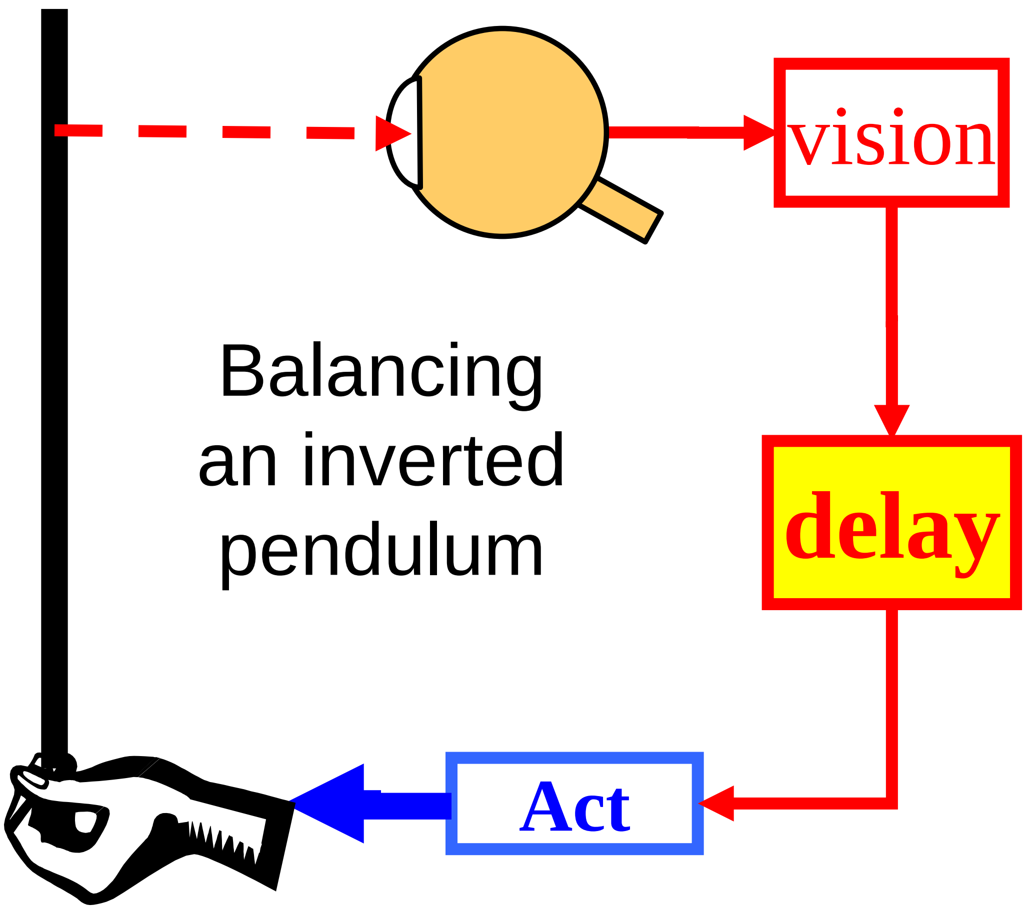
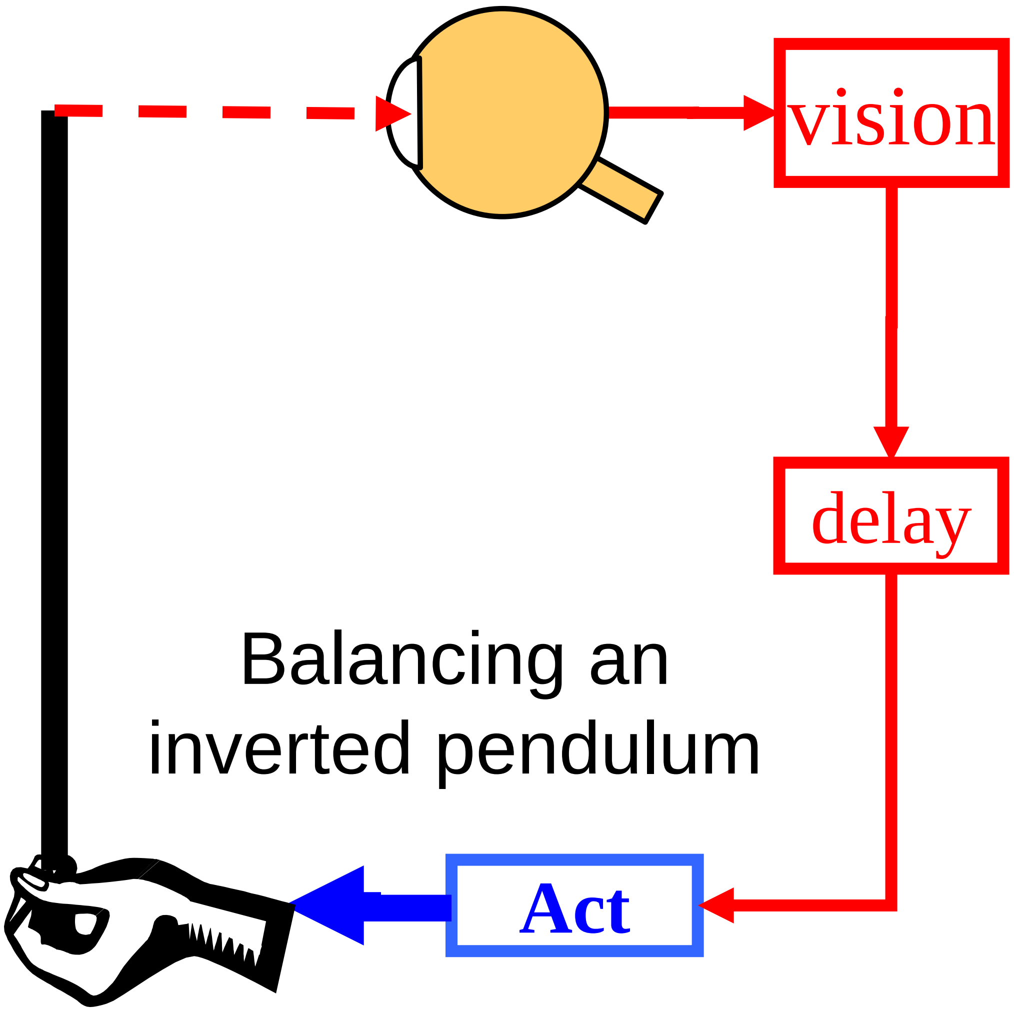
Mechanics+
Gravity +
Light +

$$\frac{1}{\pi}\int_0^{\infty} \ln\left|T(j\omega)\right|\left(\frac{p}{p^2+\omega^2}\right)d\omega \geq p\tau + \ln\left|\frac{z+p}{z-p}\right|$$

+ Neuroscience

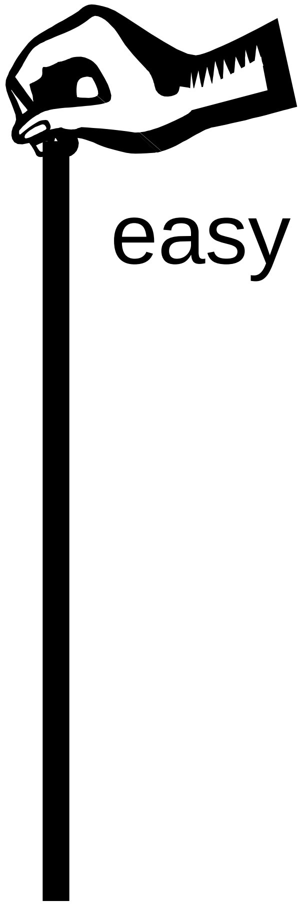




$$\frac{1}{\pi}\int_0^\infty \ln\left|T(j\omega)\right|\left(\frac{2p}{p^2+\omega^2}\right)d\omega \ge p\tau$$

Law #1 : Mechanics
(instead of chemistry)

Law #2 : Gravity
(instead of autocatalysis)



$$(M+m)\ddot{x} + ml\left(\ddot{\theta}\cos\theta - \dot{\theta}^2\sin\theta\right) = u$$

$$\ddot{x}\cos\theta + l\ddot{\theta} + g\sin\theta = 0$$

$$y = x + \alpha l\sin\theta$$

linearize

$$(M+m)\ddot{x} + ml\ddot{\theta} = u$$

$$\ddot{x} + l\ddot{\theta} \pm g\theta = 0$$

$$y = x + \alpha l\theta$$

$$(M+m)\ddot{x}+ml\left(\ddot{\theta}\cos\theta-\dot{\theta}^2\sin\theta\right)=u$$

$$\ddot{x}\cos\theta+l\ddot{\theta}+g\sin\theta=0$$

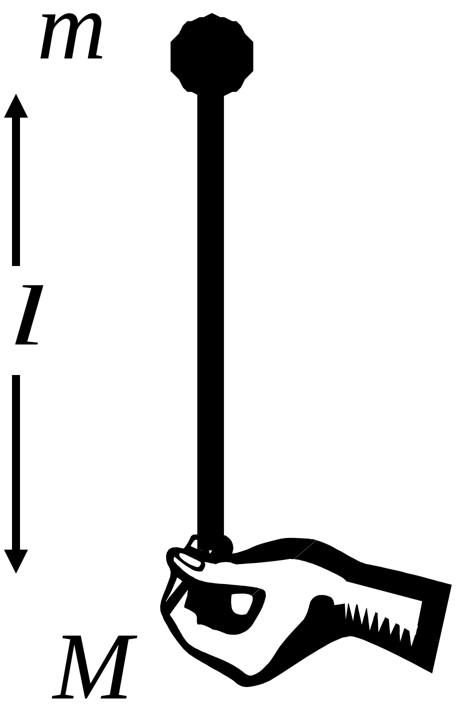
$$y=x+\alpha l\sin\theta$$

linearize

$$(M+m)\ddot{x}+ml\ddot{\theta}=u$$

$$\ddot{x}+l\ddot{\theta}\pm g\theta=0$$

$$y=x+\alpha l\theta$$



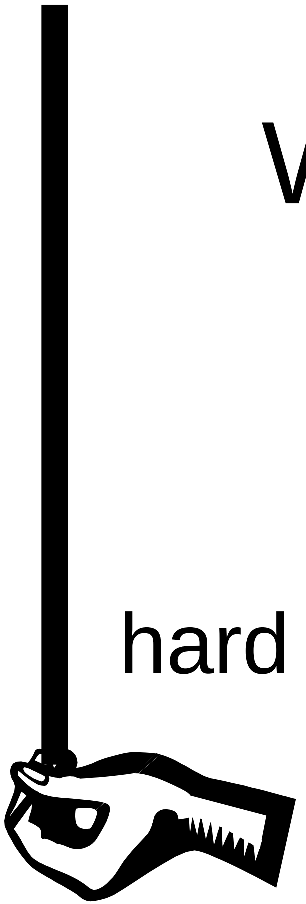
Law #3 : Light

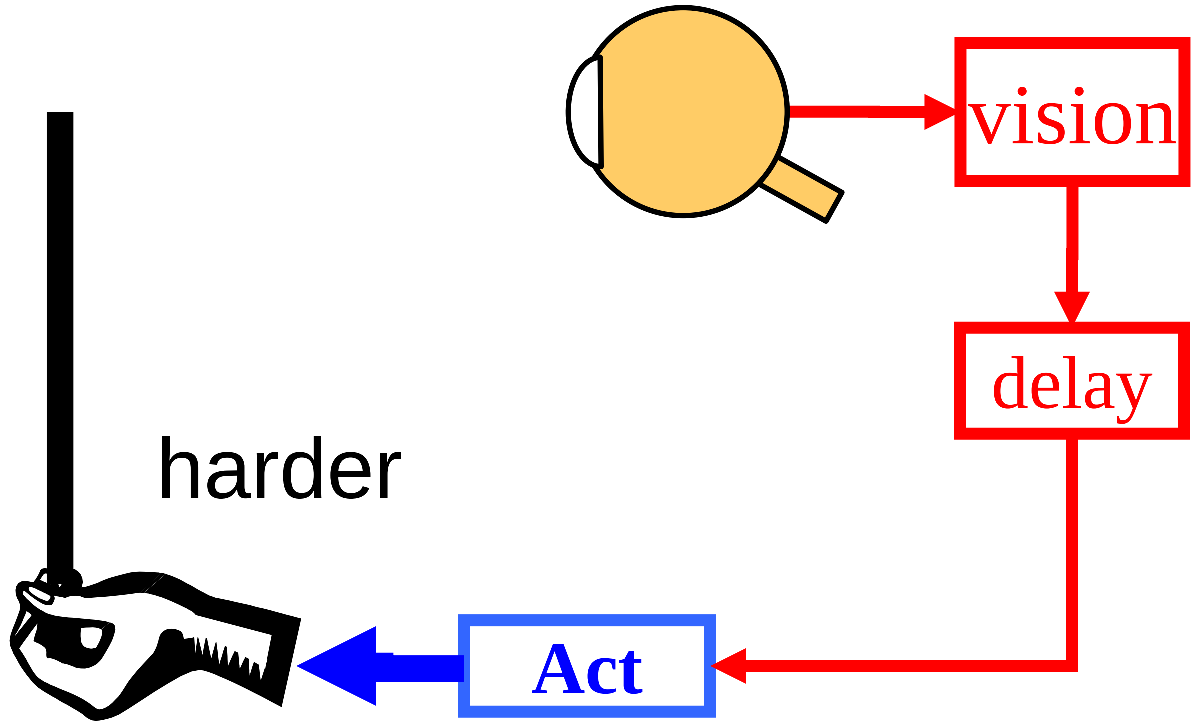
$$(M+m)\ddot{x}+ml\ddot{\theta}=u$$

$$\ddot{x}+l\ddot{\theta}\pm g\theta=0$$

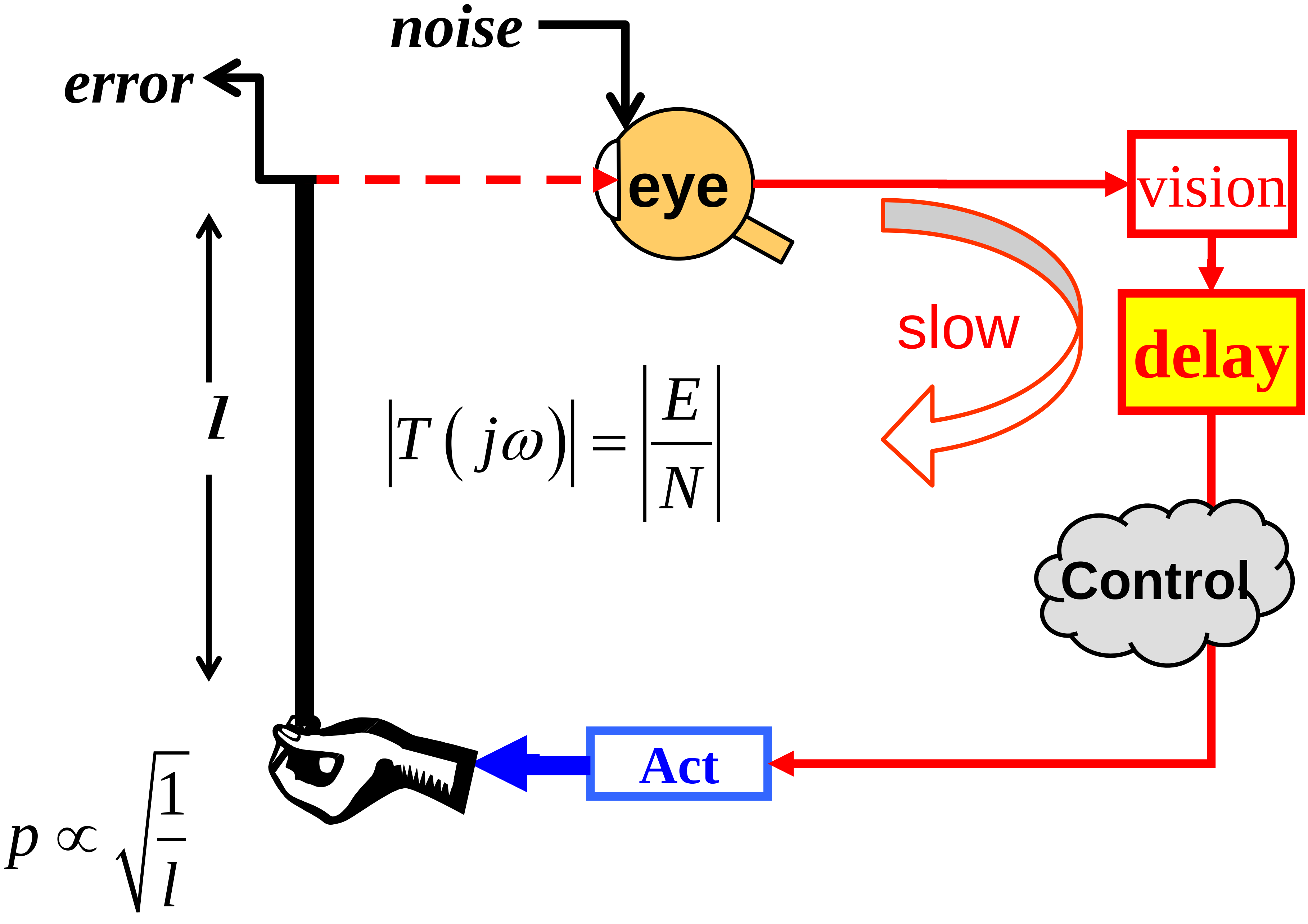
$$y=x+\alpha l\theta$$

Why?



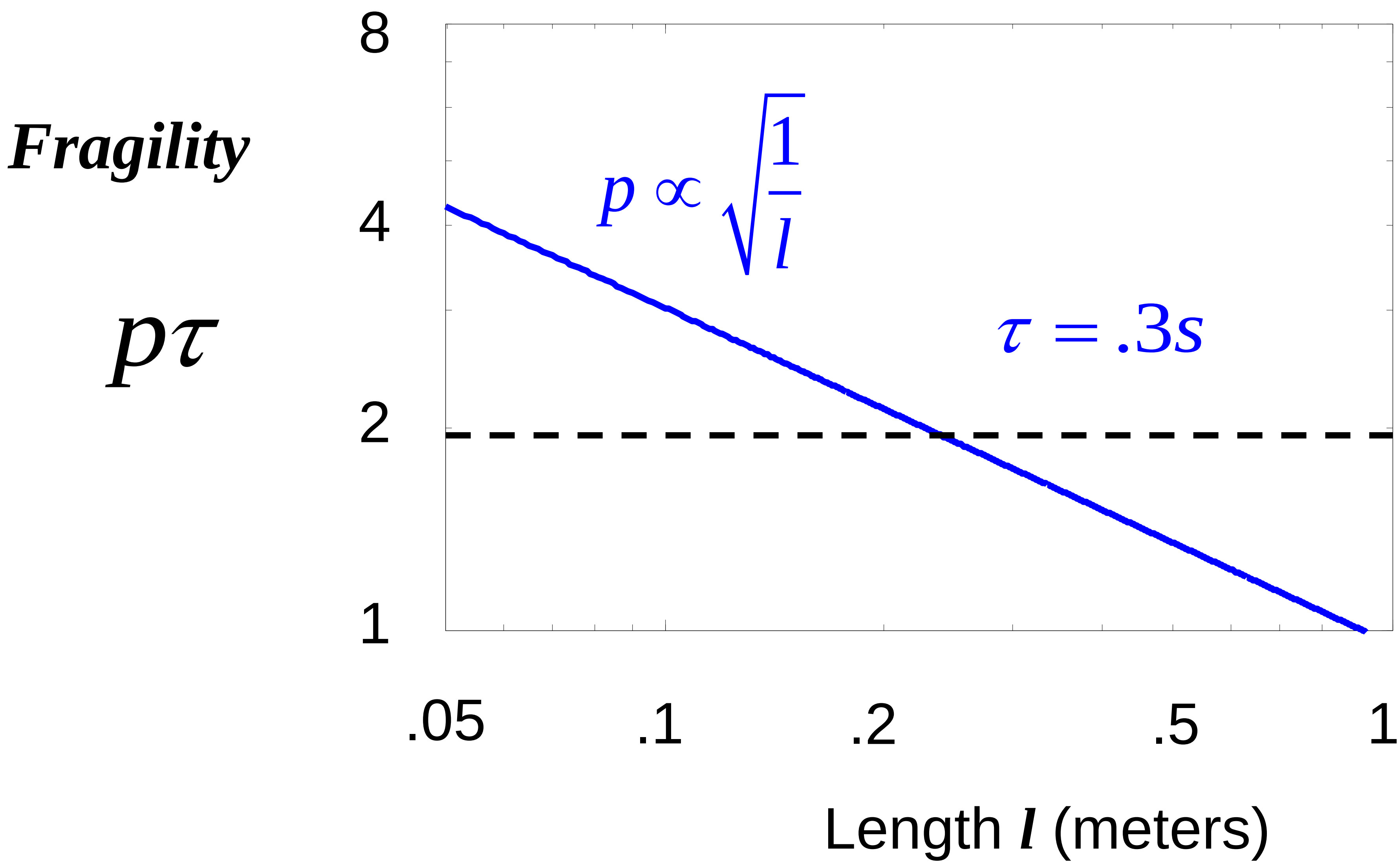


Easy to ***prove*** using simple models.



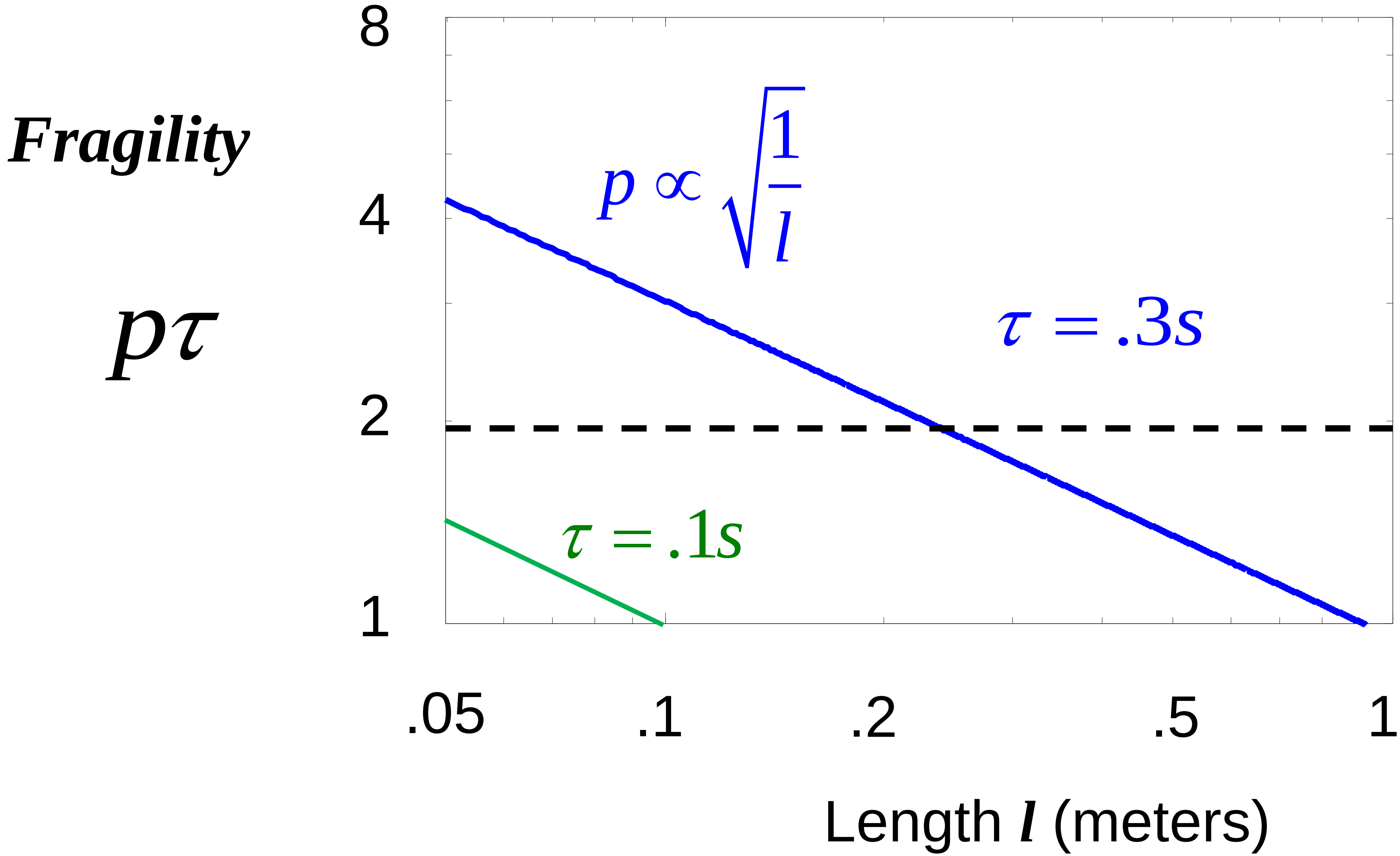
noise
error
eye
vision
slow
delay
l
$|T(j\omega)| = \left|\frac{E}{N}\right|$
Control
Act
$p \propto \sqrt{\frac{1}{l}}$

Law #4 : $$\frac{1}{\pi}\int_0^\infty \ln\left|T(j\omega)\right|\left(\frac{2p}{p^2+\omega^2}\right)d\omega \geq p\tau$$



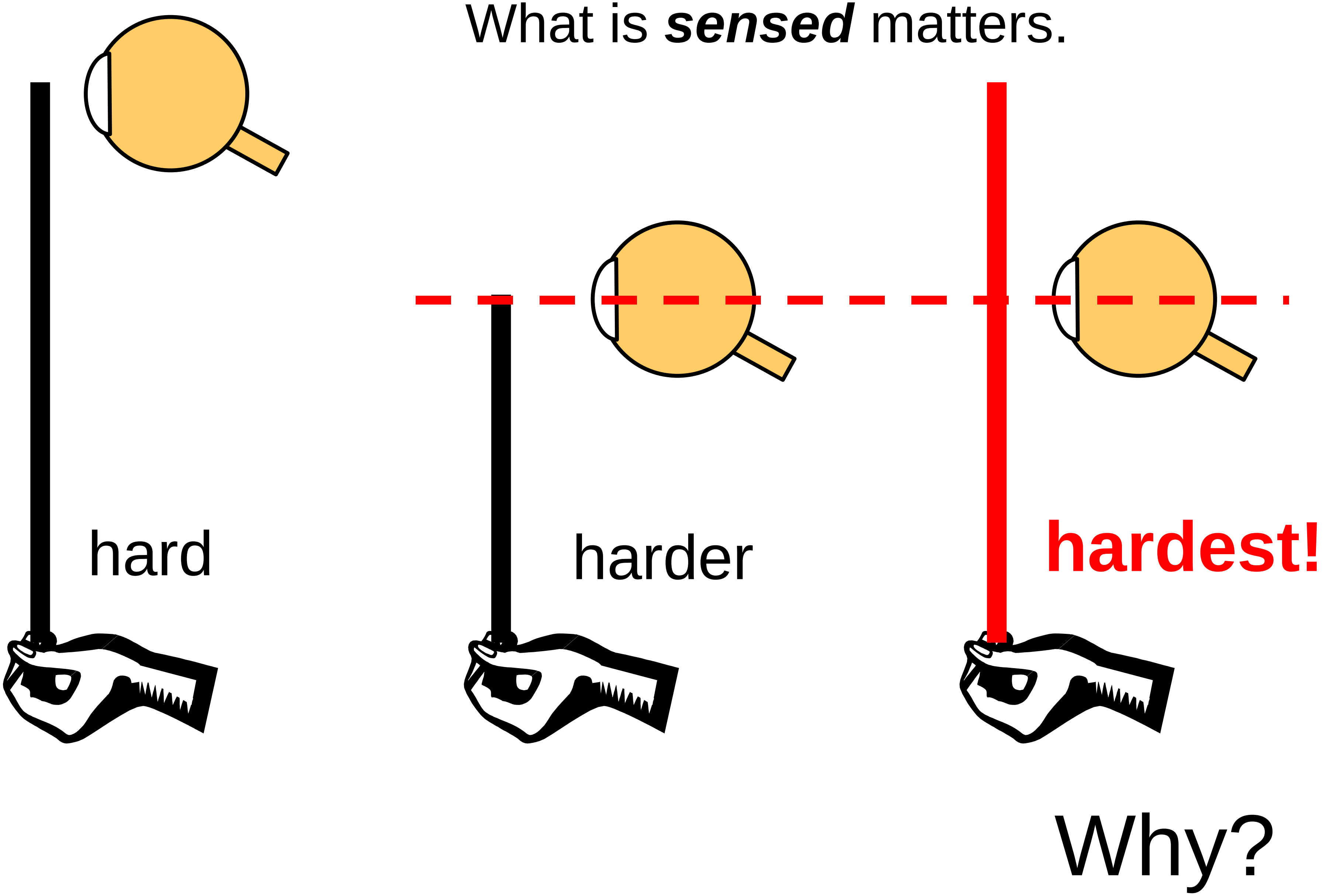
Law #4 :

$$\frac{1}{\pi}\int_0^{\infty}\ln\left|T(j\omega)\right|\left(\frac{2p}{p^2+\omega^2}\right)d\omega \geq p\tau$$

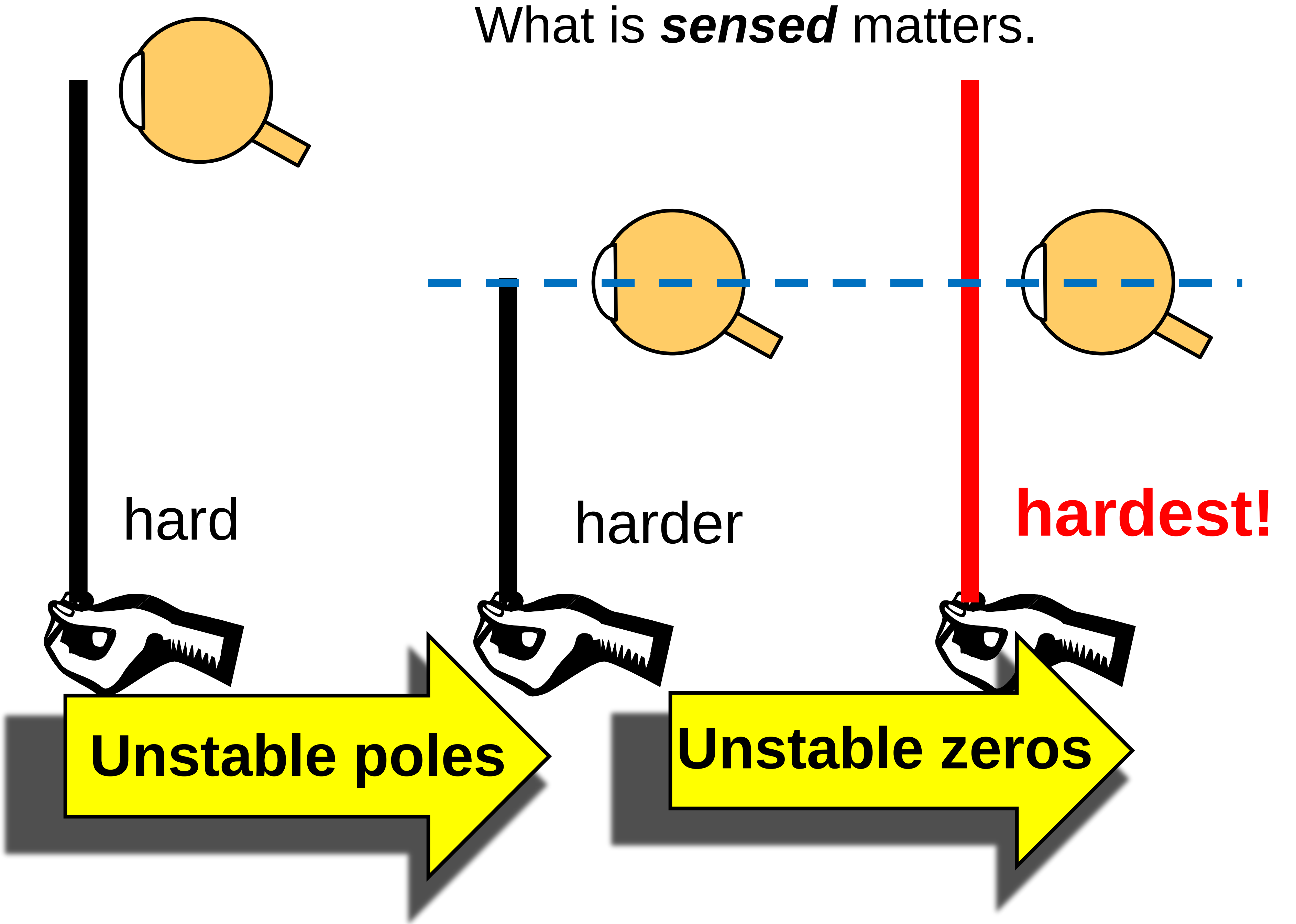


Crashes can be made rare with active control.

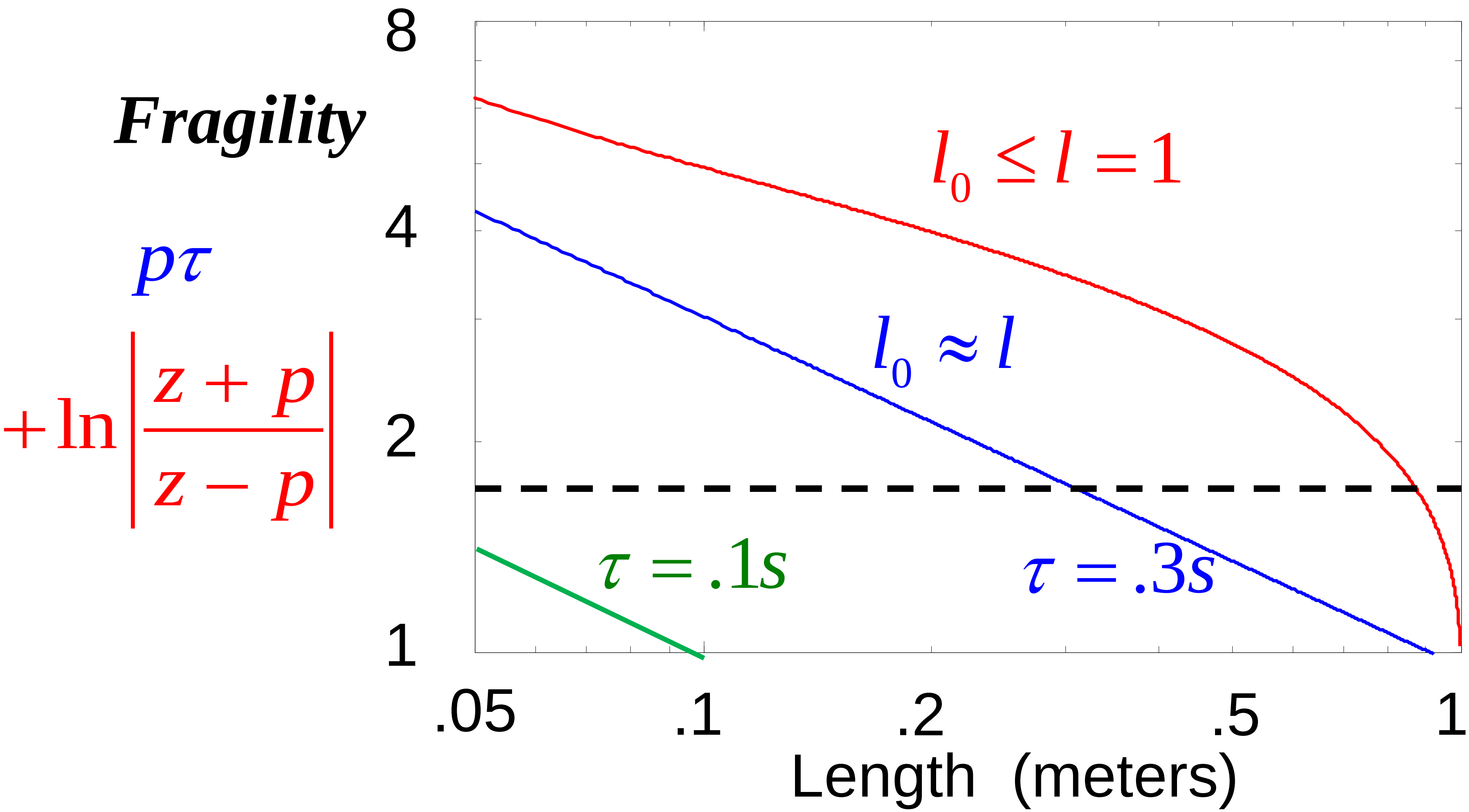
What is ***sensed*** matters.

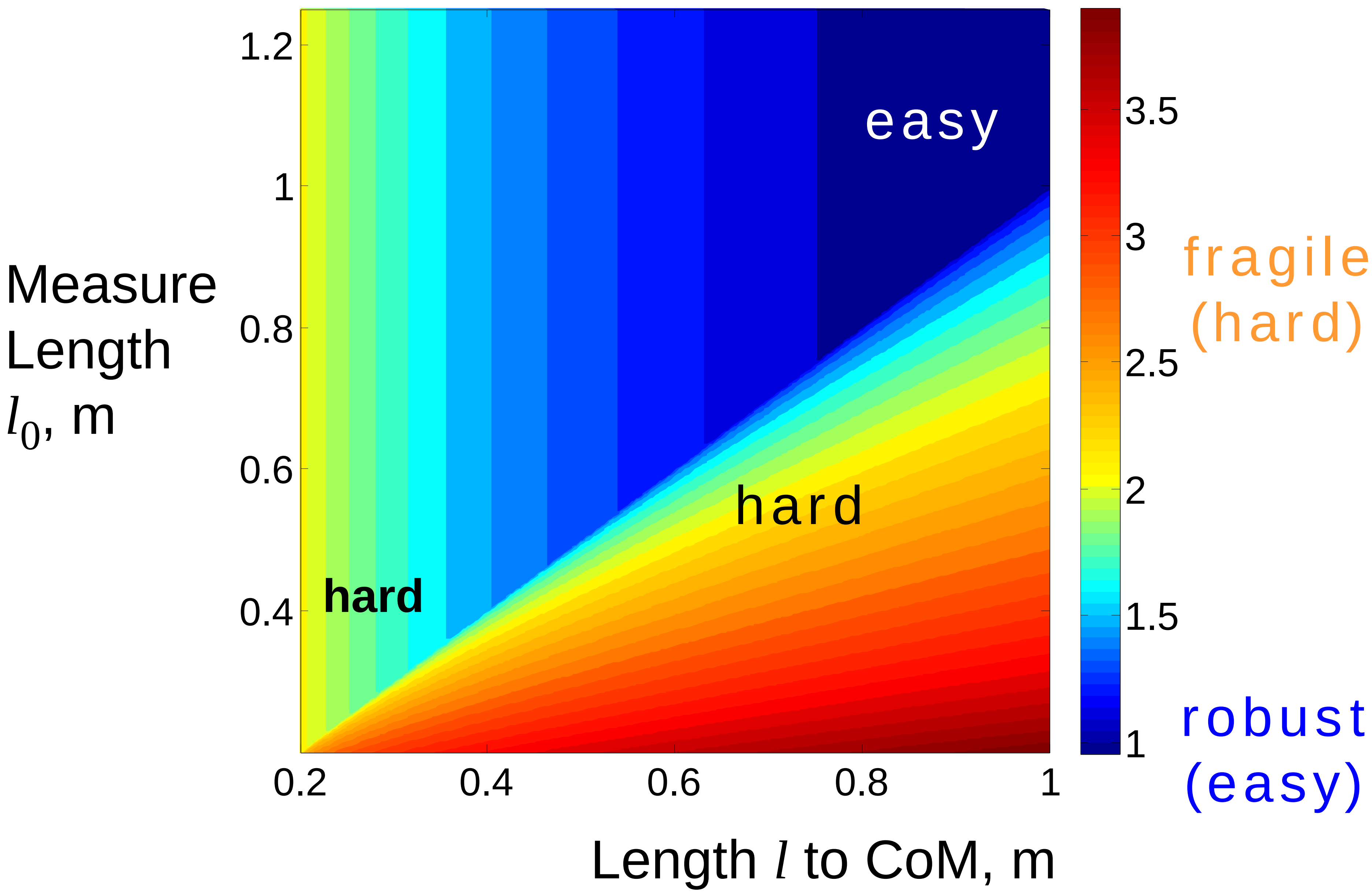


Easy to ***prove*** using simple models.


What is *sensed* matters.
hard
harder
hardest!
Unstable poles
Unstable zeros

$$\frac{1}{\pi}\int_0^\infty \ln\left|T(j\omega)\right|\left(\frac{2p}{p^2+\omega^2}\right)d\omega \geq p\tau + \ln\left|\frac{z+p}{z-p}\right|$$

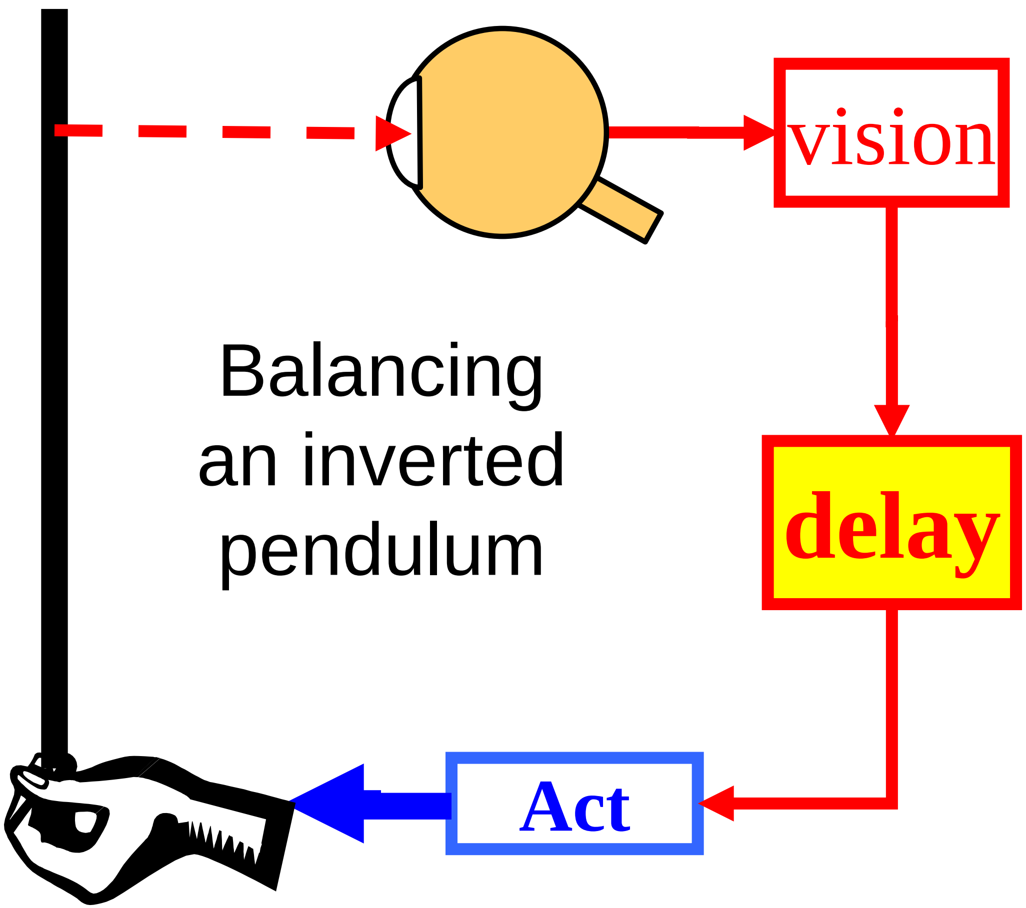




Measure Length l_0, m
1.2
1
0.8
0.6
0.4
easy
hard
hard
0.2
0.4
0.6
0.8
1
Length l to CoM, m
3.5
3
2.5
2
1.5
1
fragile (hard)
robust (easy)

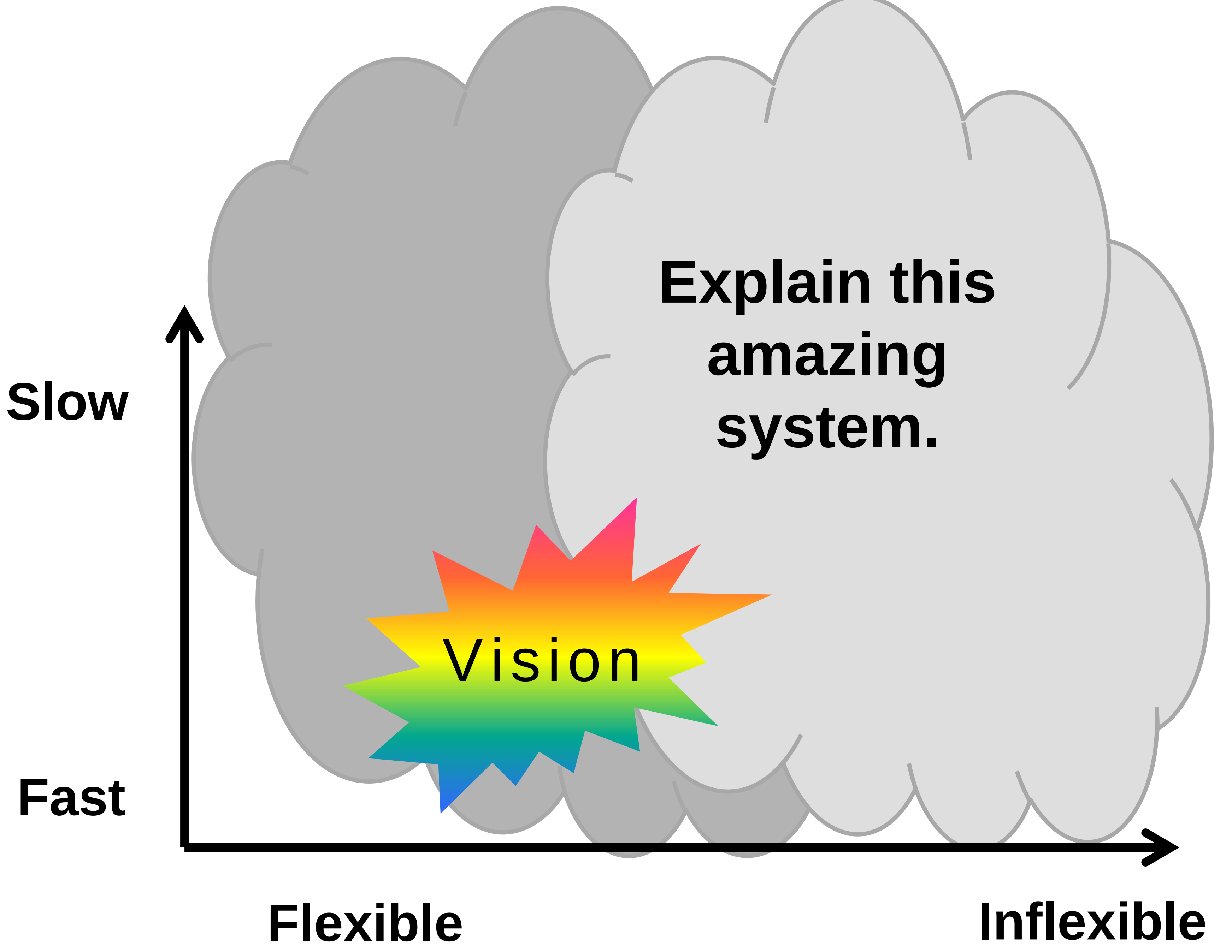
Completing the story

Mechanics+
Gravity +
Light +

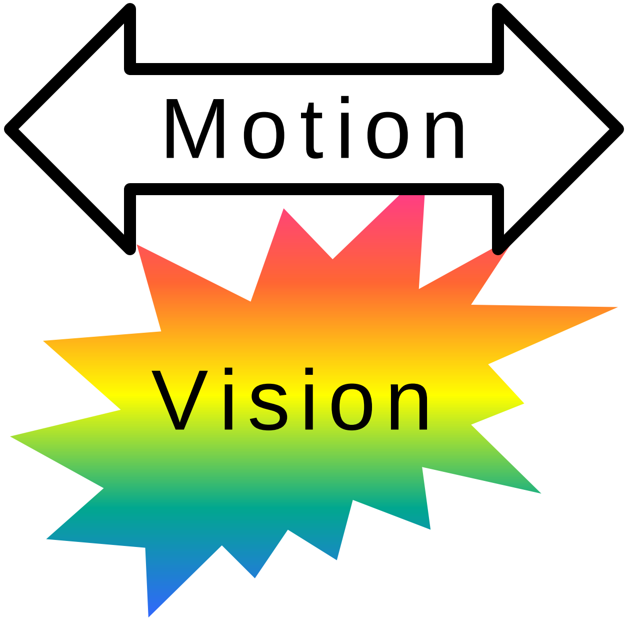


$$\frac{1}{\pi}\int_0^\infty \ln\left|T(j\omega)\right|\left(\frac{p}{p^2+\omega^2}\right)d\omega \geq p\tau + \ln\left|\frac{z+p}{z-p}\right|$$

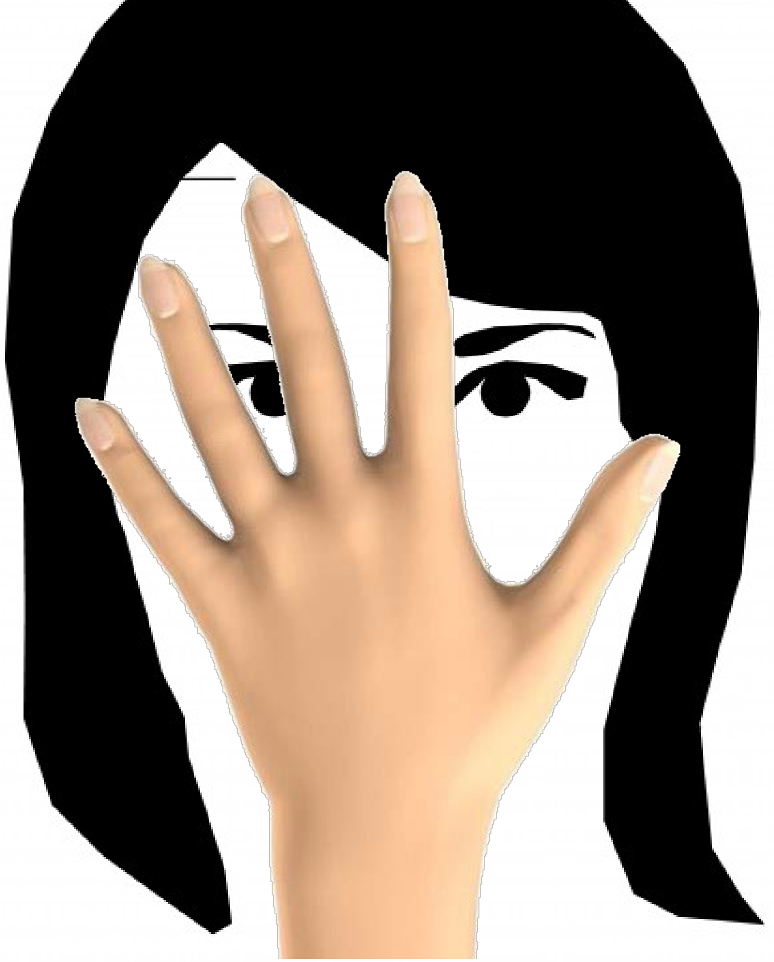
+ Neuroscience


Explain this amazing system.
Slow
Fast
Vision
Flexible
Inflexible

- **Neuroscience motivation**



Robust vision with motion



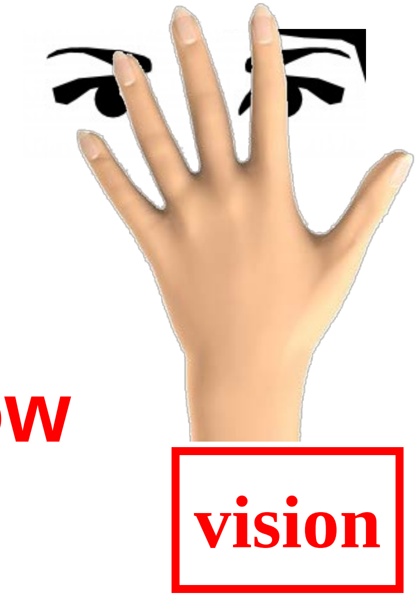
Experiment

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

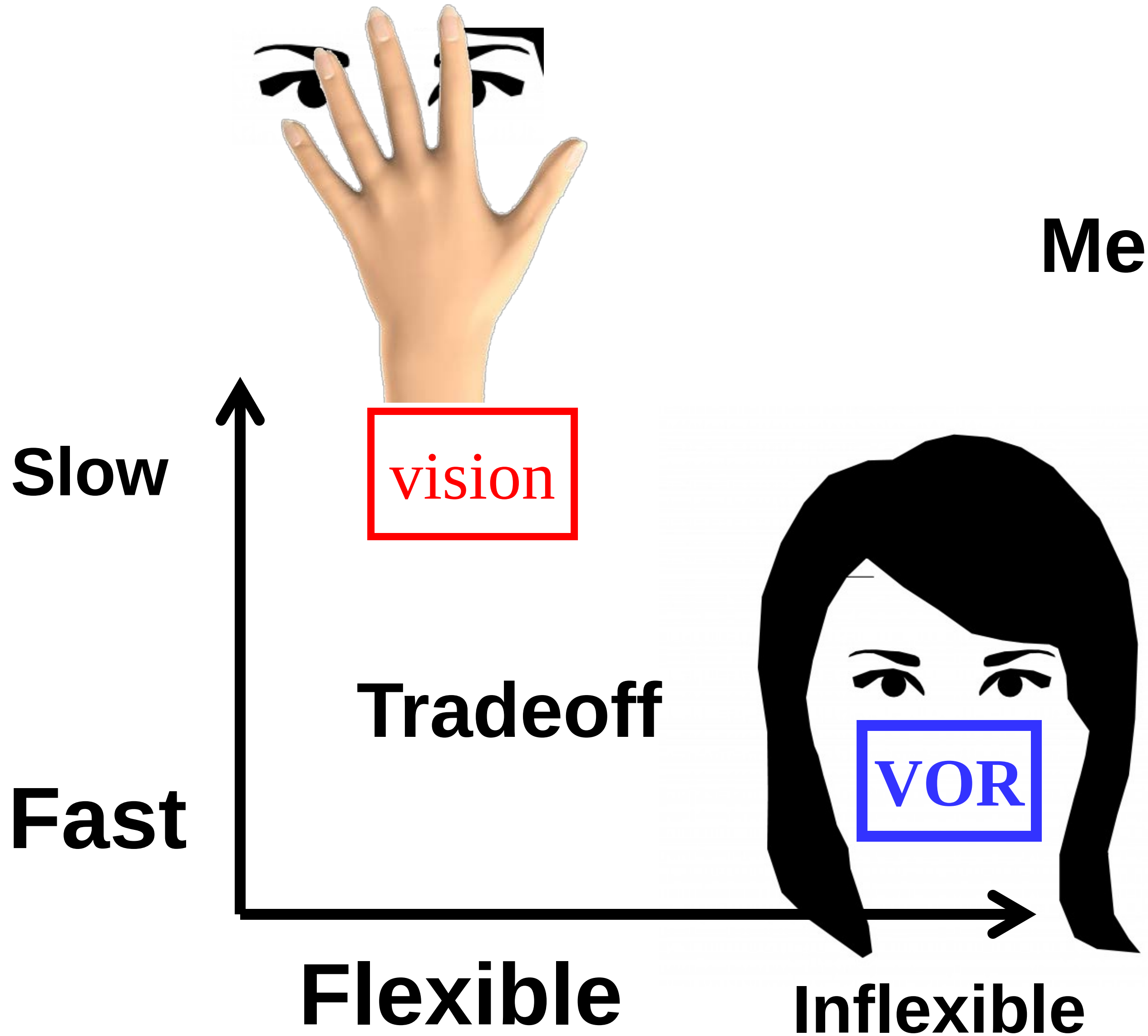
Why?

- Mechanism
- Tradeoff

Slow

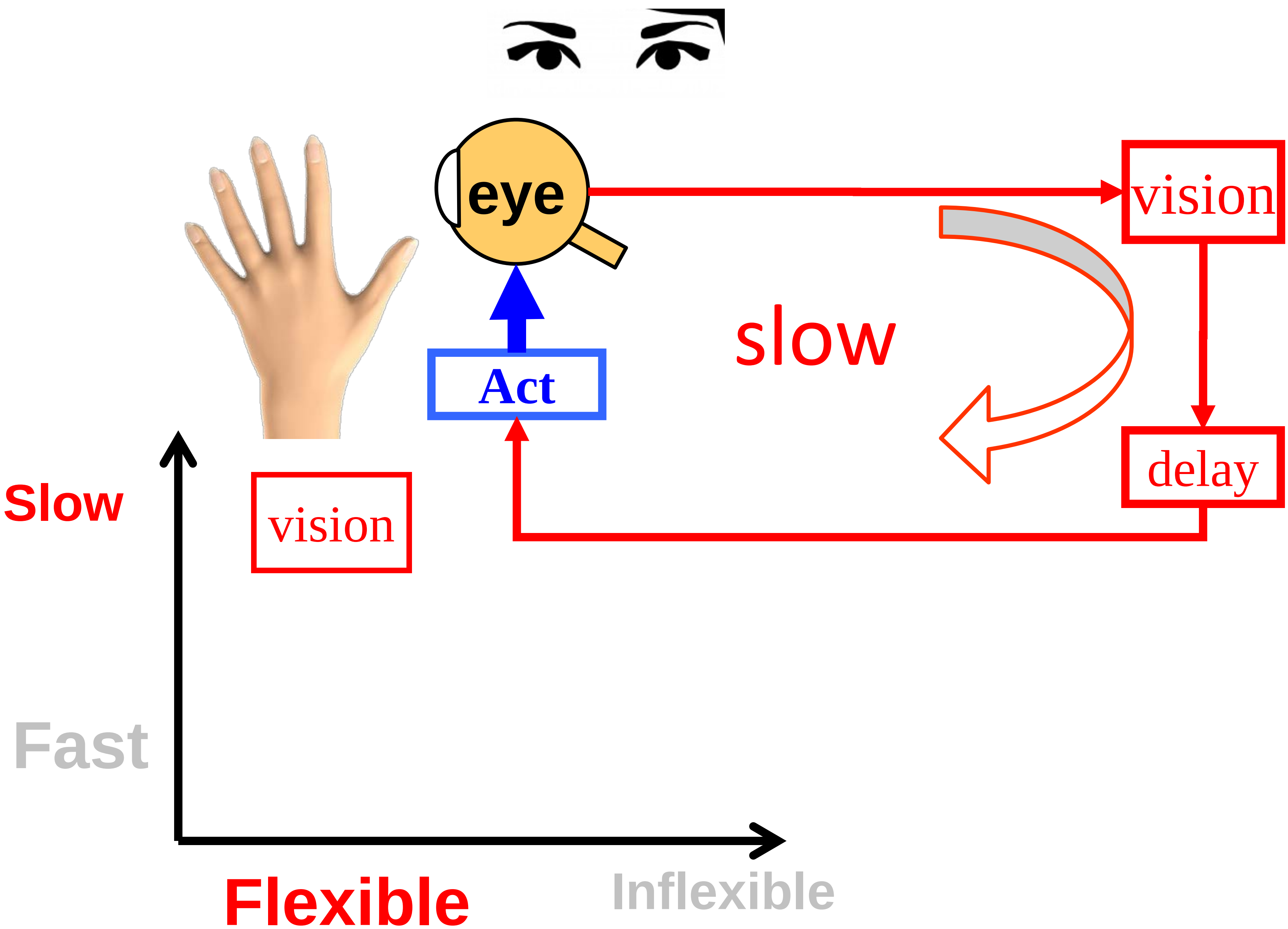


Fast

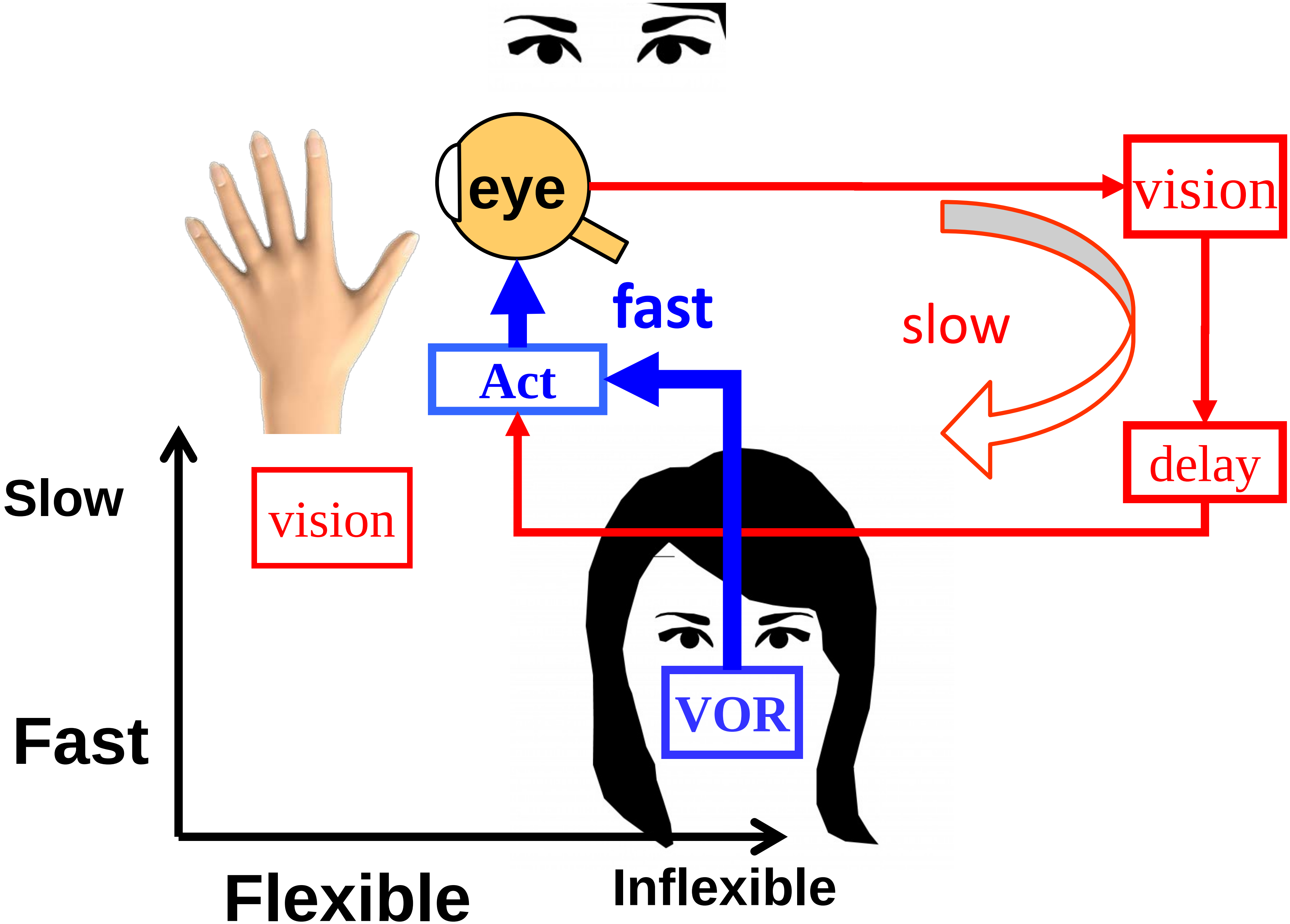


Mechanism

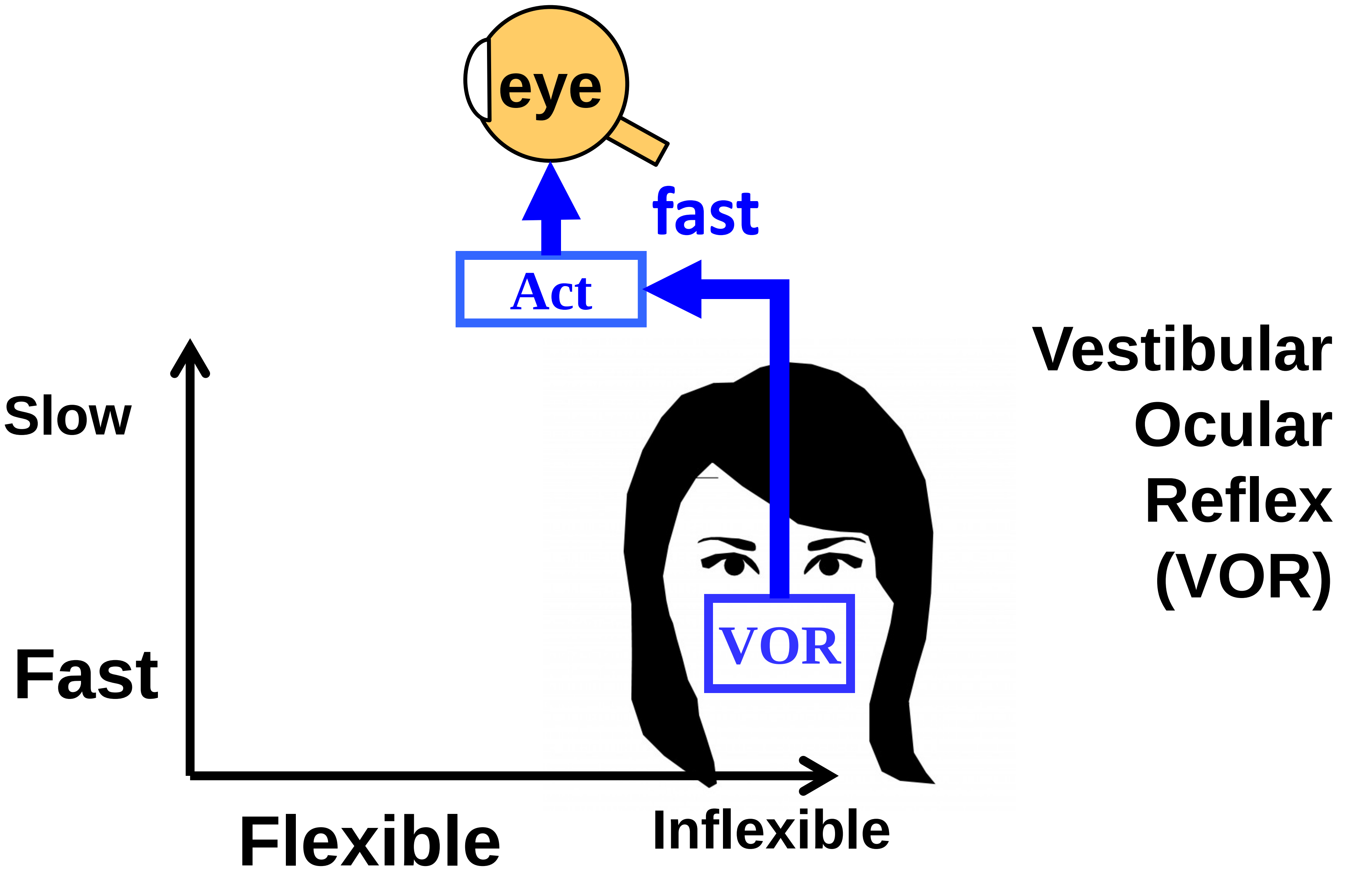
Vestibular
Ocular
Reflex
(VOR)

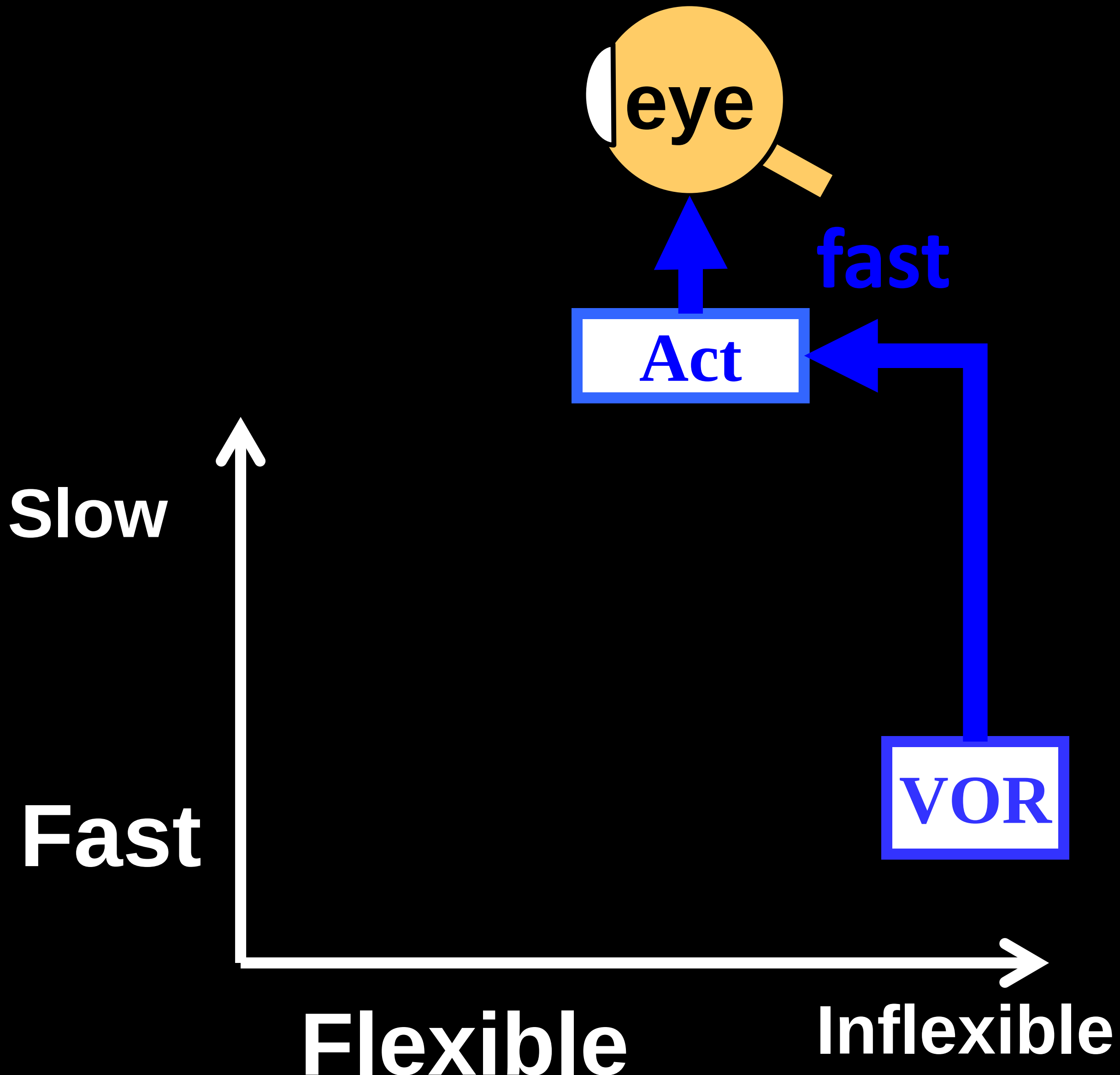


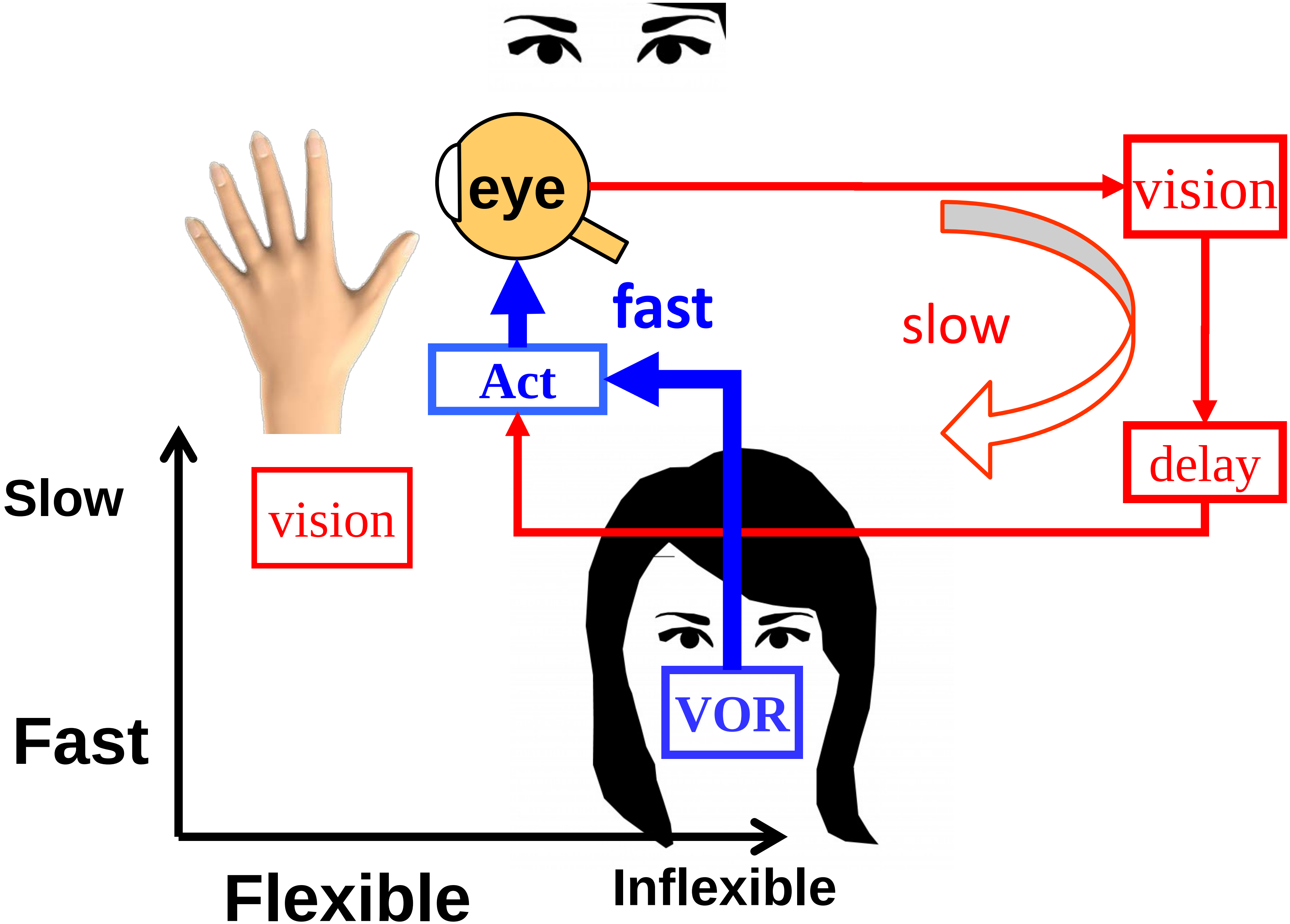
eye
vision
slow
Act
delay
Slow
vision
Fast
Flexible
Inflexible

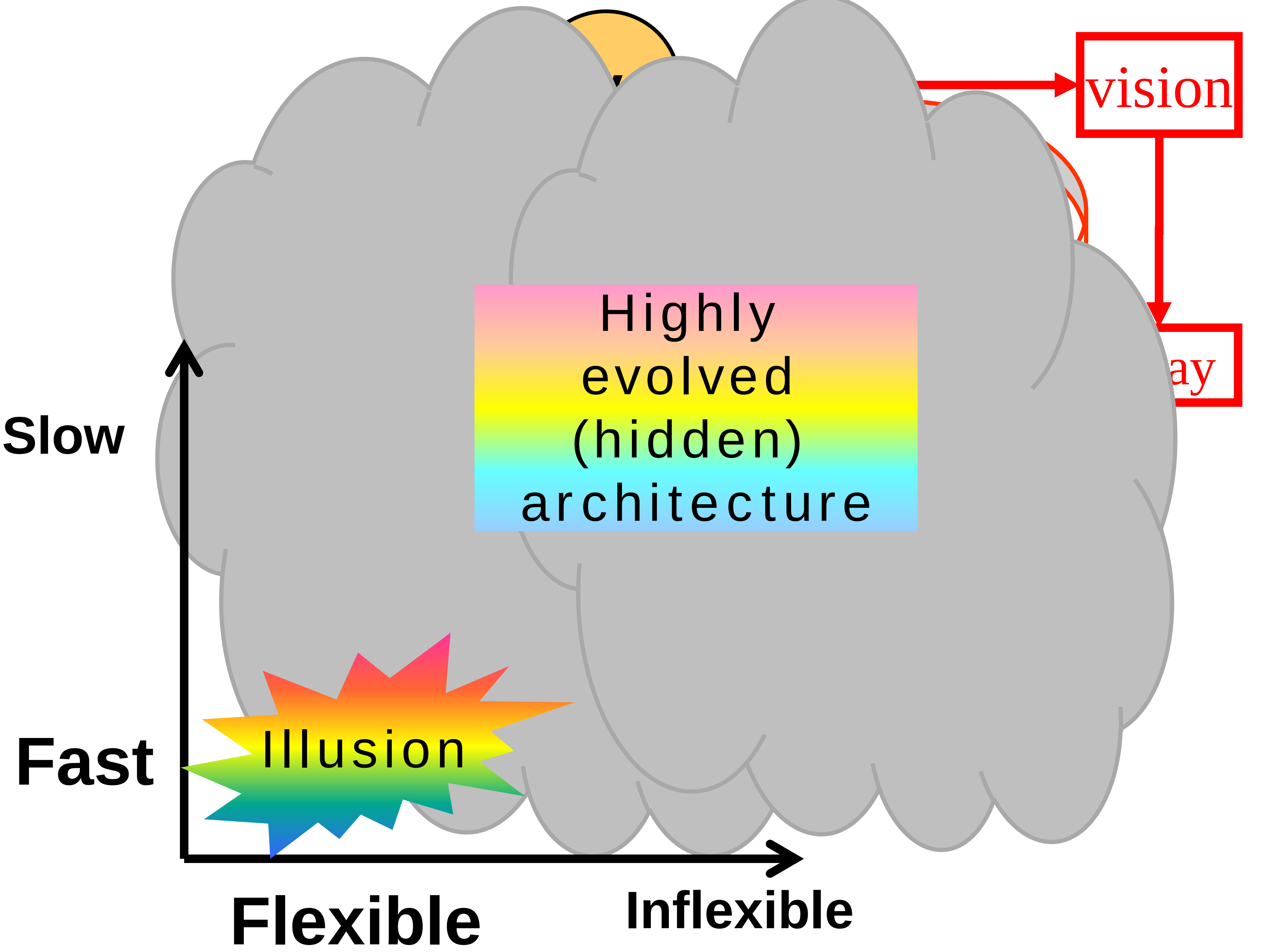


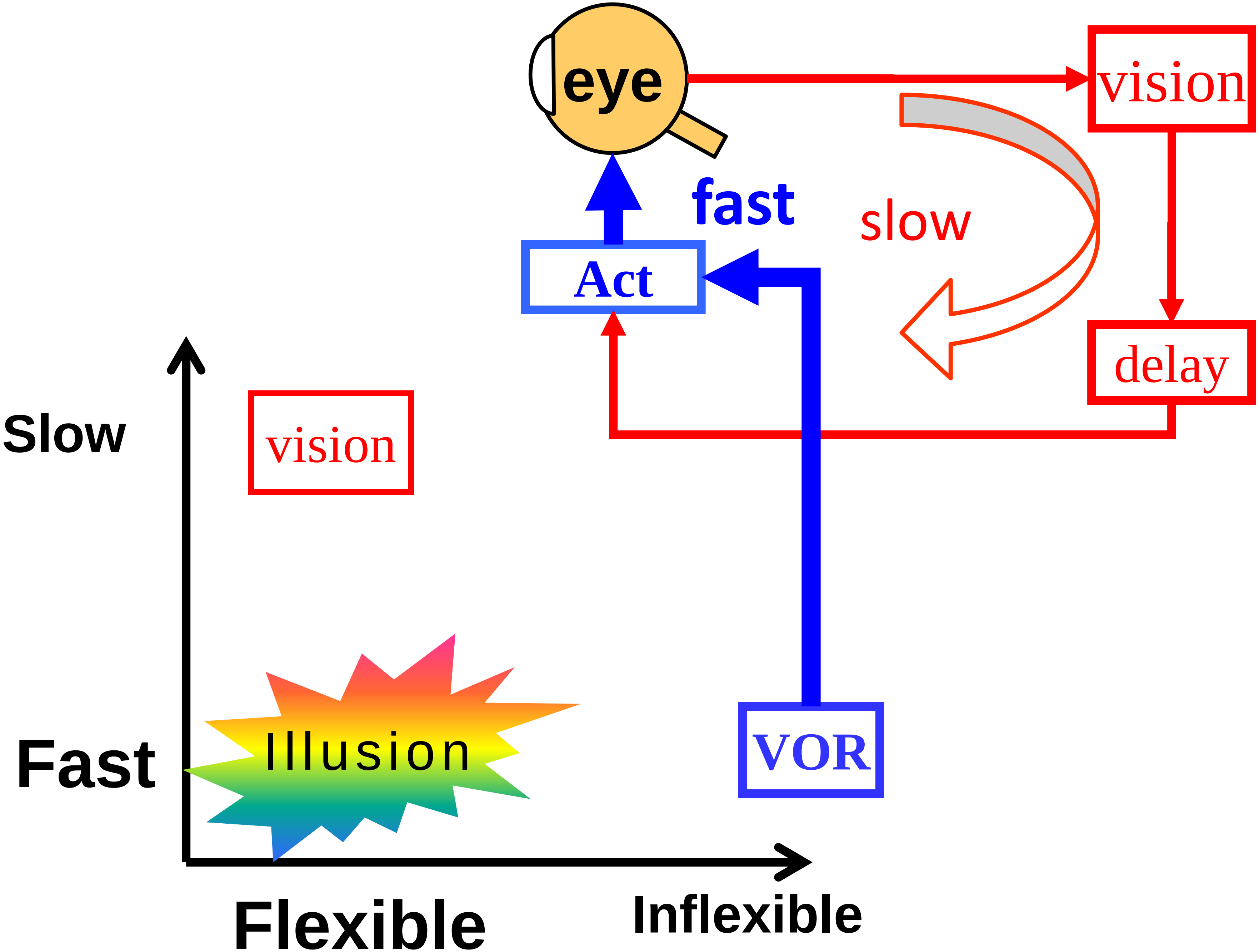
eye
vision
fast
slow
Act
delay
Slow
vision
VOR
Fast
Flexible
Inflexible


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

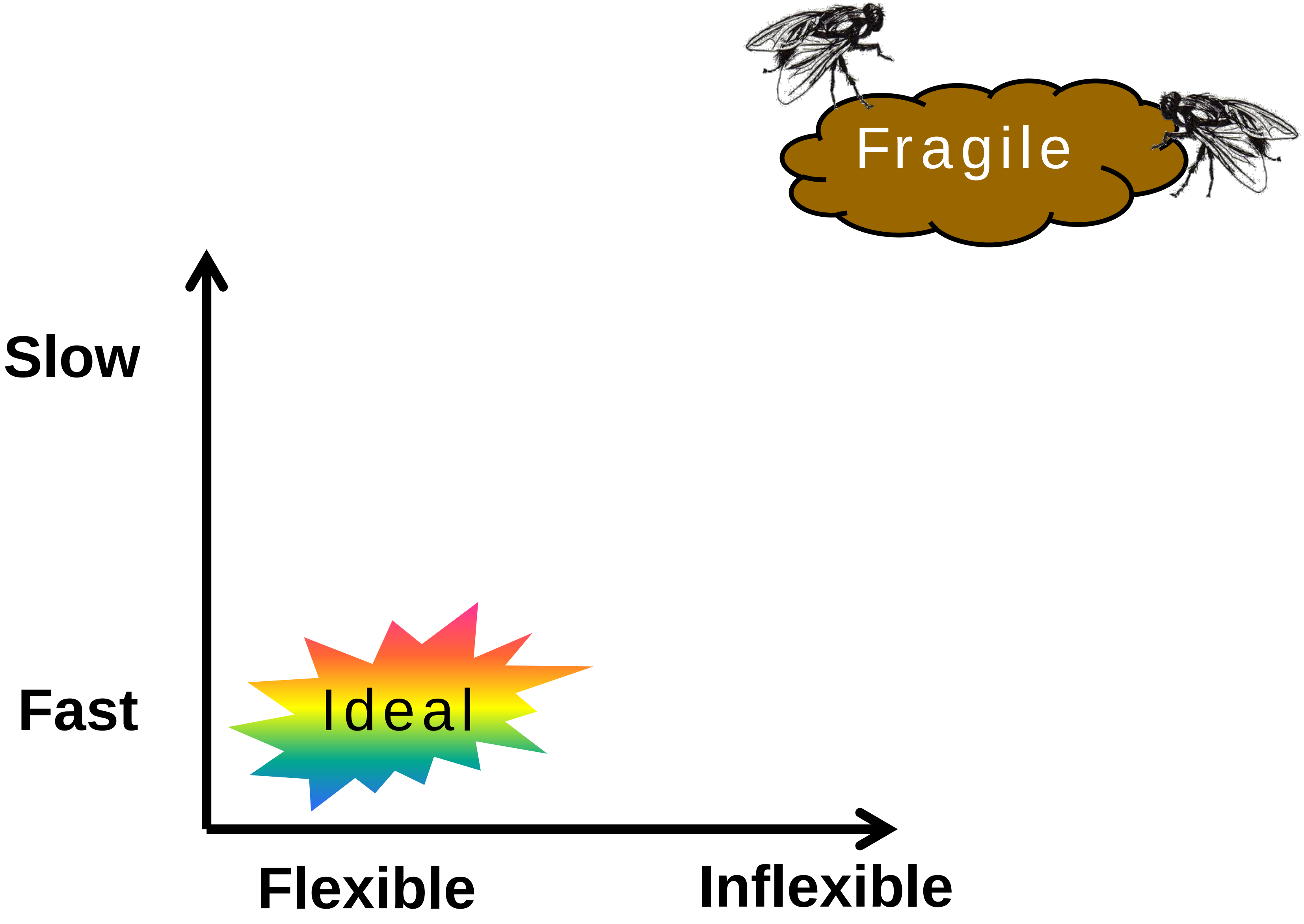

eye
fast
Act
VOR
Slow
Fast
Flexible
Inflexible


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

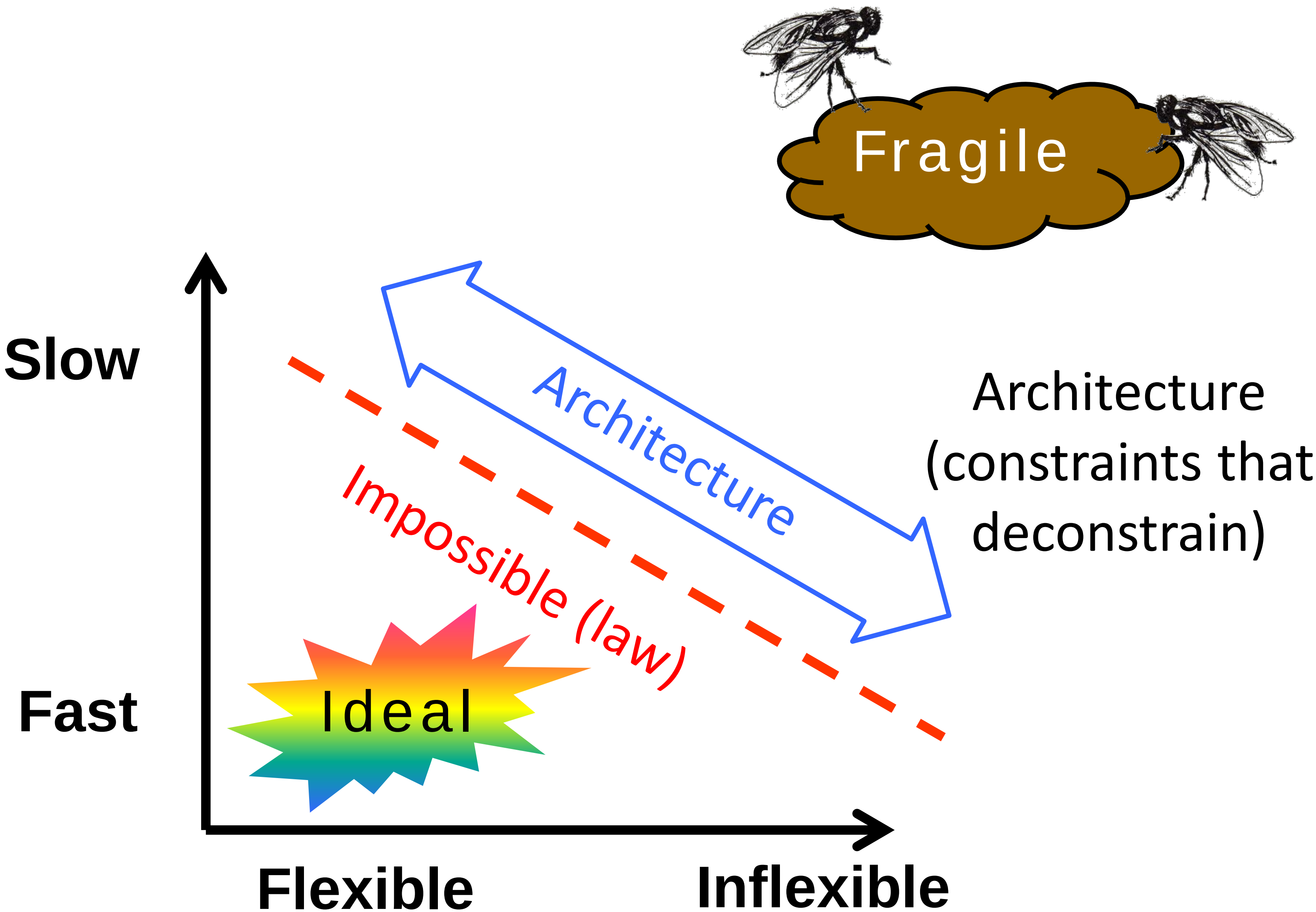

vision
ay
Highly evolved (hidden) architecture
Slow
Fast
Illusion
Flexible
Inflexible

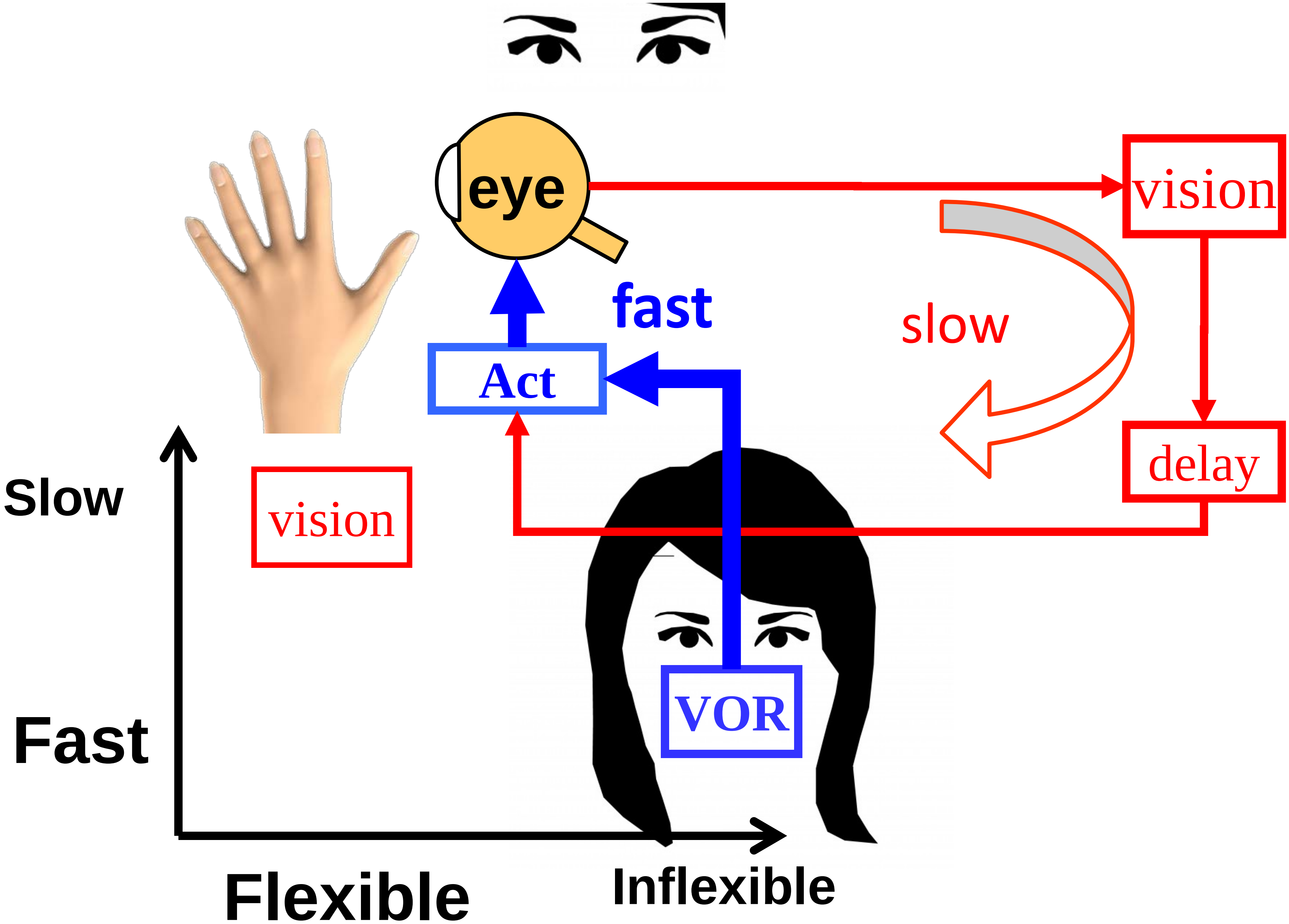


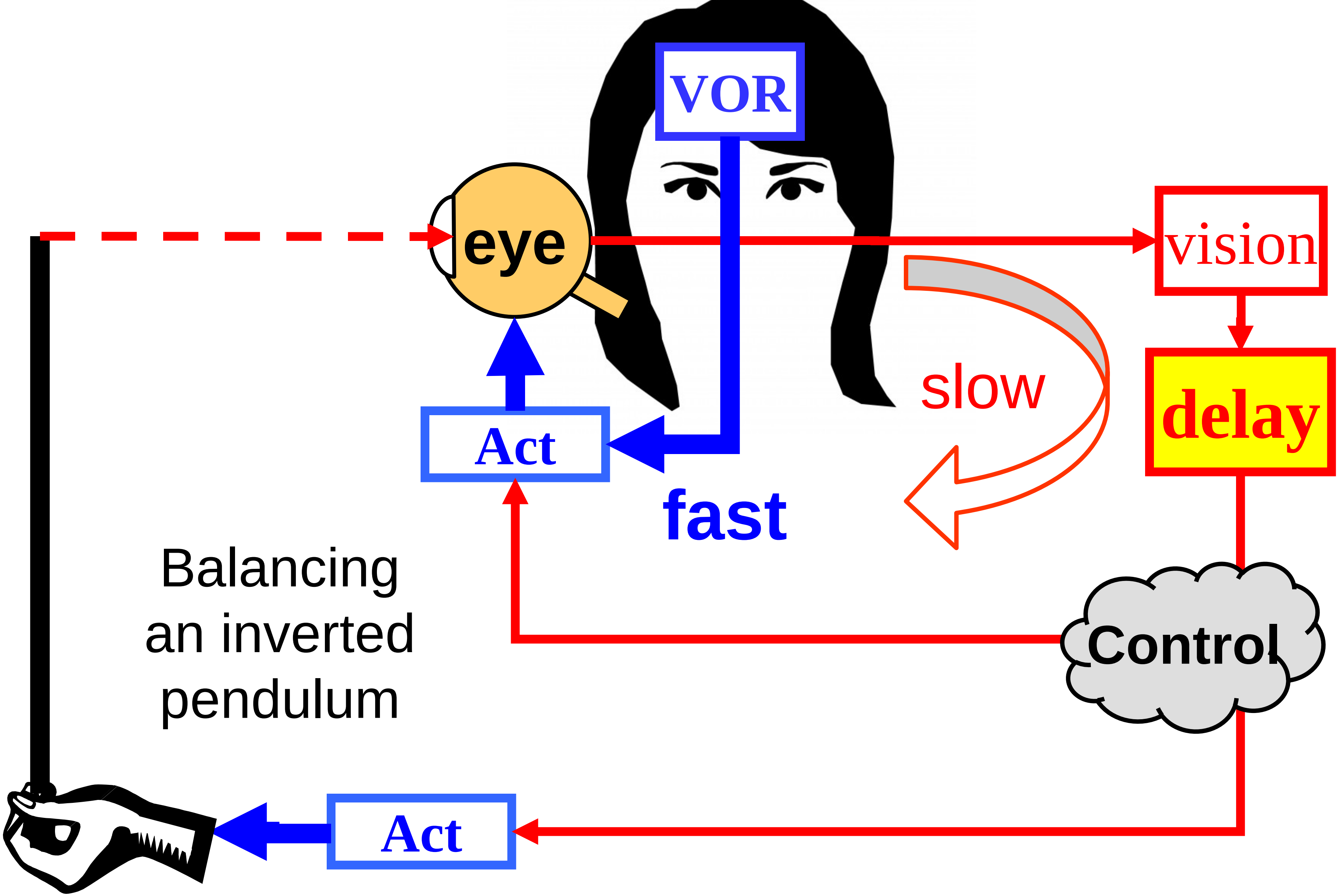
eye
vision
fast
slow
Act
delay
Slow
vision
Fast
Illusion
VOR
Flexible
Inflexible

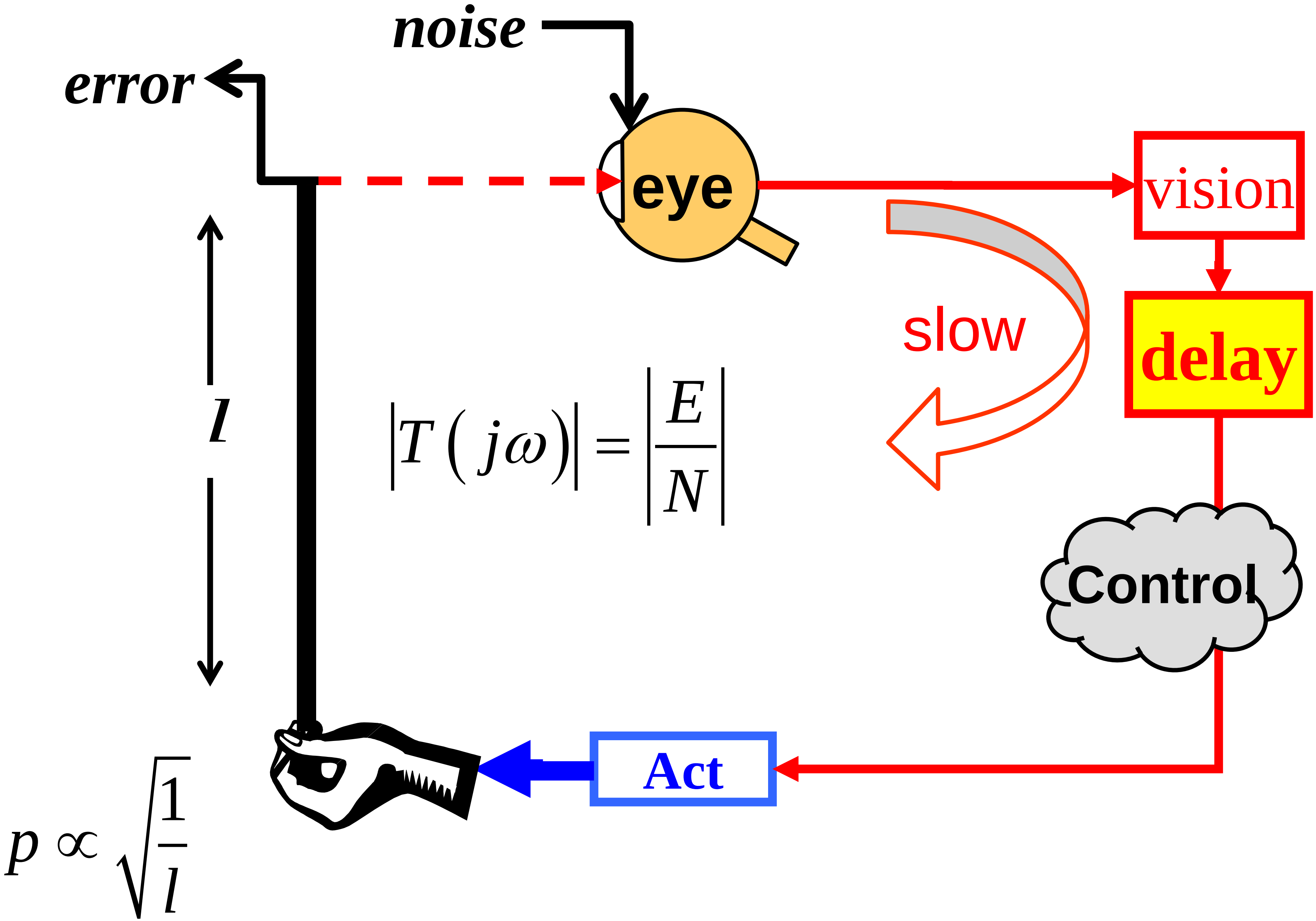


Fragile
Slow
Fast
Ideal
Flexible
Inflexible


Fragile
Slow
Fast
Architecture
Impossible (law)
Ideal
Architecture (constraints that deconstrain)
Flexible
Inflexible


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


VOR
eye
vision
slow
delay
Act
fast
Balancing
an inverted
pendulum
Control
Act

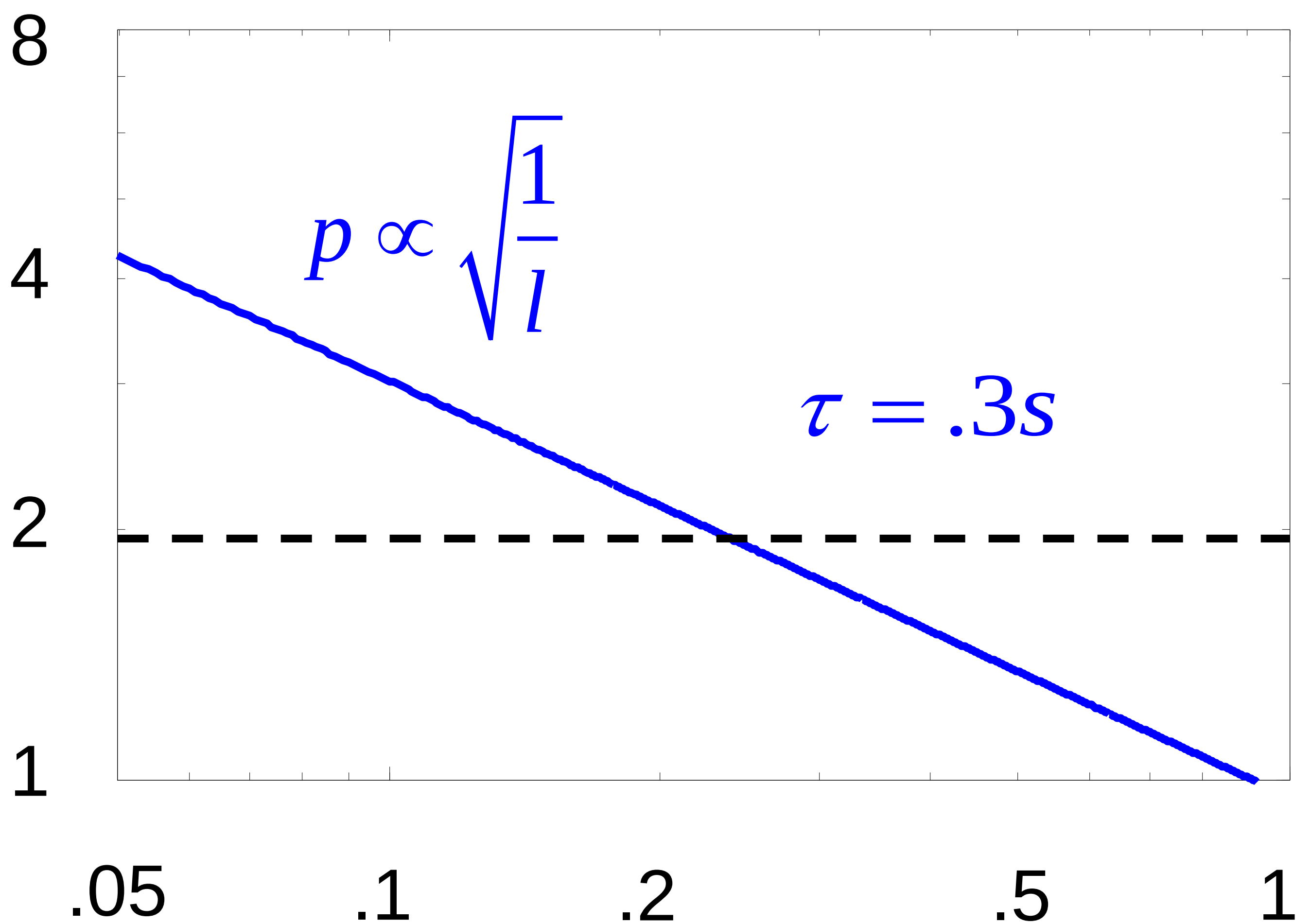

noise
error
eye
vision
slow
delay
l
$|T(j\omega)| = \left|\frac{E}{N}\right|$
Control
Act
$p \propto \sqrt{\frac{1}{l}}$

Law #4 :

$$\frac{1}{\pi}\int_0^\infty \ln\left|T(j\omega)\right|\left(\frac{2p}{p^2+\omega^2}\right)d\omega \geq p\tau$$

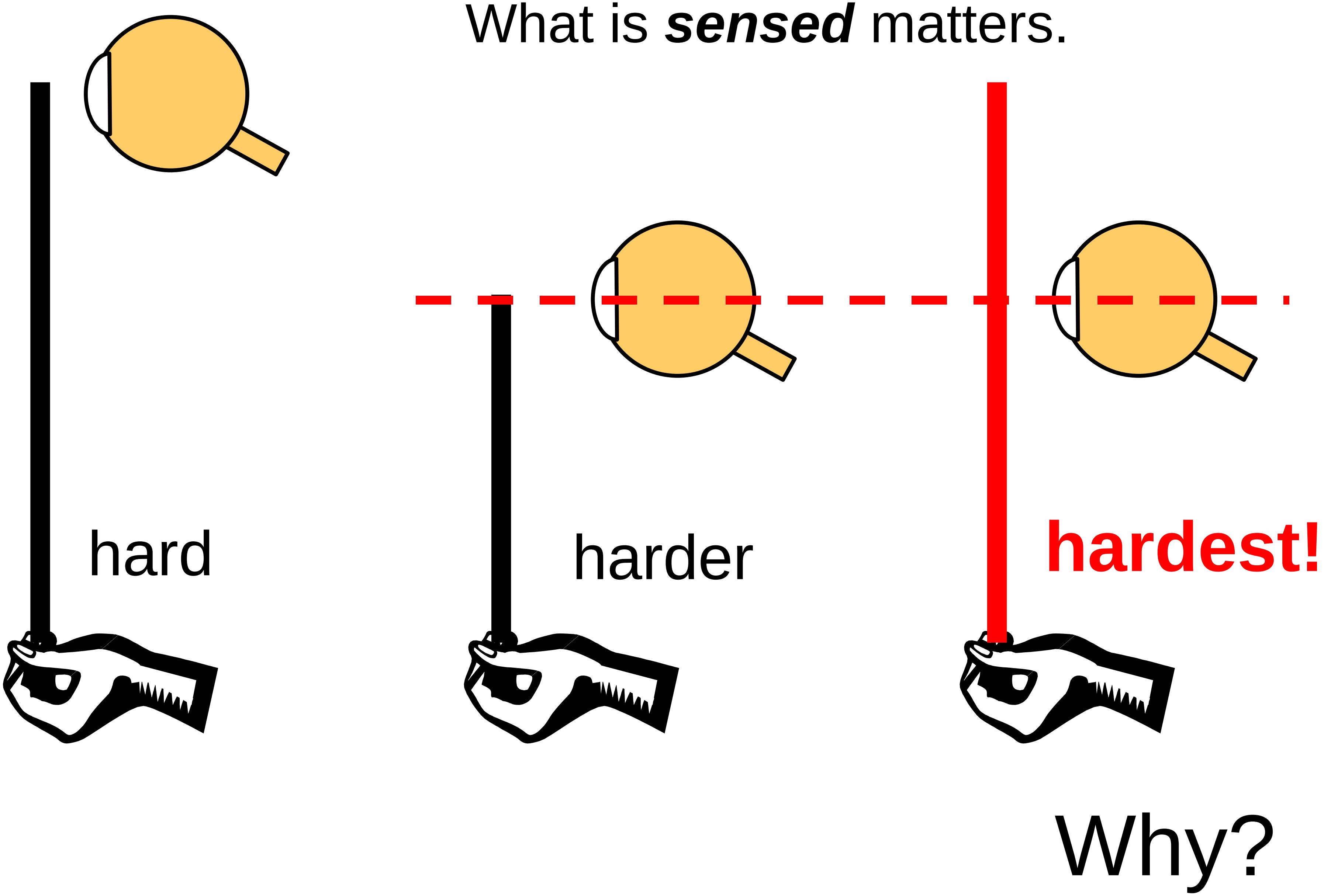
Fragility

$p\tau$

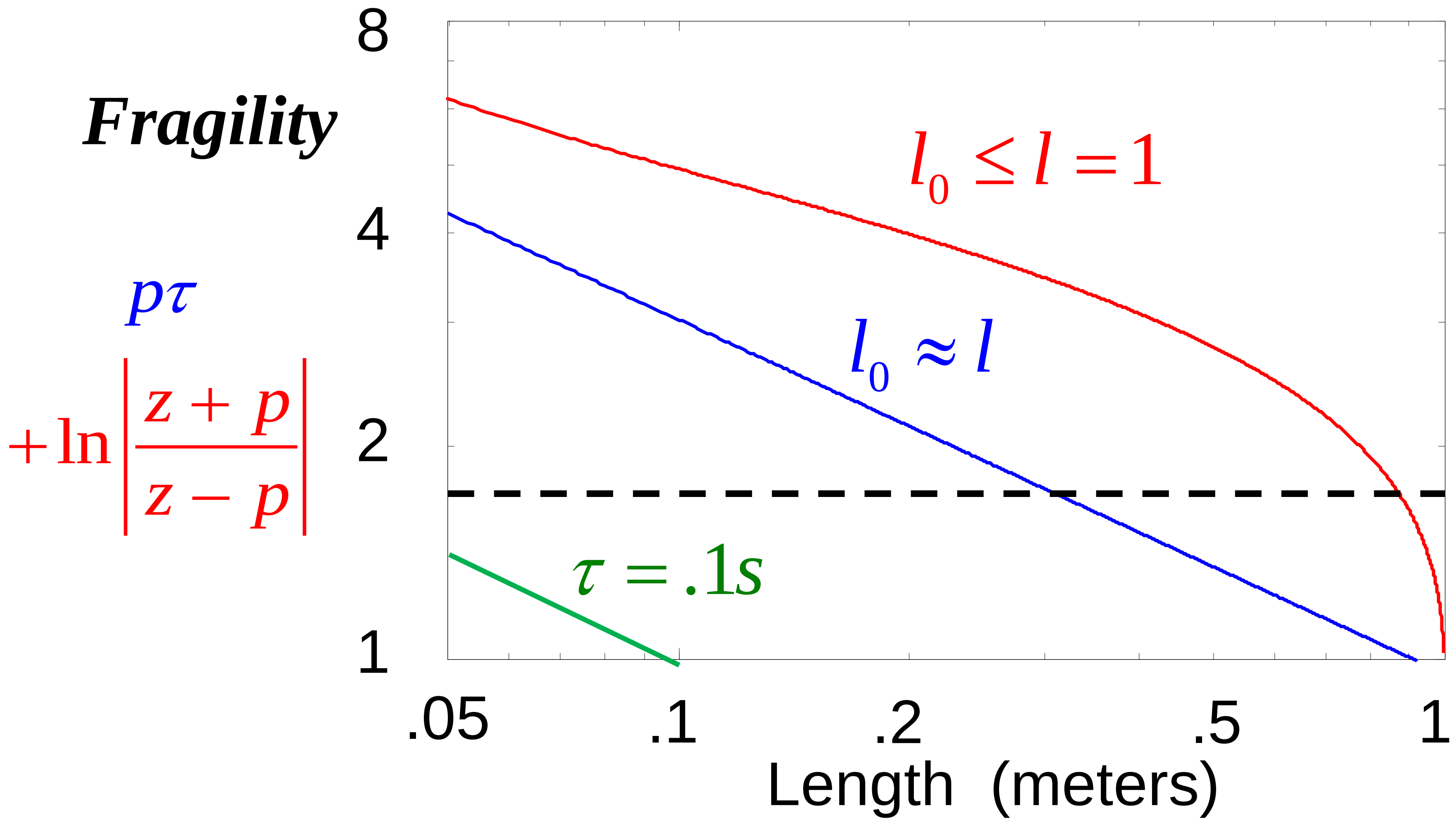


Length ***l*** (meters)

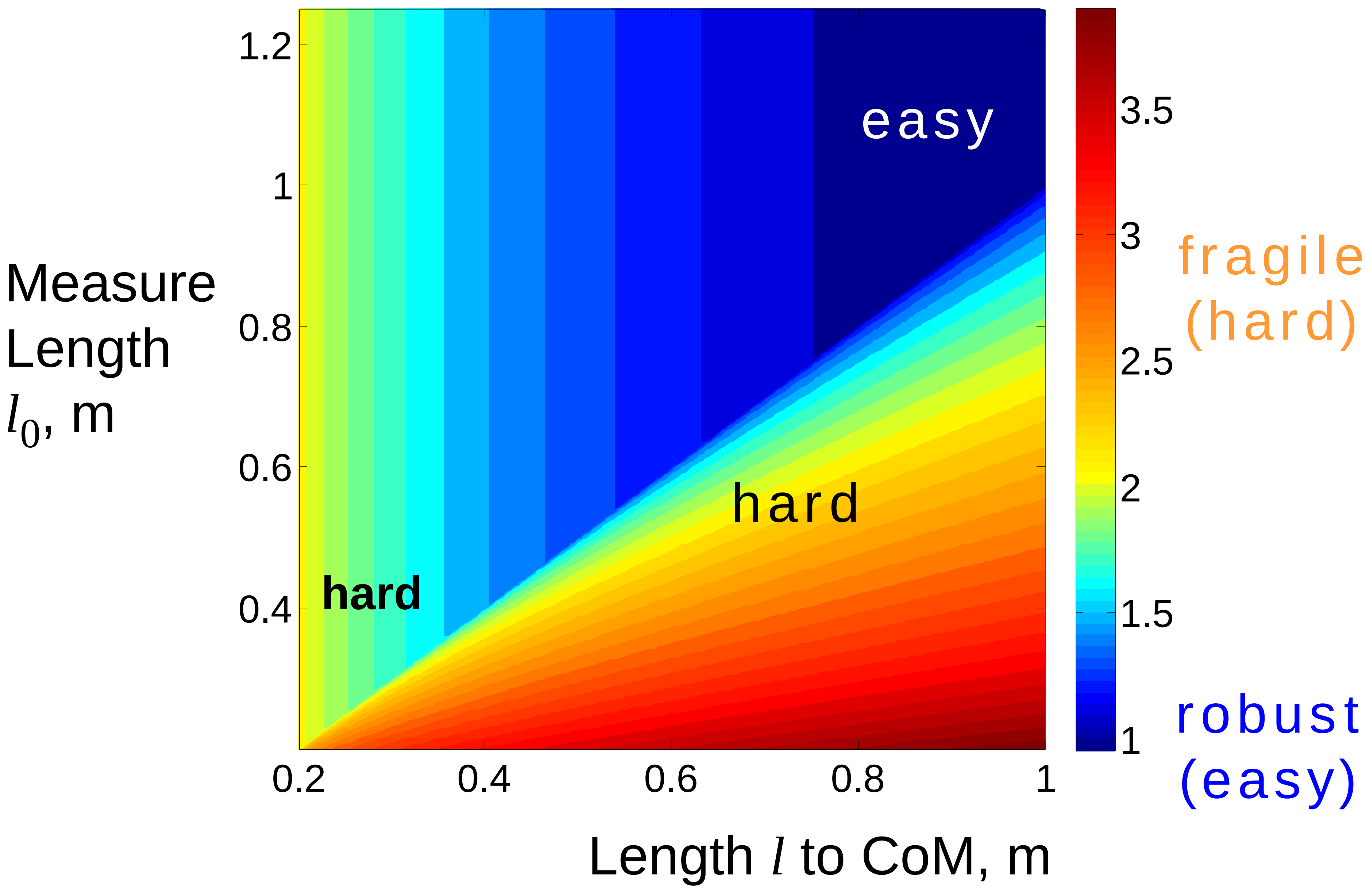
What is ***sensed*** matters.



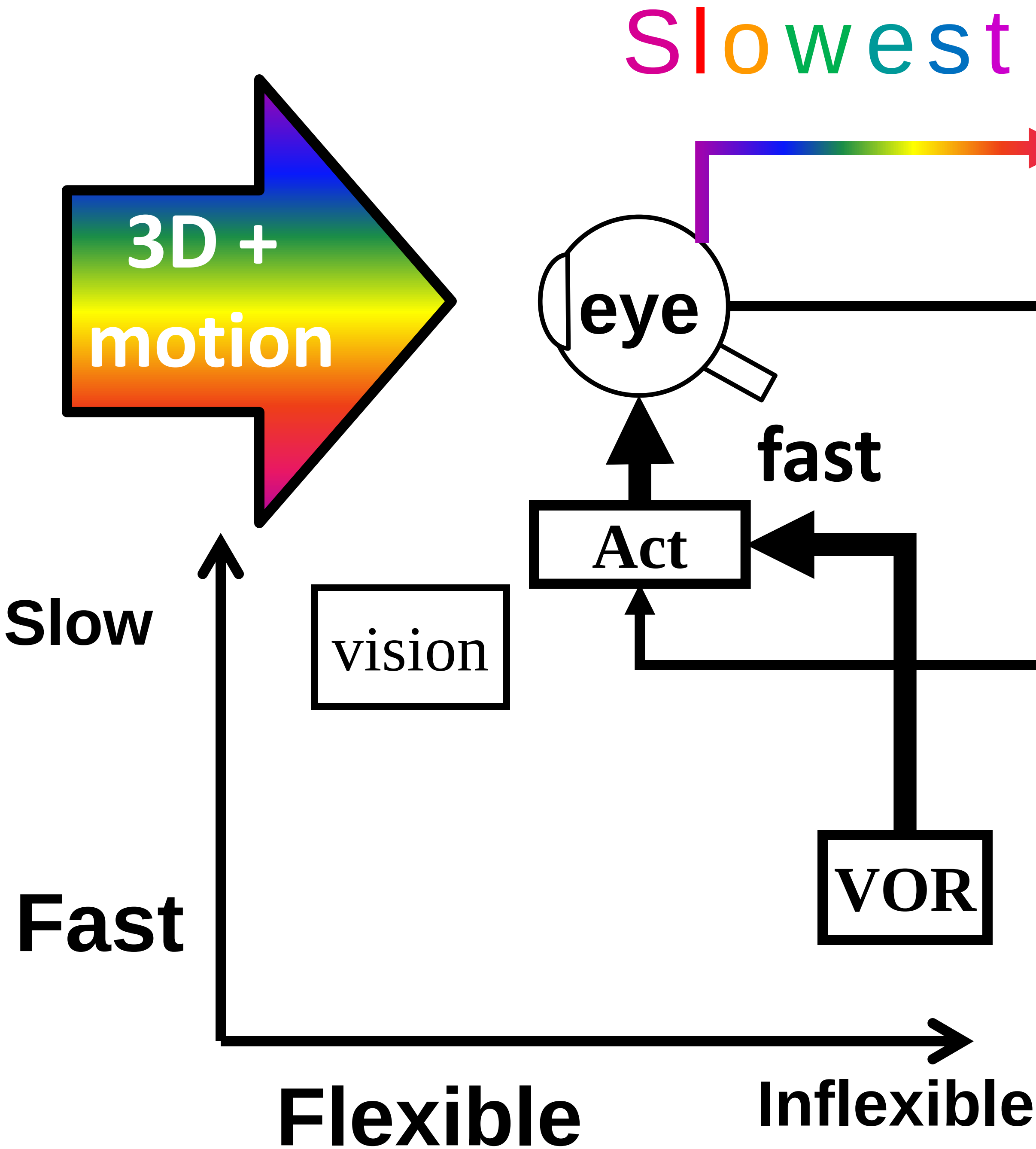
Easy to ***prove*** using simple models.



8
Fragility
4
$p\tau$
$+\ln\left|\frac{z+p}{z-p}\right|$
2
1
$l_0 \le l = 1$
$l_0 \approx l$
$\tau = .1s$
.05
.1
.2
.5
1
Length (meters)

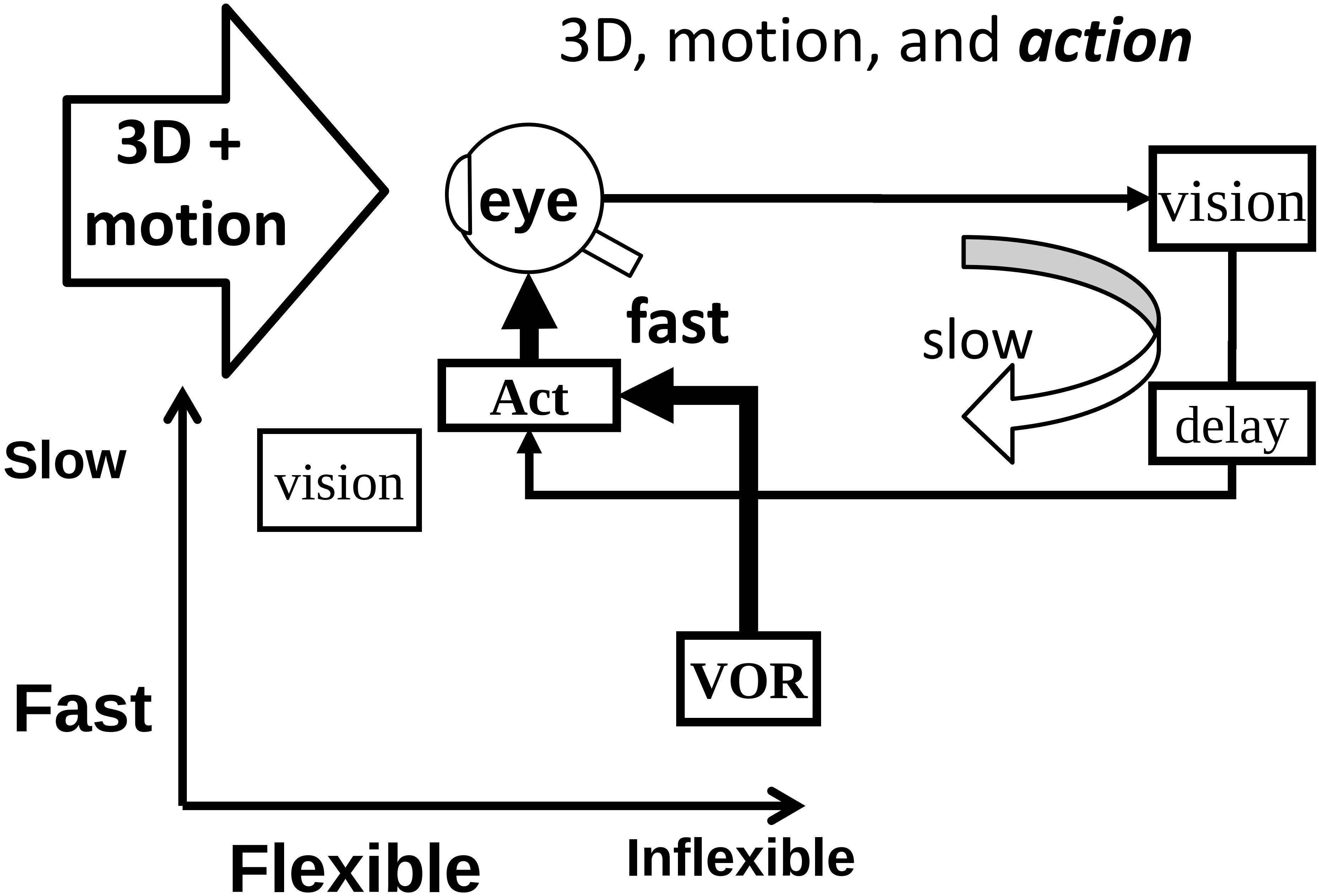


Measure
Length
l_0, m
1.2
1
0.8
0.6
0.4
0.2
0.4
0.6
0.8
1
Length l to CoM, m
easy
hard
hard
3.5
3
2.5
2
1.5
1
fragile
(hard)
robust
(easy)

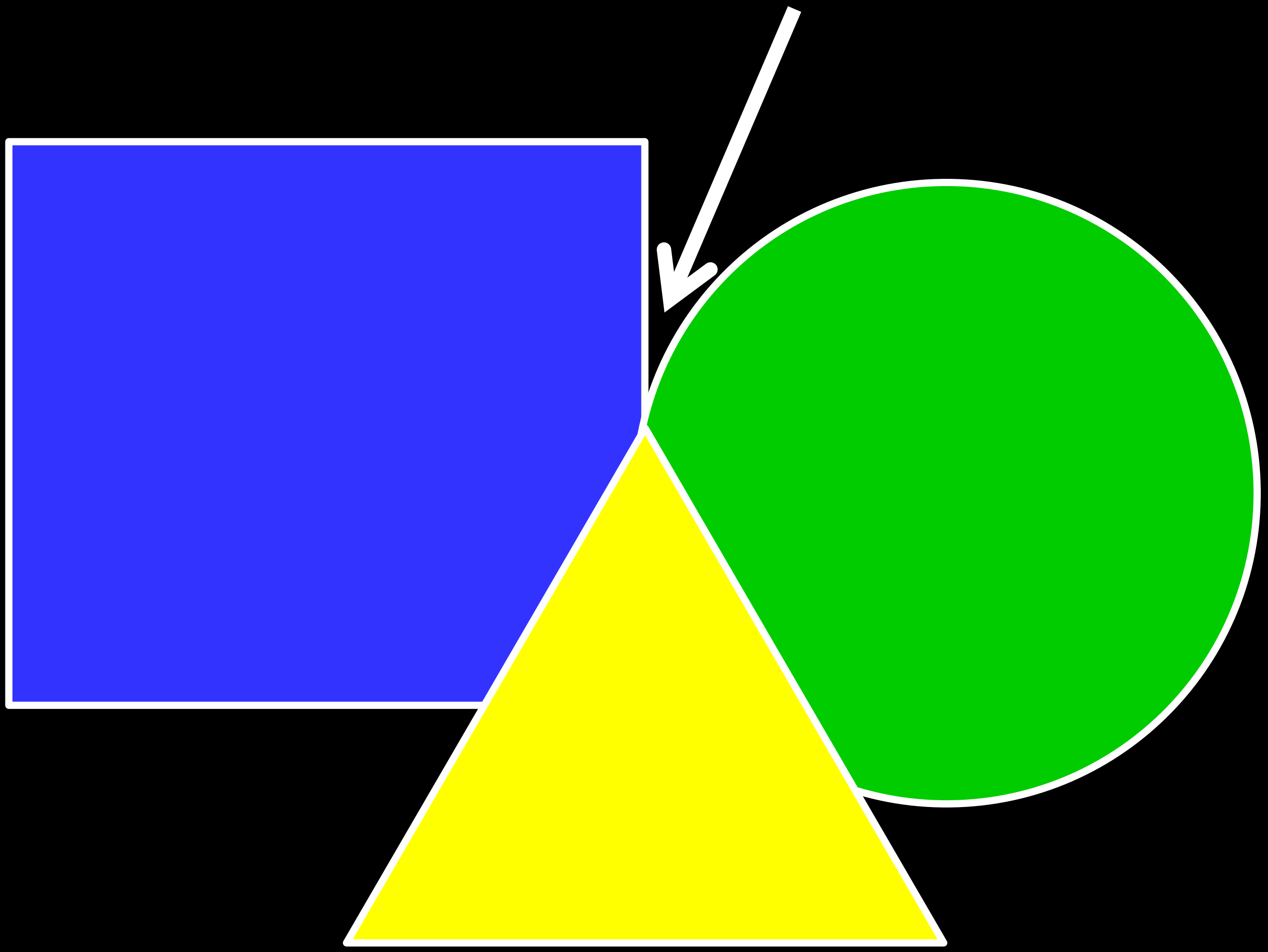


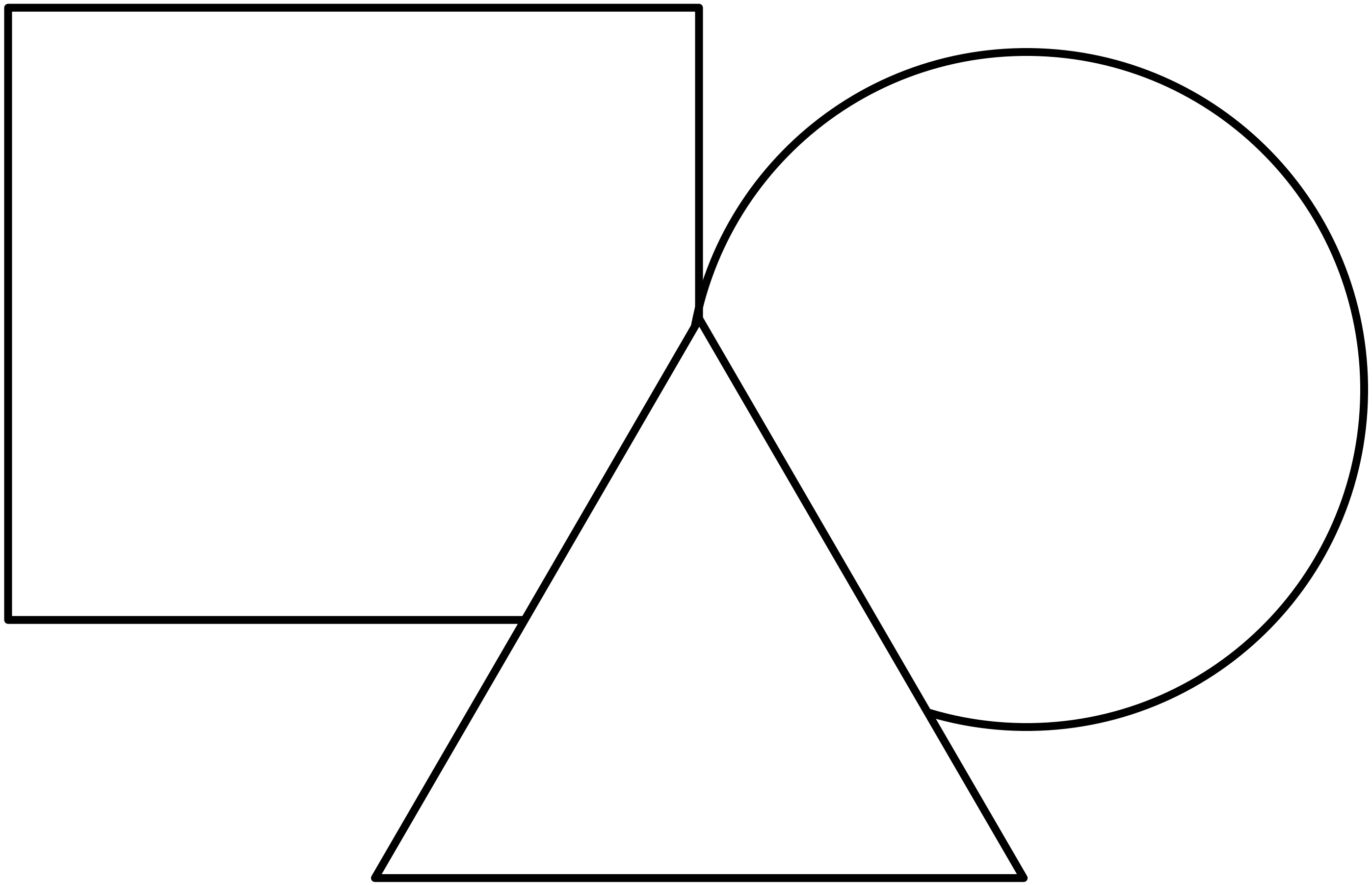
Slowest
color vision
3D + motion
eye
vision
fast
slow
Act
delay
Slow
vision
VOR
Fast
Flexible
Inflexible

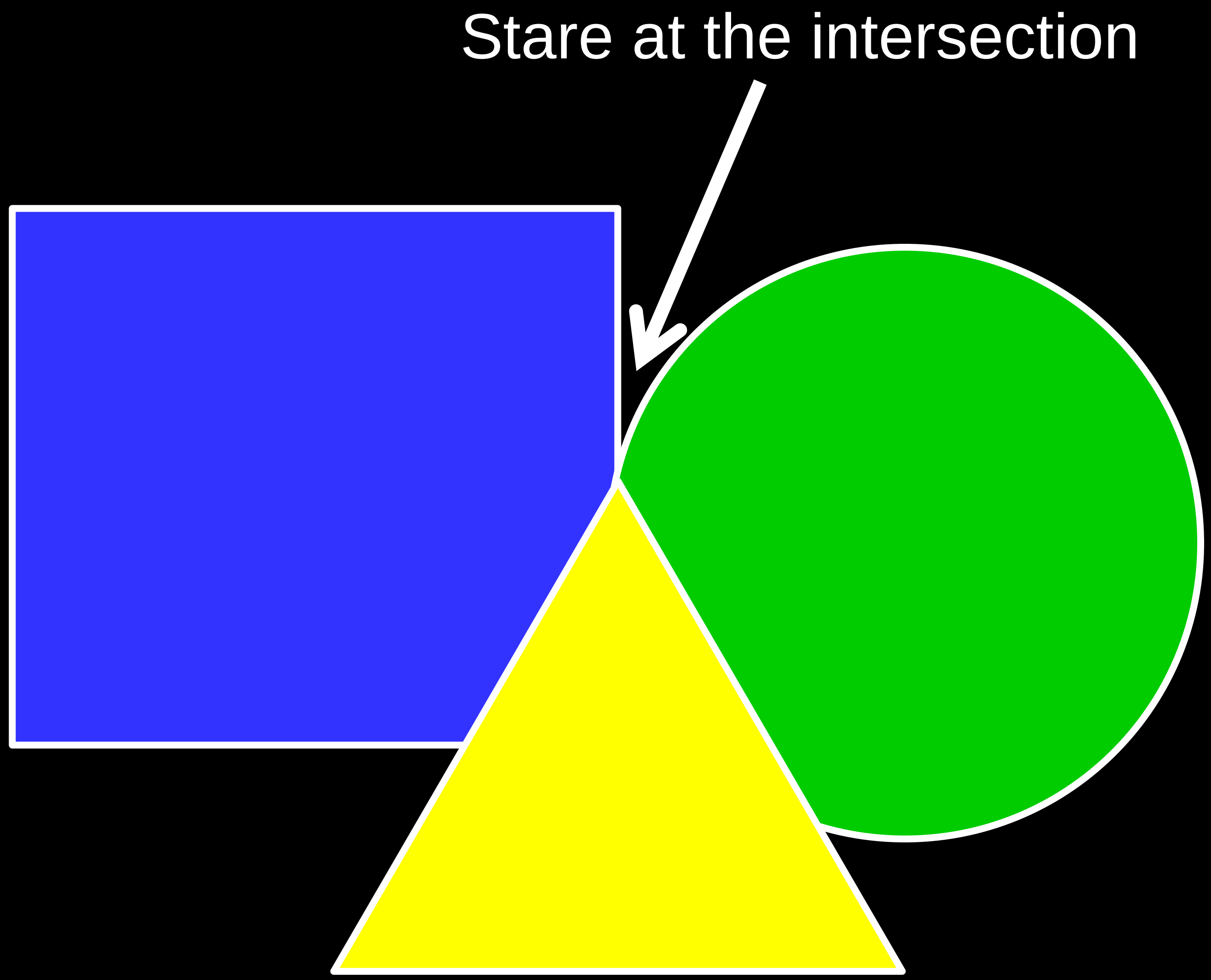
B&W (luminence only):
3D, motion, and ***action***

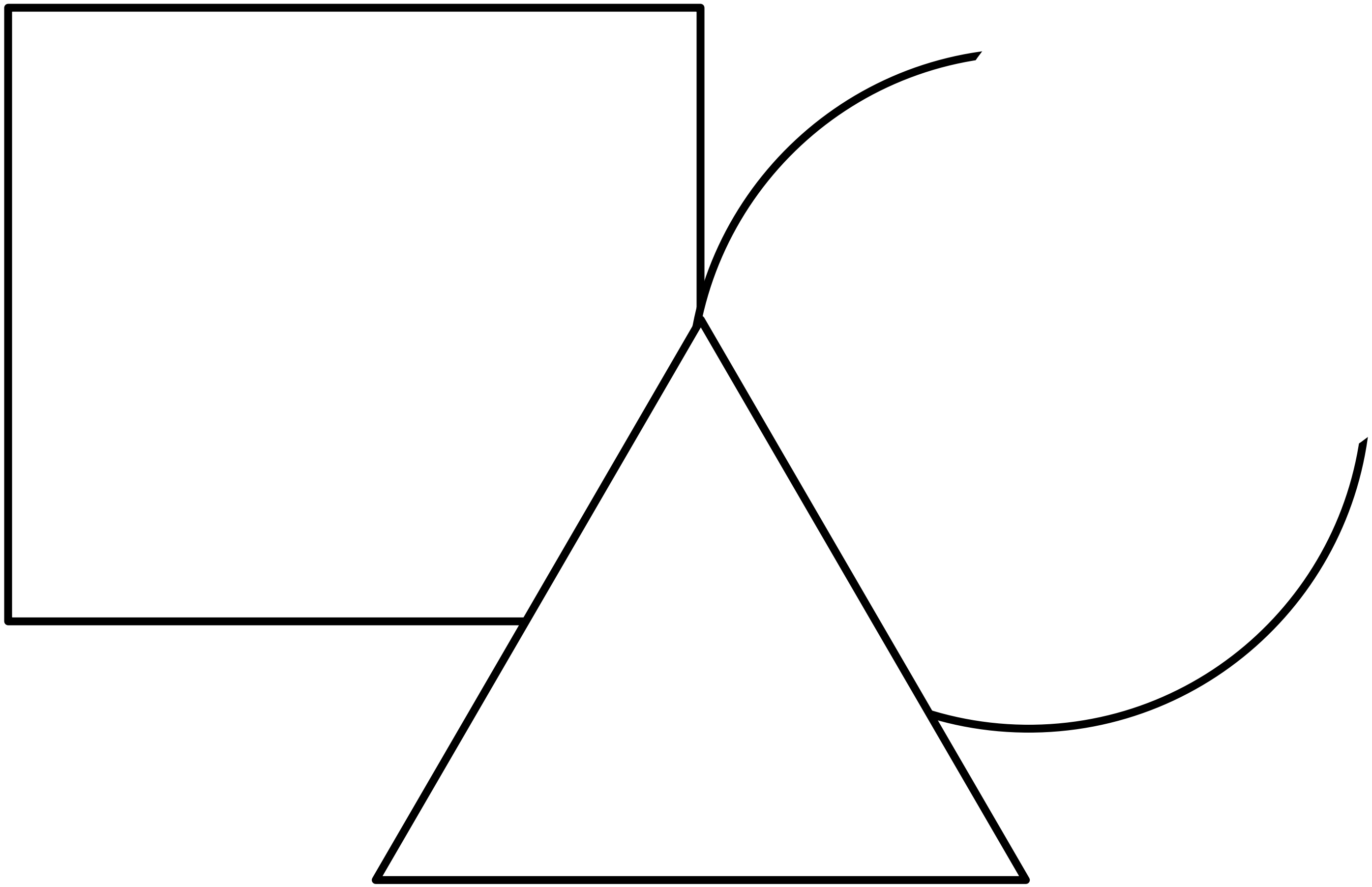


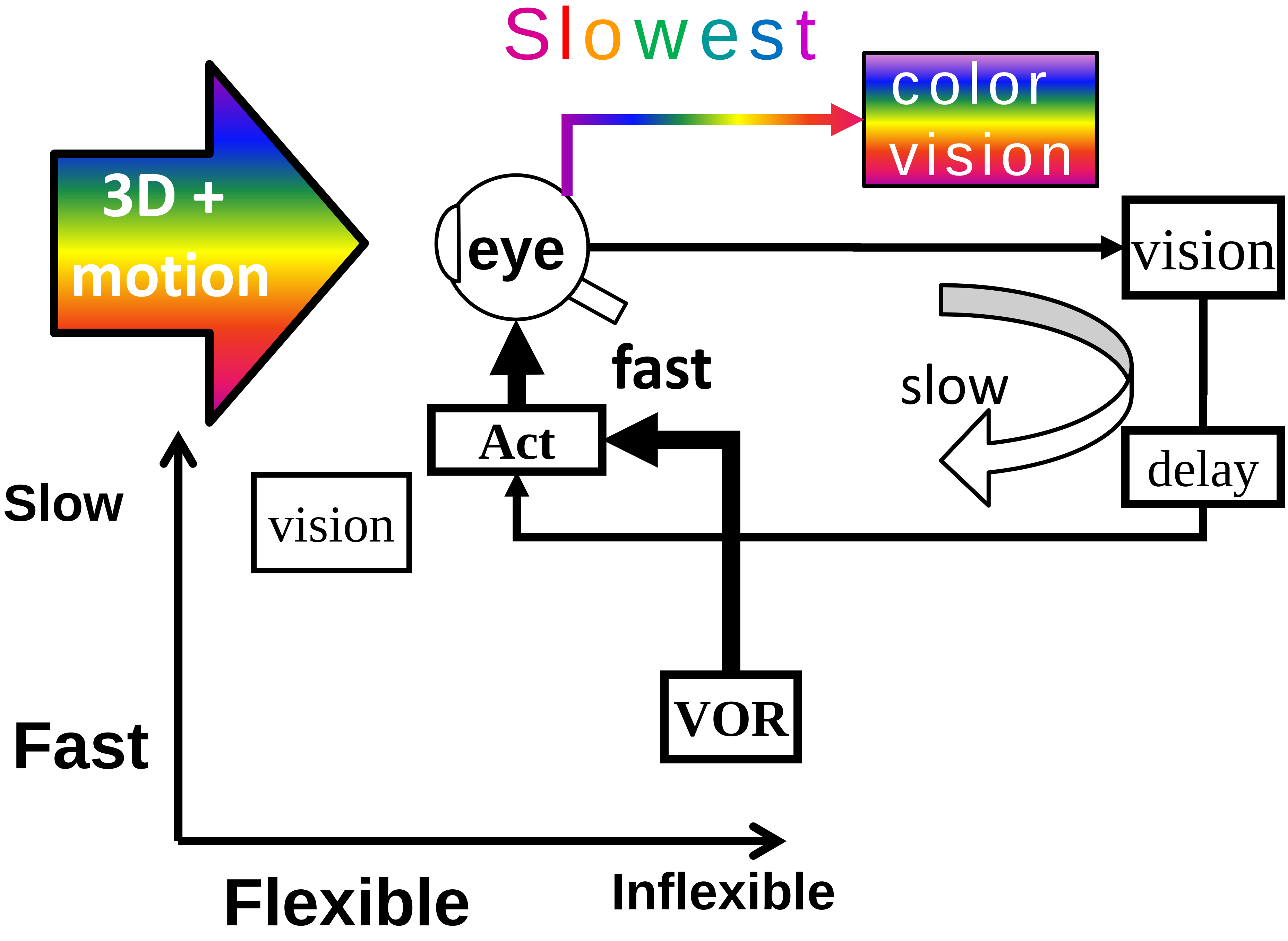
Stare at the intersection





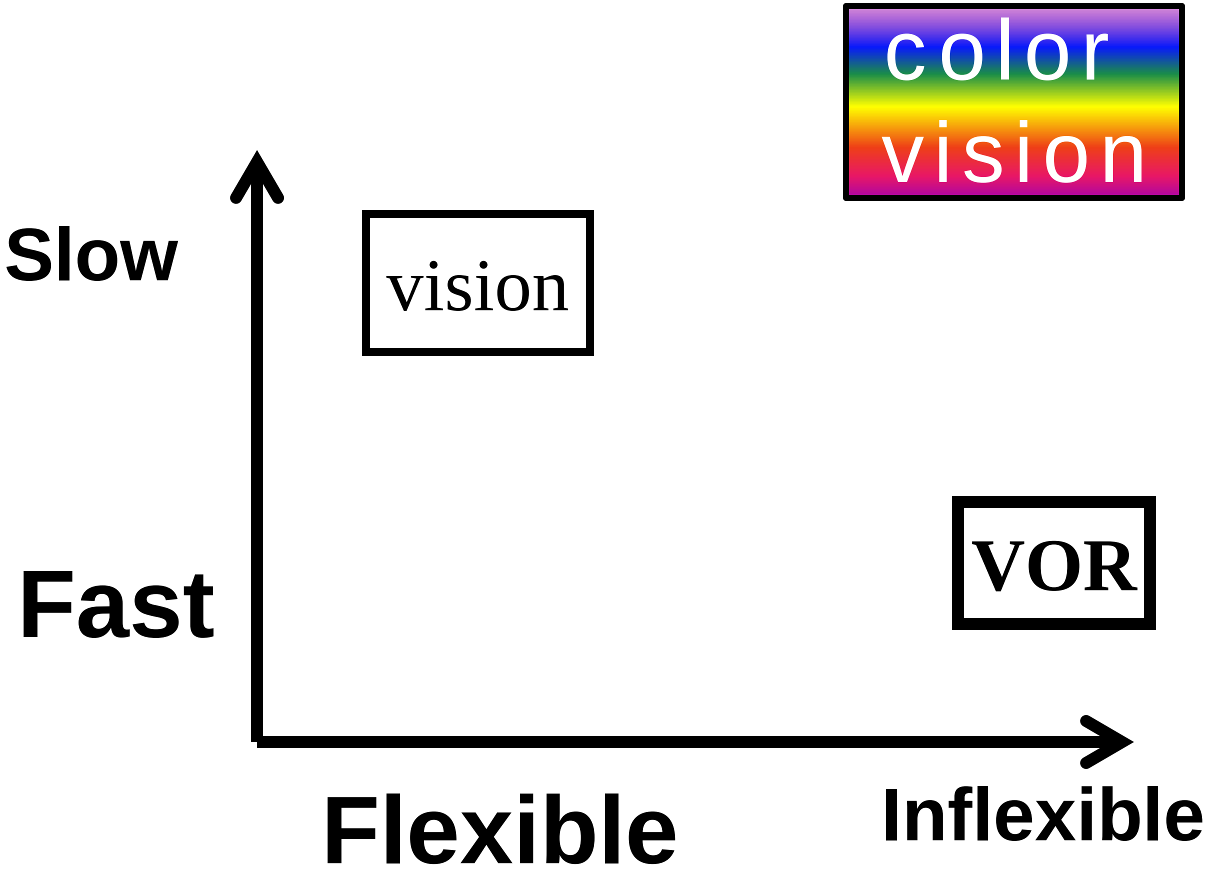

Stare at the intersection

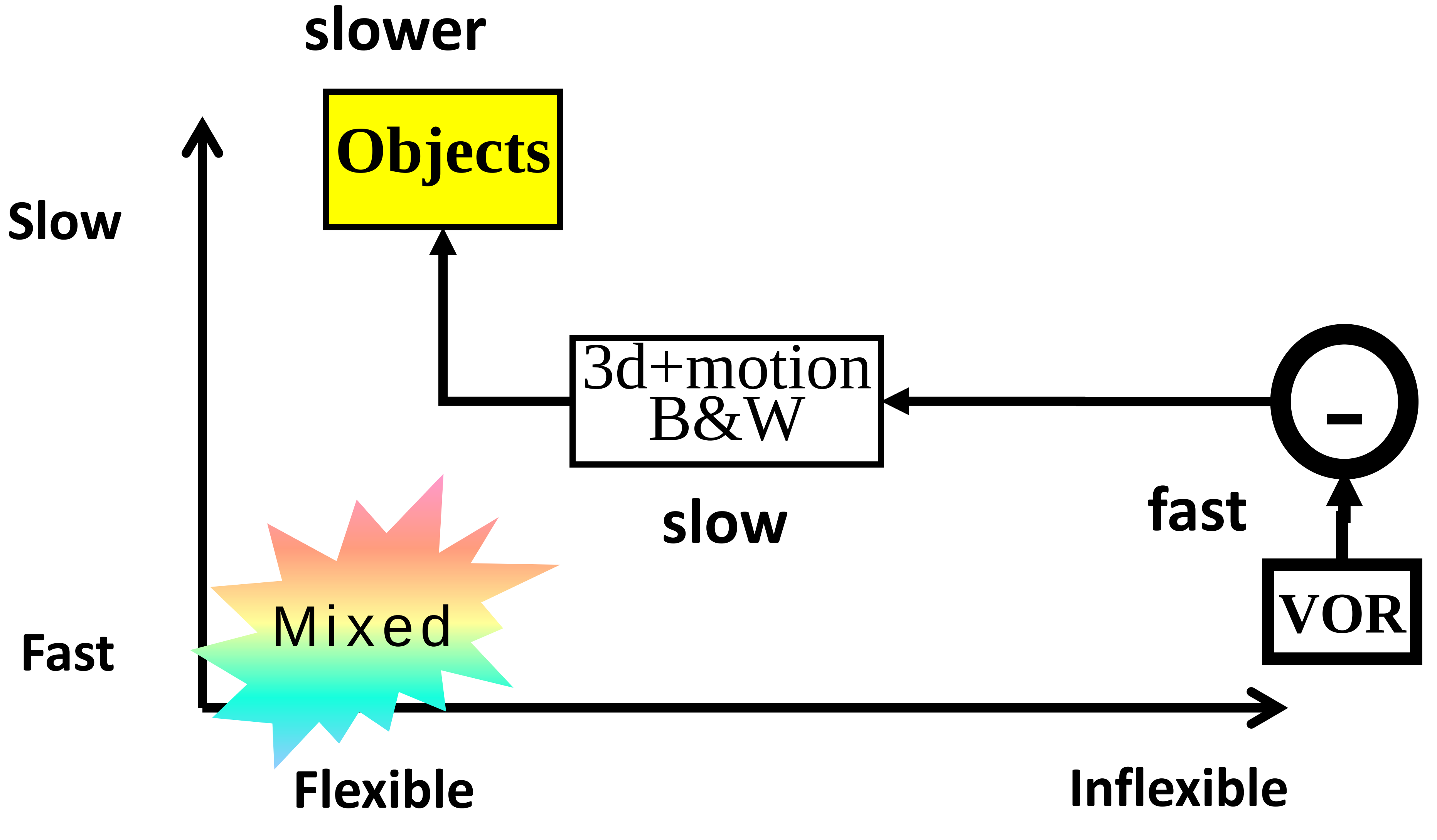




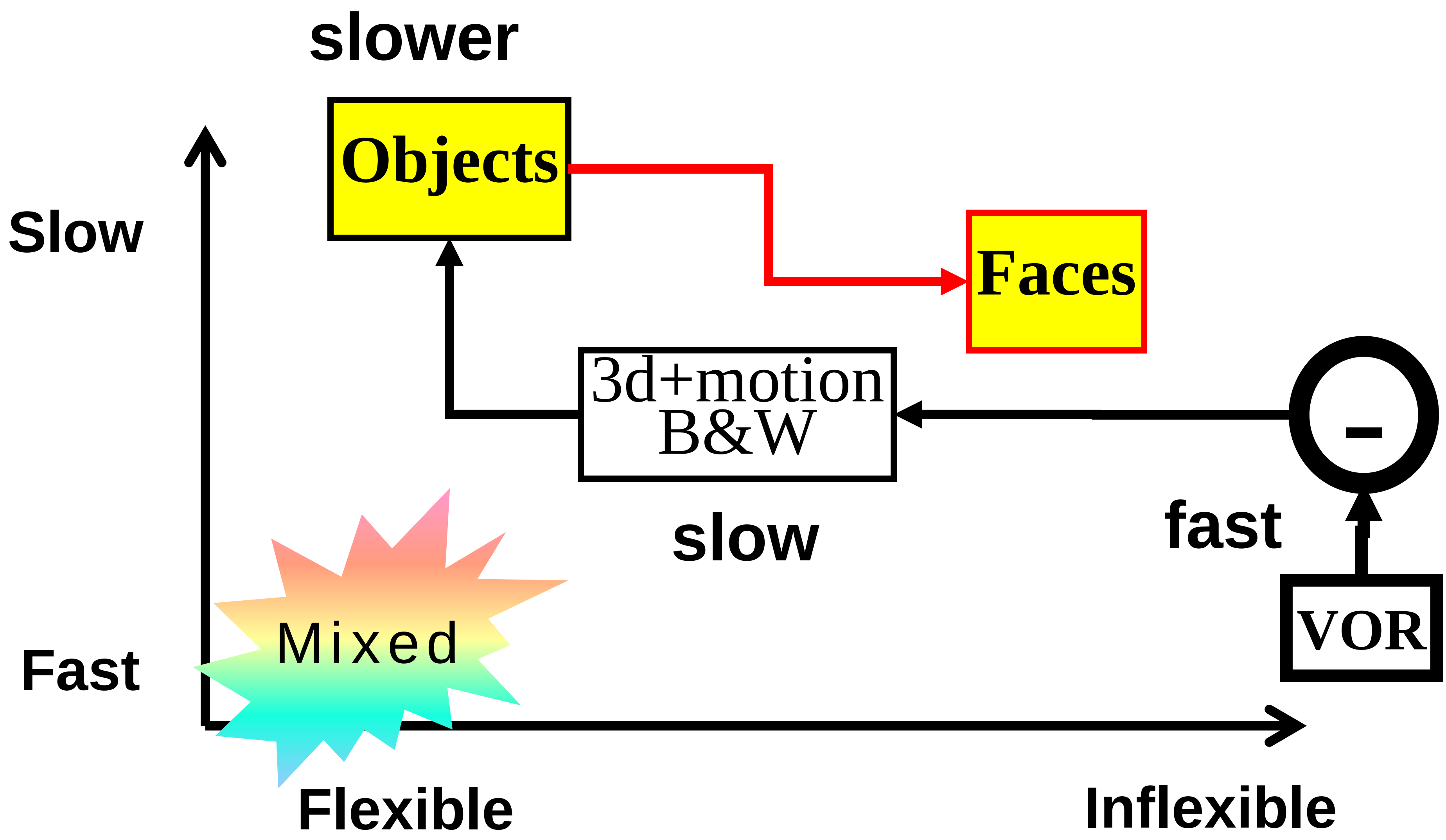
Slowest
color vision
3D + motion
eye
vision
fast
slow
Act
delay
Slow
vision
VOR
Fast
Flexible
Inflexible

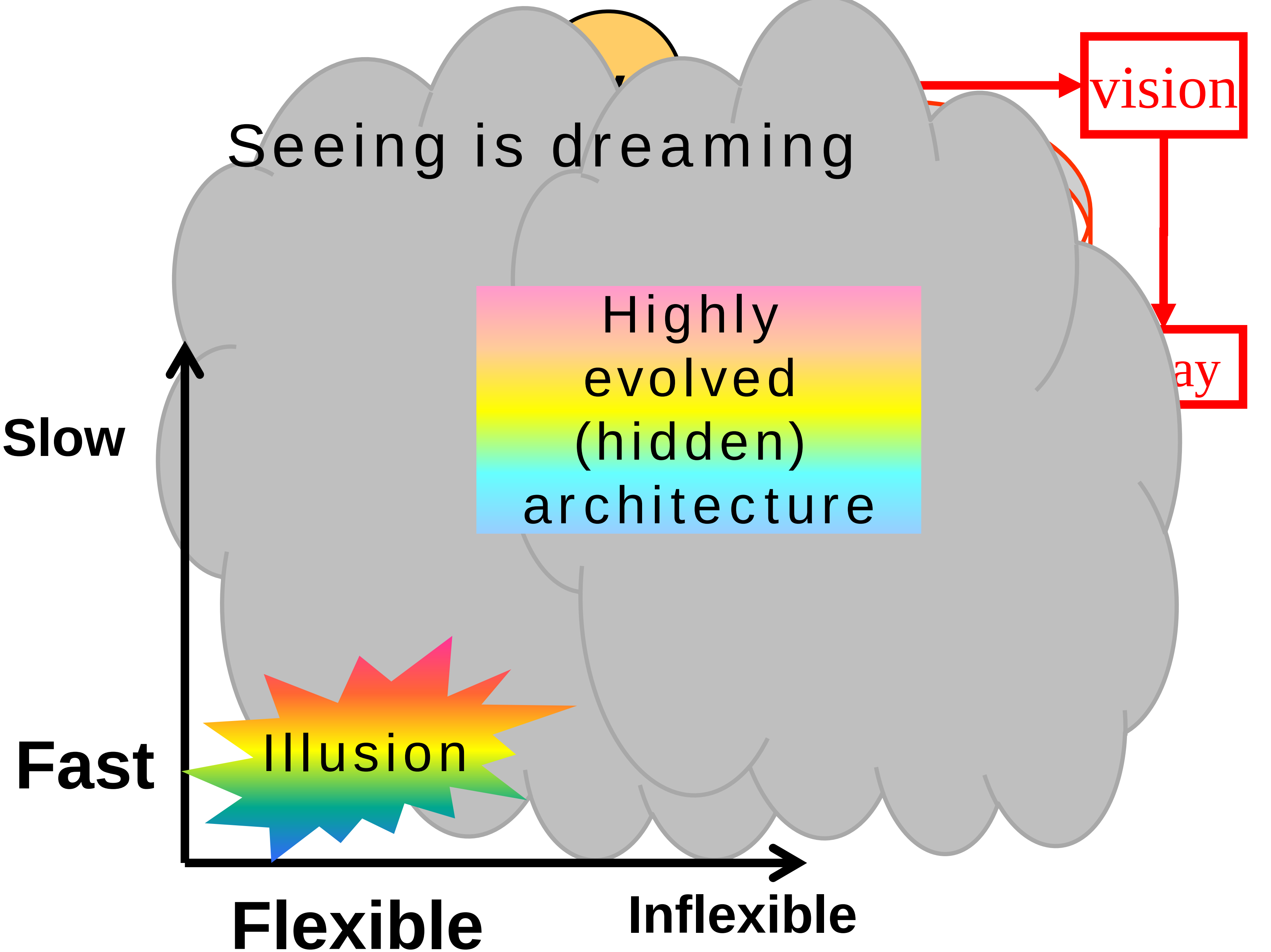
Seeing is dreaming



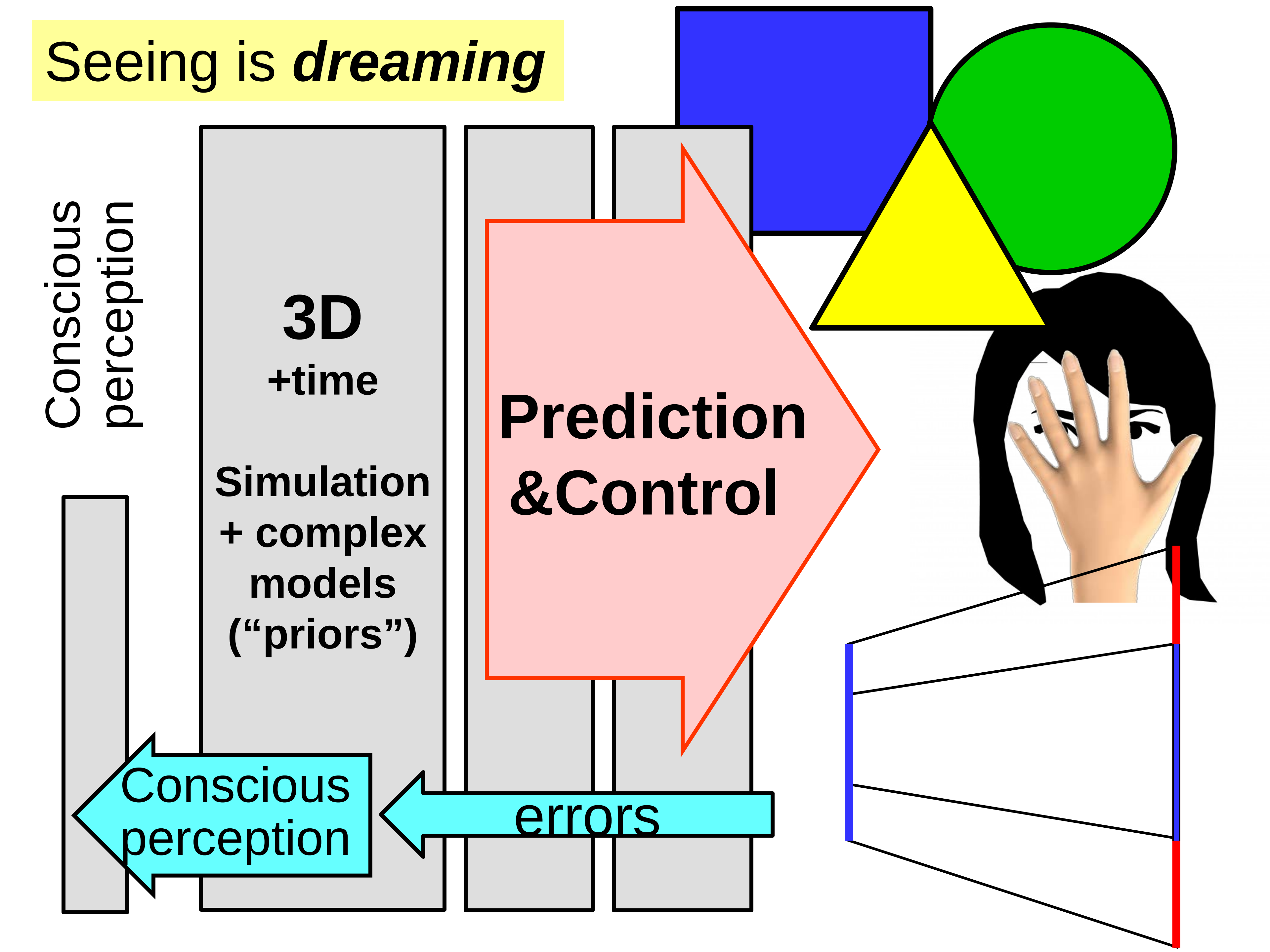

slower
Objects
Slow
3d+motion
B&W
–
fast
slow
VOR
Mixed
Fast
Flexible
Inflexible

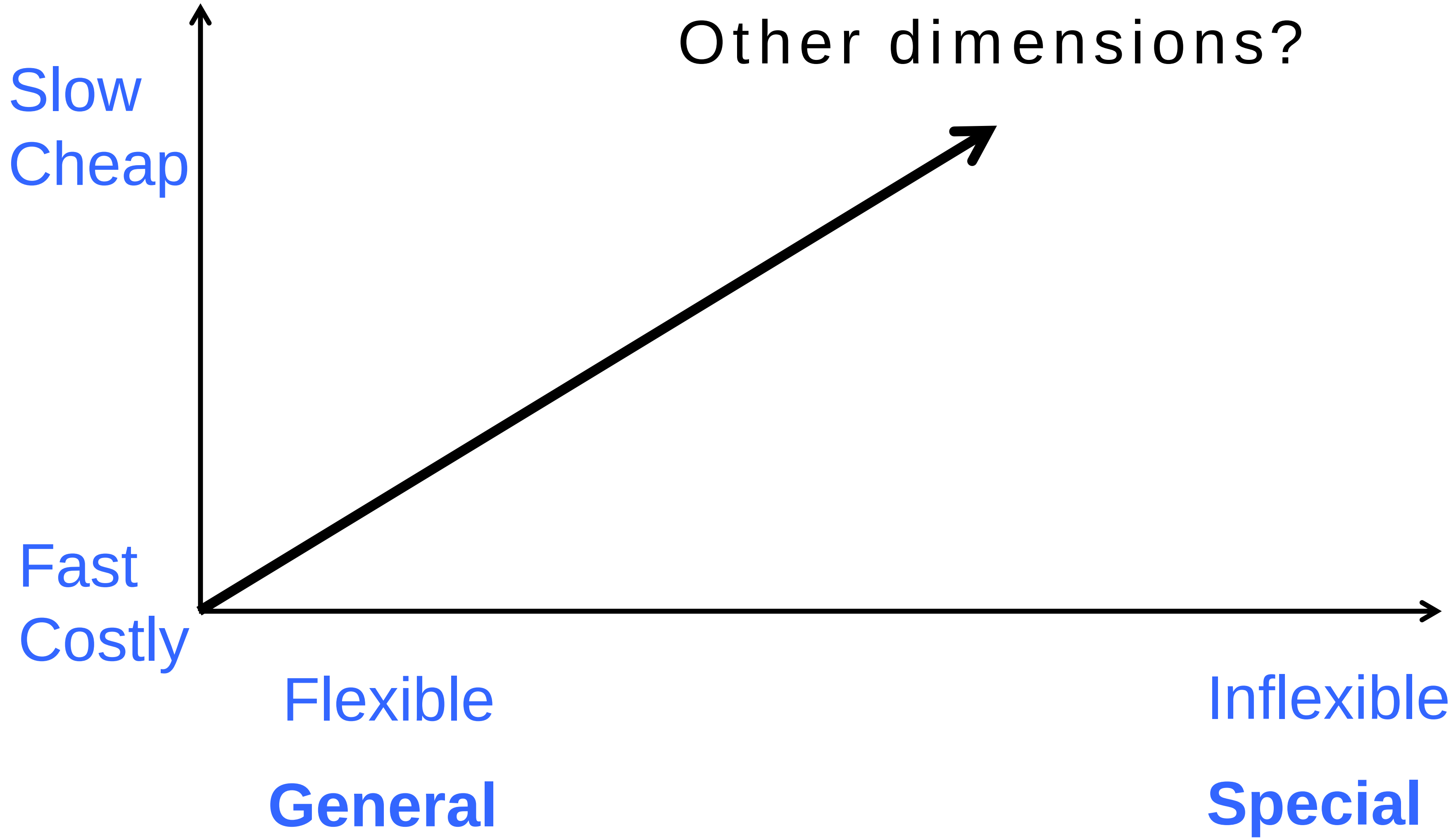
Not sure how to draw this…





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


Seeing is *dreaming*
Conscious perception
3D
+time
Simulation
+ complex
models
(“priors”)
Prediction
&Control
Conscious
perception
errors


Other dimensions?
Slow
Cheap
Fast
Costly
Flexible
Inflexible
General
Special

Requirements on systems and architectures

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

dependable
deployable
discoverable
distributable
durable
effective
efficient
evolvable
extensible
fail transparent
fast
fault-tolerant
fidelity
flexible
inspectable
installable
Integrity
interchangeable
interoperable
learnable
maintainable

manageable
mobile
modifiable
modular
nomadic
operable
orthogonality
portable
precision
predictable
producible
provable
recoverable
relevant
reliable
repeatable
reproducible
resilient
responsive
reusable
robust

safety
scalable
seamless
self-sustainable
serviceable
supportable
securable
simplicity
stable
standards
compliant
survivable
sustainable
tailorable
testable
timely
traceable
ubiquitous
understandable
upgradable
usable

Sustainable ≈ robust + efficient

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

dependable
deployable
discoverable
distributable
durable
effective
efficient
evolvable
extensible
fail transparent
fast
fault-tolerant
fidelity
flexible
inspectable
installable
Integrity
interchangeable
interoperable
learnable
maintainable

manageable
mobile
modifiable
modular
nomadic
operable
orthogonality
portable
precision
predictable
producible
provable
recoverable
relevant
reliable
repeatable
reproducible
resilient
responsive
reusable
robust

safety
scalable
seamless
self-sustainable
serviceable
supportable
securable
simple
stable
standards
survivable
sustainable
tailorable
testable
timely
traceable
ubiquitous
understandable
upgradable
usable

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

accessible
accountable
accurate
adaptable
adminis
afforda
auditab
autono
availab
compat
compos
configu
correct
custom
debuga
degrad
determ
demons

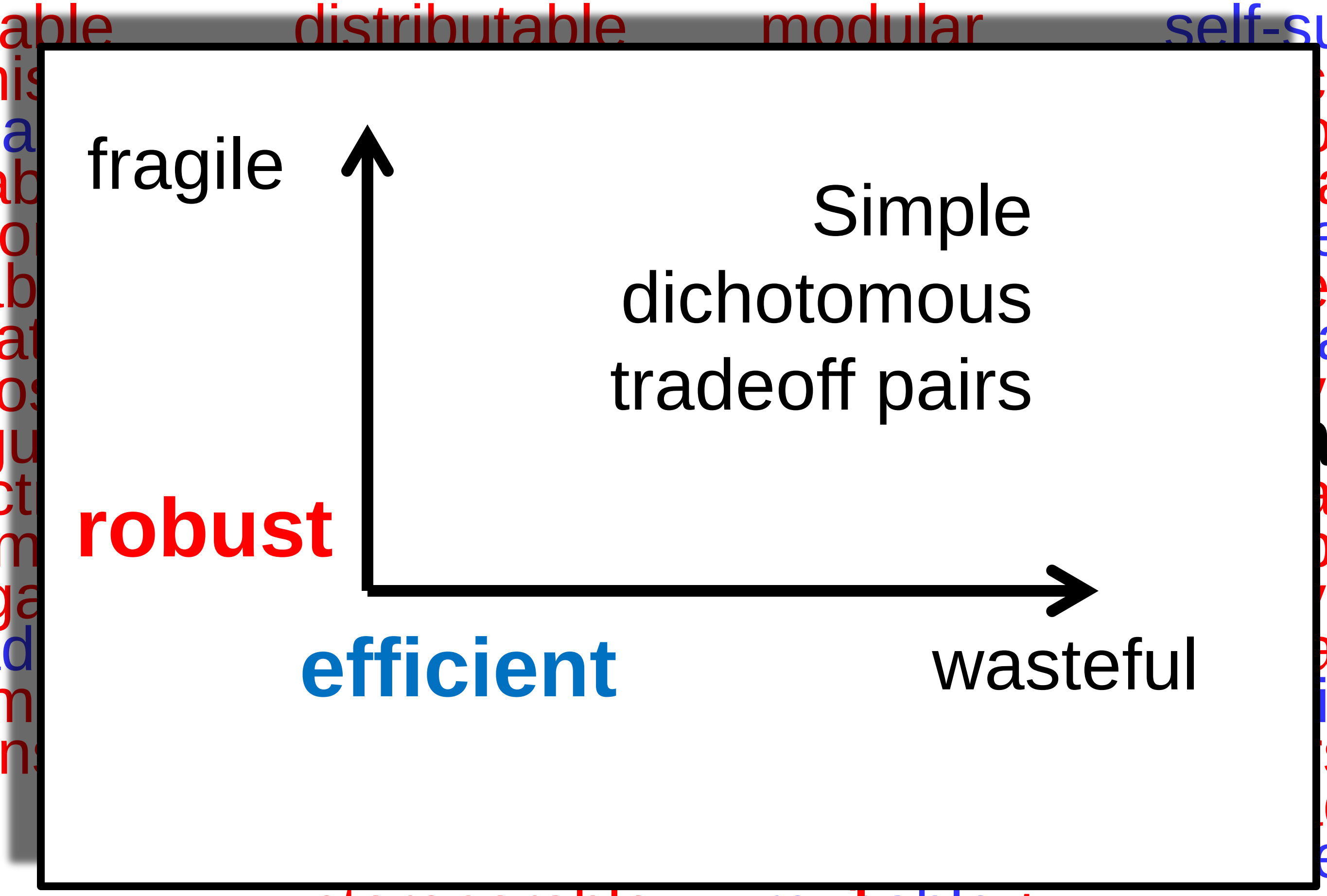
dependable
deployable
discoverable
distributable

interoperable
learnable
maintainable

manageable
mobile
modifiable
modular

reusable
robust

safety
scalable
seamless
self-sustainable
ceable
ortable
able
e
e
ards
able
inable
able
ble
y
able
itous
standable
dable
e



UG biochem, math, control theory

Glycolytic Oscillations and Limits on Robust Efficiency

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

Both engineering and evolution are constrained by trade-offs between efficiency and robustness, but theory that formalizes this fact is limited. For a simple two-state model of glycolysis, we explicitly derive analytic equations for hard trade-offs between robustness and efficiency with oscillations as an inevitable side effect. The model describes how the trade-offs arise from individual parameters, including the interplay of feedback control with autocatalysis of network products necessary to power and catalyze intermediate reactions. We then use control theory to prove that the essential features of these hard trade-off "laws" are universal and fundamental, in that they depend minimally on the details of this system and generalize to the robust efficiency of any autocatalytic network. The theory also suggests worst-case conditions that are consistent with initial experiments.

molecules are consumed upstream and four are produced downstream, which normalizes to $q = 1$ (each y molecule produces two downstream) with kinetic exponent $a = 1$. To highlight essential trade-offs with the simplest possible analysis, we normalize the concentration such that the unperturbed ($\delta = 0$) steady states are $\bar{y} = 1$ and $\bar{x} = 1/k$ [the system can have one additional steady state, which is unstable when $(1, 1/k)$ is stable]. [See the supporting online material (SOM) part I]. The basal rate of the PFK reaction and the consumption rate have been normalized to 1 (the 2 in the numerator and feedback coefficients of the reactions come from these normalizations). Our results hold for more general systems

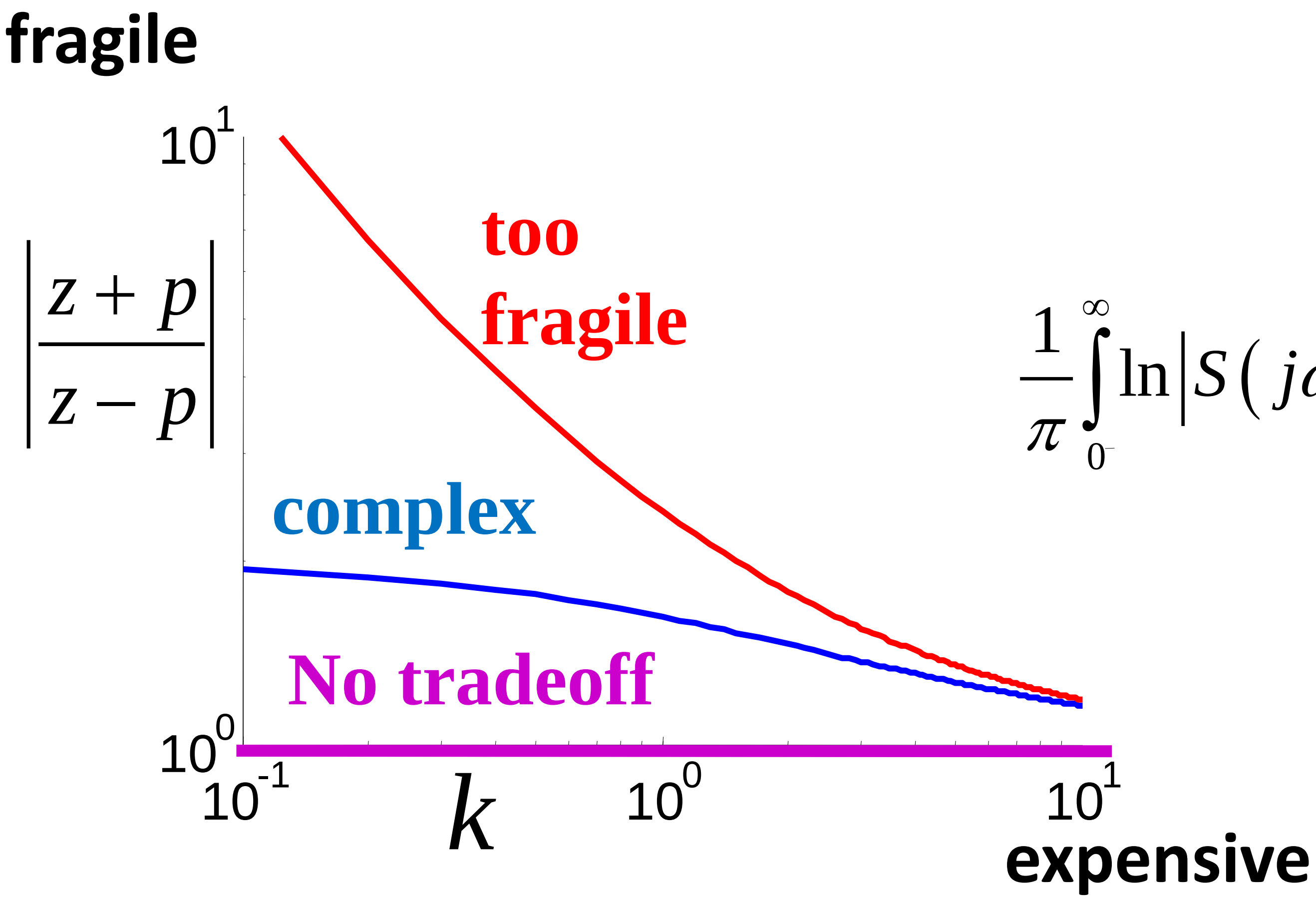
Chandra, Buzi, and Doyle

Science AAAS

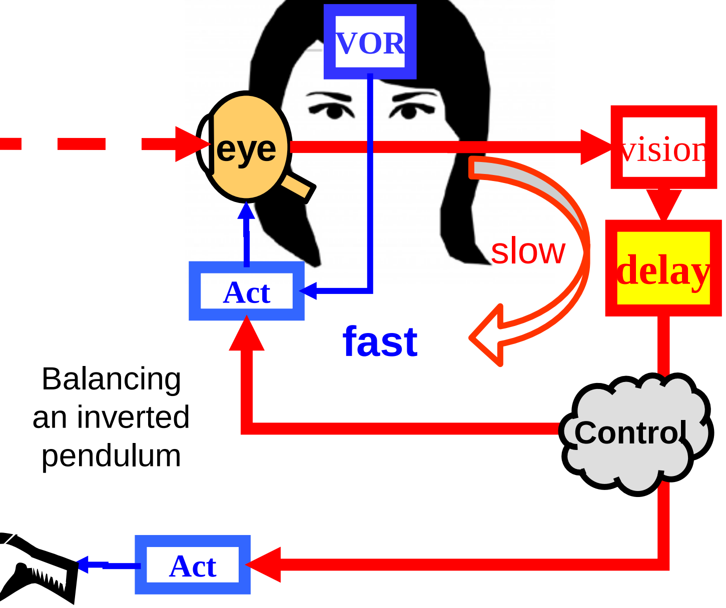
Most important paper so far.

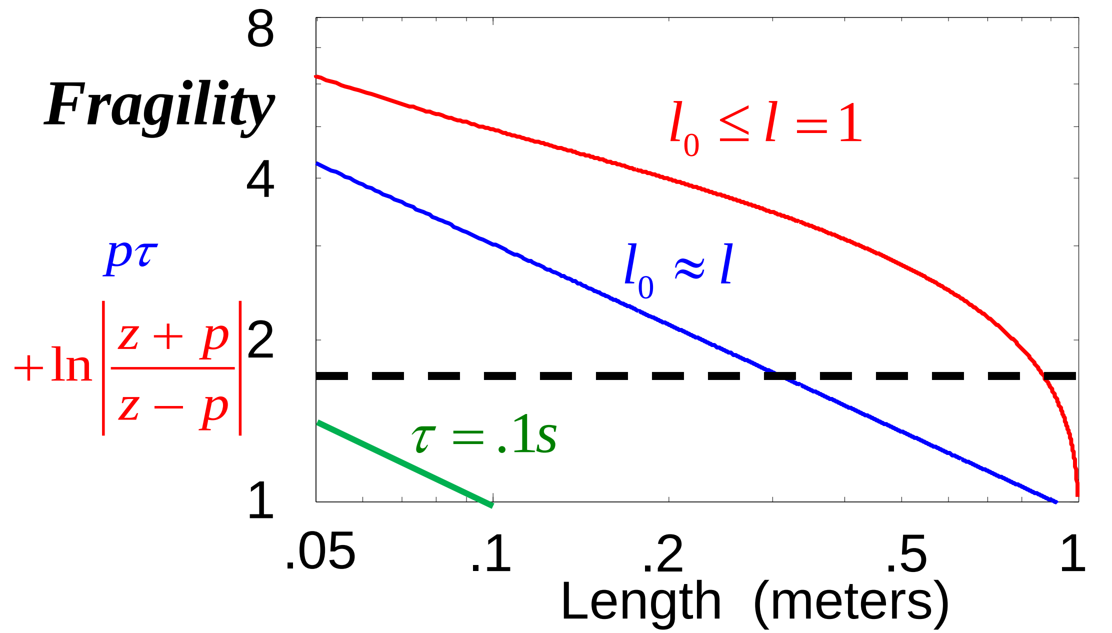
Hard tradeoff in glycolysis is

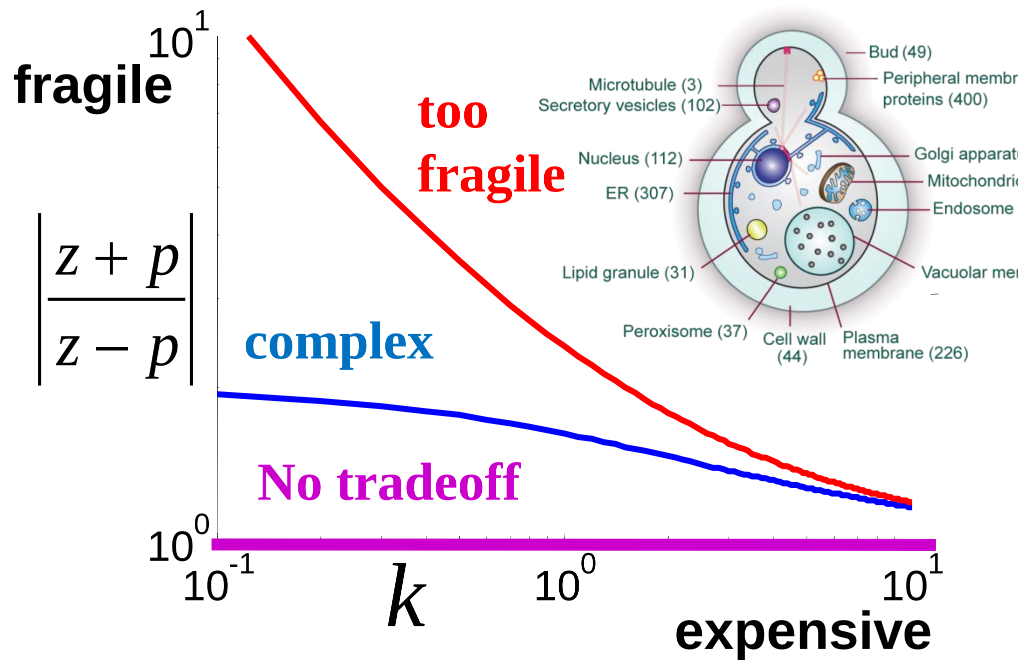
- robustness vs efficiency
- absent without autocatalysis
- too fragile with simple control
- plausibly robust with complex control

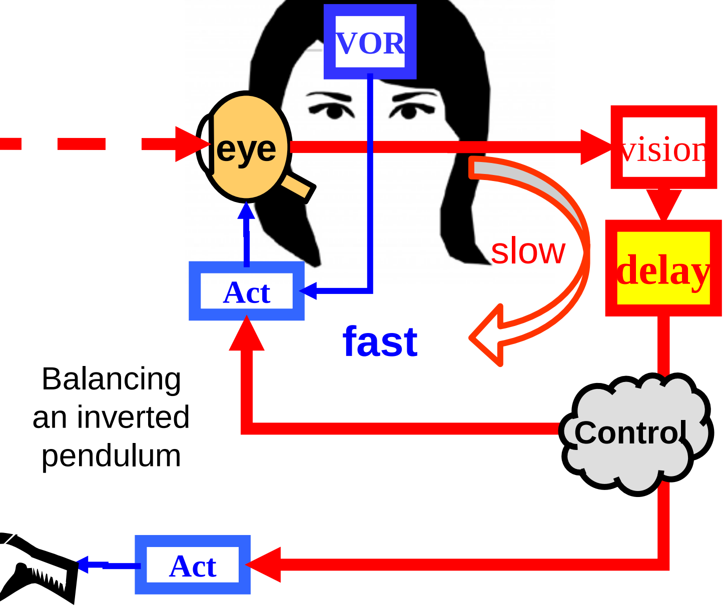


$$\frac{1}{\pi}\int_{0^-}^{\infty} \ln\left|S(j\omega)\right|\left(\frac{z}{z^2+\omega^2}\right)d\omega \geq \ln\left|\frac{z+p}{z-p}\right|$$


VOR
eye
vision
slow
delay
Act
fast
Balancing
an inverted
pendulum
Control
Act


Fragility
$p\tau + \ln\left|\frac{z+p}{z-p}\right|$
8
4
2
1
$l_0 \leq l = 1$
$l_0 \approx l$
$\tau = .1s$
.05
.1
.2
.5
1
Length (meters)


fragile
$\left|\frac{z+p}{z-p}\right|$
10^1
10^0
too
fragile
complex
No tradeoff
10^{-1}
k
10^0
10^1
expensive
Microtubule (3)
Secretory vesicles (102)
Nucleus (112)
ER (307)
Lipid granule (31)
Peroxisome (37)
Cell wall (44)
Plasma membrane (226)
Bud (49)
Endosome



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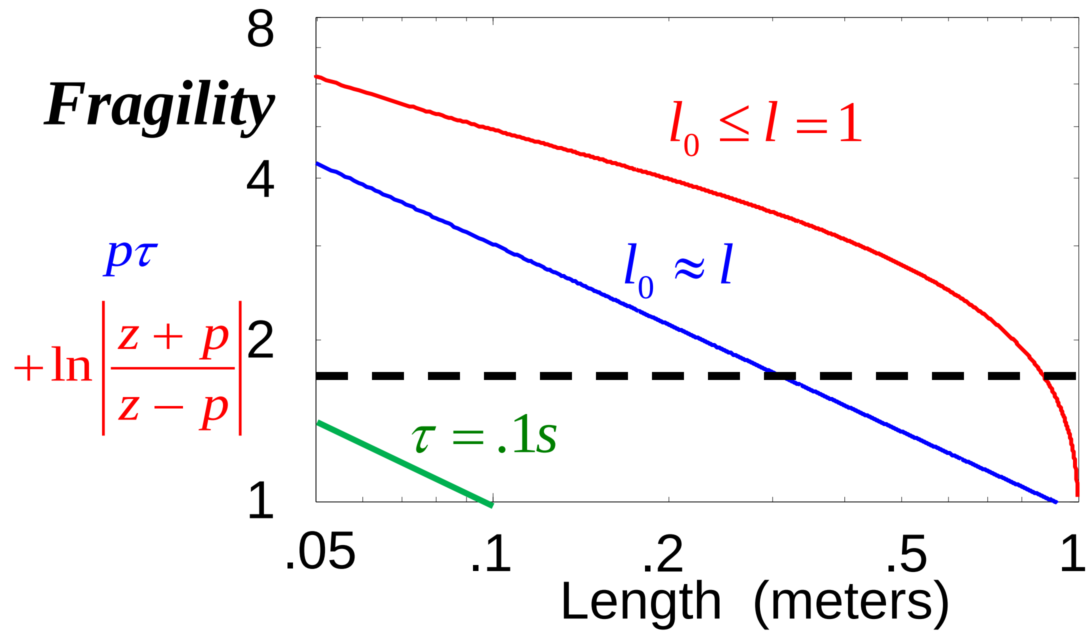

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$l_0 \le l = 1$
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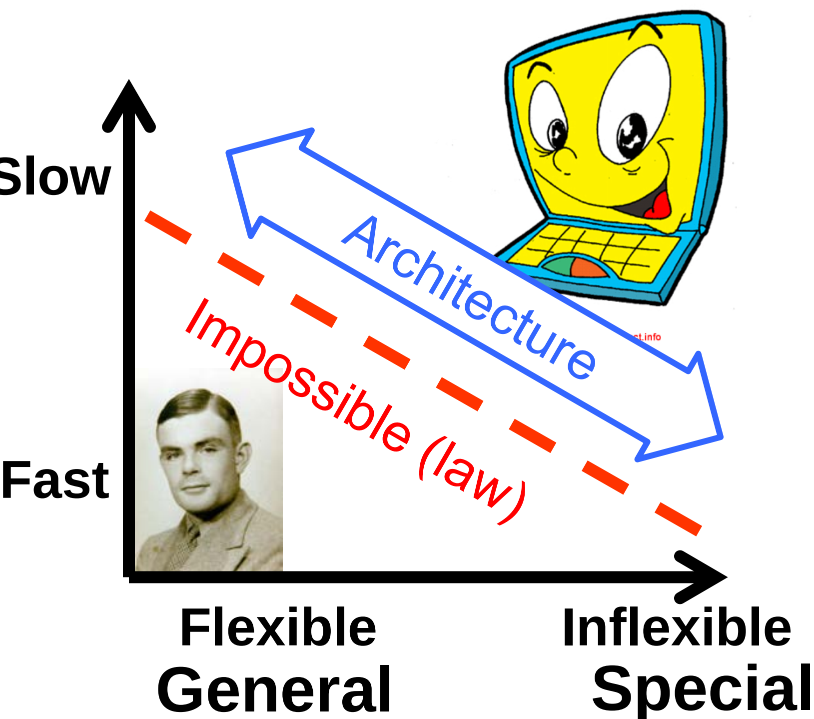
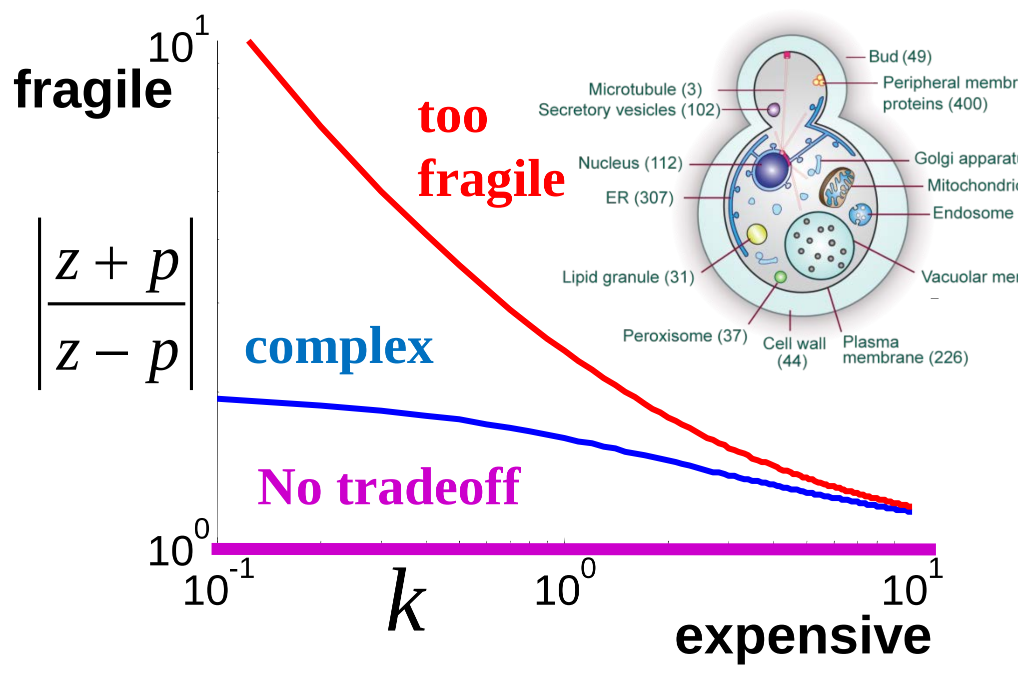


Slow
Fast
Architecture
Impossible (law)
Flexible
General
Inflexible
Special



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$\left|\frac{z+p}{z-p}\right|$
too fragile
complex
No tradeoff
10^1
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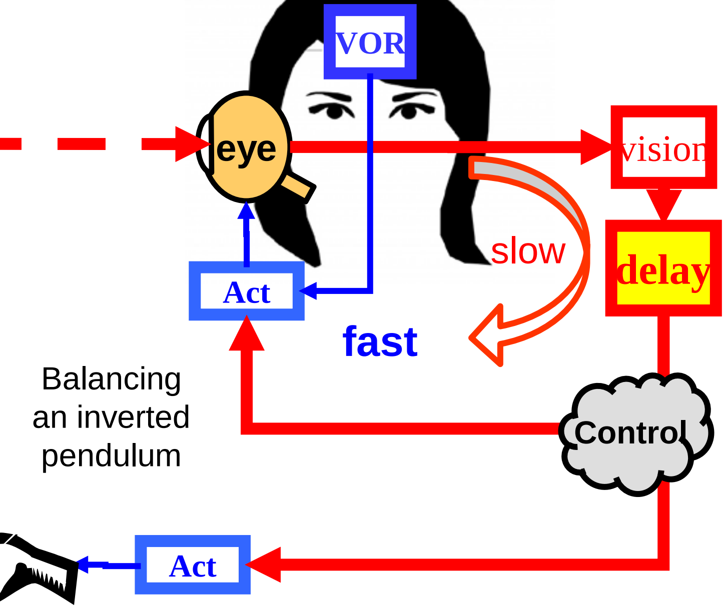
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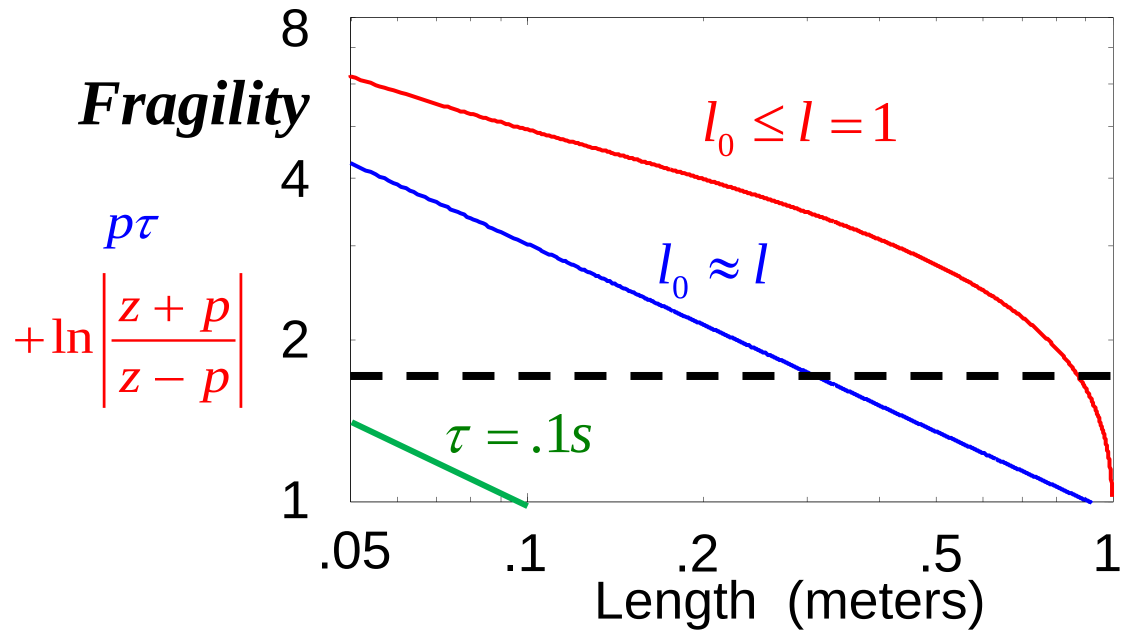
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$p\tau$
$+\ln\left|\frac{z+p}{z-p}\right|$
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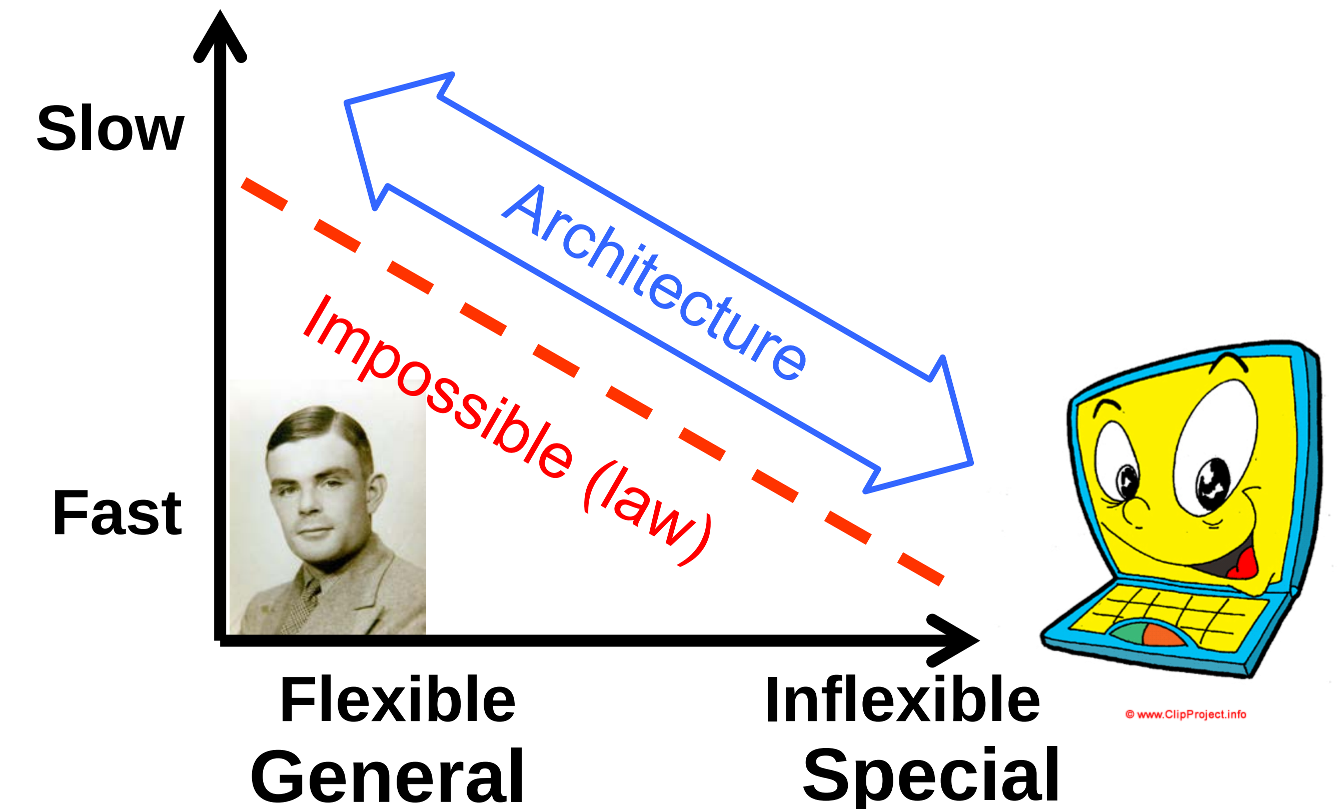
8
4
2
1
.05
.1
.2
.5
1
Length (meters)


Slow
Fast
Architecture
Impossible (law)
Flexible
General
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Special
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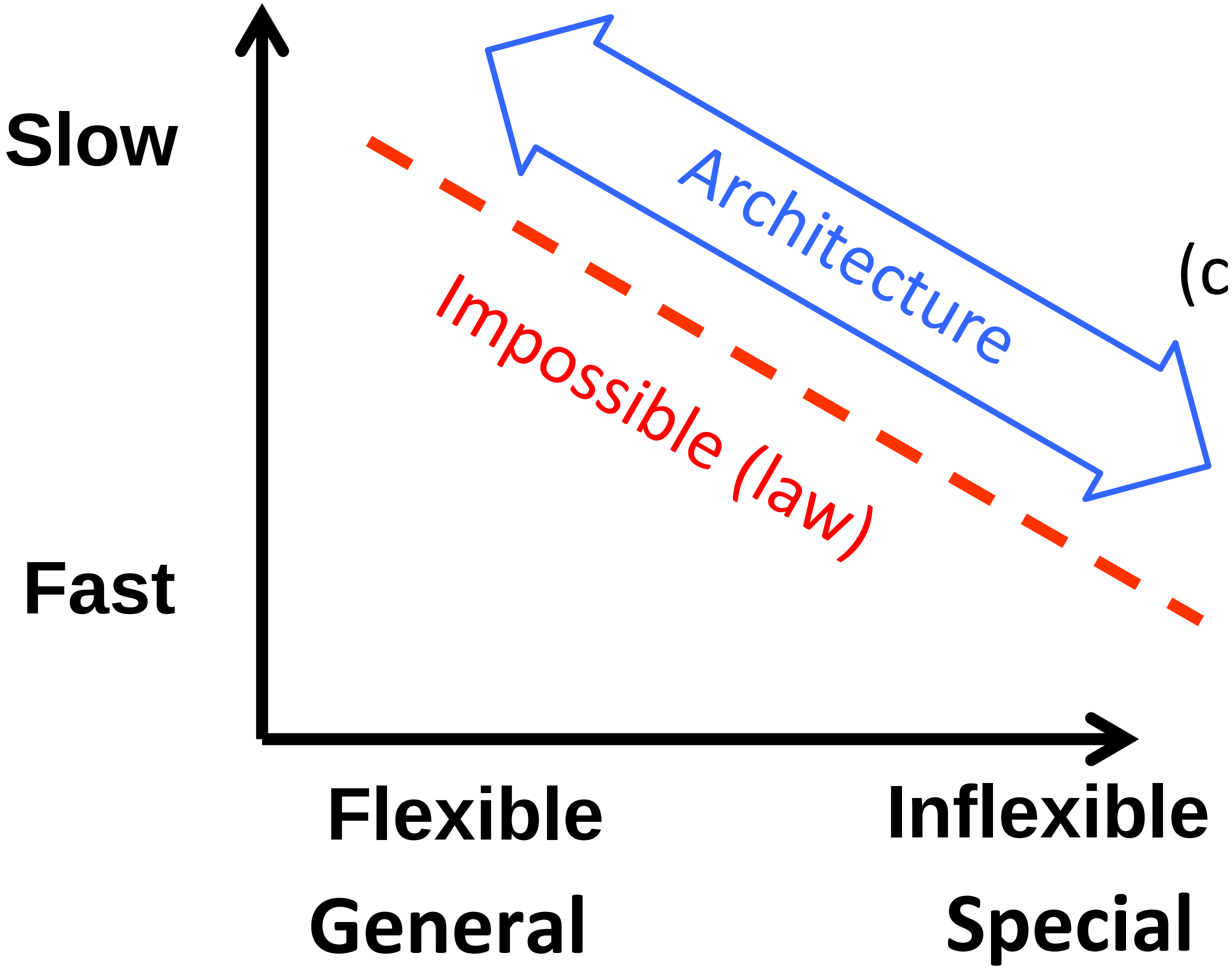
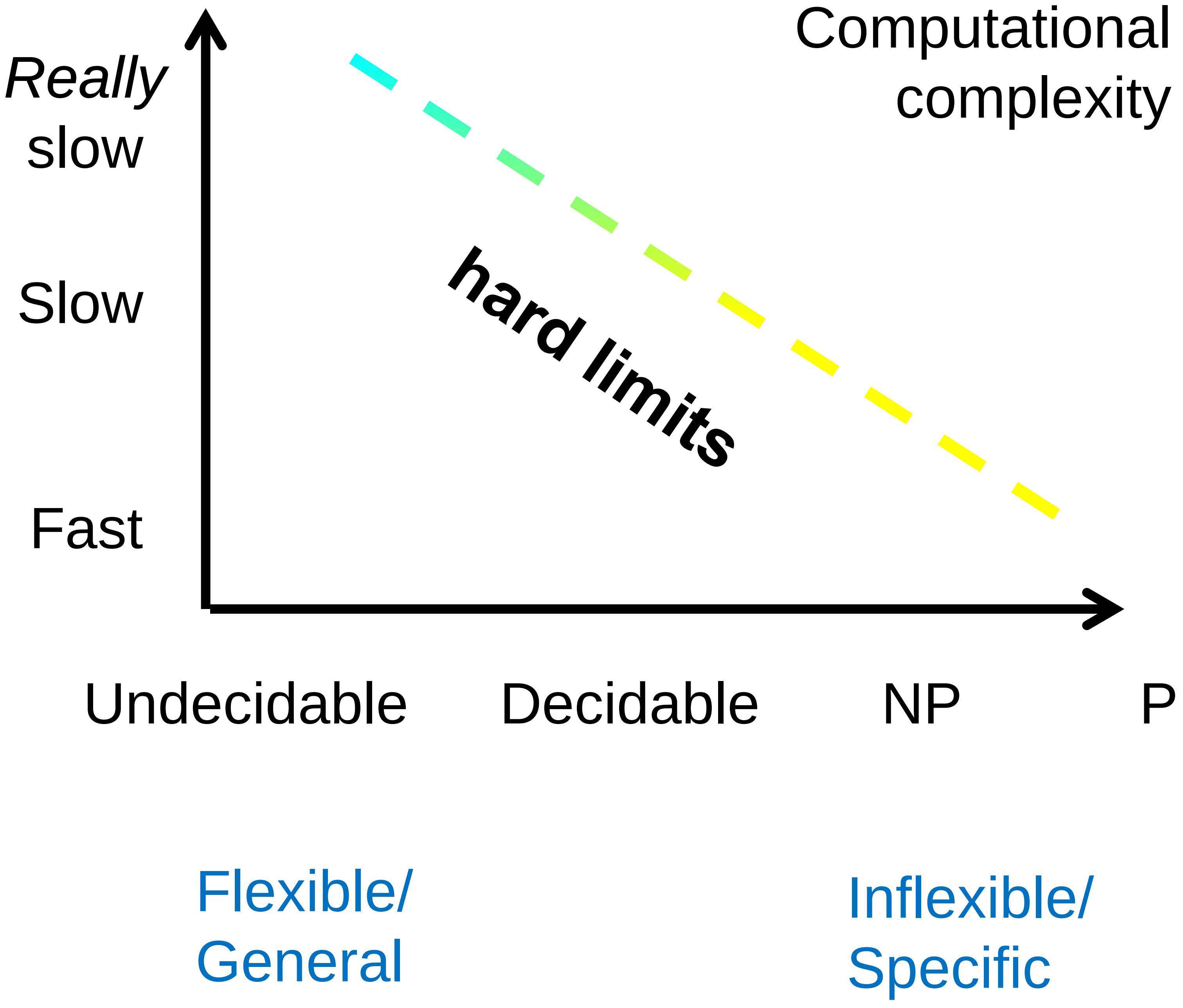
Universal laws and architectures (Turing)



Architecture (constraints that deconstrain)



Computational complexity
Really slow
Slow
Fast
hard limits
Undecidable
Decidable
NP
P
Flexible/ General
Inflexible/ Specific

Sustainable ≈ robust + efficient

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

dependable
d
d
d
d
e
e
e
e
f
f
f
f
f
inspectable
installable
Integrity
interchangeable
interoperable
learnable
maintainable

Issues
Fast
Robust
Flexible
Efficient
Stochastics
Memory

manageable
mobile
odifiable
odular
omadic
perable
rthogonality
ortable
recision
redictable
roducible
rovable
coverable
levant
reliable
repeatable
reproducible
resilient
responsive
reusable
robust

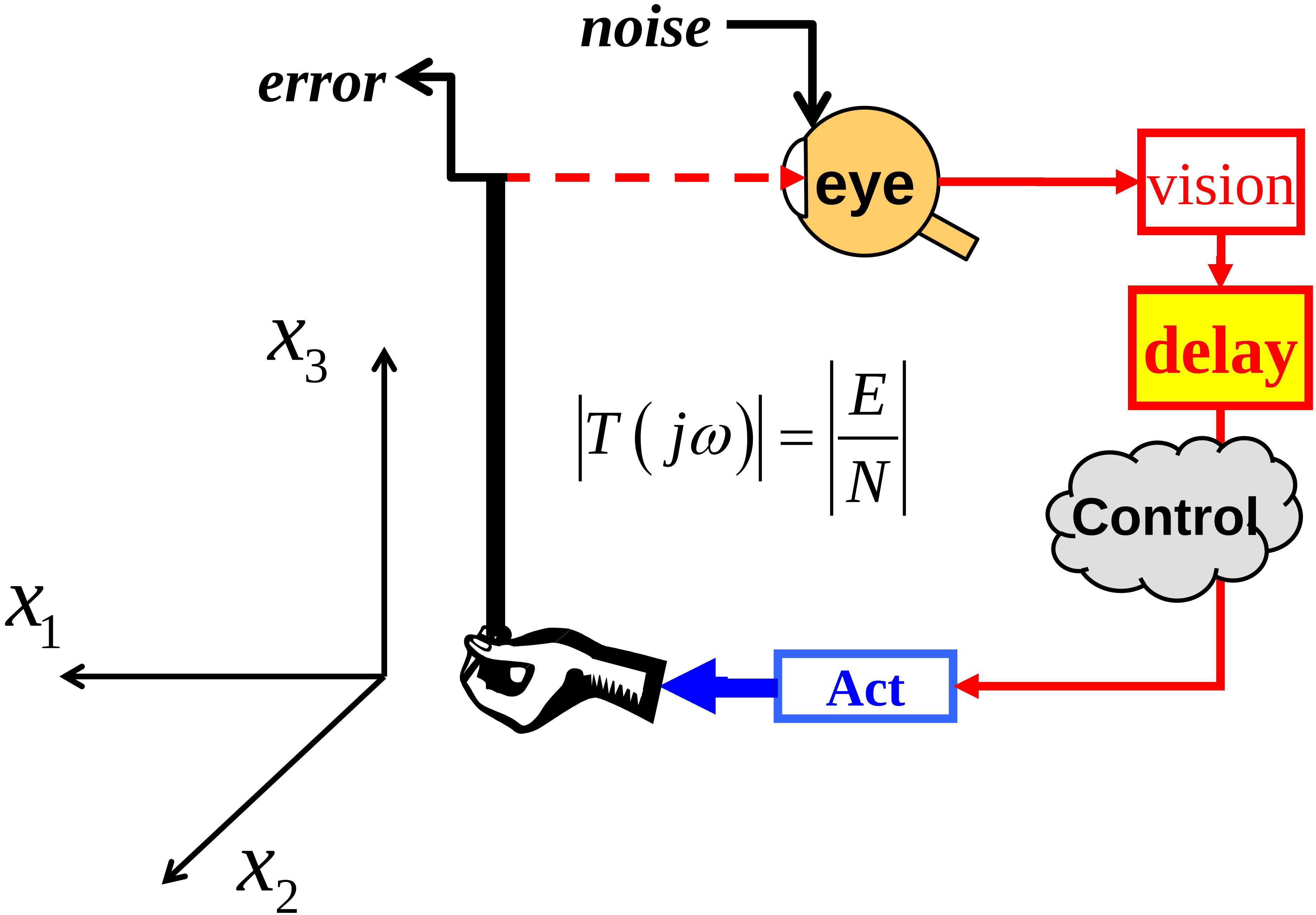
safety
scalable
seamless
self-sustainable
serviceable
supportable
securable
simple
stable
standards
survivable
sustainable
tailorable
testable
timely
traceable
ubiquitous
understandable
upgradable
usable

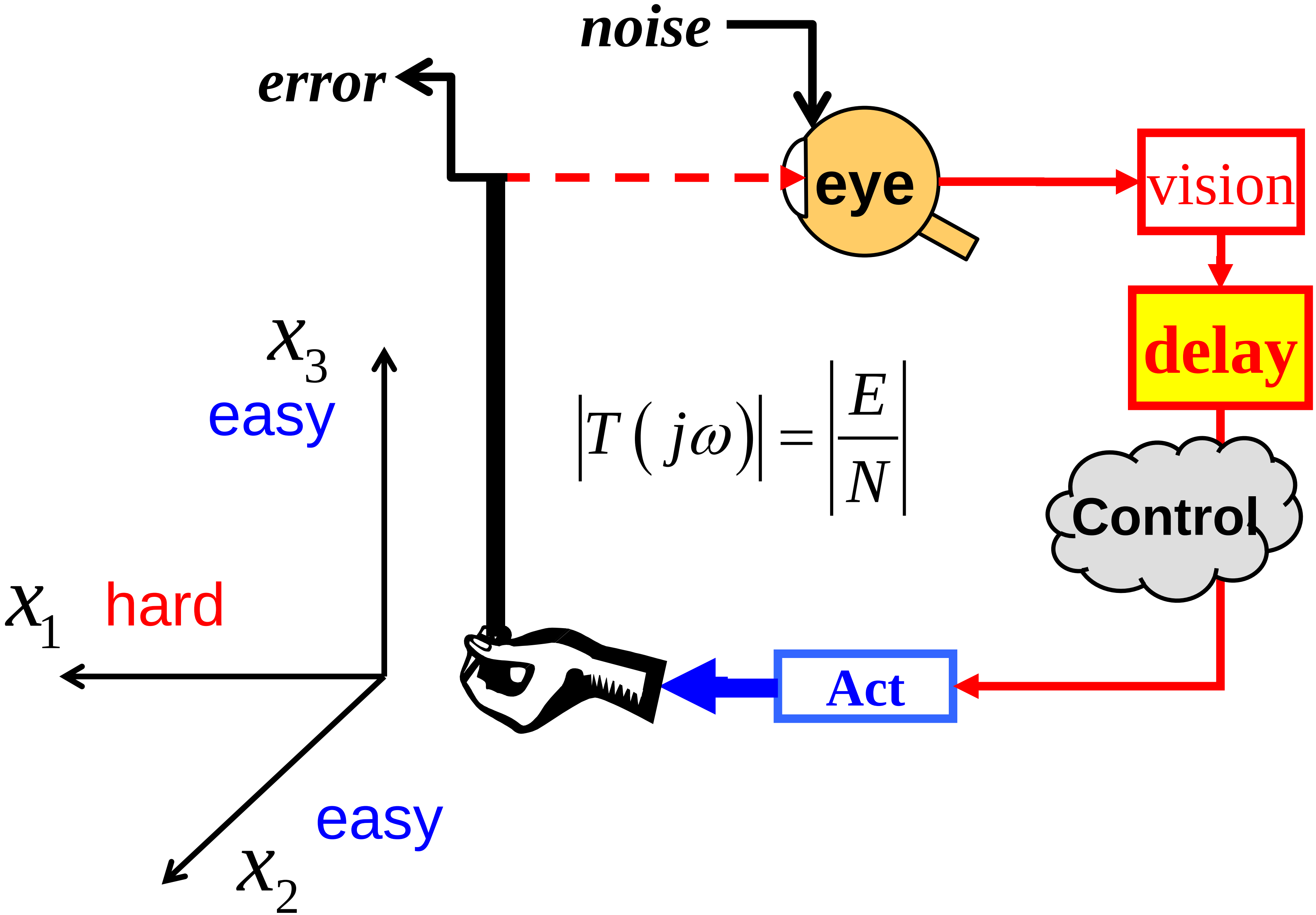
Weaknesses so far

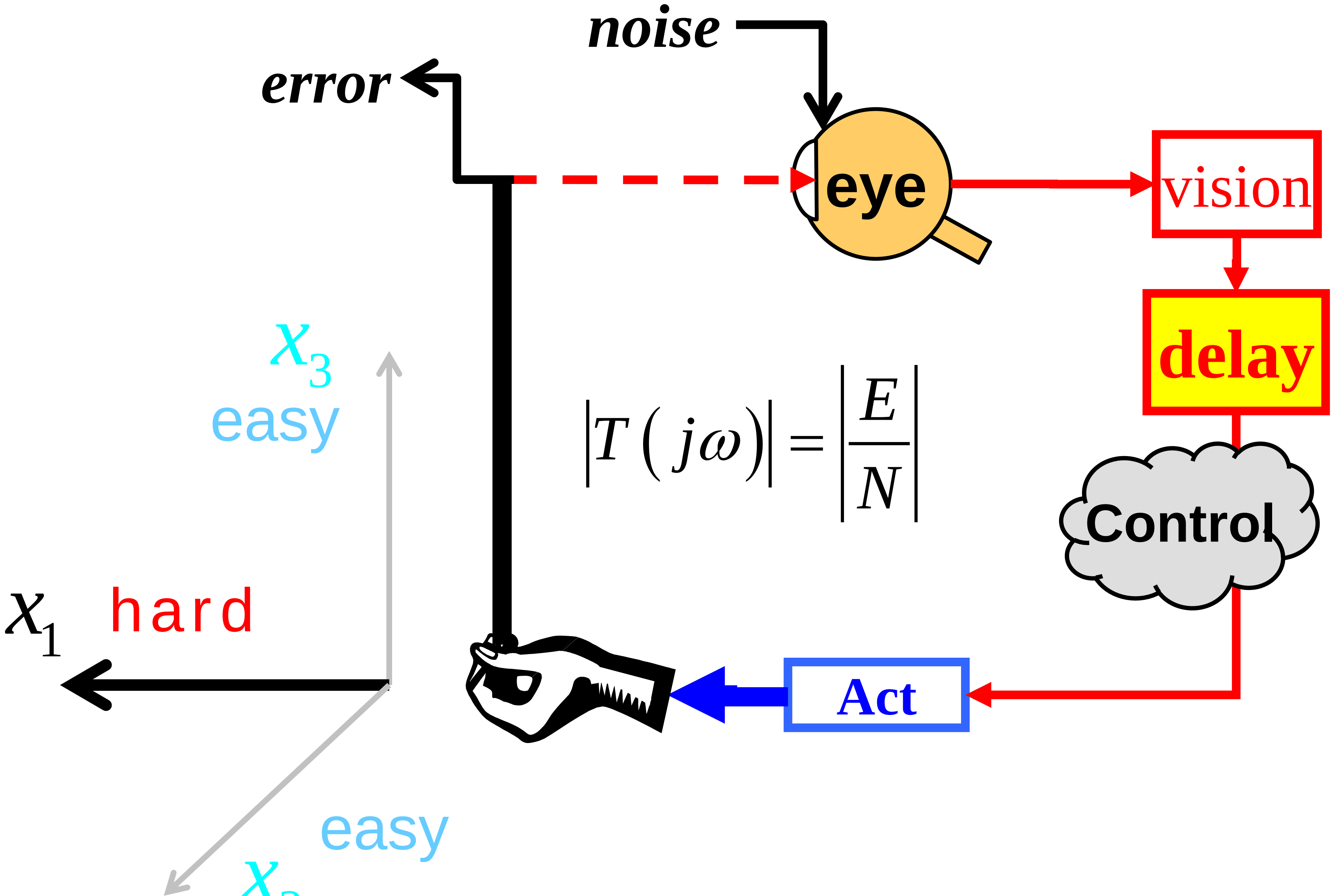
- Some flaws as presented
- See if we can find the flaws and fix them
- What could be improved?
  - Model
  - Theory
  - Experiment
- Suggestions?

Model?

- 1 dimension with 4 states?
- What about the other 2 dimensions?
- Let’s imagine (but not derive) a 10 state model and see what would happen
- New issues arise


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


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


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

Model to Theory?

- Linearization? Mostly ok.
- Actuation and sensing, mostly ok.
- Noise model? Needs work. Why?
- Noise and delay is from measuring distance using stereopsis . How to model this?

- What about all the detailed physiology of muscle, joints, bone, nerves, etc?
- Need layered control architectures.

Theory

- Analytic results are not scalable
- Aim not analytic formulas but tractable algos

Main lessons

- Theory: hard limits on closed loop performance, aggravated by
  - Instability (unstable poles)
  - Delay
  - Unstable zeros
- Neuroscience specific

Instabilities in technology

- Efficiency
- Autocatalysis

Select instabilities in biology

Working backwards

- Society/agriculture/weapons/etc
- Bipedalism
- Maternal care
- Warm blood
- Flight
- Mitochondria
- Translation (ribosomes)
- Glycolysis (see 2011 Science paper)