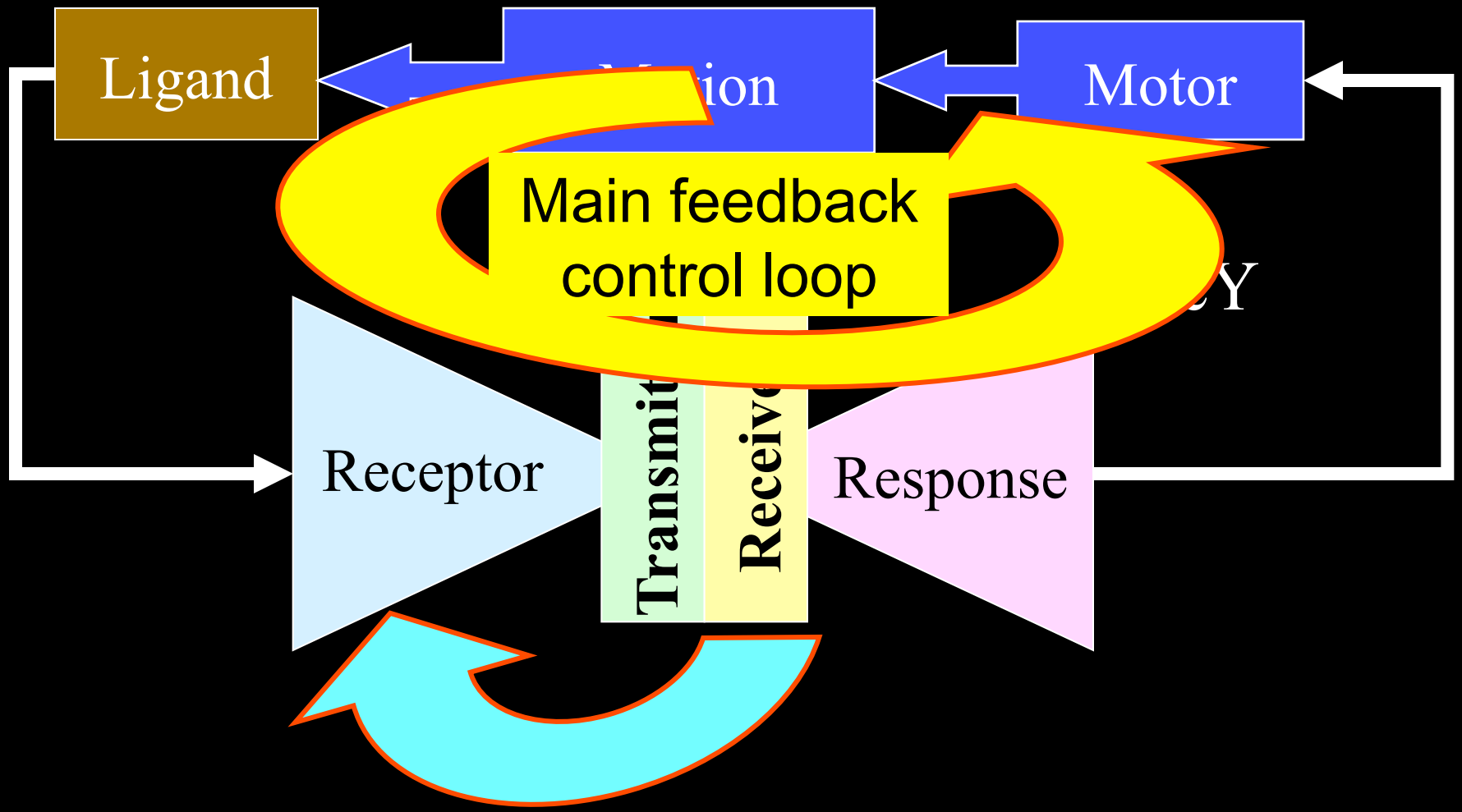

ENERGY TAXIS
CHEMOTAXIS
Serine
H+
NADH
Q
H+
FAD
FAD
O2
Aer
Tsr
Tar
Tap
Aspartate
Ribose
RBP
Dipeptide
Enz1
HPr
PEP
EnzII
Man-6-P
Mannose
PTS TAXIS
Variety
of receptors
& ligands
Transmitter
Receiver
Motor


Ligand
Motion
Motor
CheY
Variety
of receptors
& ligands
Transmitter
Receiver
Motor

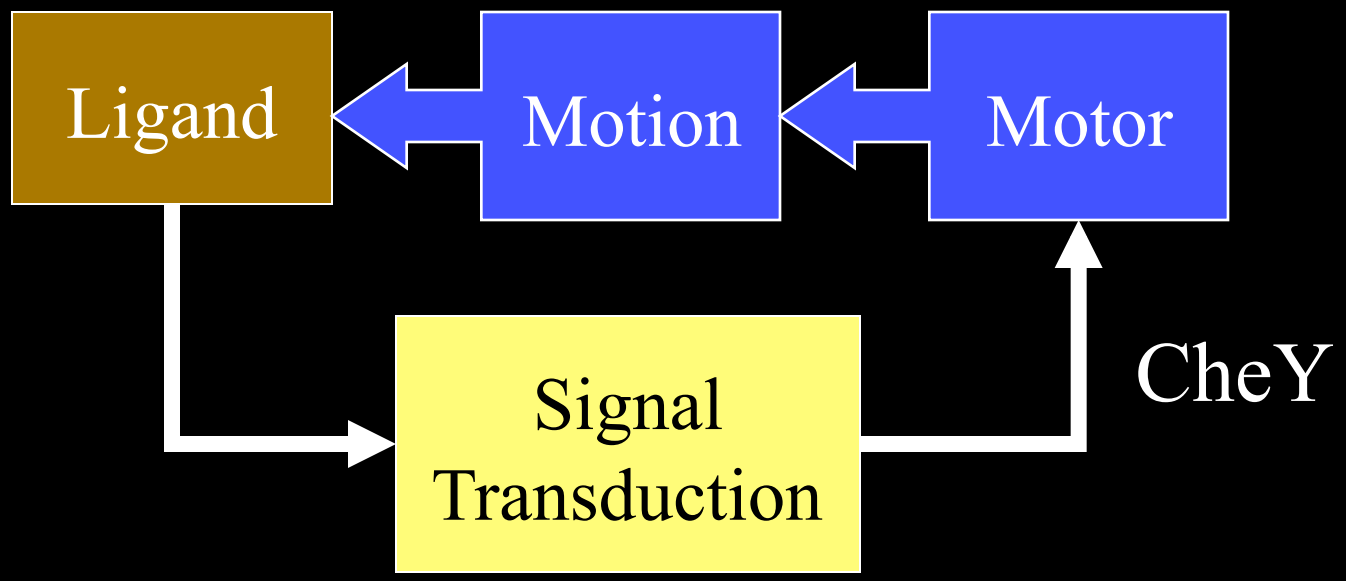

ENERGY TAXIS
CHEMOTAXIS
Serine
H+
NADH
Q
FAD
FAD
O2
Tsr
Tar
Trg
Tap
Aspartate
Ribose
RBP
Dipeptide
PEP
HPr
Enz1
EnzII
Man-6-P
Mannose
PTS TAXIS

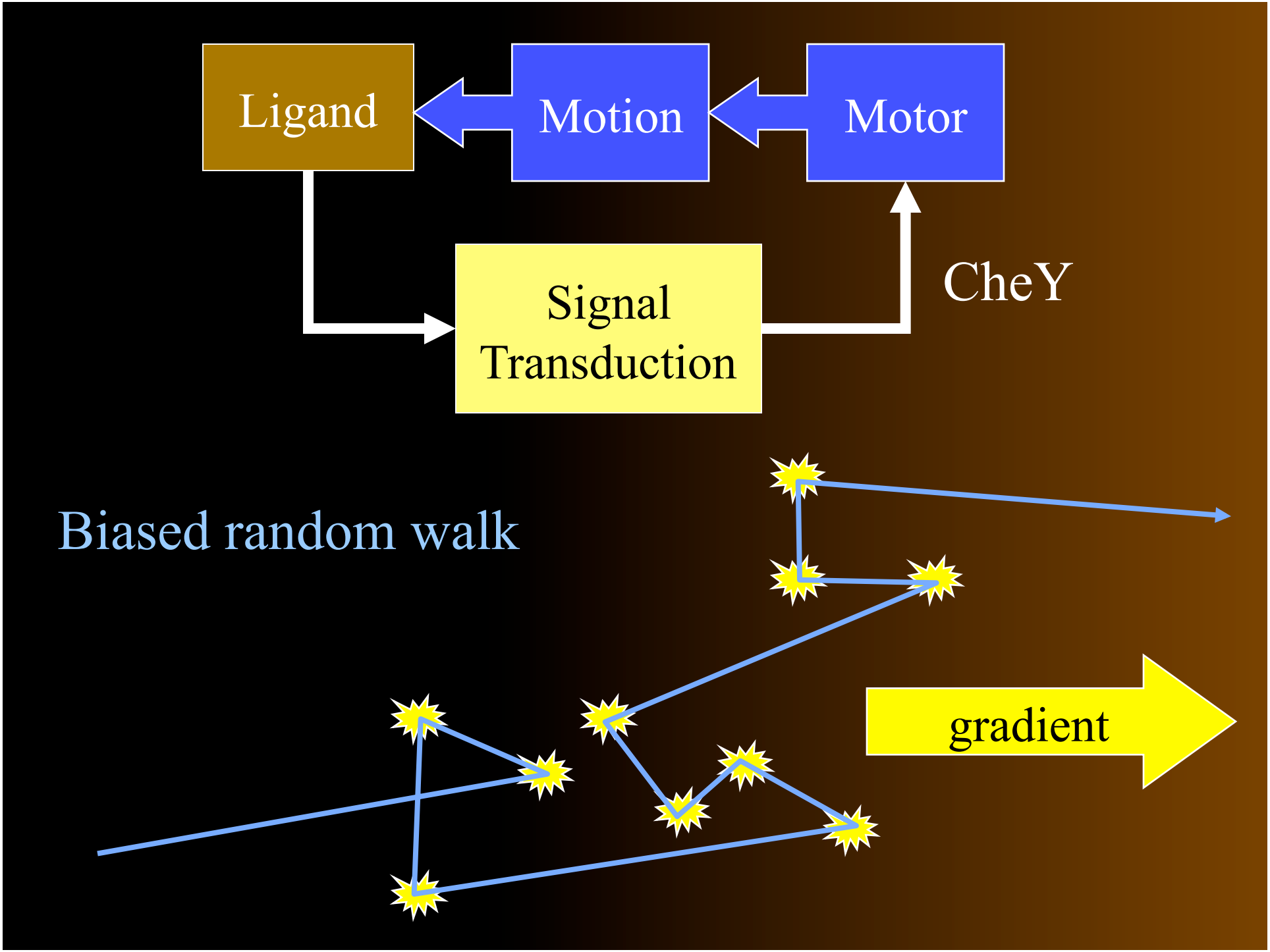


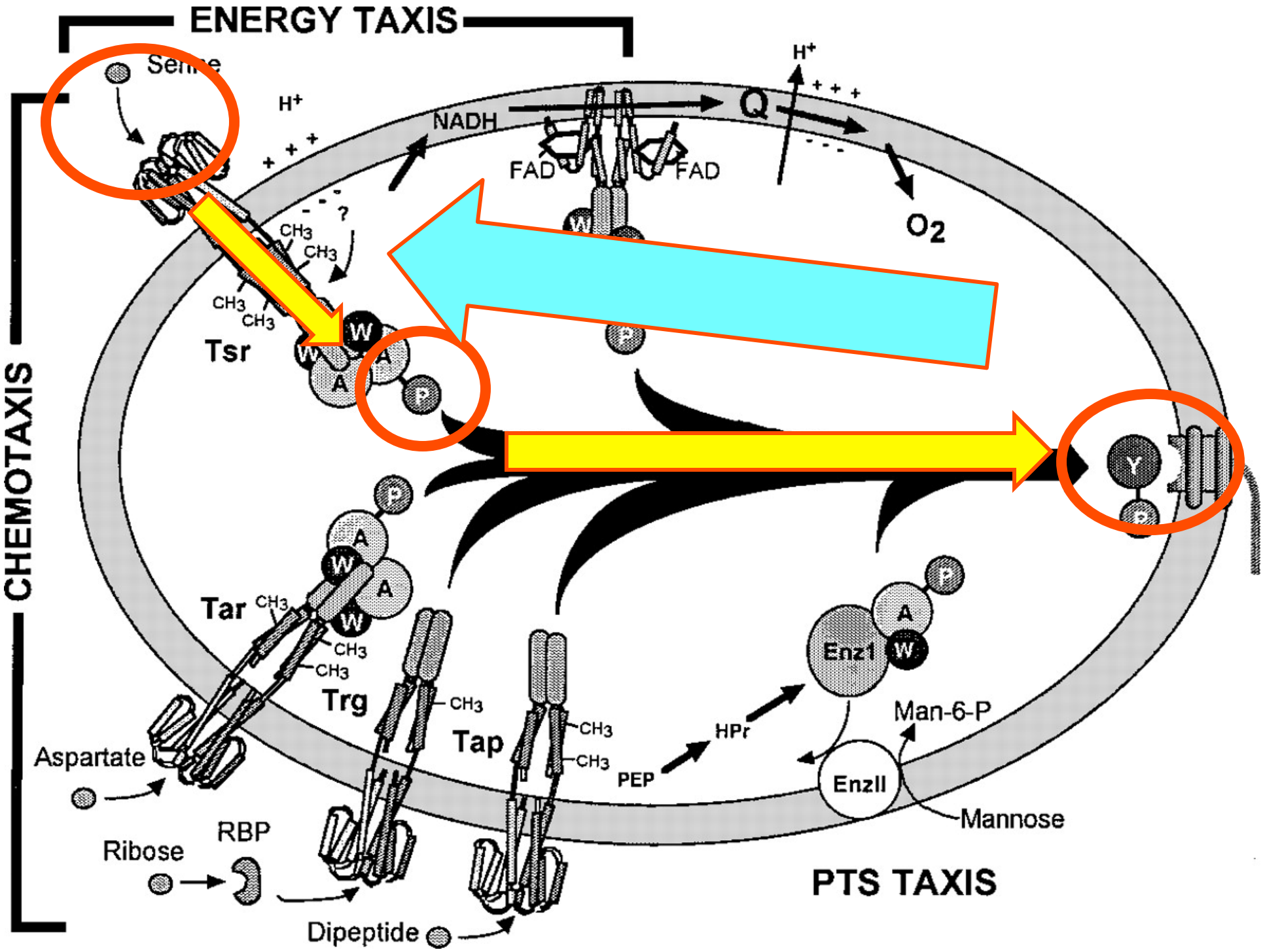
Integral feedback internal to signaling network



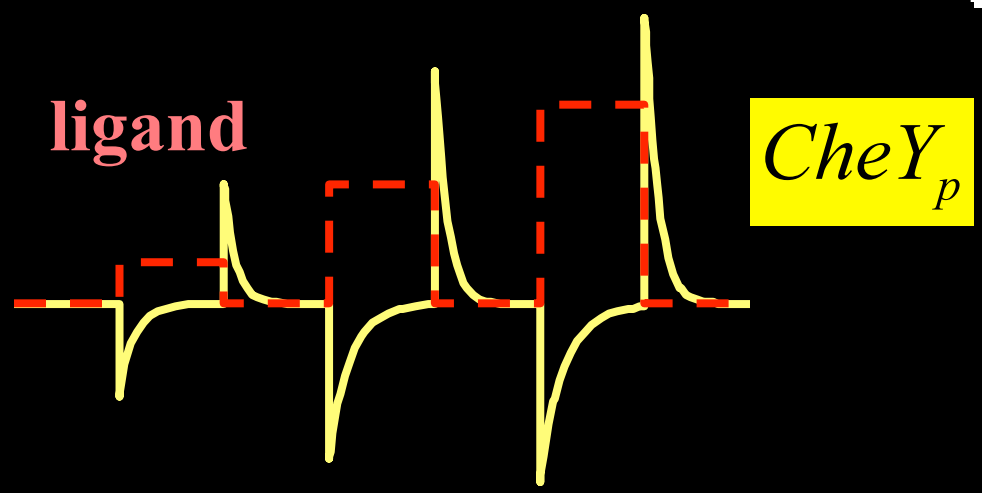
Integral feedback
internal to signaling
network

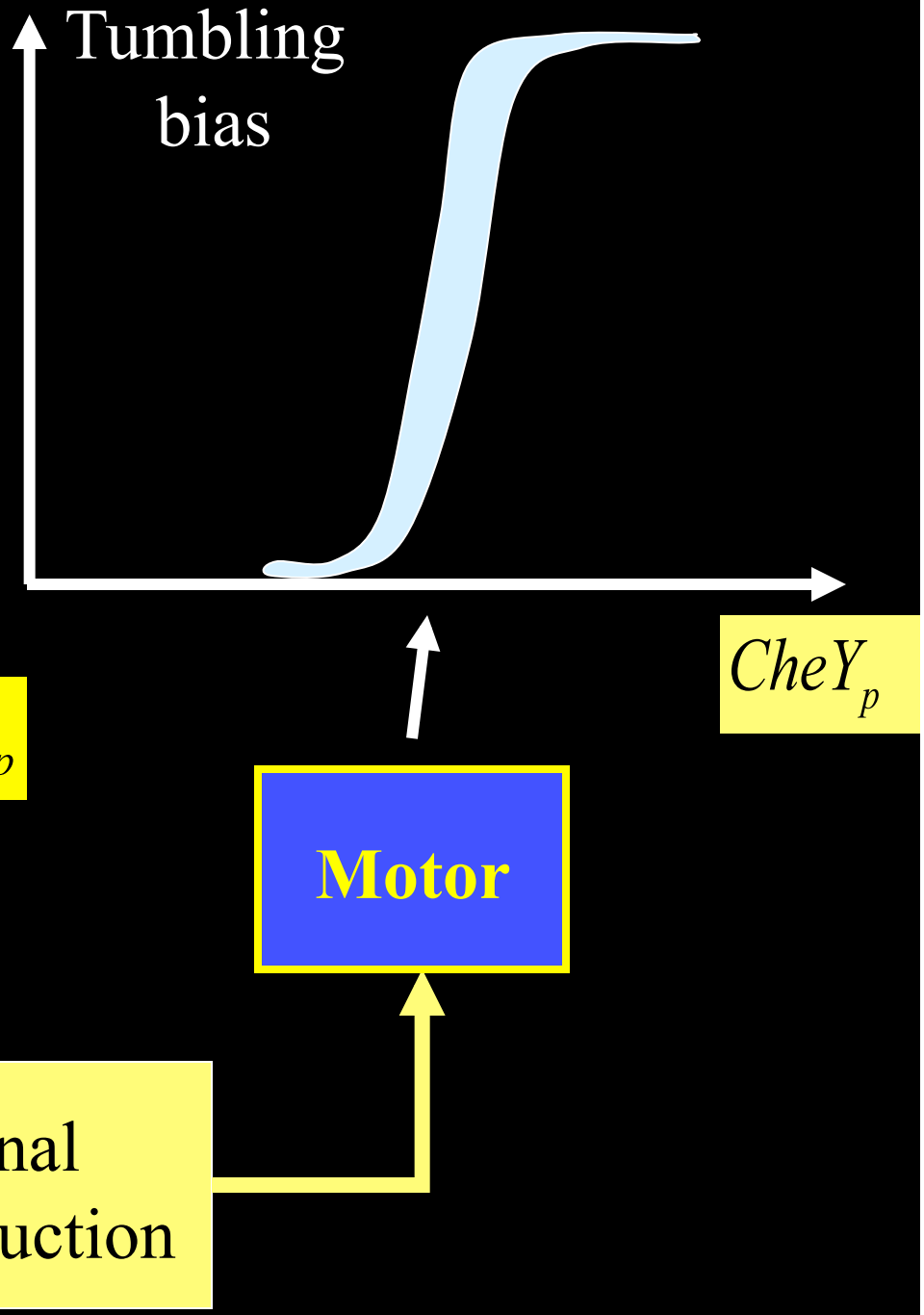

Ligand
Motion
Motor
Signal
Transduction
CheY


Ligand
Motion
Motor
Signal Transduction
CheY
Biased random walk
gradient


ENERGY TAXIS
CHEMOTAXIS
Serine
H+
NADH
Q
FAD
FAD
O2
Tsr
Tar
Trg
Tap
Aspartate
Ribose
RBP
Dipeptide
PEP
HPr
Enz1
EnzII
Man-6-P
Mannose
PTS TAXIS

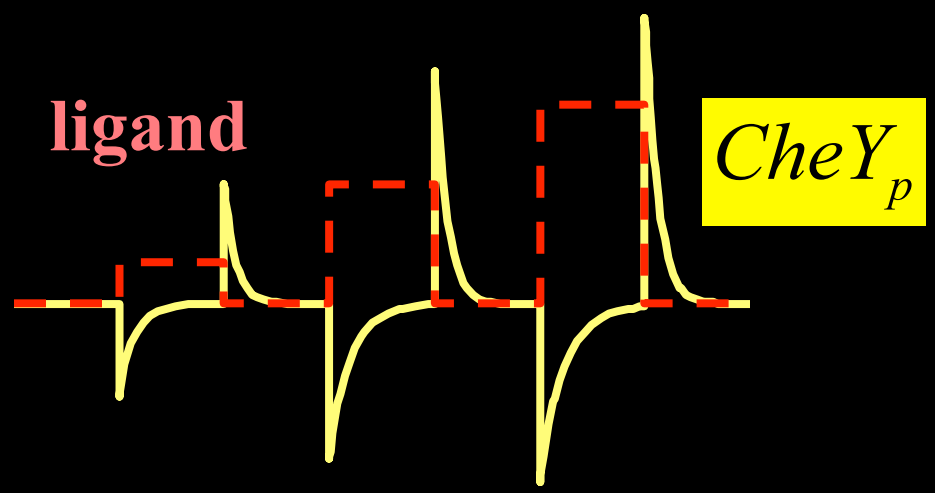
Perfect adaptation is ***necessary*** …

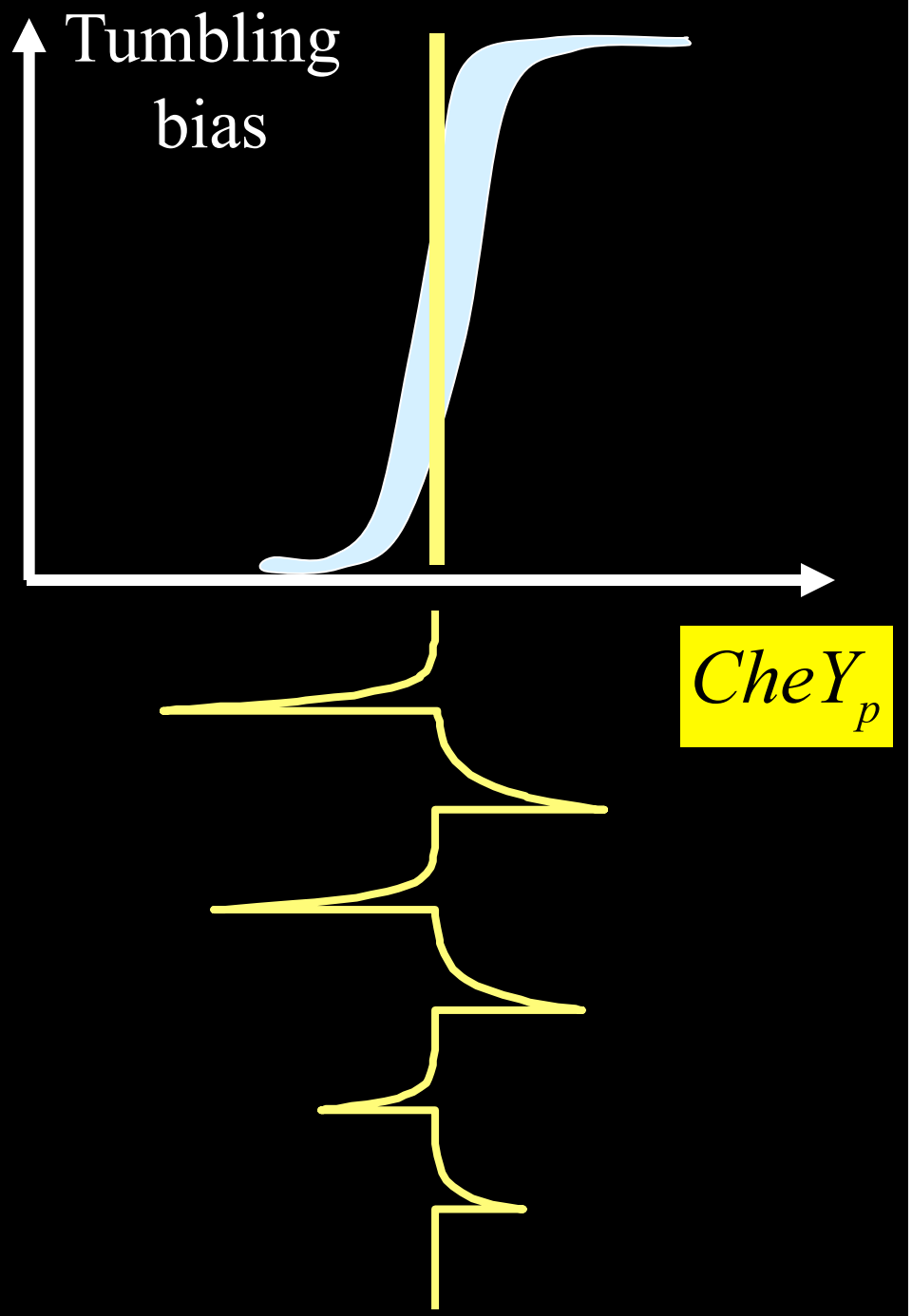


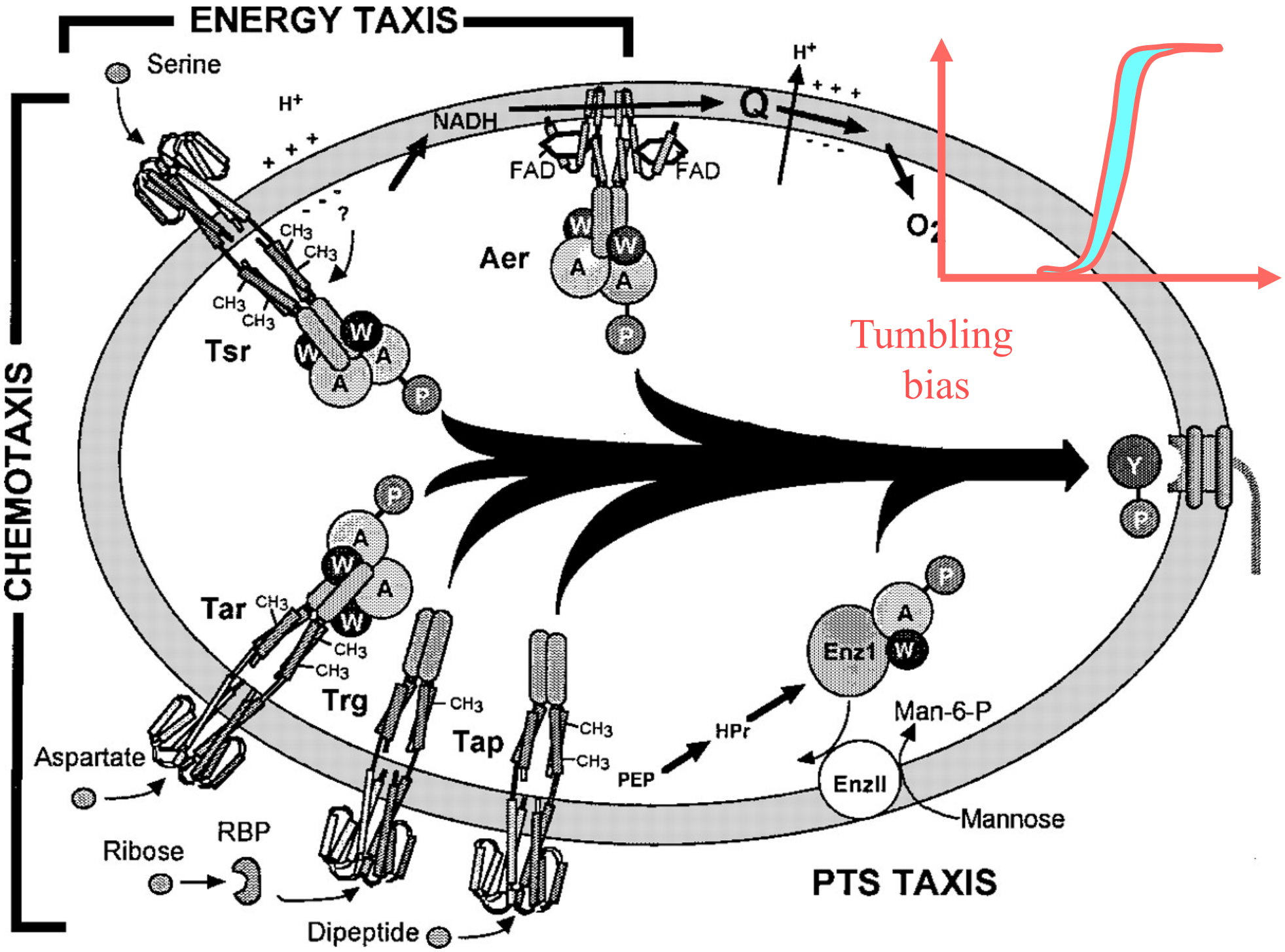


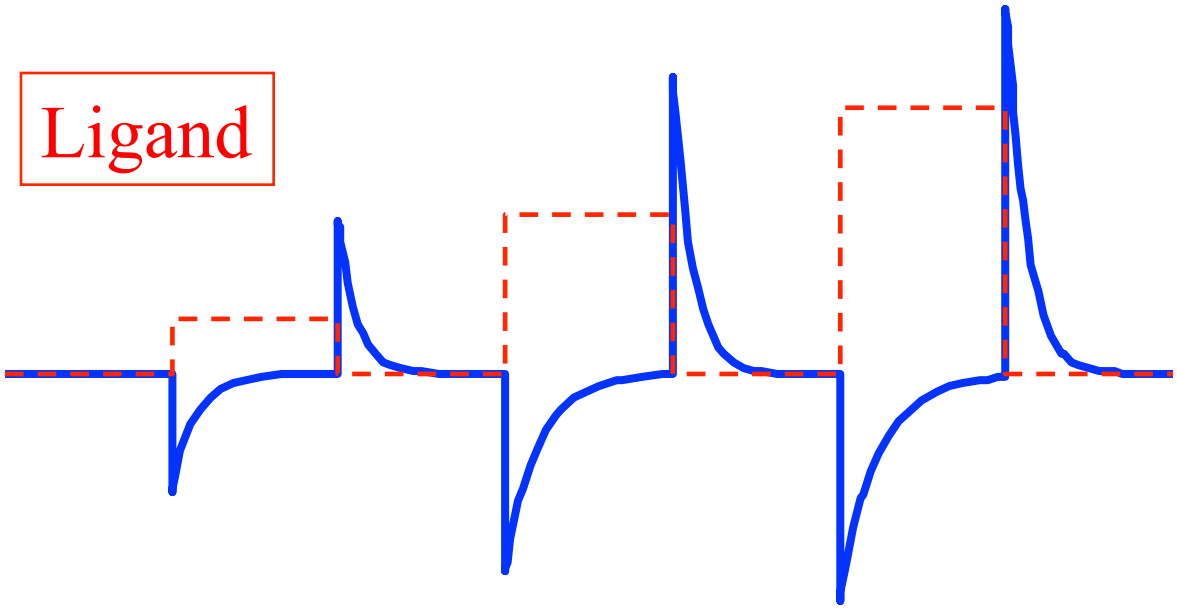
Perfect adaptation is ***necessary*** …

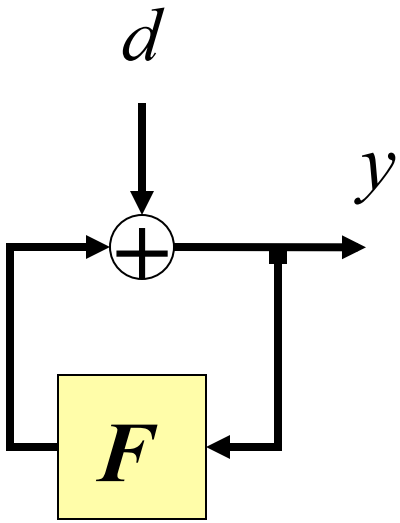
…to keep CheYp in the responsive range of the motor.






ENERGY TAXIS
CHEMOTAXIS
Serine
H+
NADH
Q
FAD
FAD
Aer
Tsr
CH3
W
A
P
Tar
Trg
Tap
Aspartate
Ribose
RBP
Dipeptide
PEP
HPr
Enz1
EnzII
Man-6-P
Mannose
Y
PTS TAXIS
Tumbling
bias





Integral feedback

$F \rightarrow -\infty$

$\ln(S) \rightarrow -\infty$

$$F(s) = \frac{\hat{F}(s)}{s}, \quad \hat{F}(0) < 0$$

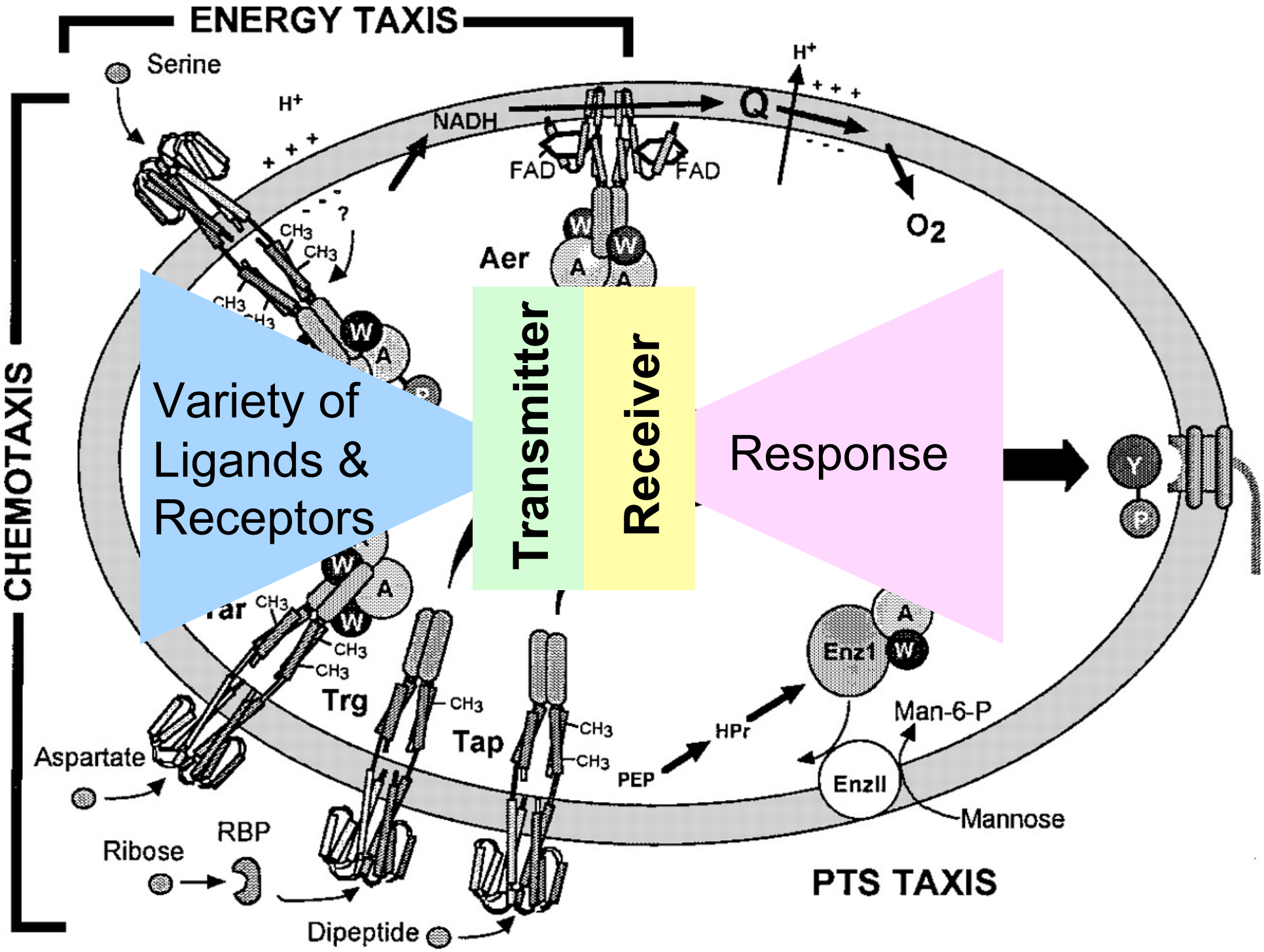
$$\Updownarrow$$

$$F(0) = -\infty$$

$$\Updownarrow$$

$$S(0) = 0$$

$$S \equiv \frac{y}{d} = \frac{1}{1-F}$$


ENERGY TAXIS
CHEMOTAXIS
Serine
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NADH
Q
FAD
FAD
O2
Aer
Tar
Trg
Tap
Aspartate
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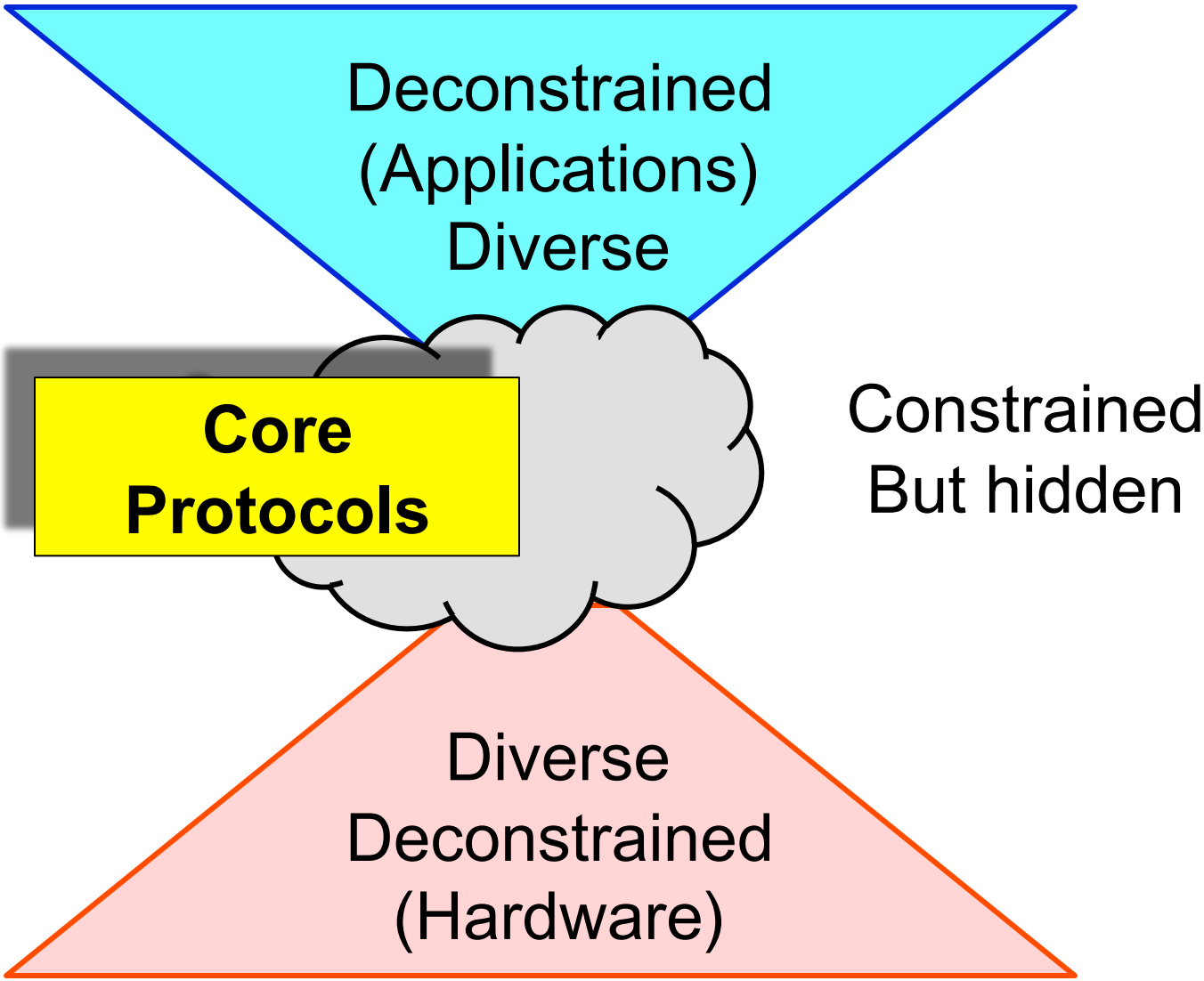
RBP
Dipeptide
PEP
HPr
Enz1
EnzII
Man-6-P
Mannose
PTS TAXIS
Variety of Ligands & Receptors
Transmitter
Receiver
Response

Layered architectures

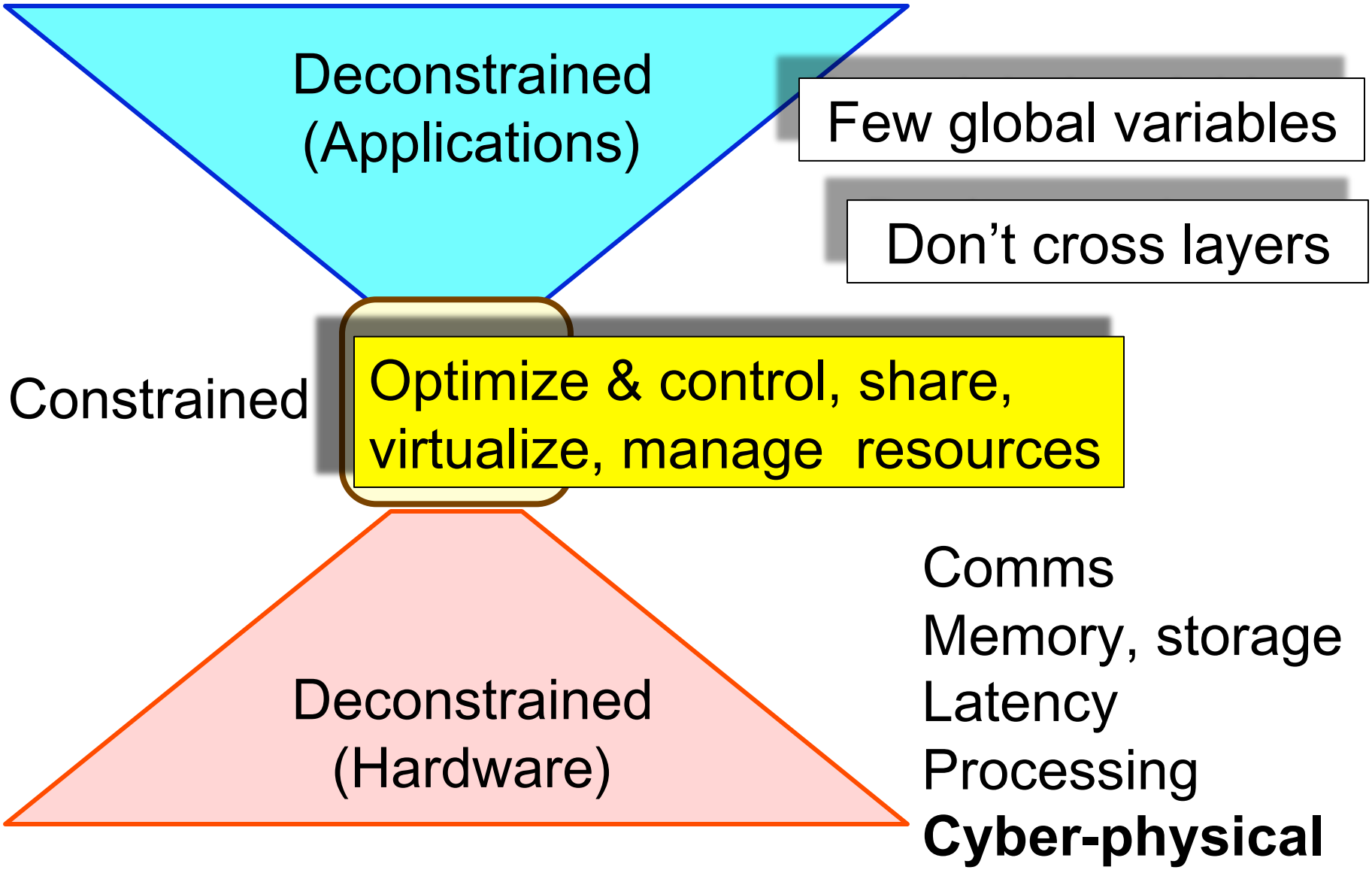


Apps

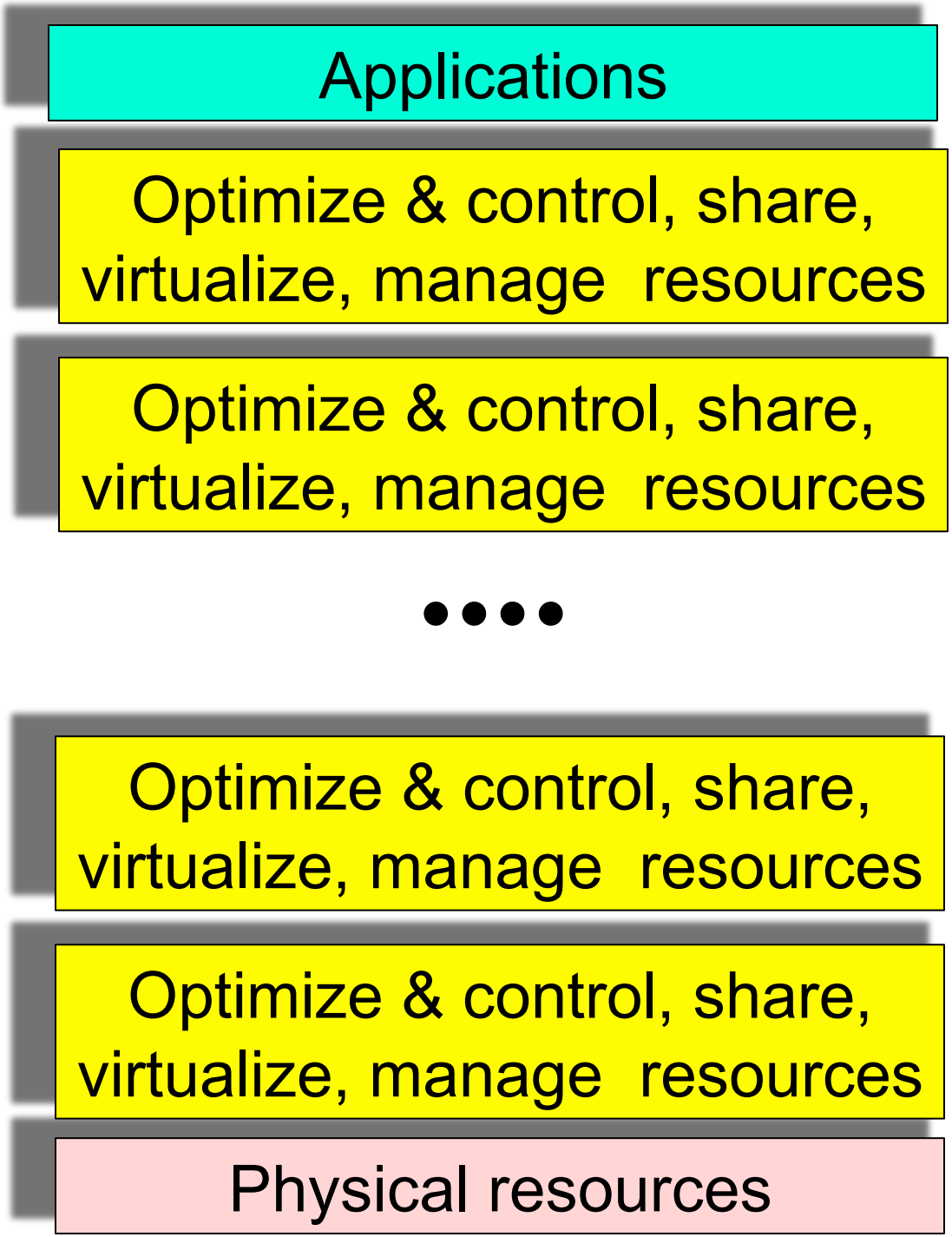
OS

HW

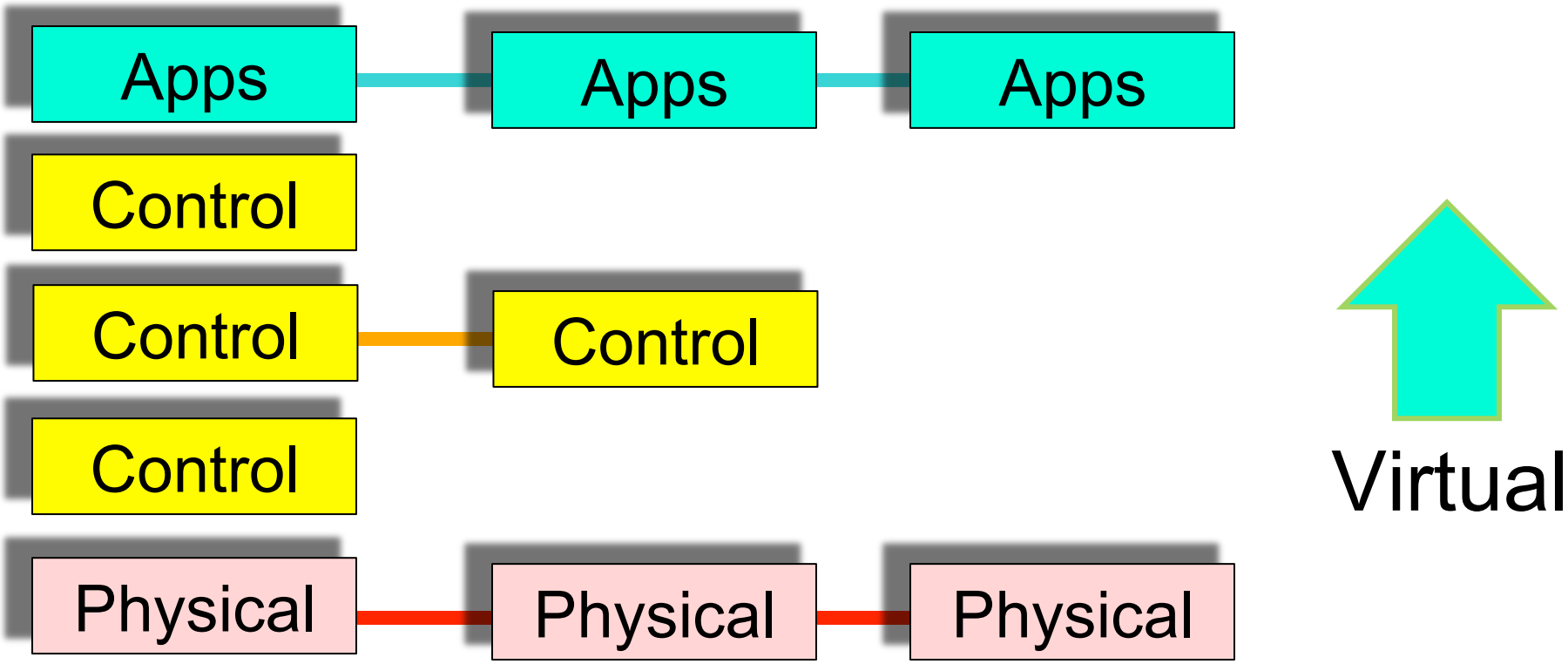
Next layered architectures (SDN)



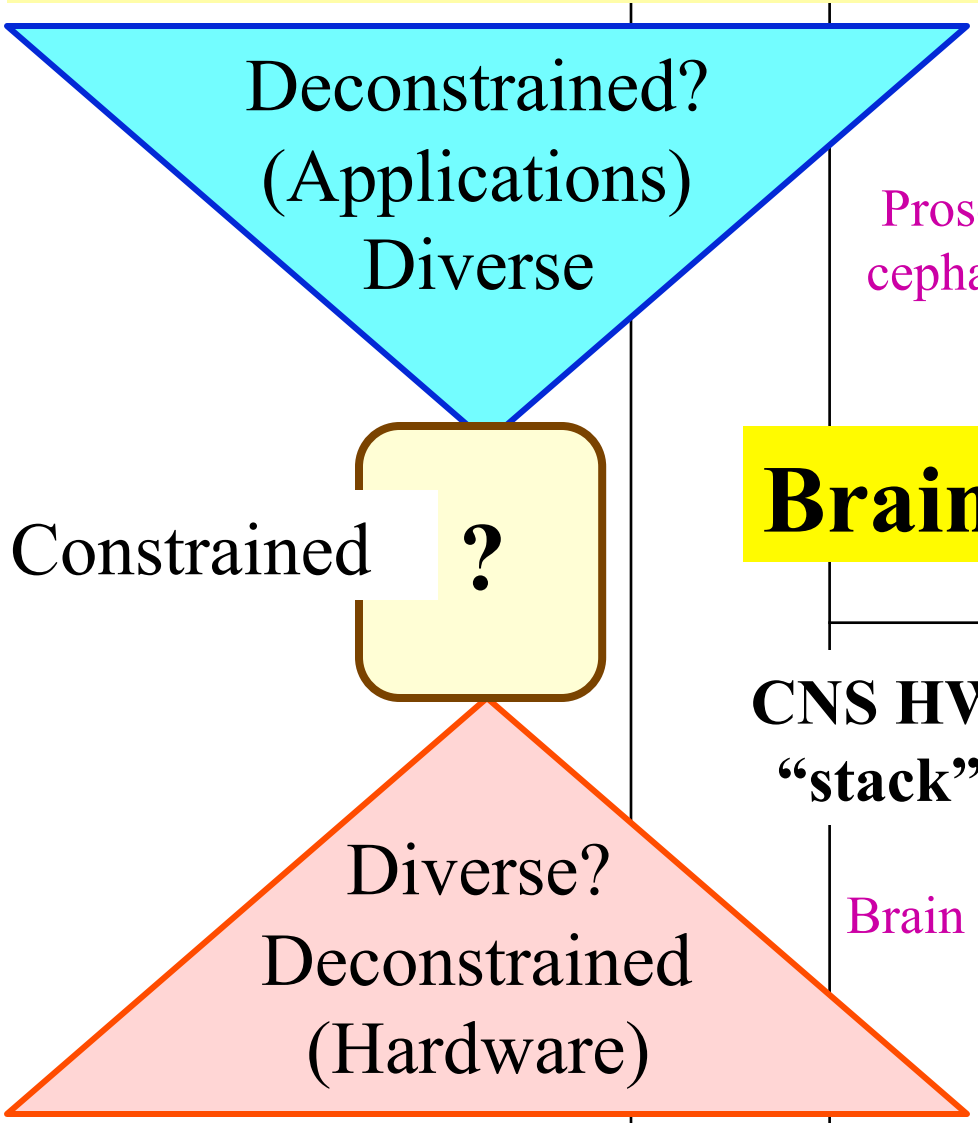
The essence of layering



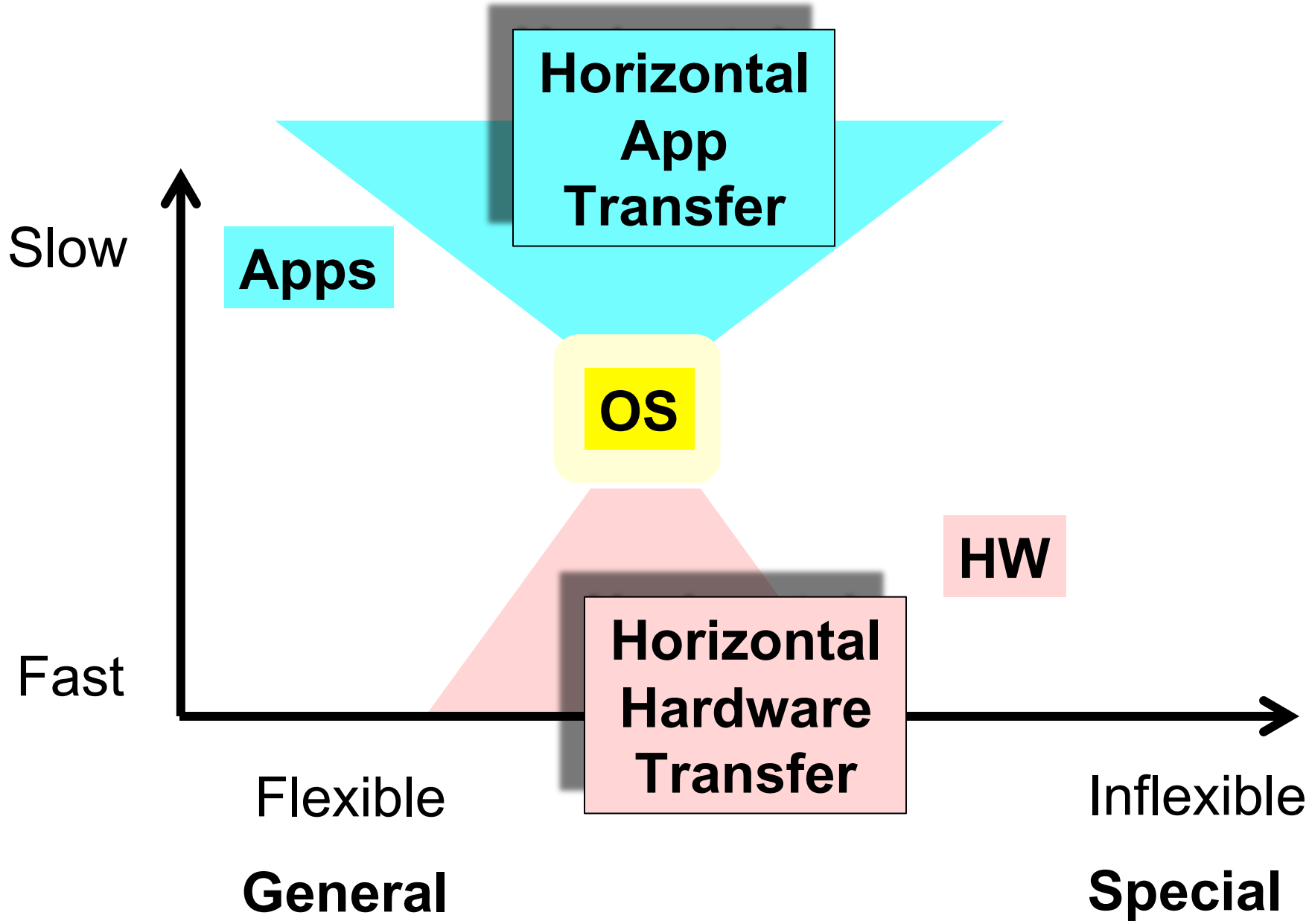
The essence of networking



Layered architectures??

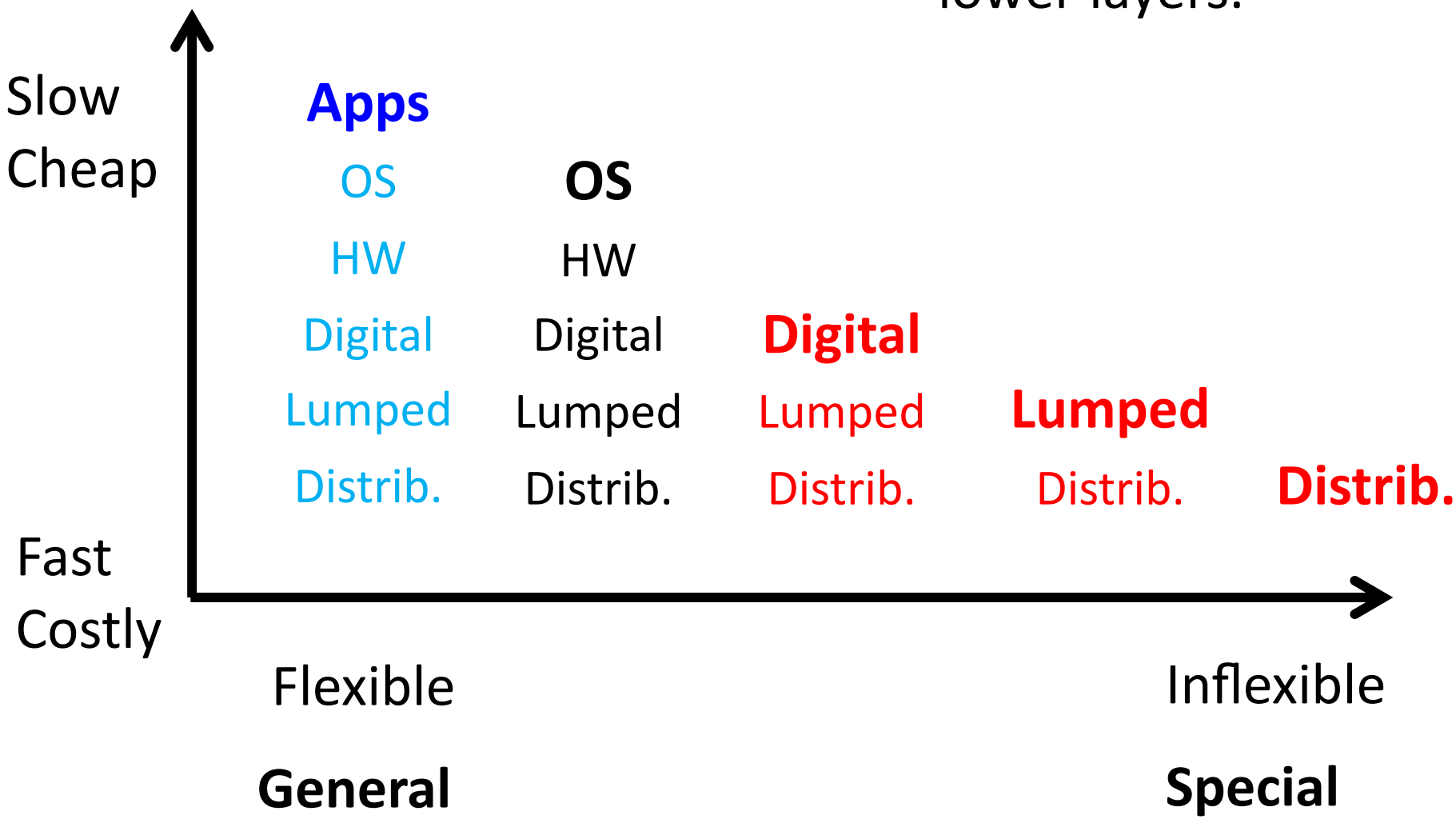


Brain	Prosen-cephalon	Telen-cephalon	Rhinencephalon, Amygdala, Hippocampus, Neocortex, Basal ganglia, Lateral ventricles	
		Dien-cephalon	Epithalamus, Thalamus, Hypothalamus, Subthalamus, Pituitary gland, Pineal gland, Third ventricle	
CNS HW "stack"	Brain stem	Mesen-cephalon	Tectum, Cerebral peduncle, Pretectum, Mesencephalic duct	
		Rhomb-encephalon	Meten-cephalon	Pons, **Cerebellum**
			Myelen-cephalon	Medulla oblongata
Spinal cord				

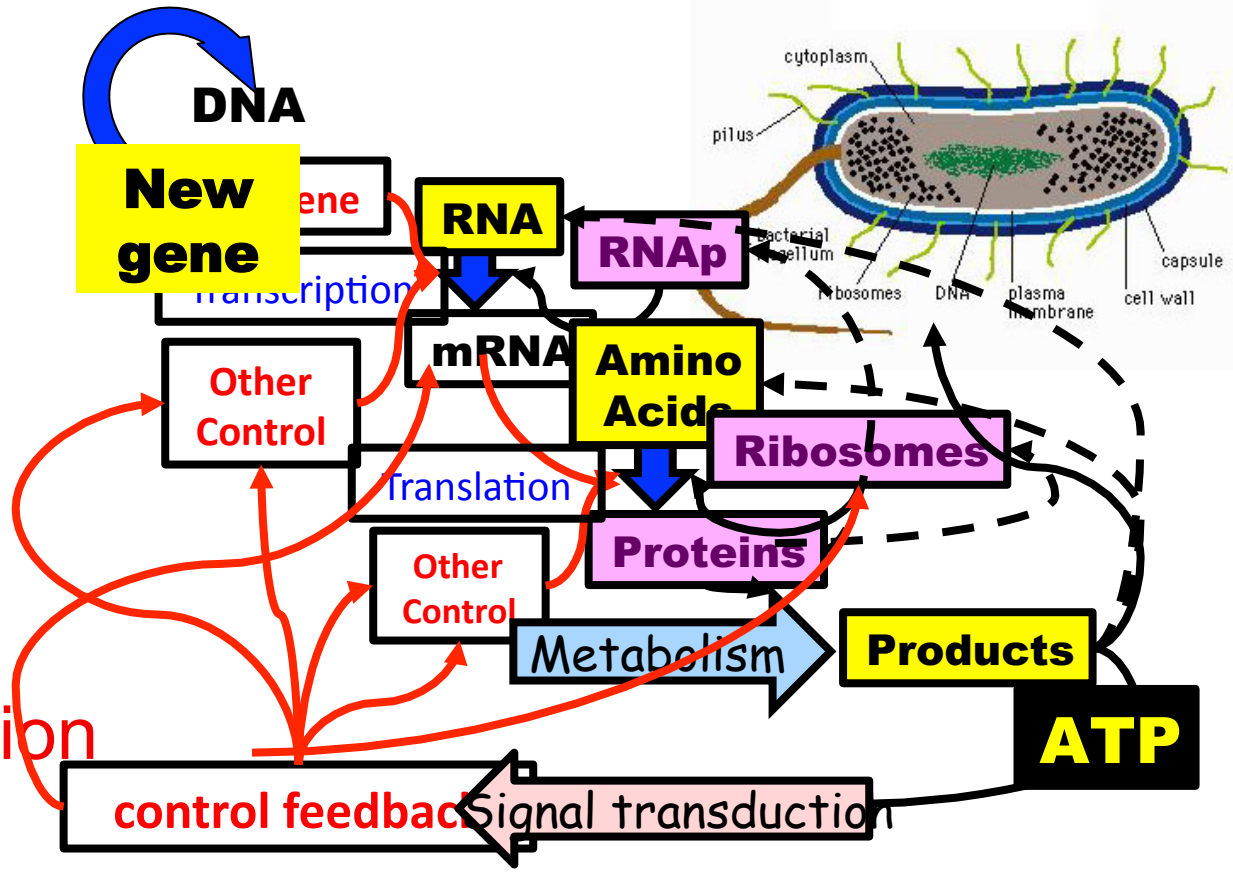

Horizontal
App
Transfer
Slow
Apps
OS
HW
Fast
Horizontal
Hardware
Transfer
Flexible
Inflexible
General
Special

Layered Architecture

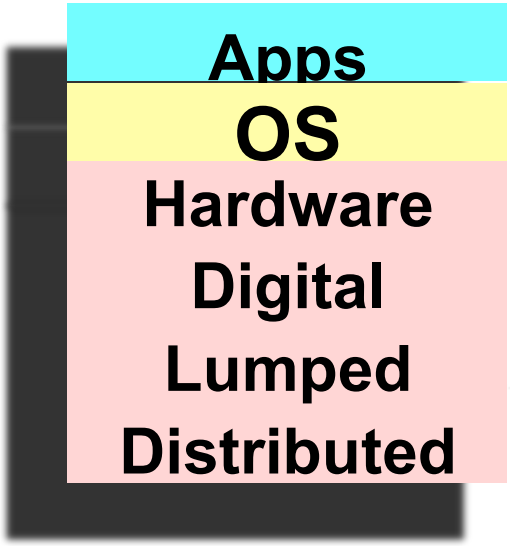
Any layer needs all lower layers.

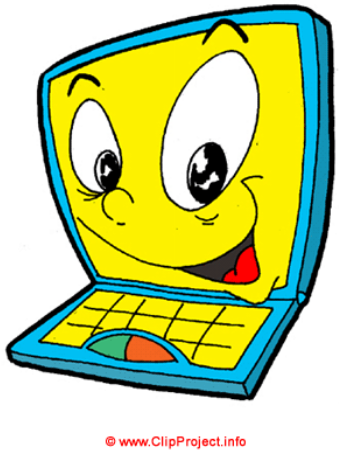


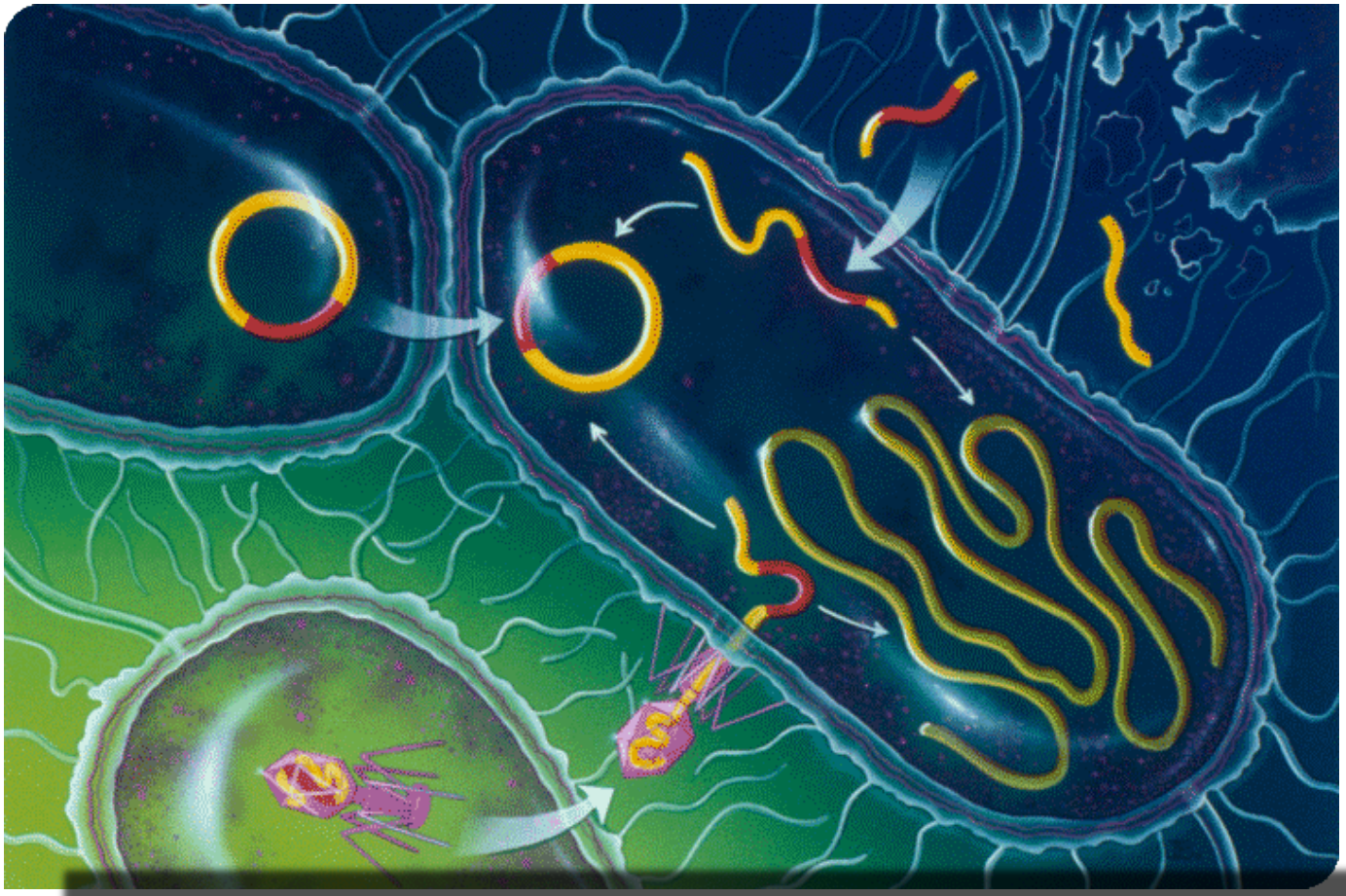
0. **HGT**
1. DNA repair
2. Mutation
3. DNA replication
4. Transcription
5. Translation
6. Metabolism
7. Signal transduction
8. …



Any layer needs all lower layers.



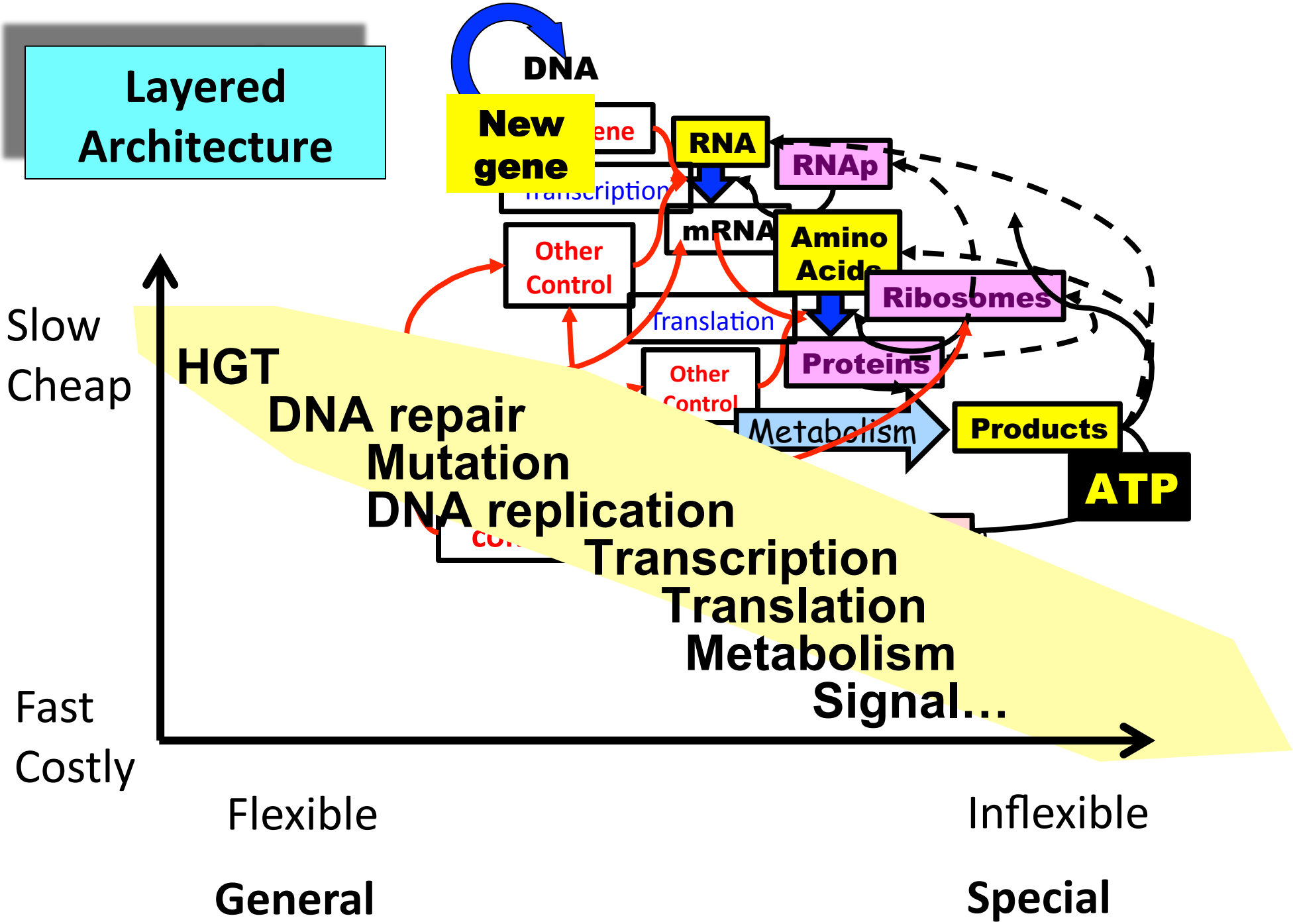


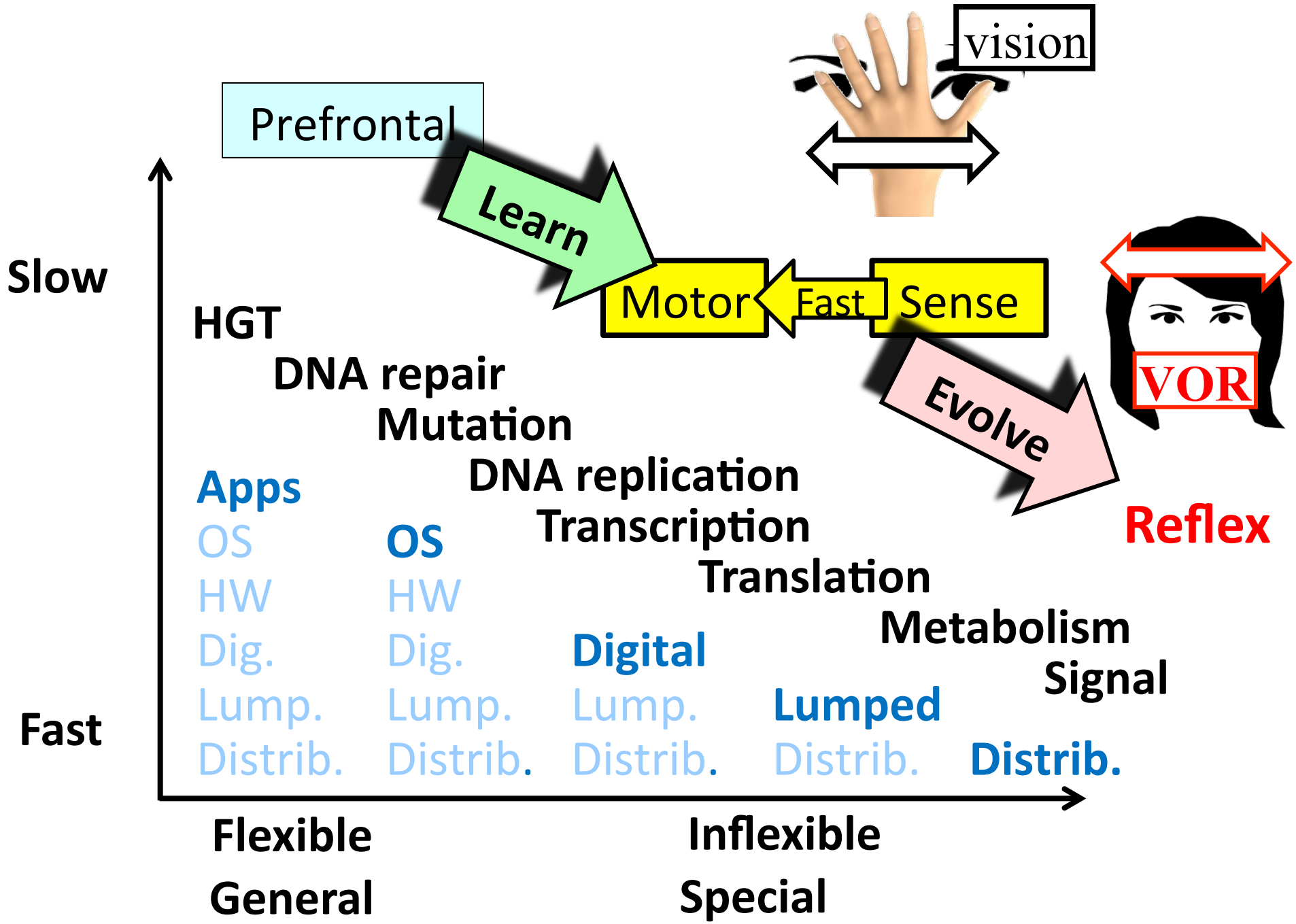


Horizontal Gene Transfer

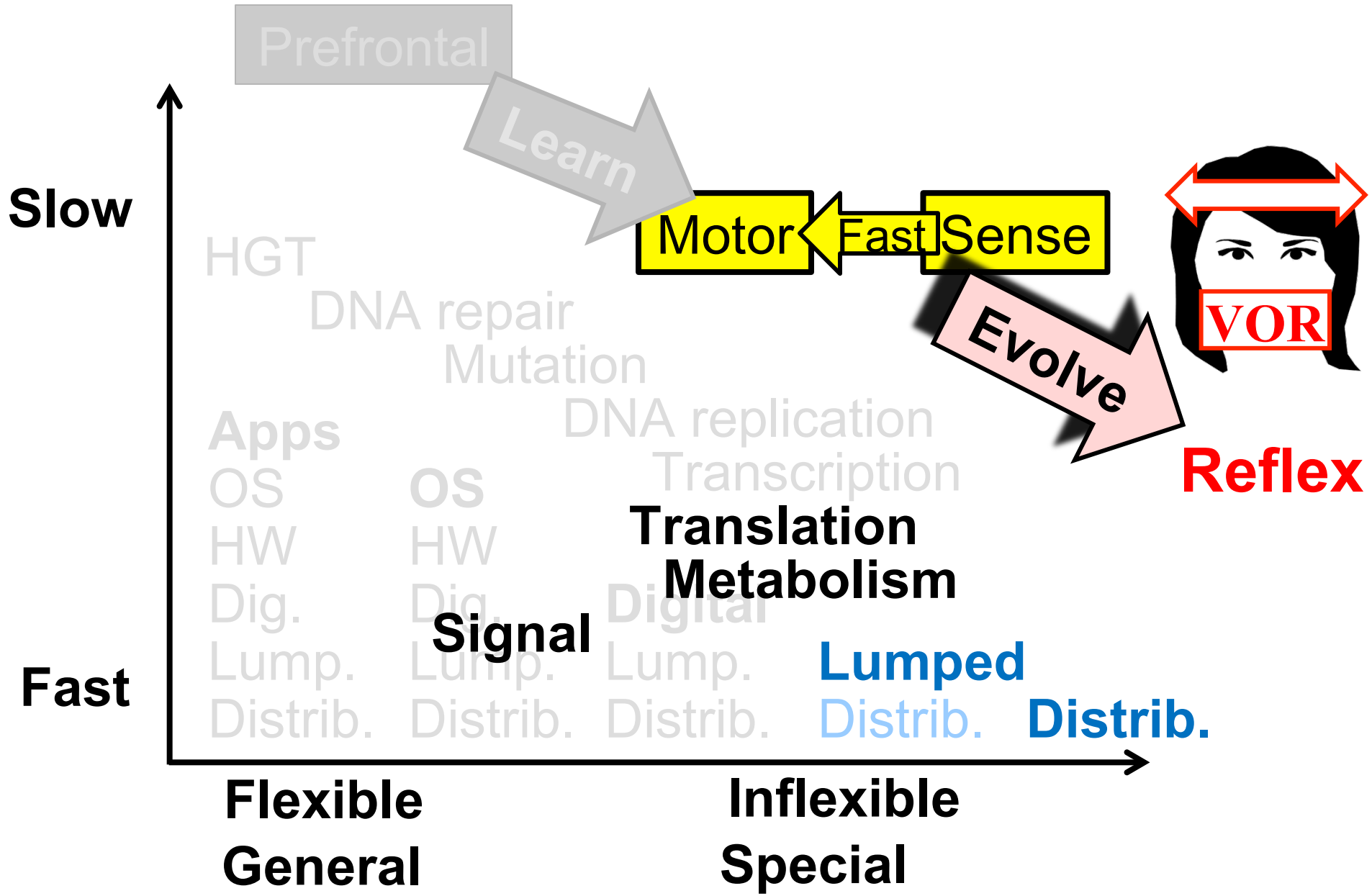
Sequence ~100 E Coli (*not* chosen randomly)

- ~ 4K genes per cell
- ~20K *different* genes in total (pangenome)
- ~ 1K universally shared genes
- ~ 300 essential (minimal) genes

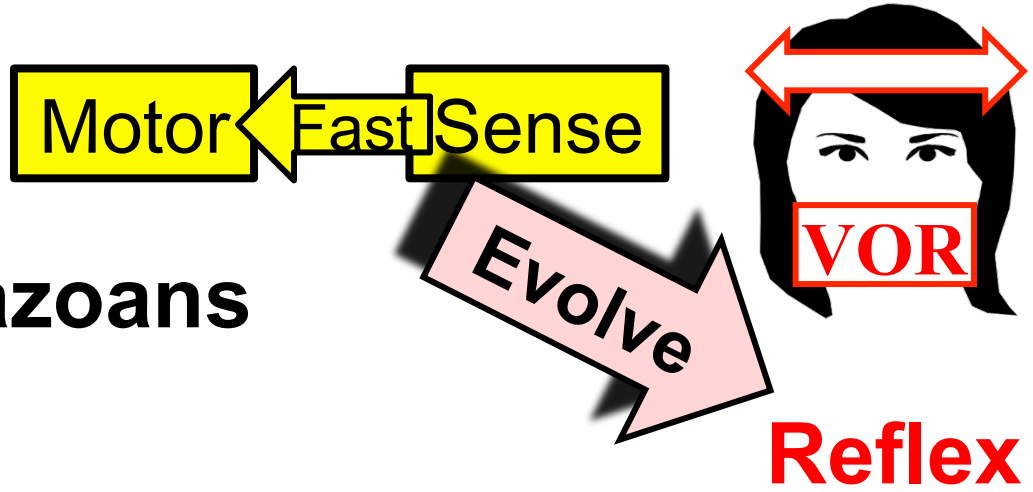

Layered Architecture
DNA
New gene
RNA
RNAp
mRNA
Amino Acids
Other Control
Ribosomes
Translation
Proteins
Other Control
Metabolism
Products
ATP
Slow
Cheap
HGT
DNA repair
Mutation
DNA replication
Transcription
Translation
Metabolism
Signal…
Fast
Costly
Flexible
Inflexible
General
Special


vision
Prefrontal
Learn
Motor
Fast
Sense
Evolve
VOR
Slow
Fast
HGT
DNA repair
Mutation
DNA replication
Transcription
Translation
Metabolism
Signal
Reflex
Apps
OS
HW
Dig.
Lump.
Distrib.
OS
HW
Dig.
Lump.
Distrib.
Digital
Lump.
Distrib.
Lumped
Distrib.
Distrib.
Flexible
Inflexible
General
Special

Many systems/organisms only use lower layers



Many systems/organisms **only use lower layers**



Most metazoans

Red blood cells

Metabolism

Signal

Normocephalic anucleosis

Analog

Lumped

Distrib.

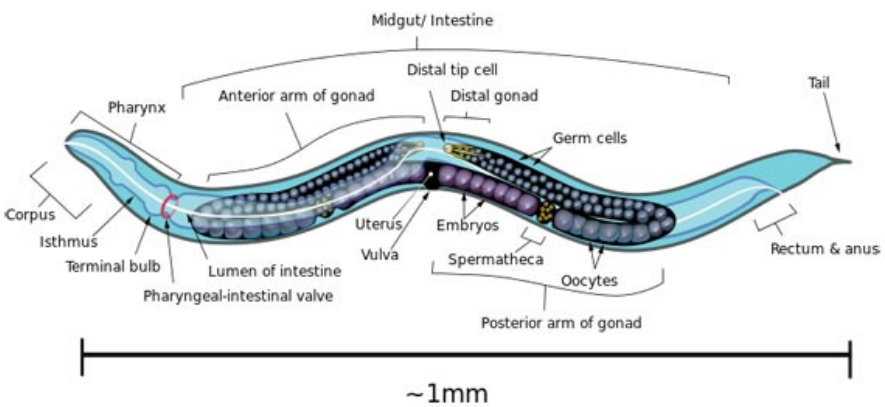
Distrib.

Motor ← Fast Sense

Evolve

Reflex

Most metazoans



Analog?

Many systems/organisms only use lower layers

Most metazoans

Red blood cells

Normocephalic anucleosis

Metabolism

Signal

Analog

Lumped

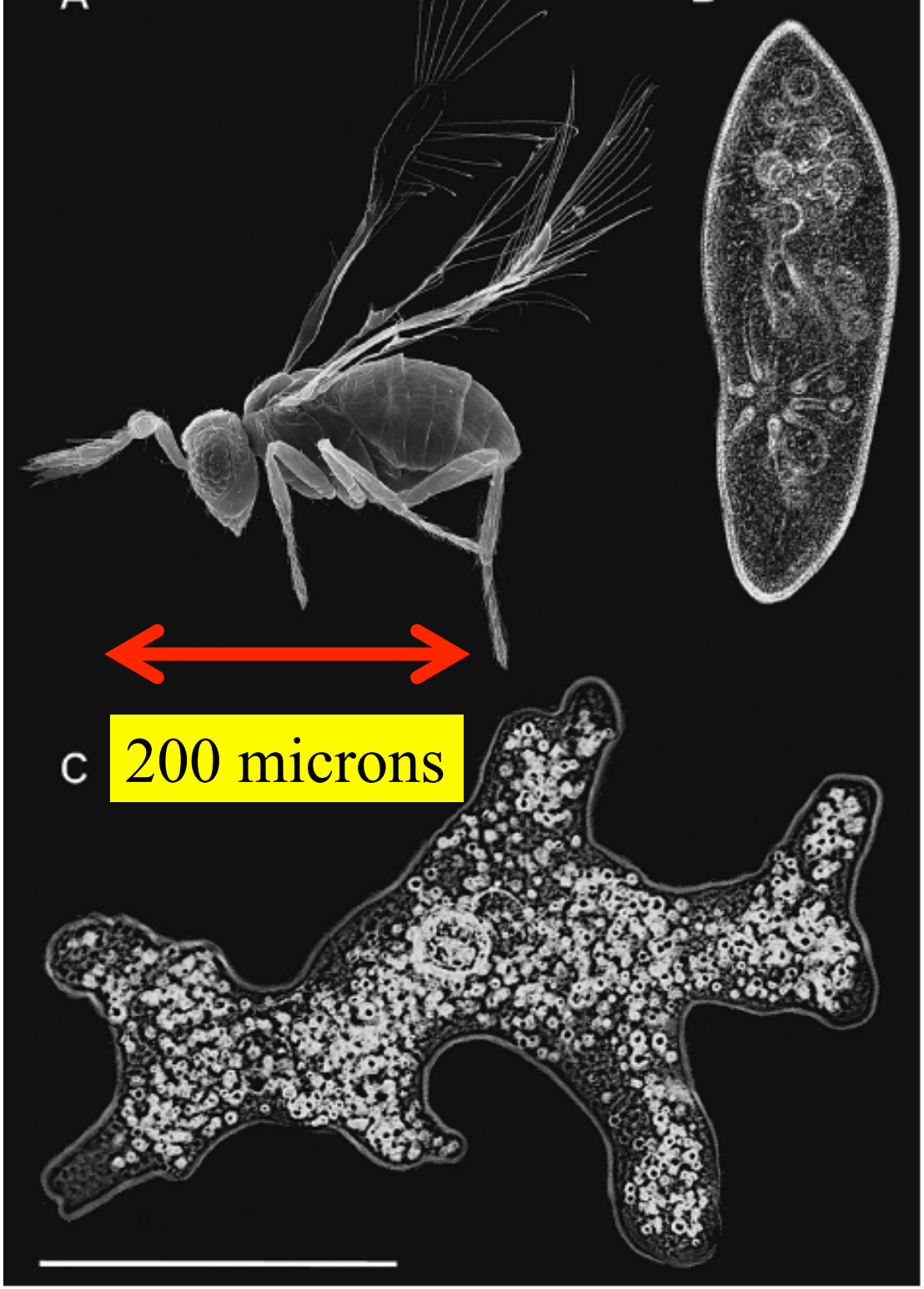
Distrib.

Distrib.

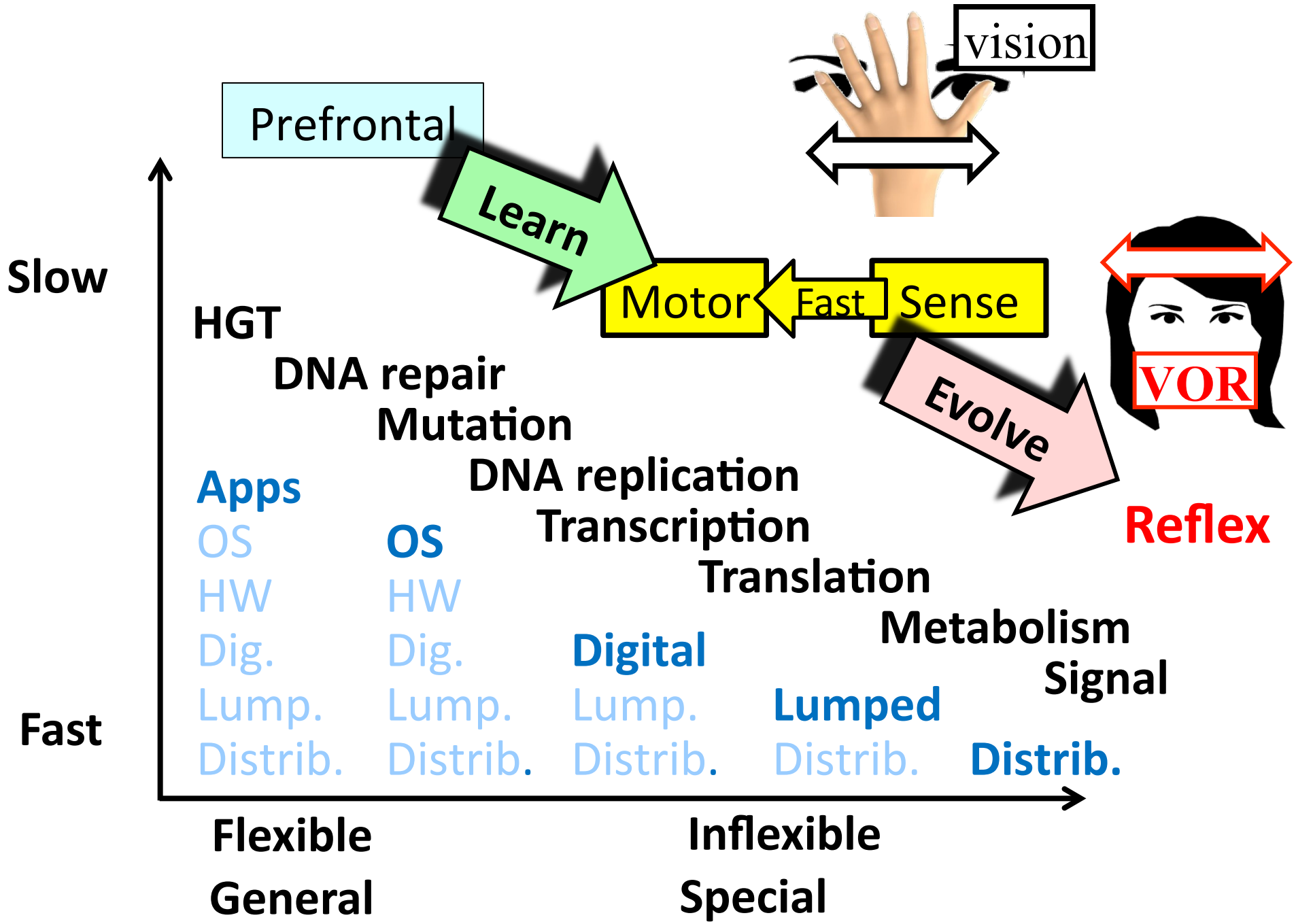
Normocephalic anucleosis

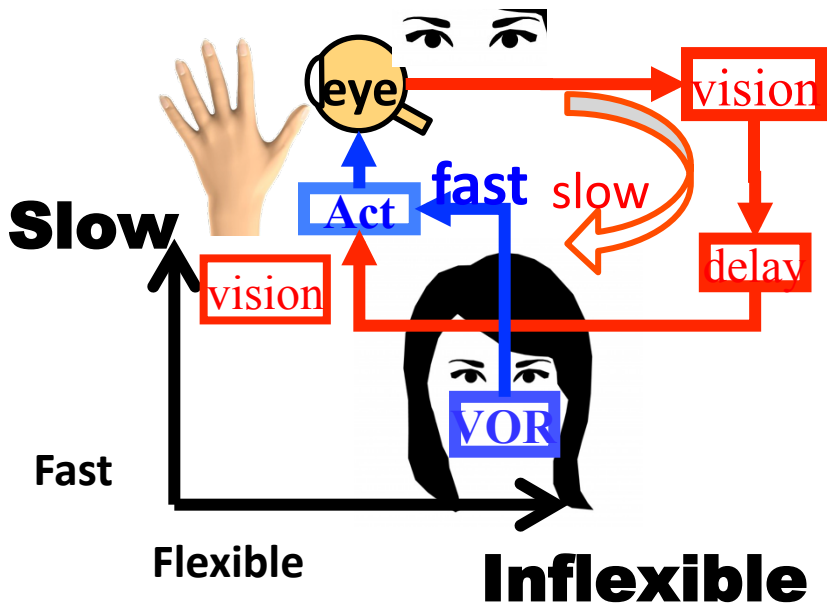
Denucleated neurons

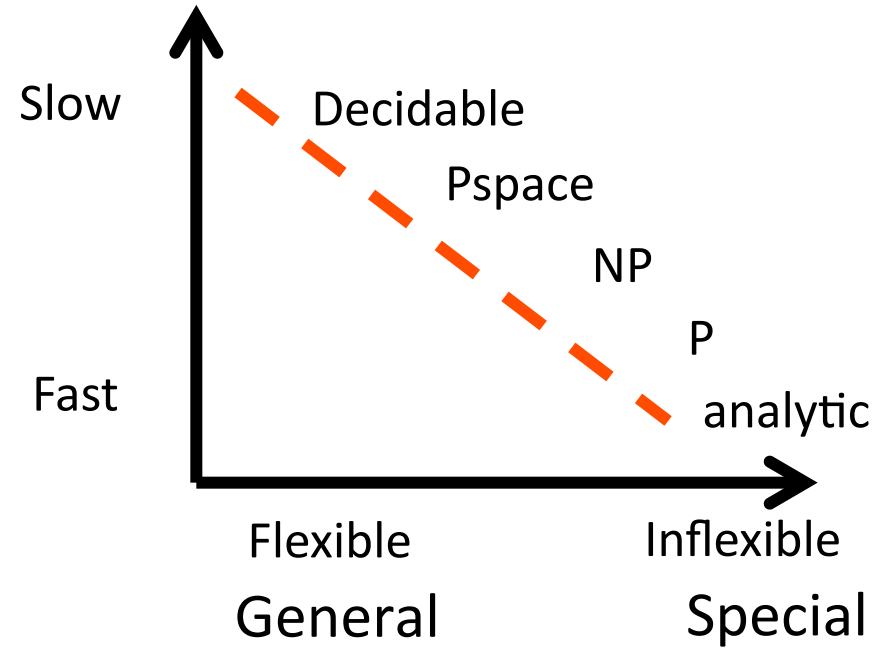
Megaphragma mymaripenne

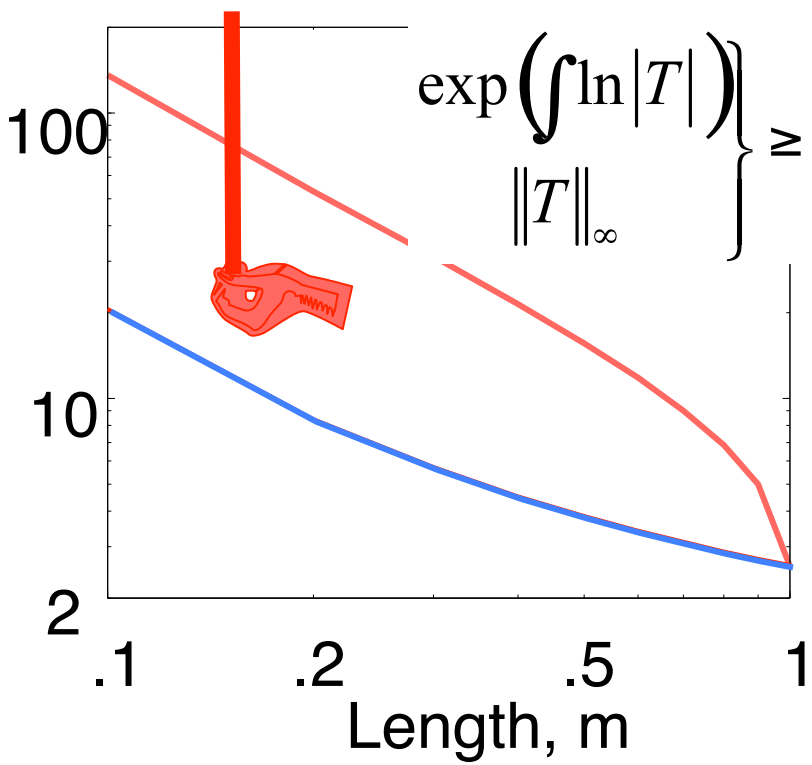


5 day lifespan
7,400 neurons
vs
housefly 340,000
honeybee 850,000.

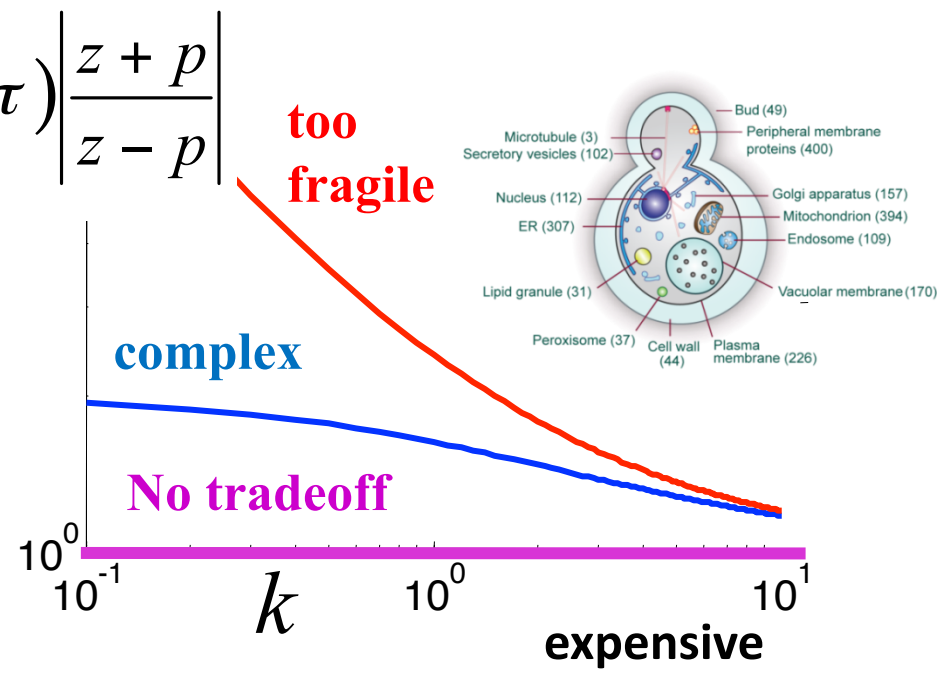

vision
Prefrontal
Learn
Motor
Fast
Sense
Evolve
VOR
Slow
Fast
HGT
DNA repair
Mutation
DNA replication
Transcription
Translation
Metabolism
Signal
Reflex
Apps
OS
HW
Dig.
Lump.
Distrib.
OS
HW
Dig.
Lump.
Distrib.
Digital
Lump.
Distrib.
Lumped
Distrib.
Distrib.
Flexible
Inflexible
General
Special

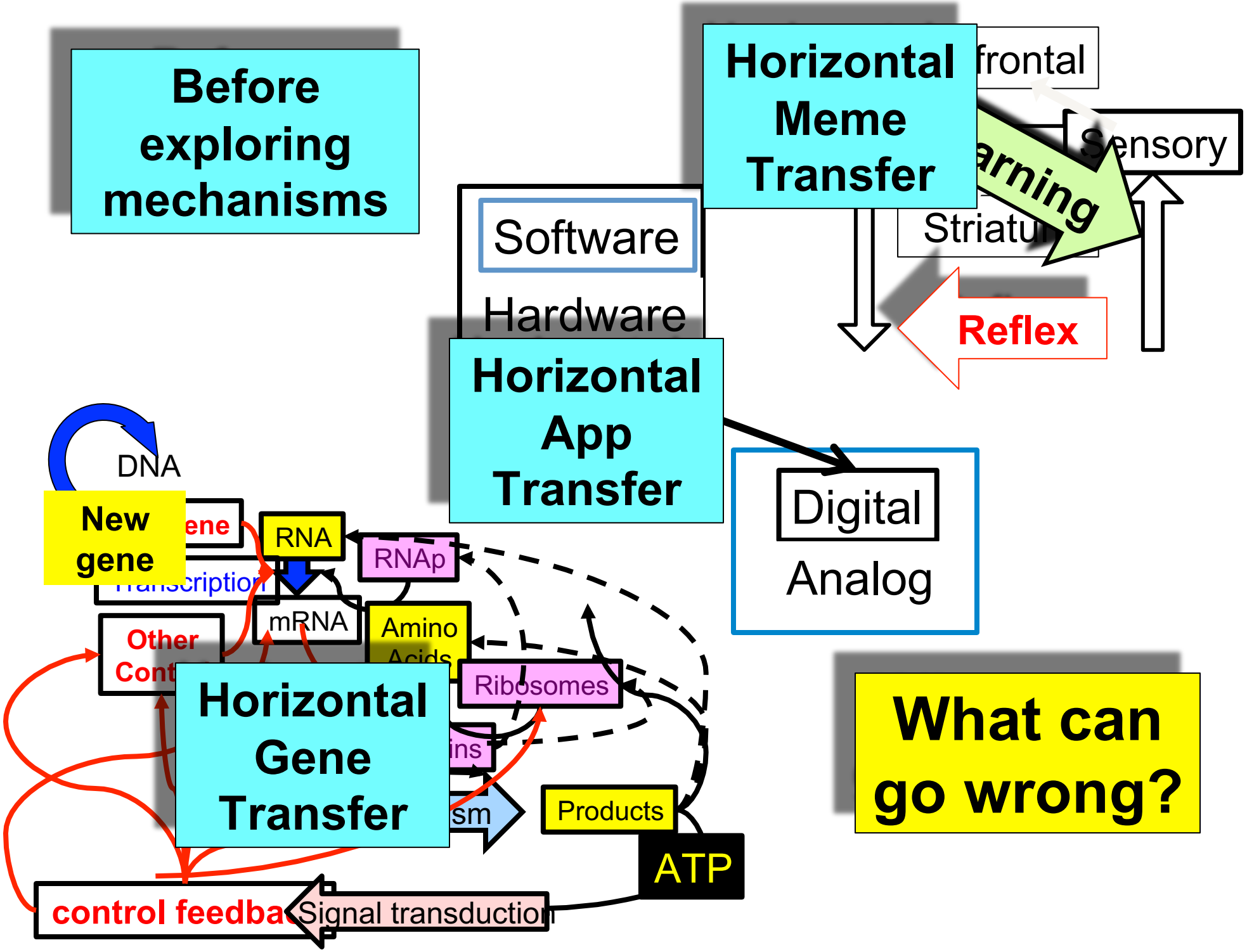






$$\left.\begin{matrix}\exp\left(\int \ln|T|\right) \\ \|T\|_\infty\end{matrix}\right\} \geq \exp(p\tau)\left|\frac{z+p}{z-p}\right|$$




Before exploring mechanisms
Horizontal Meme Transfer
frontal
Sensory
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Striatu
Reflex
Software
Hardware
Horizontal App Transfer
Digital
Analog
DNA
New gene
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RNA
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Transcription
mRNA
Amino Acids
Other Cont
Ribosomes
Horizontal Gene Transfer
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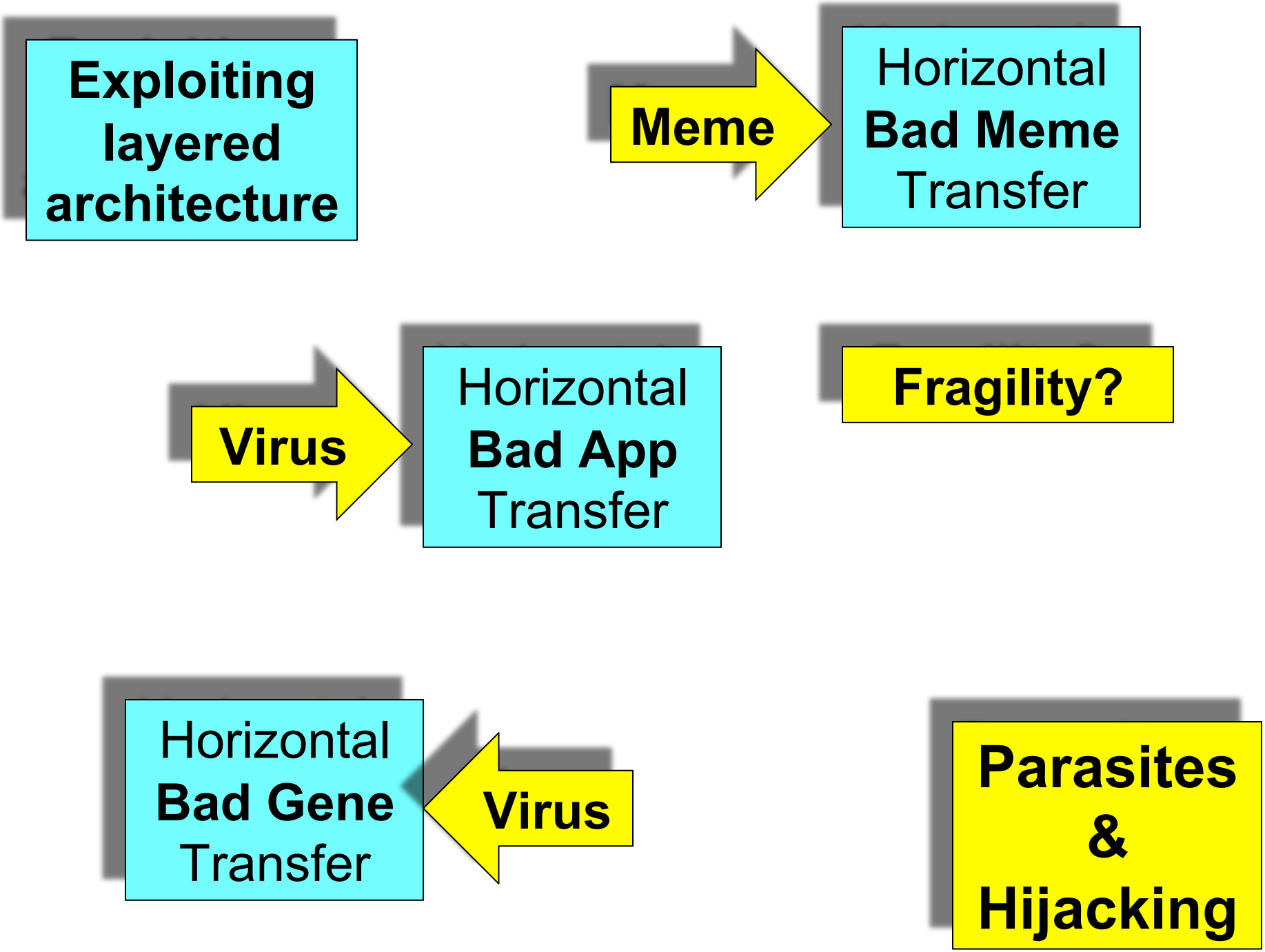
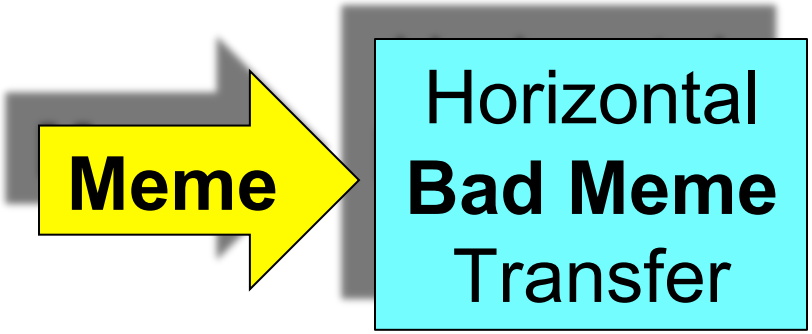
Products
ATP
control feedba
Signal transduction
What can go wrong?


Exploiting layered architecture
Meme
Horizontal Bad Meme Transfer
Virus
Horizontal Bad App Transfer
Fragility?
Horizontal Bad Gene Transfer
Virus
Parasites & Hijacking



Many human beliefs are:

- False
- Unhealthy

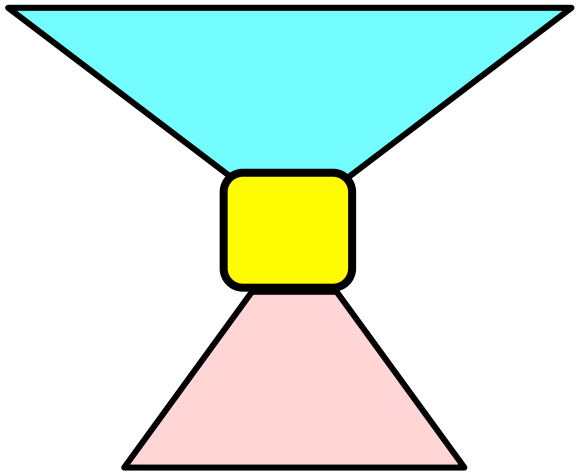
Meme

Horizontal Bad Meme Transfer

Many human beliefs are:

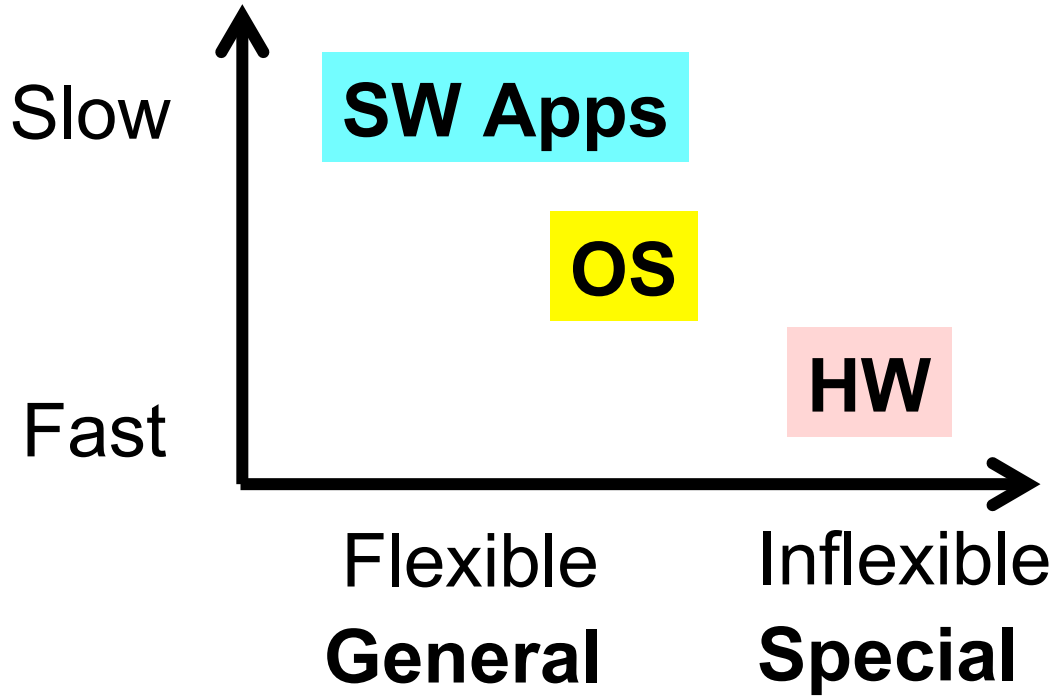
- False
- Unhealthy

Our greatest fragility?



- **Masculinity**
- ~~**Compassion**~~

Universal laws



Universal architectures