J. Barkley Rosser Memorial Lecture

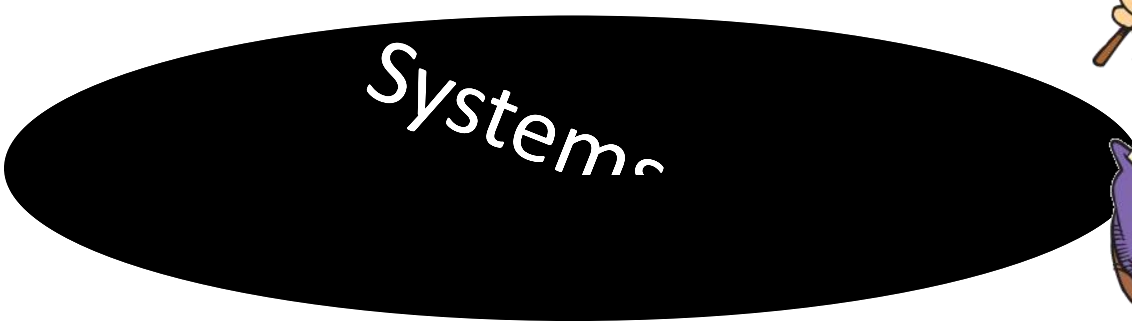
Universal laws and architectures

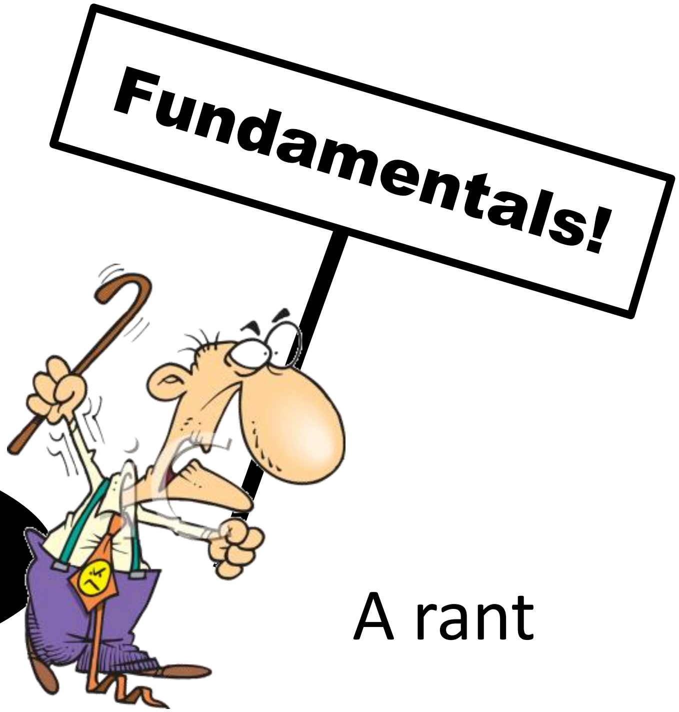
J. Comstock Doyle
John G Braun Professor
Control and Dynamical Systems, EE, BE
Caltech

“Universal laws and architectures?”

- **Universal “conservation laws” (constraints)**
- Universal architectures (constraints that deconstrain)
- Mention recent papers*
- Focus on broader context not in papers
- Lots of case studies (motivate & illustrate)
- You can have all of the slides

*try to get you
to read them?





A rant

Supplementary talk

Tomorrow, 12:30pm

Engineering Hall Rm 2305

Details and more rants

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.**

Most accessible
No math

Architecture, constraints, and behavior

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

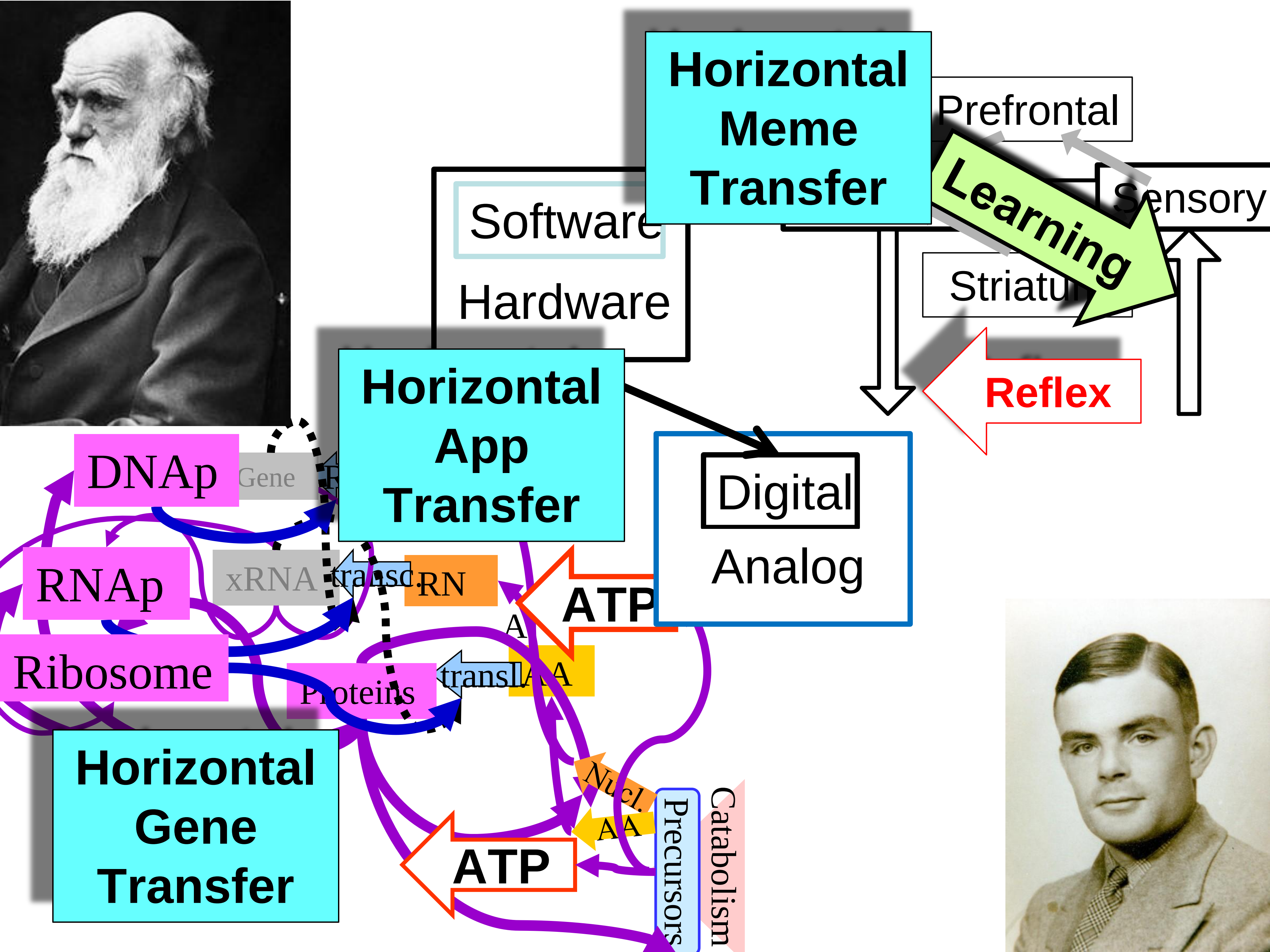
[a]Control and Dynamical Systems, California Institute of Technology, Pasadena, CA 91125; and [b]Department of Anesthesiology, University of California, San Diego, CA 92103

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

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

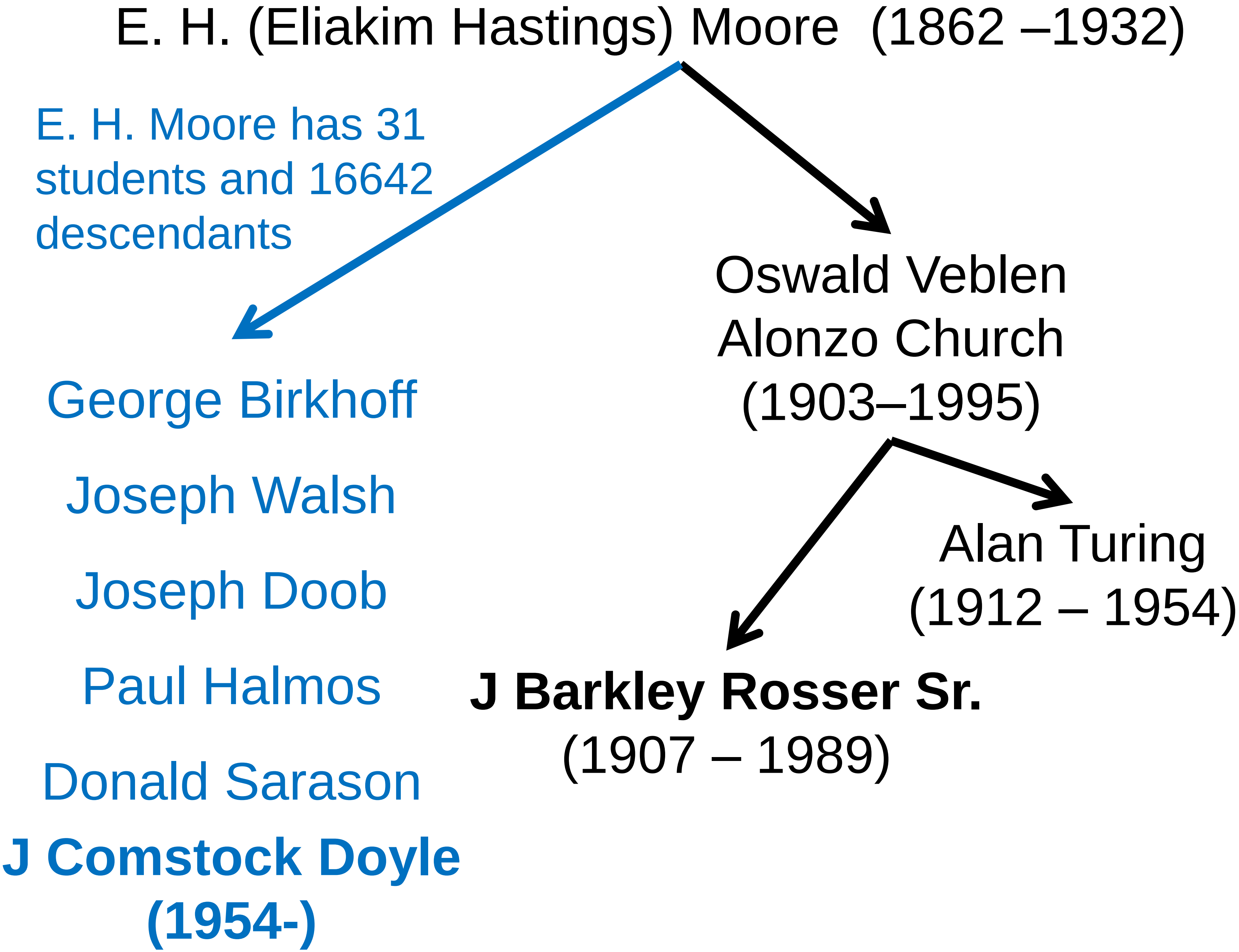

Horizontal Meme Transfer
Prefrontal
Learning
Sensory
Striatum
Reflex
Software
Hardware
Horizontal App Transfer
Digital
Analog
ATP
DNAp
Gene
RNAp
xRNA
transc.
RN
A
Ribosome
Proteins
transl.
AA
Nucl.
AA
Precursors
Catabolism
ATP
Horizontal Gene Transfer

Math genealogy

Alonzo Church
(1903–1995)

Alan Turing
(1912 – 1954)

J Barkley Rosser Sr.
(1907 – 1989)


E. H. (Eliakim Hastings) Moore (1862 –1932)
E. H. Moore has 31 students and 16642 descendants
George Birkhoff
Joseph Walsh
Joseph Doob
Paul Halmos
Donald Sarason
J Comstock Doyle (1954-)
Oswald Veblen
Alonzo Church (1903–1995)
Alan Turing (1912 – 1954)
J Barkley Rosser Sr. (1907 – 1989)

Happy families are all alike; every unhappy family is unhappy in its own way.

Leo Tolstoy,
Anna Karenina,
Chapter 1, first line

- What does this mean?
- Given ***diversity*** of people and environments?
- $\Rightarrow$ About organization and ***architecture***.
- Happy $\approx$ empathy + cooperation + simple rules?

- ***Constraints*** on components and architecture

System

Architecture
=Constraints
(that deconstrain)

"Laws" =
hard limits,
tradeoffs

data

TM

UTM

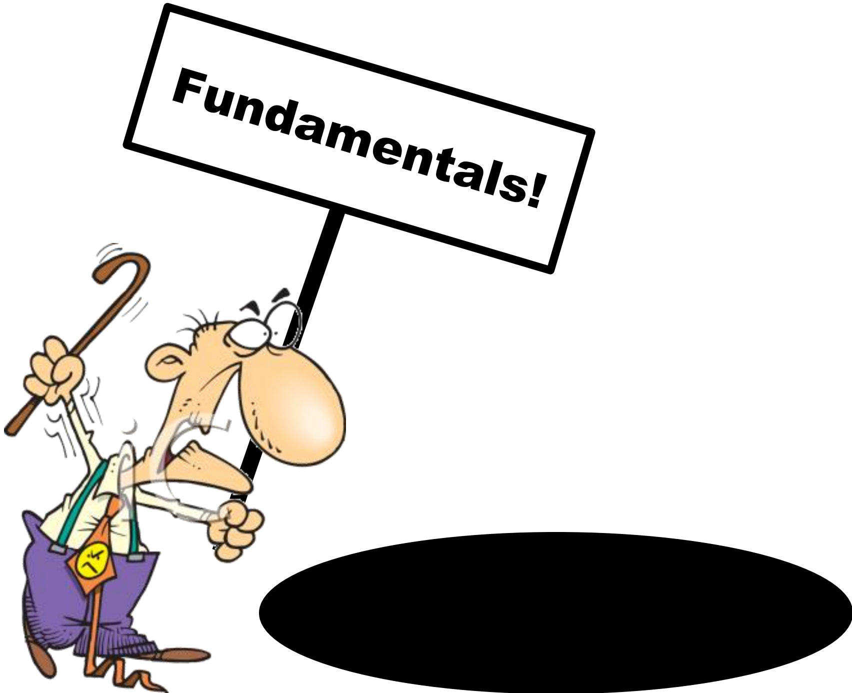
Protocols

Four types of constraints

Components

- **Cell biology**
- **Networking**
- **Neuroscience**
- **Medical physiology**
- Smartgrid, cyber-phys
- Wildfire ecology
- Earthquakes
- Lots of aerospace
- Physics:
  - turbulence,
  - stat mech (QM?)
- “Toy”:
  - Lego,
  - clothing,
- Buildings, cities
- **Synesthesia**

today’s
and other
case
studies



Case studies (focus)

- Bacterial biosphere
- Internet, PC, smartphone, etc
- Human brain and mind
- Human physiology

- ***Amazing*** evolvability (sustainability?)
- Illustrate architecture in (hopefully) accessible way

- Cyber-physical architecture is the technology challenge

Case studies (purpose)

- Illustrate/motivate theory and universals
  - Laws (constraints, hard limits, tradeoffs)
  - Architectures (design, forward and reverse engineering, organization)
- Impact for domain experts
  - Frameworks to organize existing, isolated facts
  - Suggests new experiments

Architecture case studies comparison

	Bacteria[+]	Internet[+]	Brain
Understood?	☺	☺☺	☹
By scientists?	☺	☹☹	☹
Live demos?!?	☹	☺	☺
Who cares?	☹*	☺	☺☺
Design quality?	☺☺	☺☹	☺☹
∃ Math?	☺	☺☺	☺☹

*Except for a few bacteriophiles (LC, SR, JD, ?)

[+]See also “Bacterial Internet” (LC)

“vertical” +“horizontal” evolution in Bacteria/Internet/Brain in Genes/Apps/Memes

- Vertical (lineages)
  - accumulation of small increments
  - de novo invention
  - Accelerated RosenCaporalian evolution
- Horizontal
  - Swap existing gene/app/meme
  - Source of most individual change?
- Both essential to large scale (r)evolution

“vertical” +“horizontal” evolution
in Bacteria/Internet/Brain
in Genes/Apps/Memes

- Evolution is ***not*** only (or even primarily) due to slow accumulation of random mutations
- Effective architectures facilitate ***all*** aspects of “evolvability”
- Lamarckian and Darwinian

“Evolvability”

- Robustness of lineages to large changes on long timescales
- Essentially an architectural question
  - What makes an architecture evolvable?
  - What does “architecture” mean here?
- What are the limits on evolvability?
- How does architecture, evolvability, robustness, and complexity relate?

- Key: tradeoffs, robustness, layering

"Nothing in *biology* makes sense except in the light of *evolution*."

T Dobzhansky

"Nothing in *evolution* makes sense except in the light of *biology*."

Tony Dean (U Minn) paraphrasing T Dobzhansky

When concepts fail, words arise

Faust, Goethe

Mephistopheles. …Enter the templed hall of Certainty.

Student. Yet in each word some concept there must be.

Mephistopheles. Quite true! But don't torment yourself too anxiously;
For at the point where concepts fail,
At the right time a word is thrust in there…

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
failure transparent
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

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Long term

Simplified, minimal requirements

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accountable
accurate
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administrable
affordable
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credible
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upgradable
usable

Lumping requirements into simple groups

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accurate
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affordable
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traceable
ubiquitous
understandable
upgradable
usable

Requirements on systems and architectures

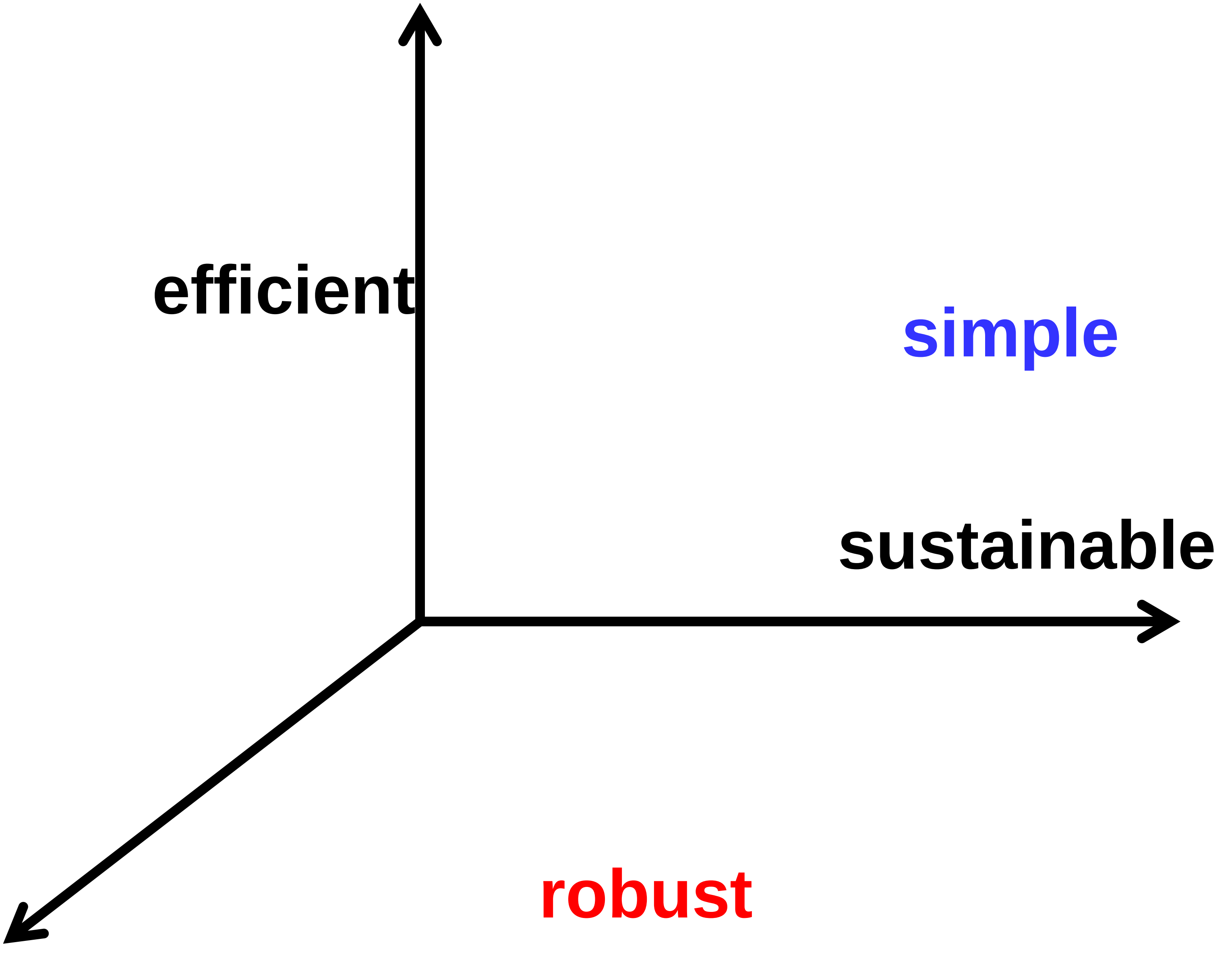
efficient

simple

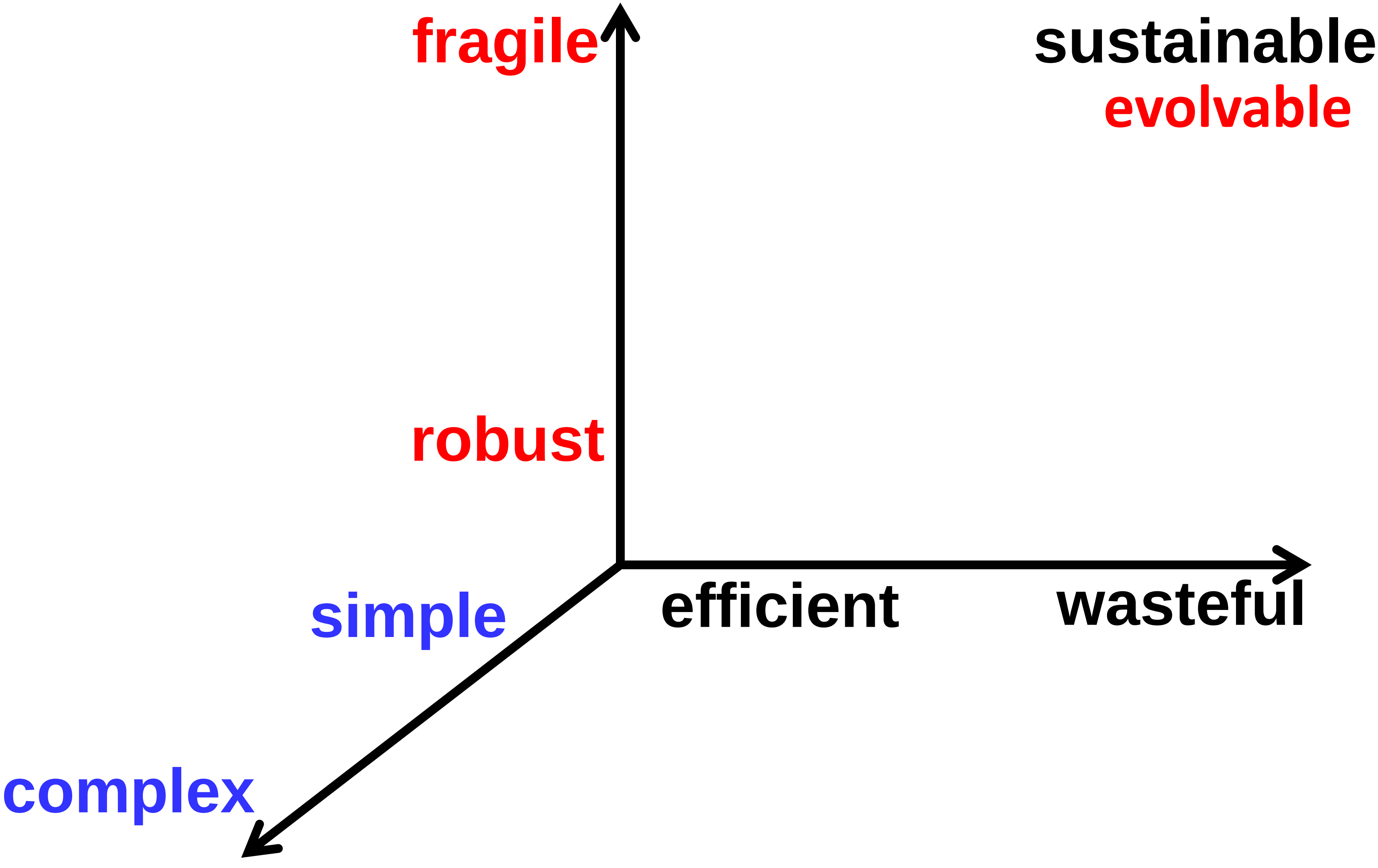
sustainable

robust

Requirements on systems and architectures

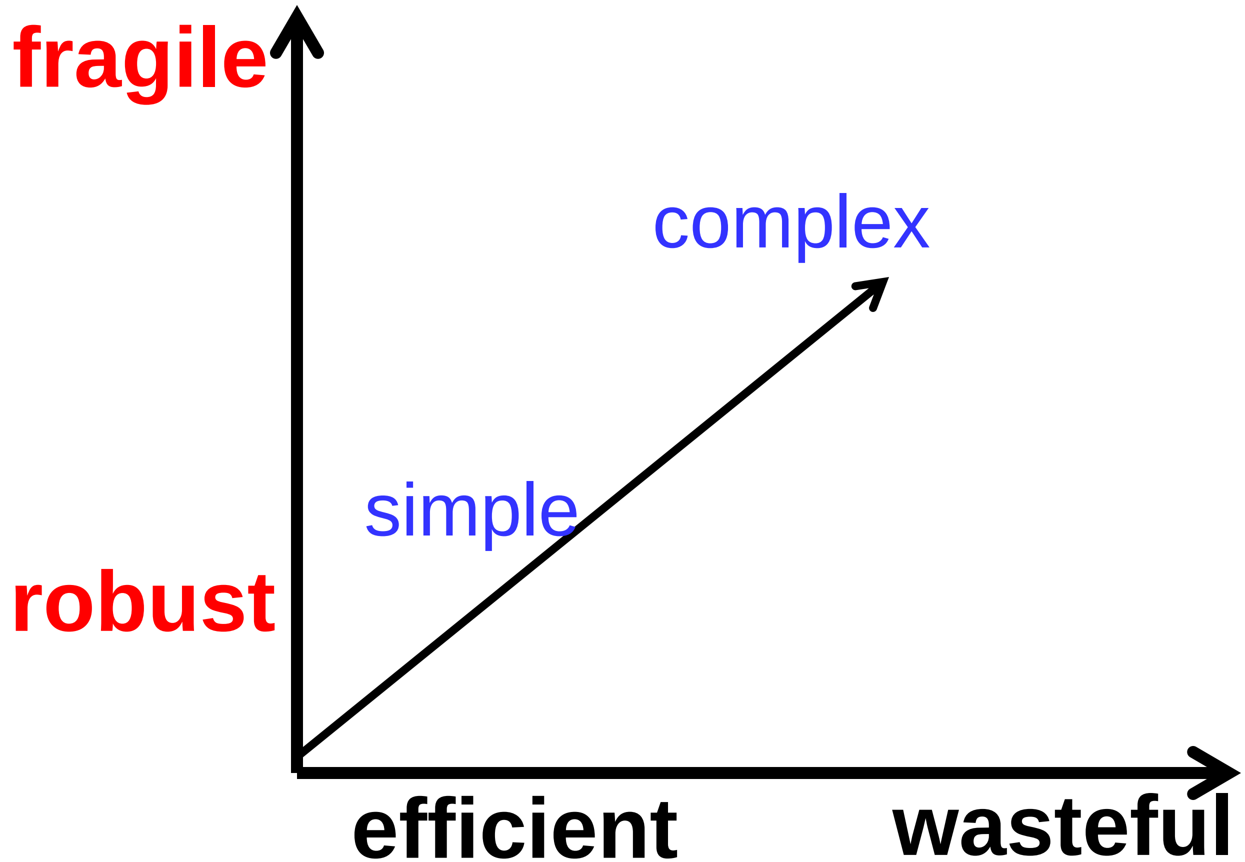


Requirements on systems and architectures

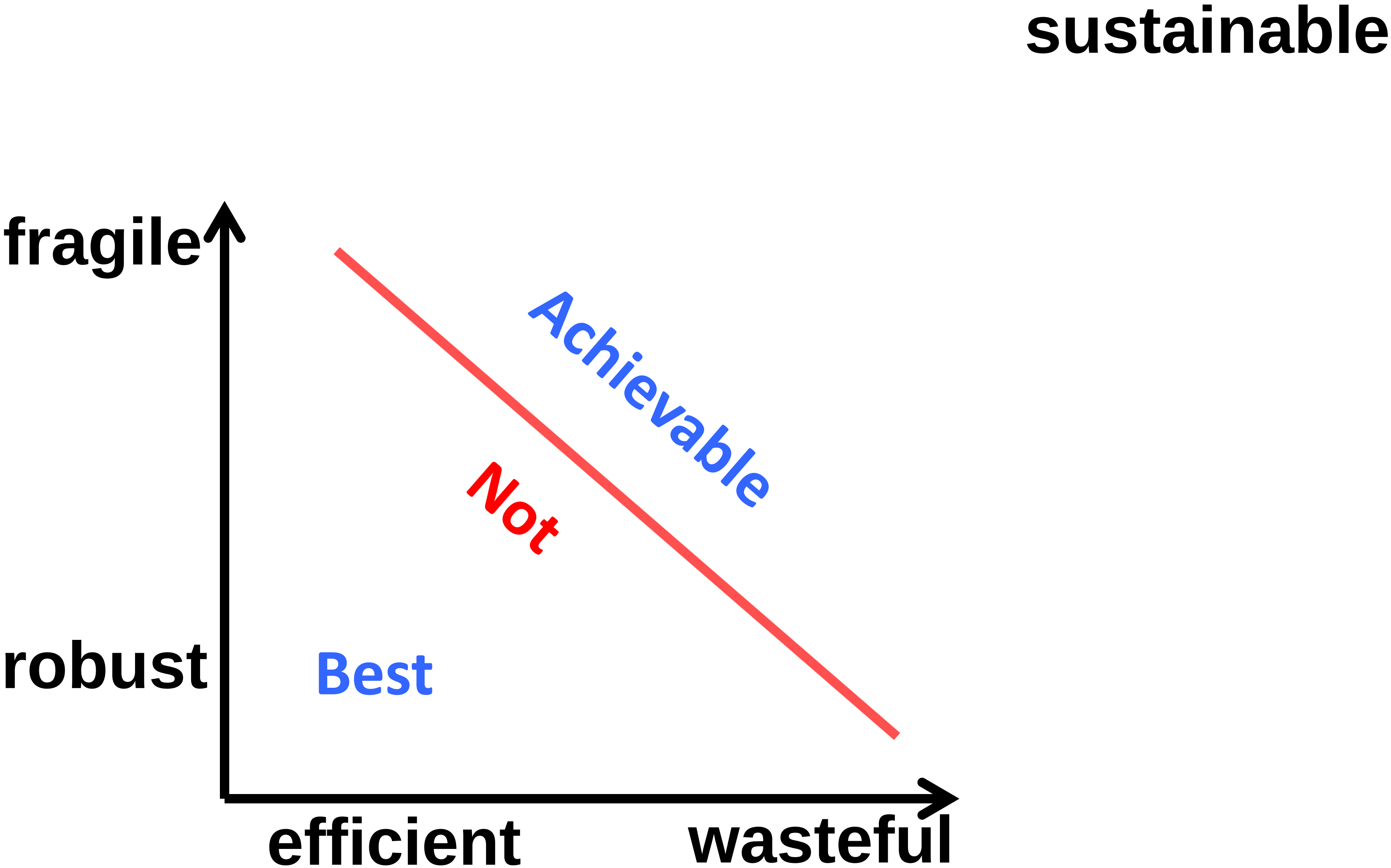


Requirements on systems and architectures

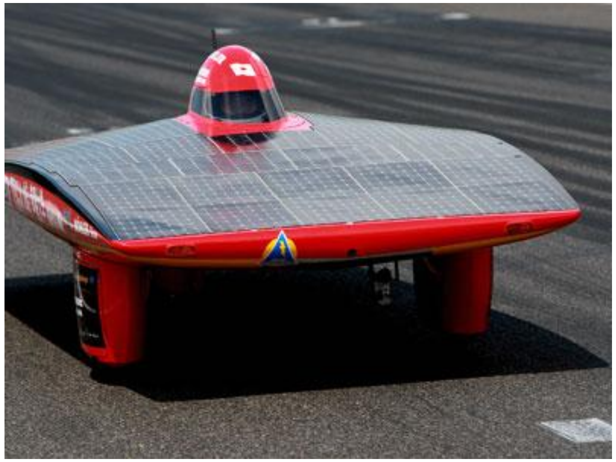
sustainable



Requirements on systems and architectures



Current Technology?



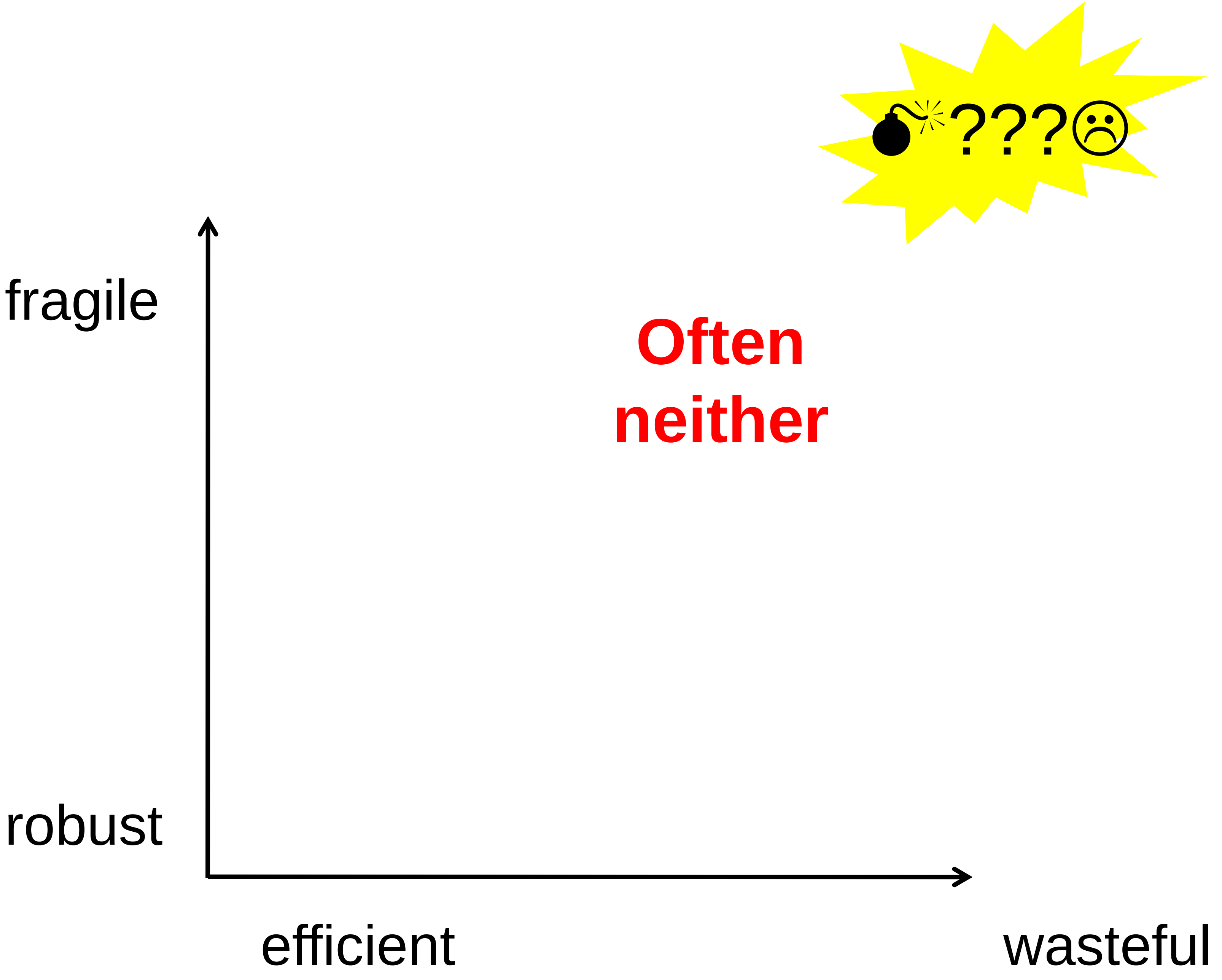
fragile

At best we get one

robust

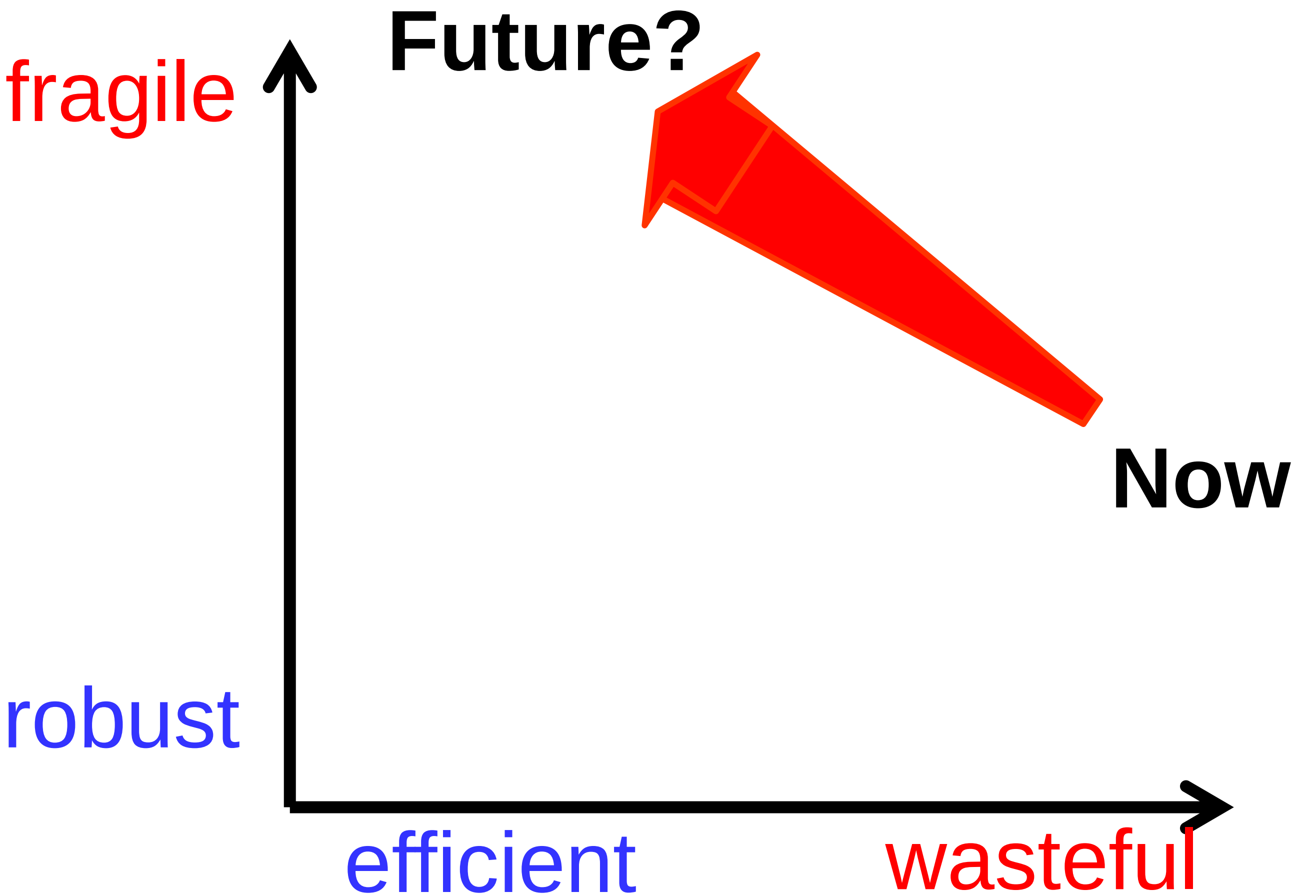
efficient

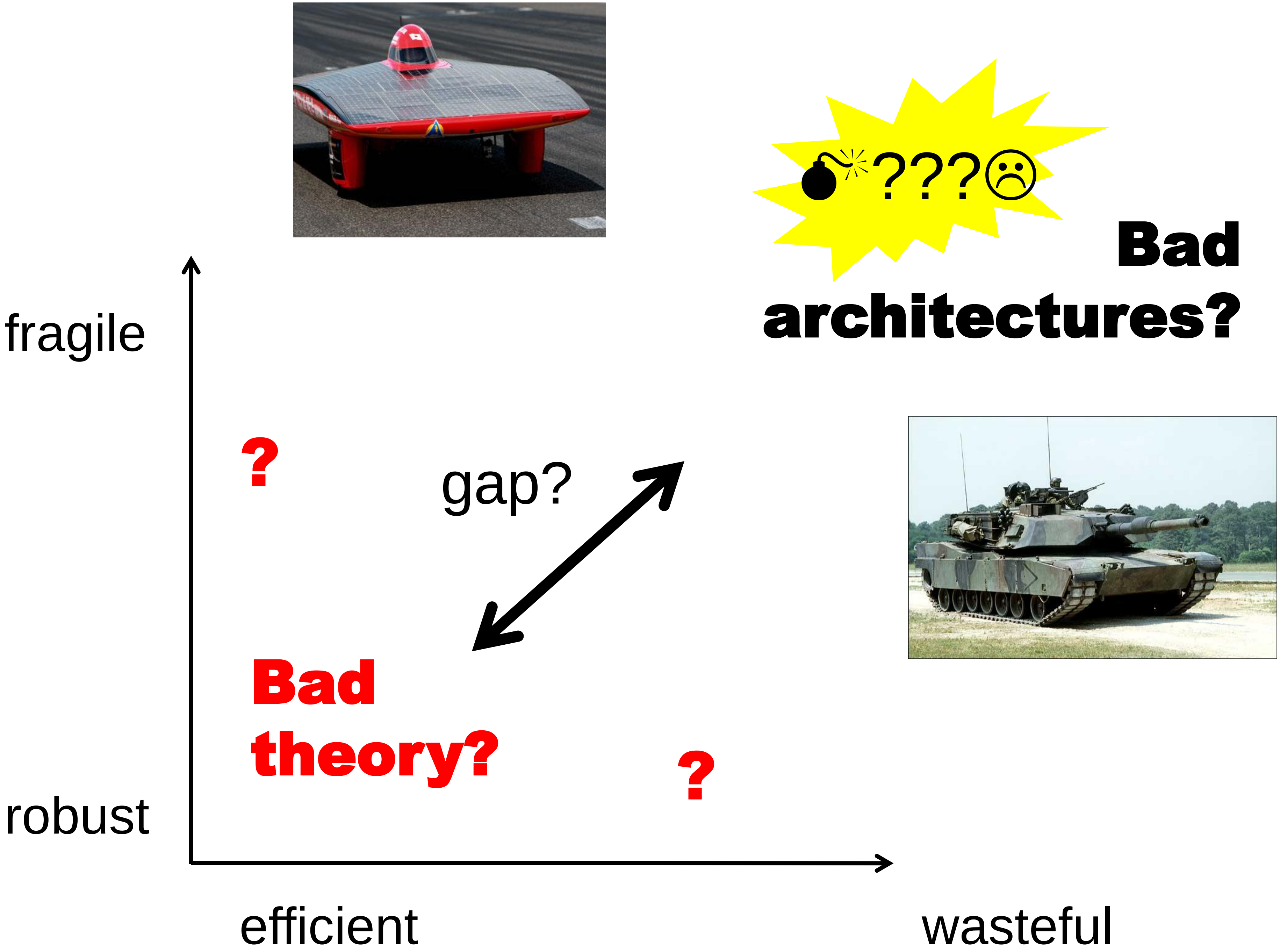
wasteful

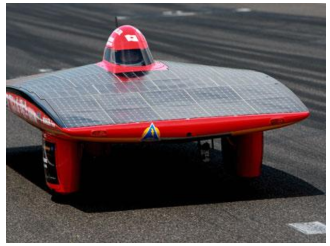


???☹
fragile
Often
neither
robust
efficient
wasteful

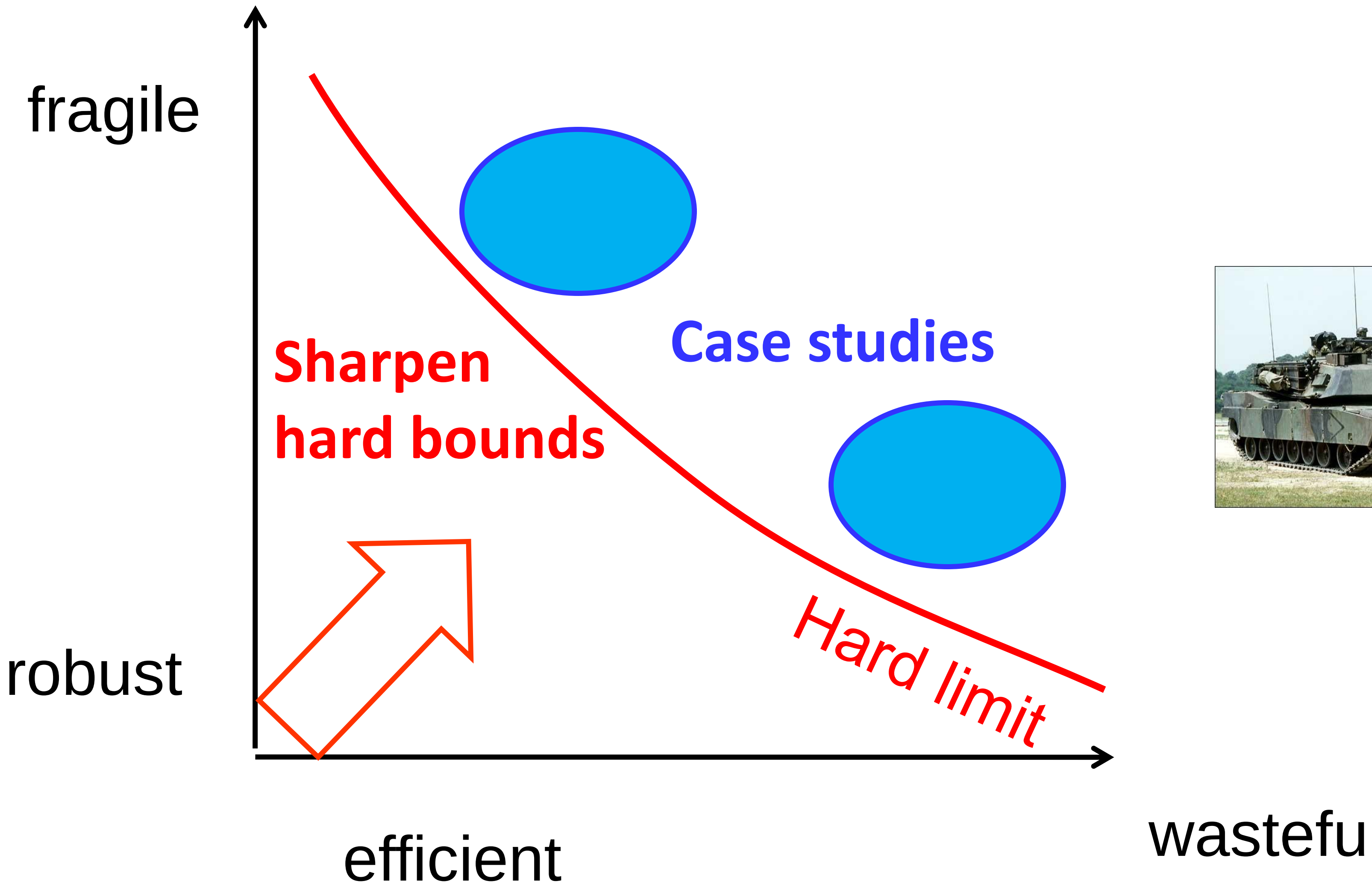
Future evolution of the "smart" grid?



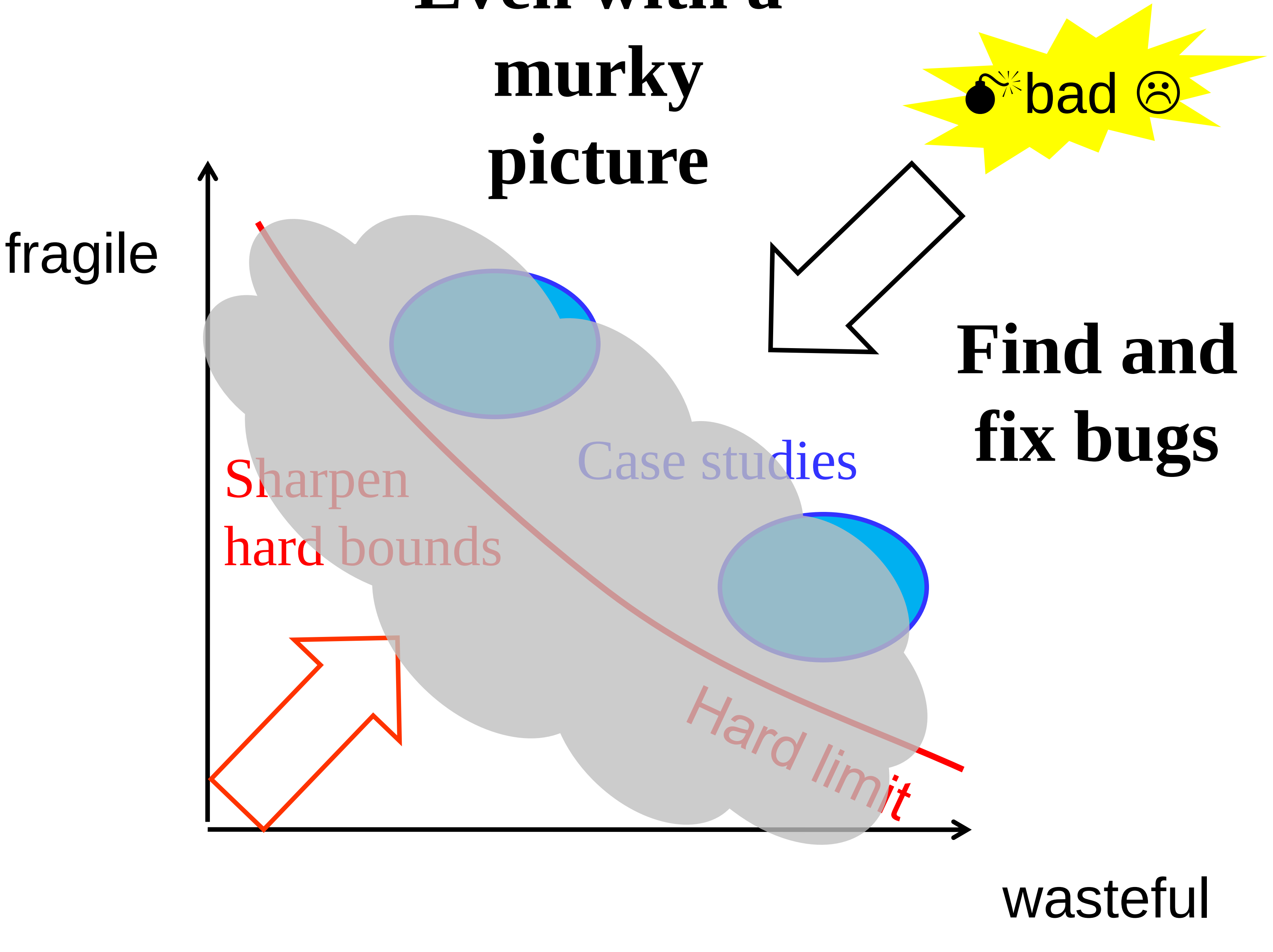

???☹
Bad architectures?
fragile
robust
?
gap?
Bad theory?
?
efficient
wasteful



laws and architectures?



Even with a murky picture



Compute

Godel

Comms

Turing

Shannon

Von
Neumann

Theory?

Deep, but fragmented,
incoherent, incomplete

Nash

Bode

Carnot

Pontryagin

Boltzmann

Heisenberg

Kalman

Control, OR

Einstein

Physics

Compute

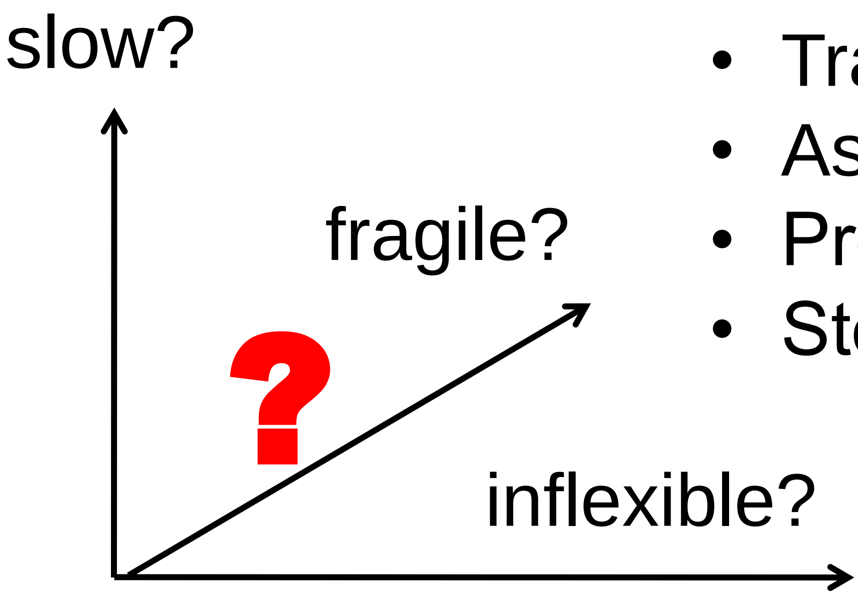
Godel

Turing

Comms

Shannon

- Each theory ≈ one dimension
- Tradeoffs ***across*** dimensions
- Assume architectures a priori
- Progress is encouraging, but…
- Stovepipes are an obstacle…



Carnot

Boltzmann

Bode

Heisenberg

Control

Physics

Einstein

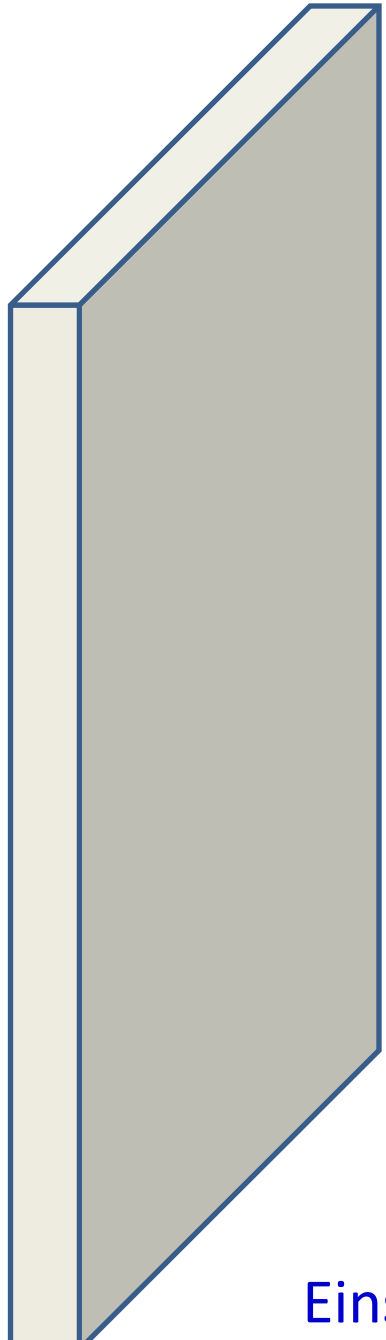
Compute

Turing

Delay is *most* important

Bode

Control, OR



Communicate

Shannon

Delay is *least* important

Carnot

Boltzmann

Heisenberg

Einstein

Physics

Compute

Communicate

Turing

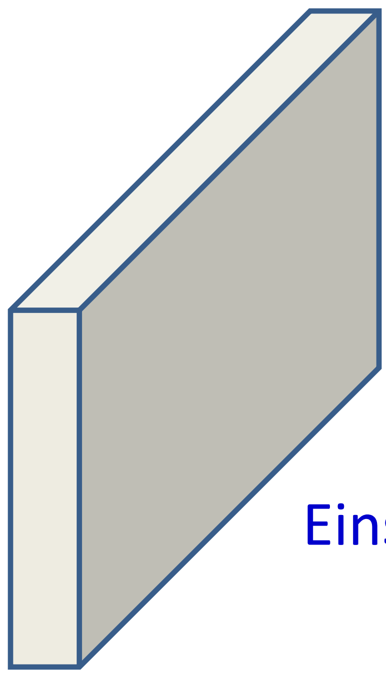
Lowering the barrier

Shannon

Delay is *most* important

New progress!

Delay is ~~*least*~~ important



Carnot

Boltzmann

Bode

Heisenberg

Control, OR

Einstein

Physics

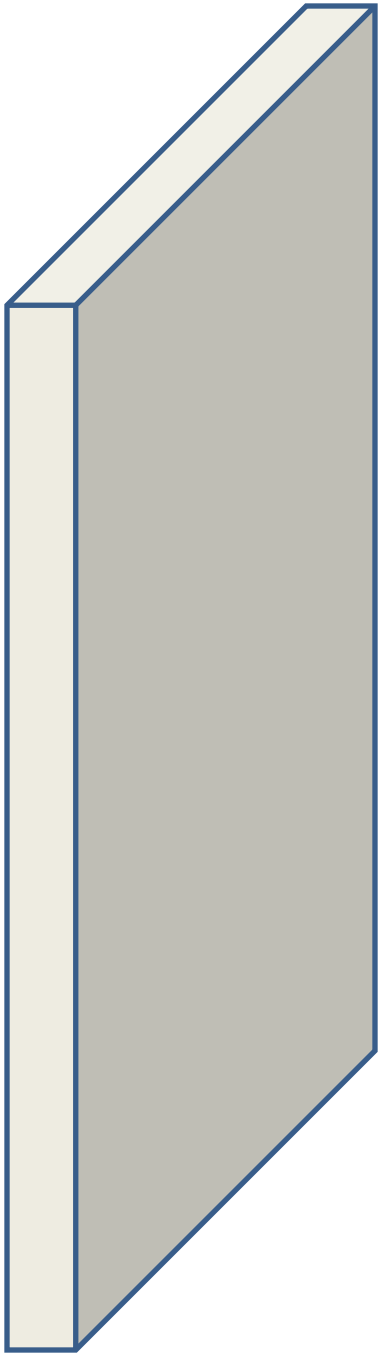
Compute

Turing

Delay is *most* important

Bode

Control, OR



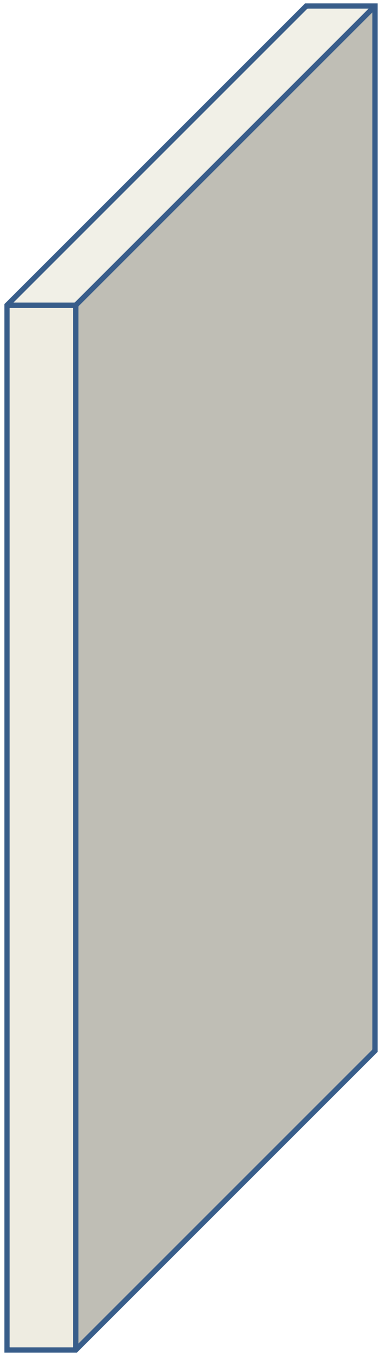
Compute

Turing

Delay is *most* important

Bode

Control, OR



Compute

Turing

large $t \to \infty$

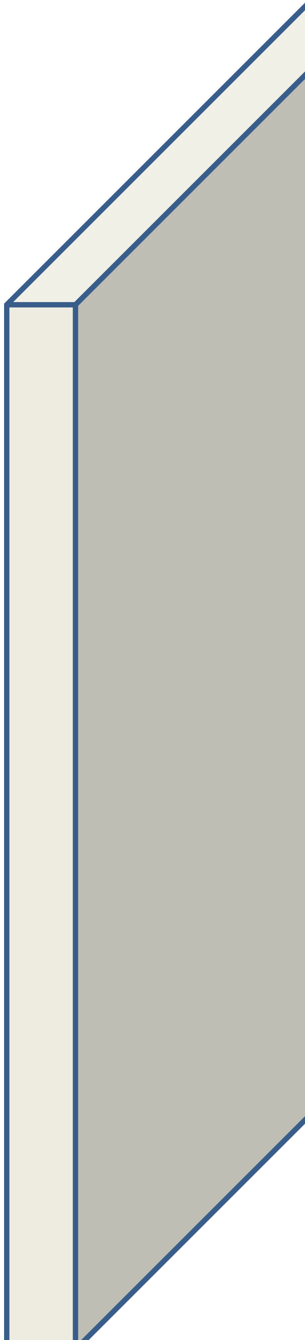
Differences?

Delay is *most* important

small t (hopefully)

Bode

Control, OR



Compute

Turing (1912-1954)

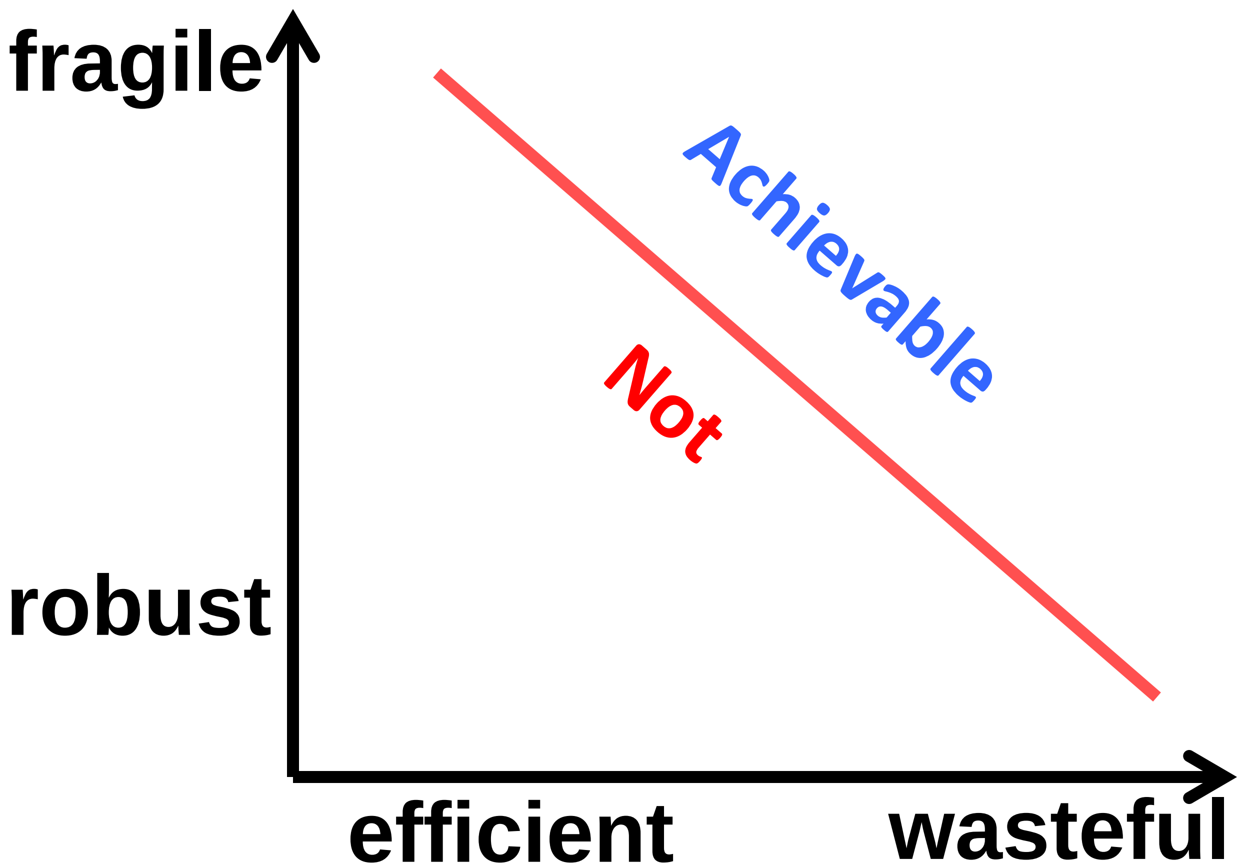
- Turing 100th birthday in 2012
- Turing
  - machine (math, CS)
  - test (AI, neuroscience)
  - pattern (biology)
- Arguably greatest*
  - all time math/engineering combination
  - WW2 hero
  - “invented” software

*Also world-class runner.

Key papers/results

- Theory (1936): Turing machine (TM), computability, (un)decidability, universal machine (UTM)
- Practical design (early 1940s): code-breaking, including the design of code-breaking machines
- Practical design (late 1940s): general purpose digital computers and software, layered architecture
- Theory (1950): Turing test for machine intelligence
- Theory (1952): Reaction diffusion model of morphogenesis, plus practical use of digital computers to simulate biochemical reactions

Components of robustness



Components of robustness

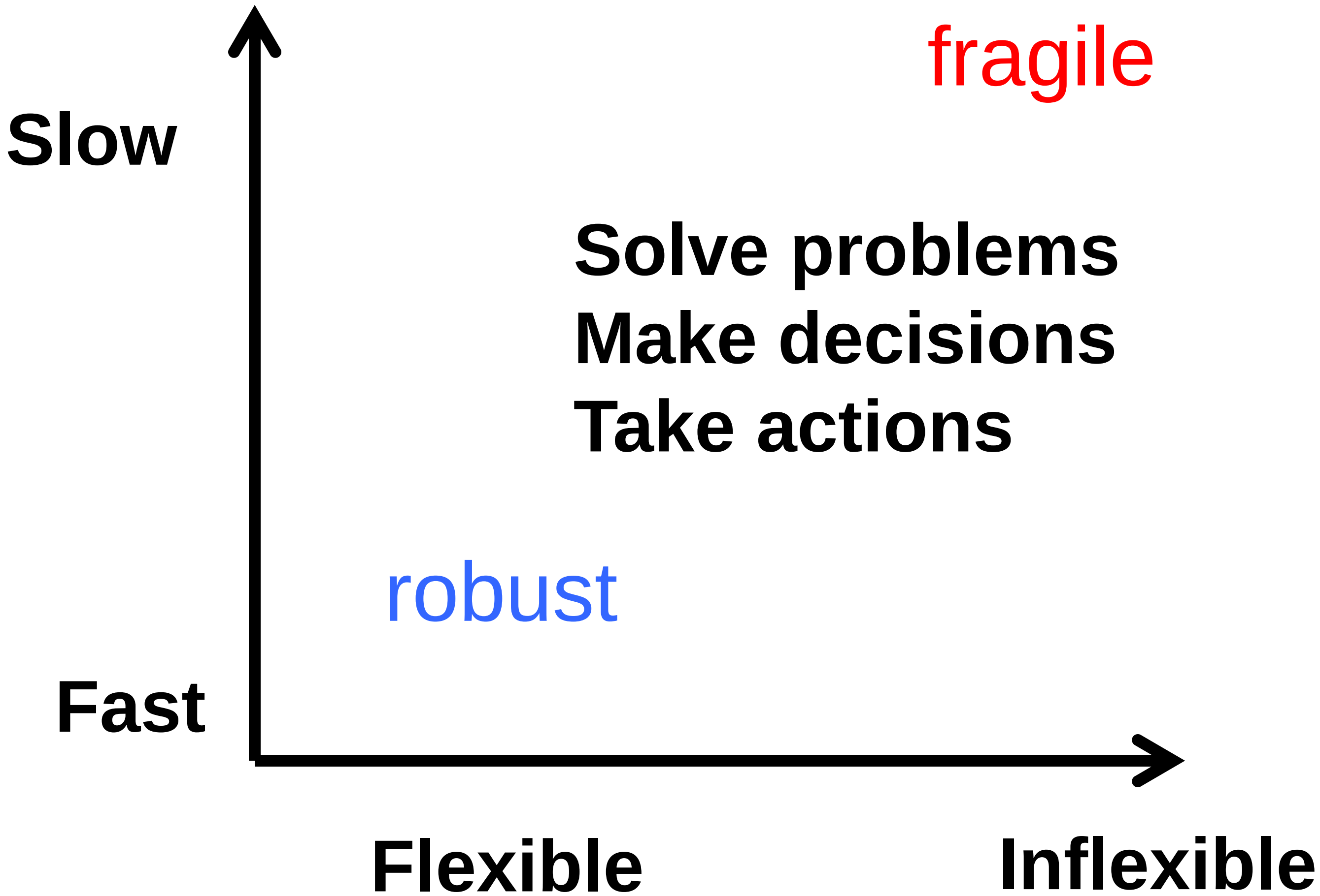
fragile

fragile

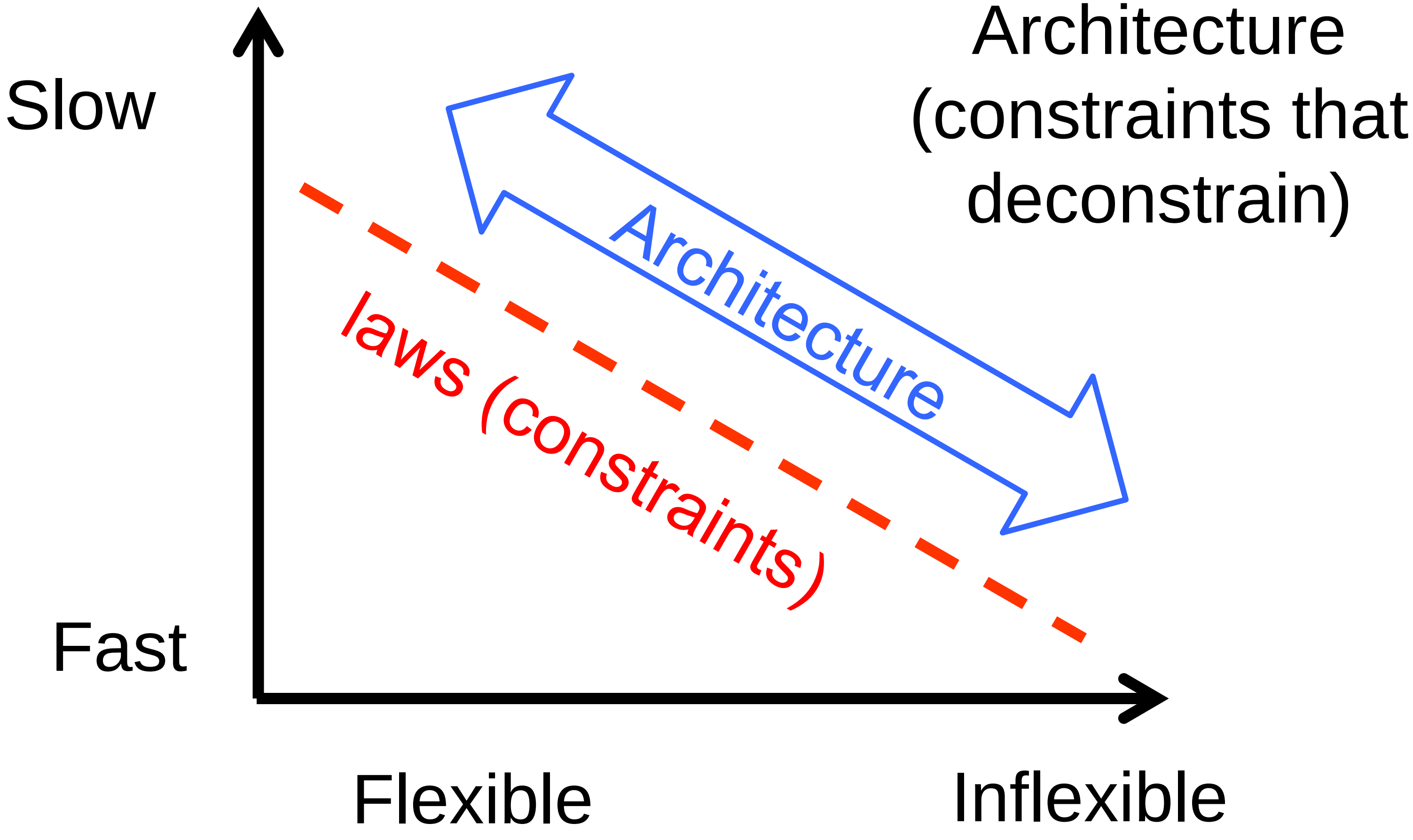
robust

robust

Speed and flexibility



Laws and architectures



big picture from high level with a bit of Internet

	Bacteria	Internet	Brain
Understood?	☺	☺☺	☹
By scientists?	☺	☹☹	☹
Live demos?!?	☹	☺	☺
Who cares?	☹*	☺	☺☺
Design quality?	☺☺	☺☹	☺☹
∃ Math?	☺	☺☺	☺☹

Apps

OS

Hardware

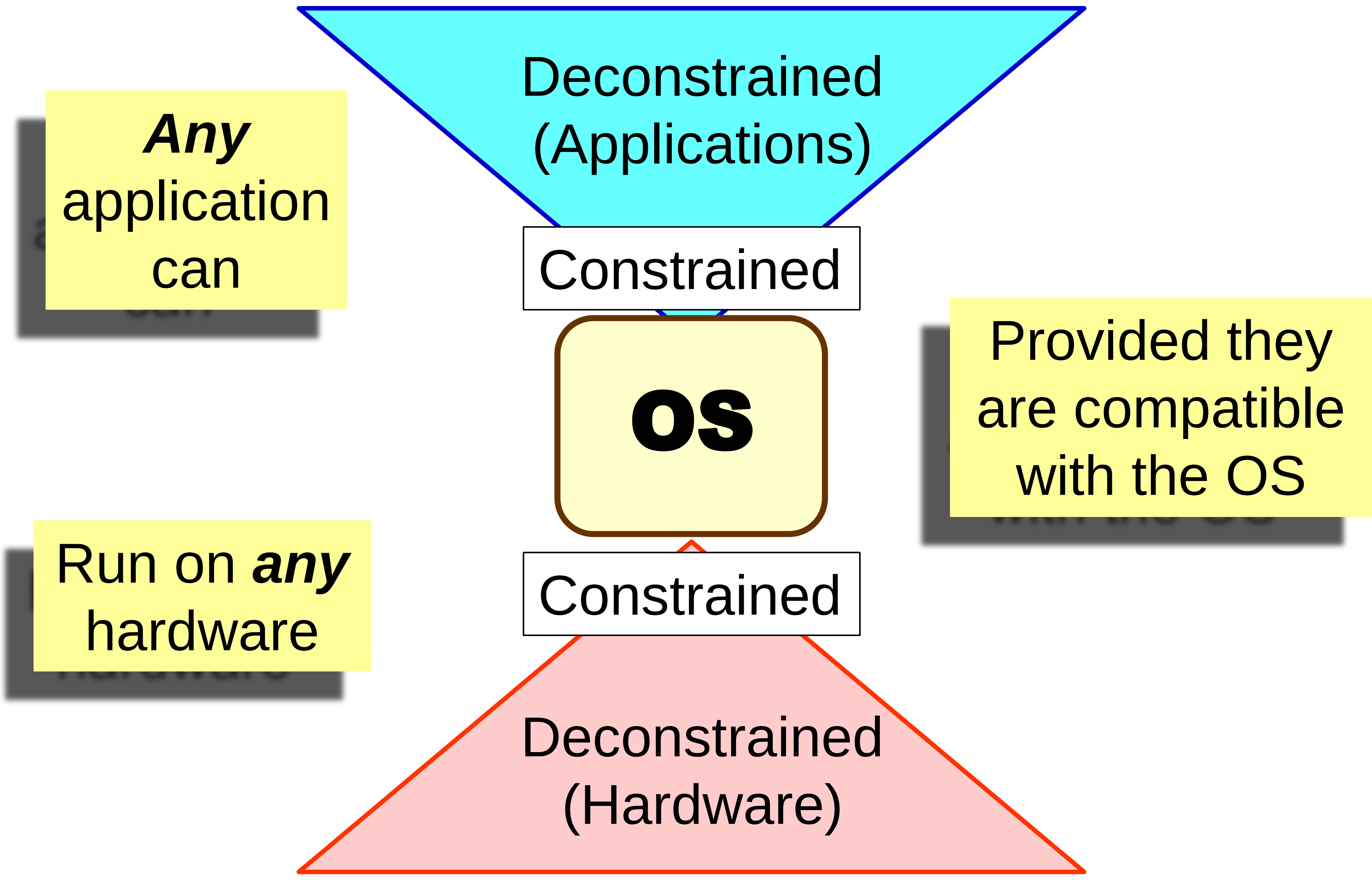
Digital

Lumped

Distributed

Familiar layered architecture:
PC, smartphone, router, etc

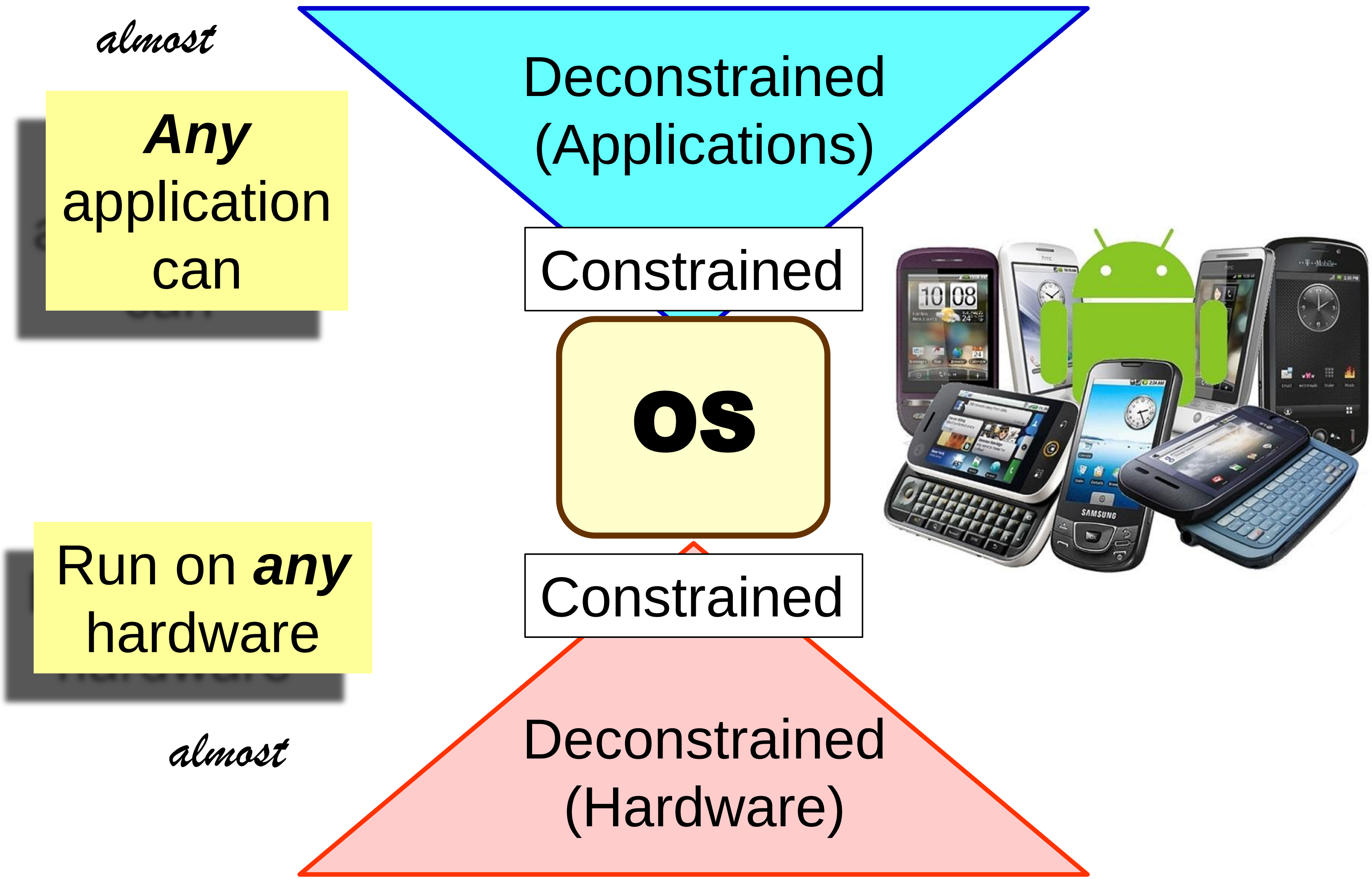
“hourglass”


Deconstrained
(Applications)
Constrained
OS
Constrained
Deconstrained
(Hardware)
Any application can
Provided they are compatible with the OS
Run on any hardware

“hourglass”


Deconstrained
(Applications)
Constrained
OS
Many applications can
Run on *this* hardware

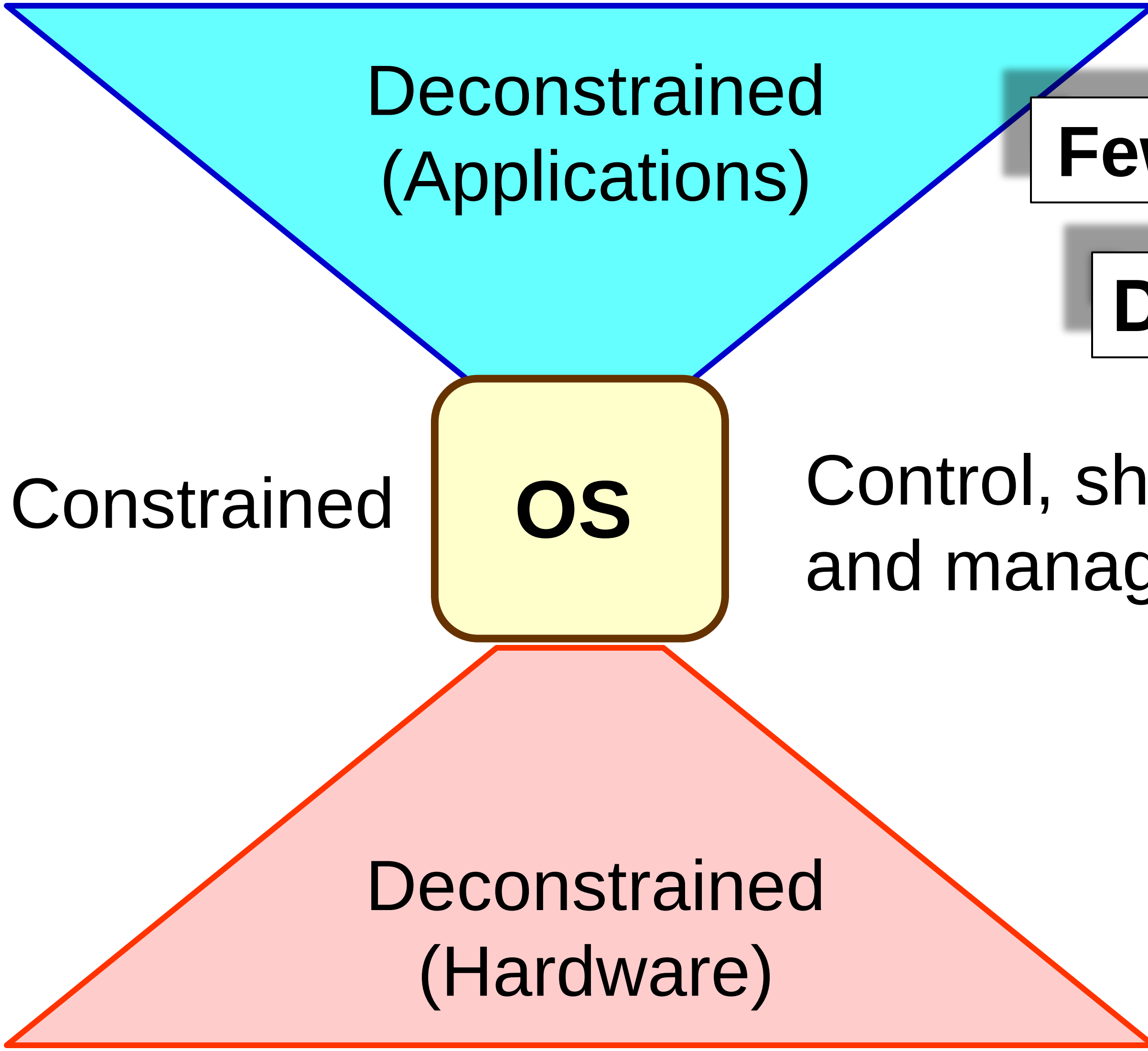
“hourglass”



almost
Any application can
Run on any hardware
almost
Deconstrained (Applications)
Constrained
OS
Constrained
Deconstrained (Hardware)
SAMSUNG

Layered architectures

Essentials CS 101

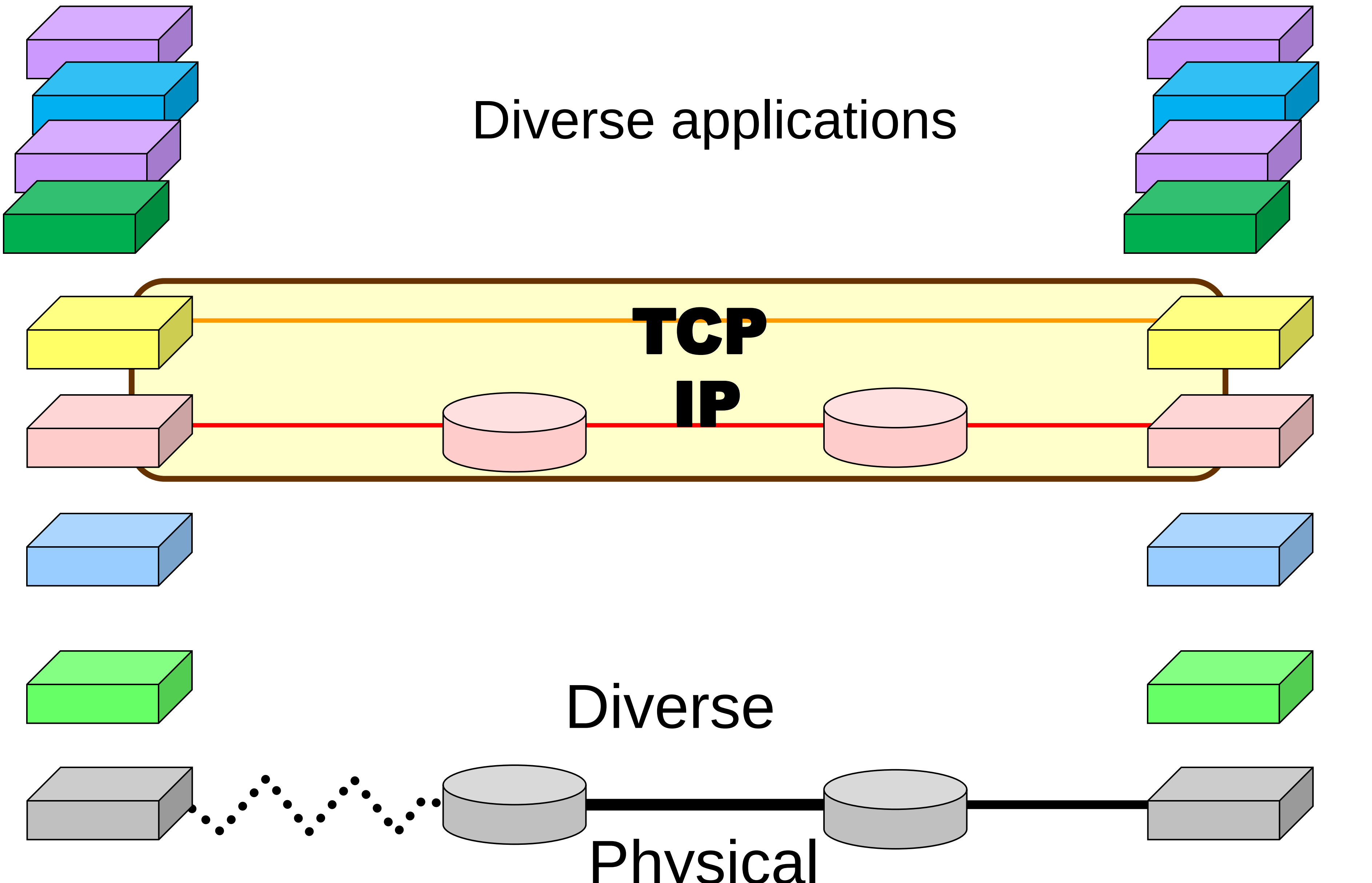


Few global variables

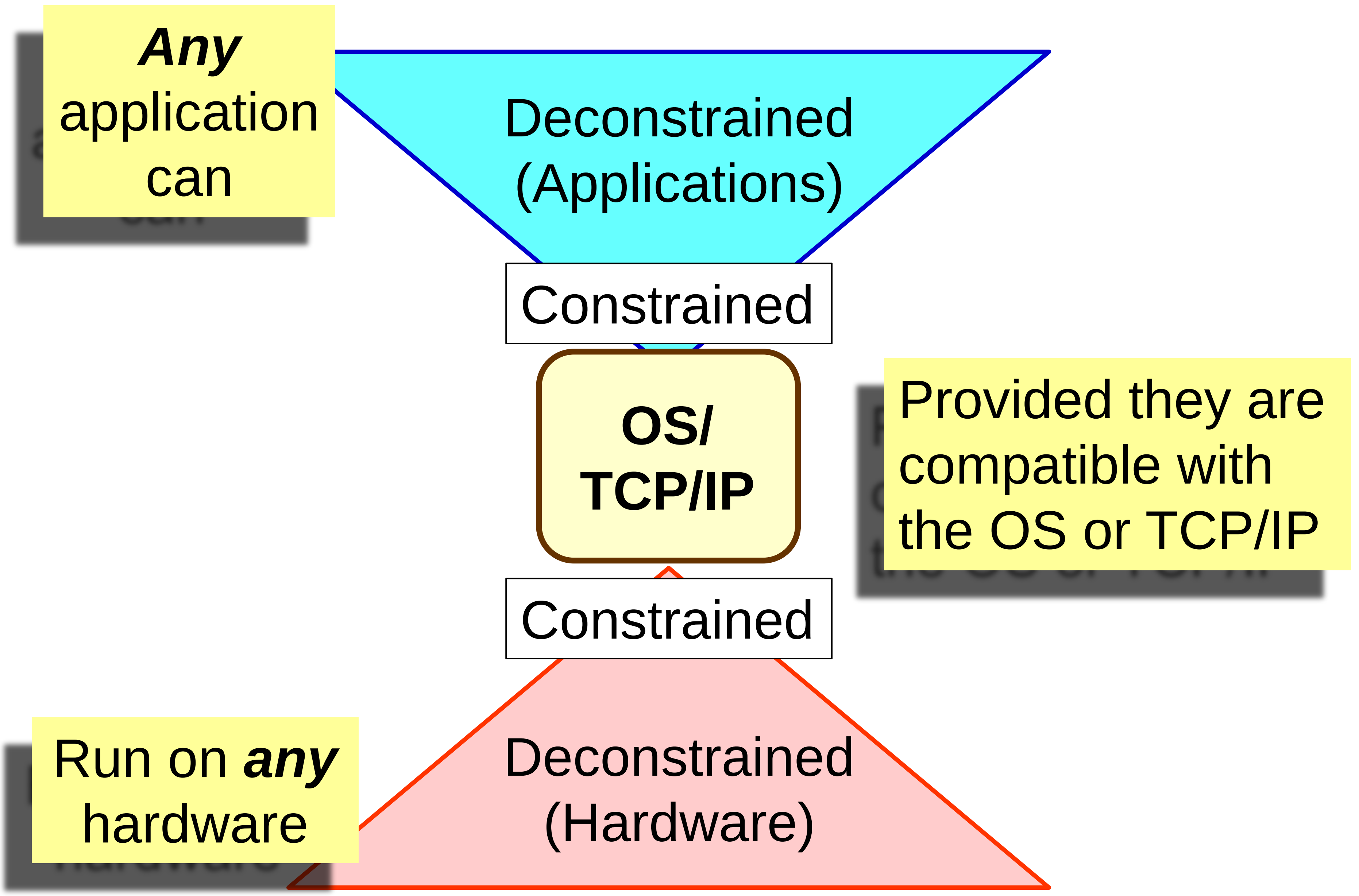
Don't cross layers

Control, share, virtualize, and manage resources

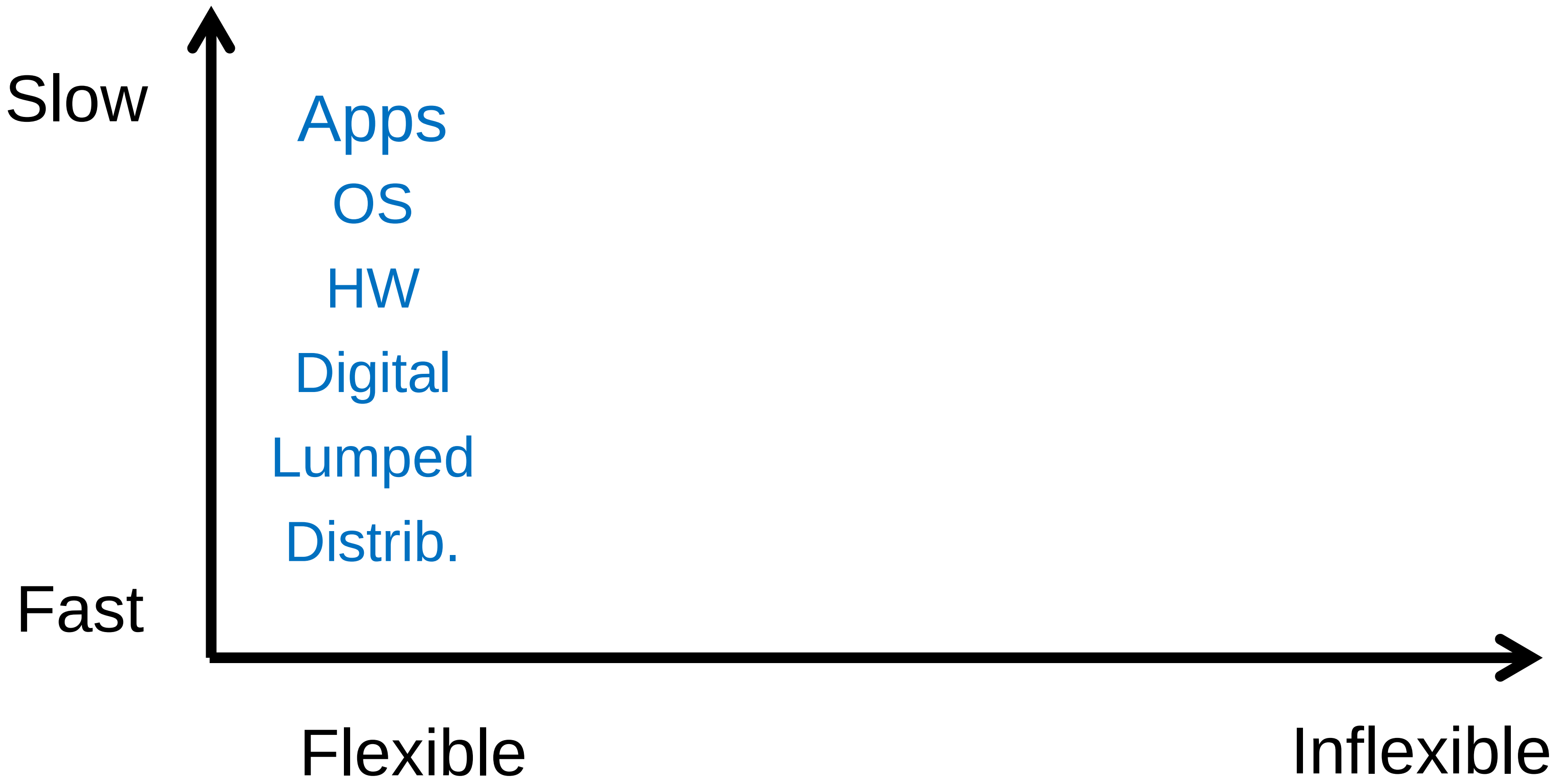
Processing
Memory
I/O



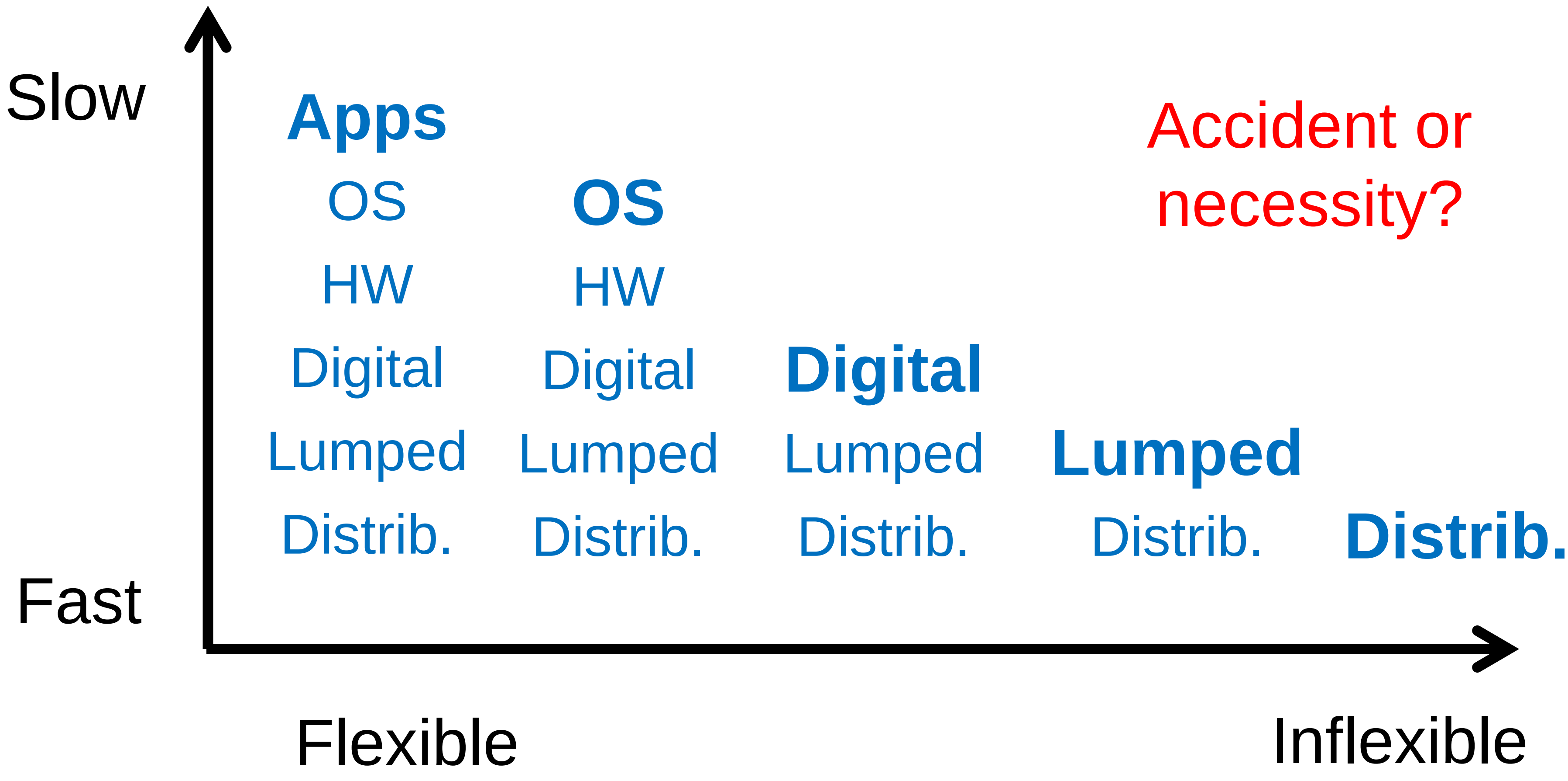
Diverse applications
TCP
IP
Diverse
Physical


Any application can
Deconstrained (Applications)
Constrained
OS/ TCP/IP
Provided they are compatible with the OS or TCP/IP
Constrained
Run on ***any*** hardware
Deconstrained (Hardware)

Tradeoffs:
PC, smartphone, router, etc



Tradeoffs:
PC, smartphone, router, etc



Slow

Apps

OS **OS**

Architecture?

HW HW

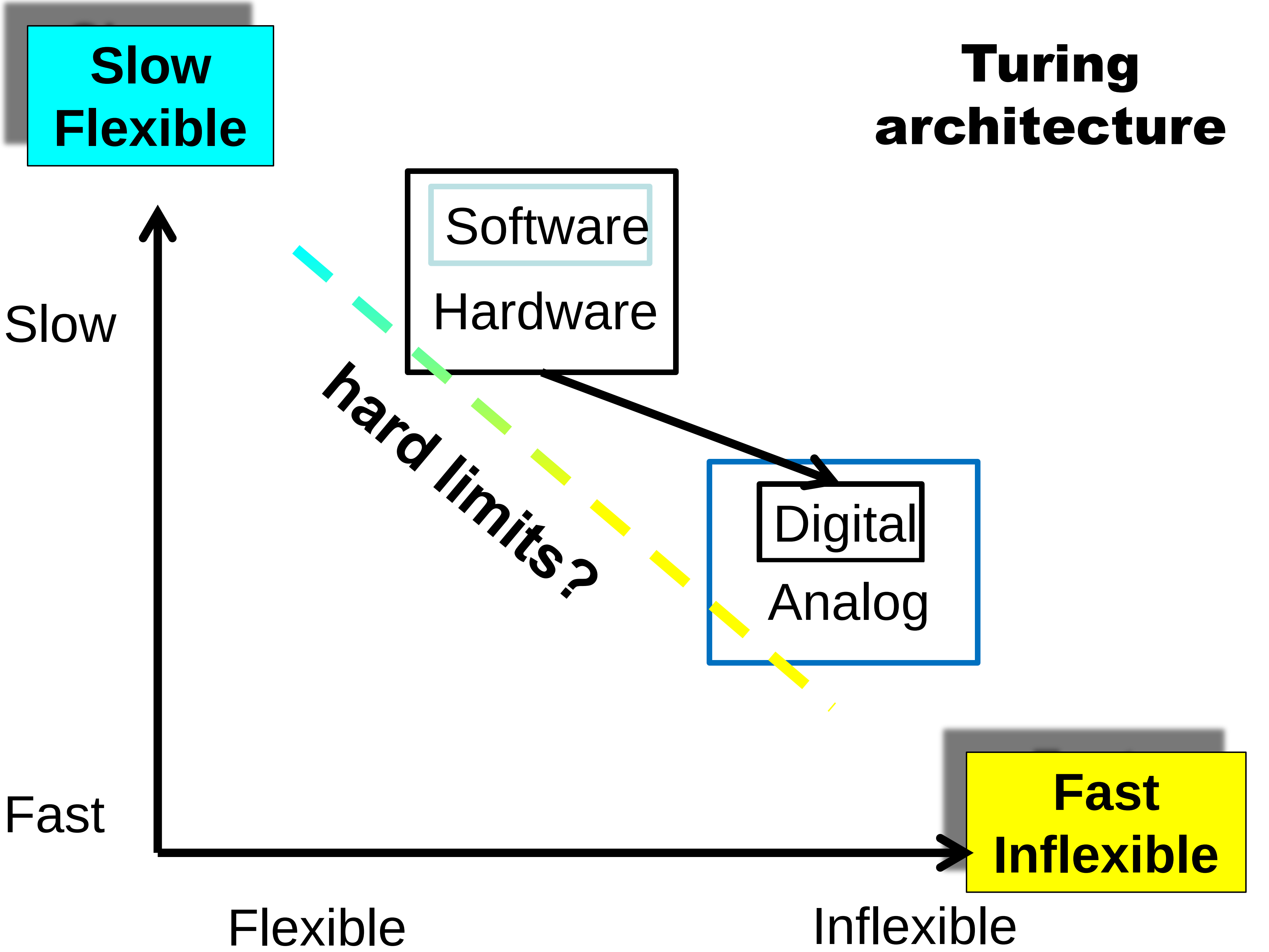
Digital Digital Digital

Lumped Lumped Lumped Lumped

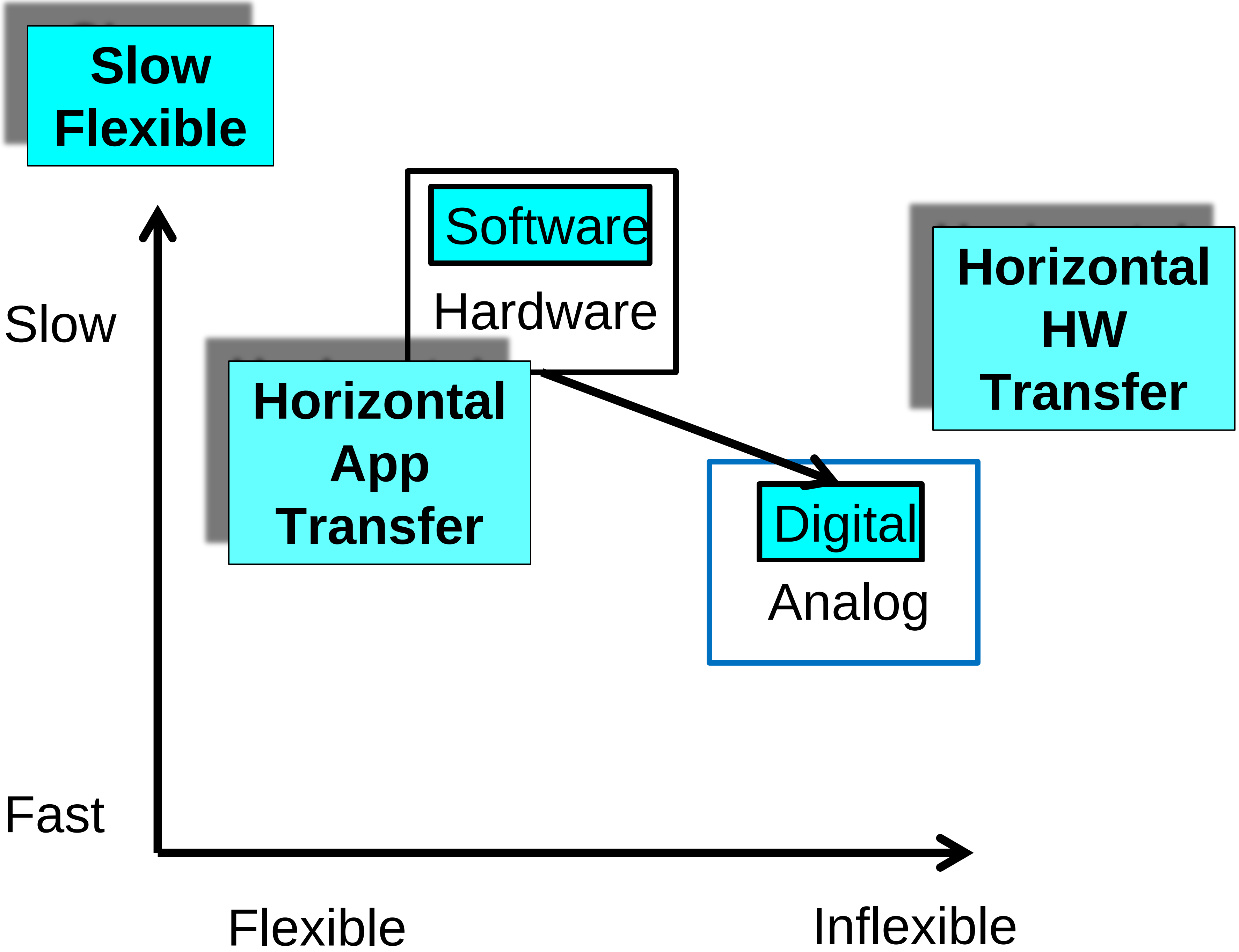
Distrib. Distrib. Distrib. Distrib. Distrib.

Fast

Flexible Inflexible

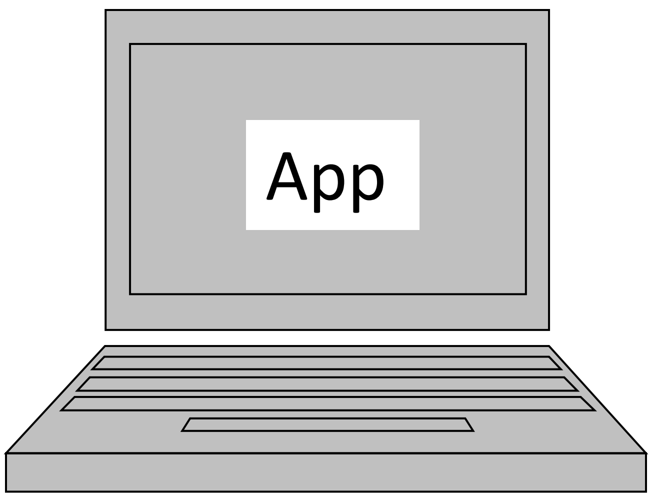


Slow
Flexible
Turing
architecture
Software
Hardware
Slow
hard limits?
Digital
Analog
Fast
Fast
Inflexible
Flexible
Inflexible



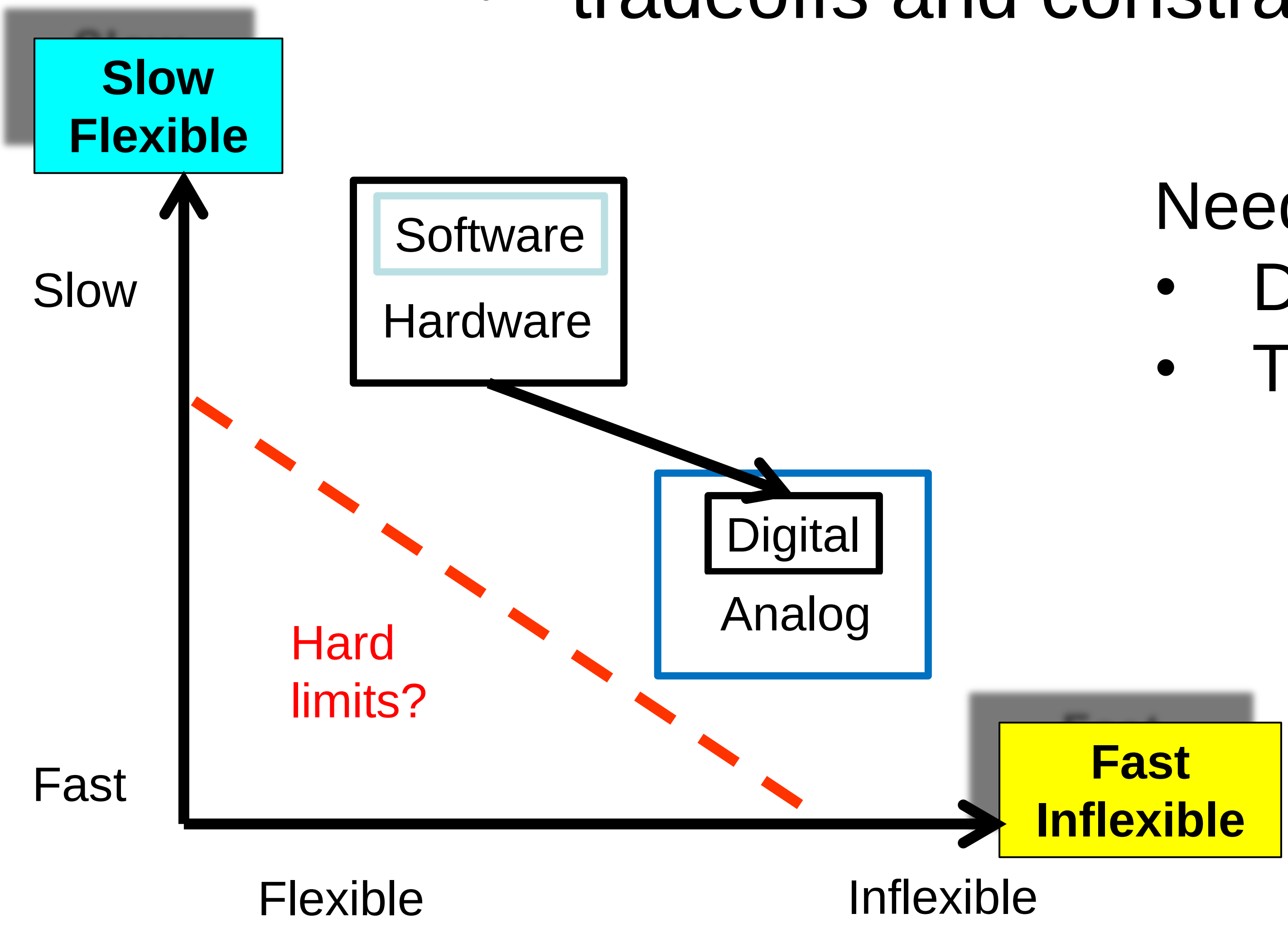
Slow
Flexible
Software
Hardware
Horizontal
HW
Transfer
Slow
Horizontal
App
Transfer
Digital
Analog
Fast
Flexible
Inflexible

**What you see:
The hardware interface and the application function**

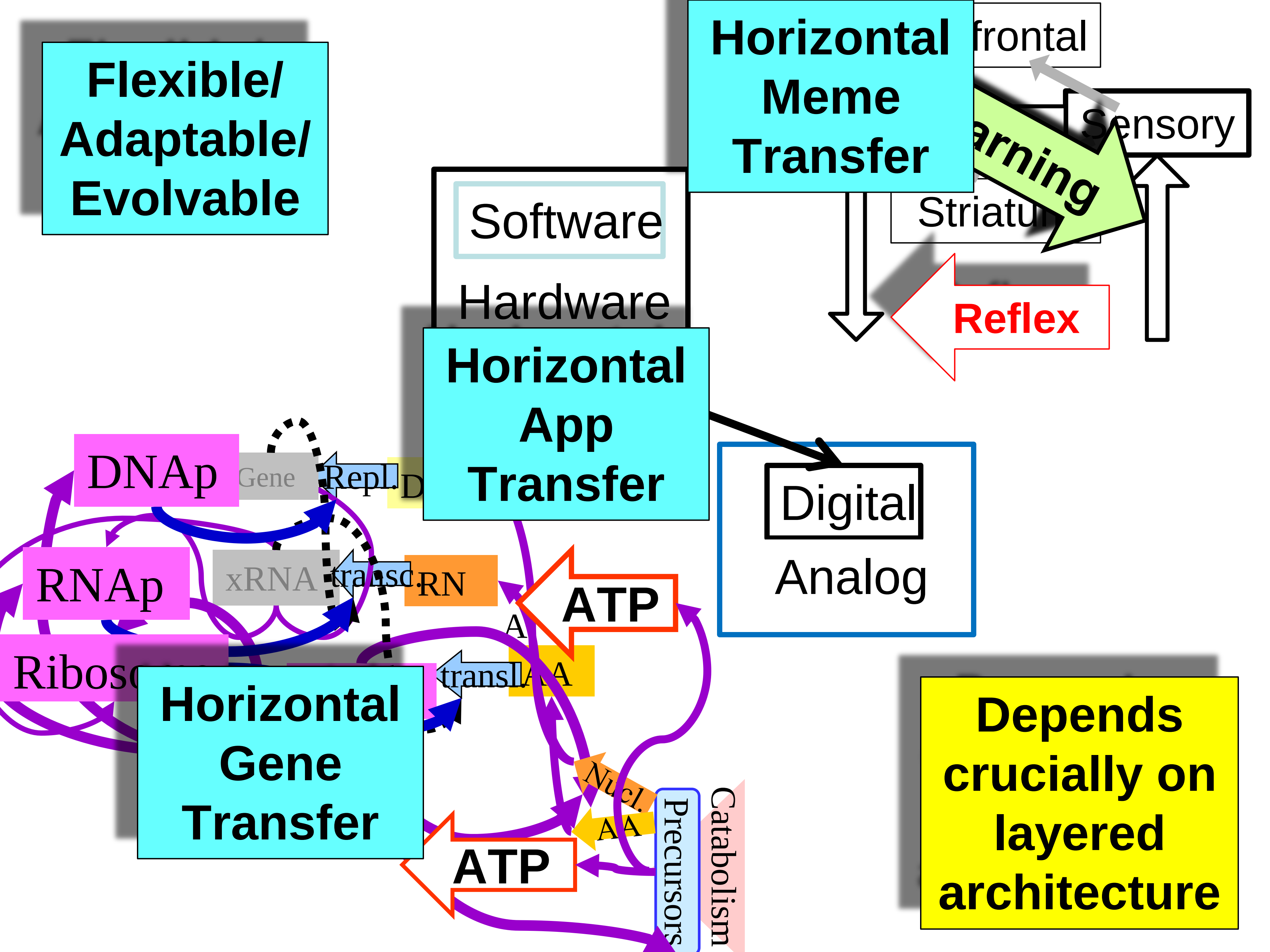


Shared architecture and infrastructure is and ***must be*** mostly hidden

Bacteria and brains have similar:
- layered architectures
- tradeoffs and constraints



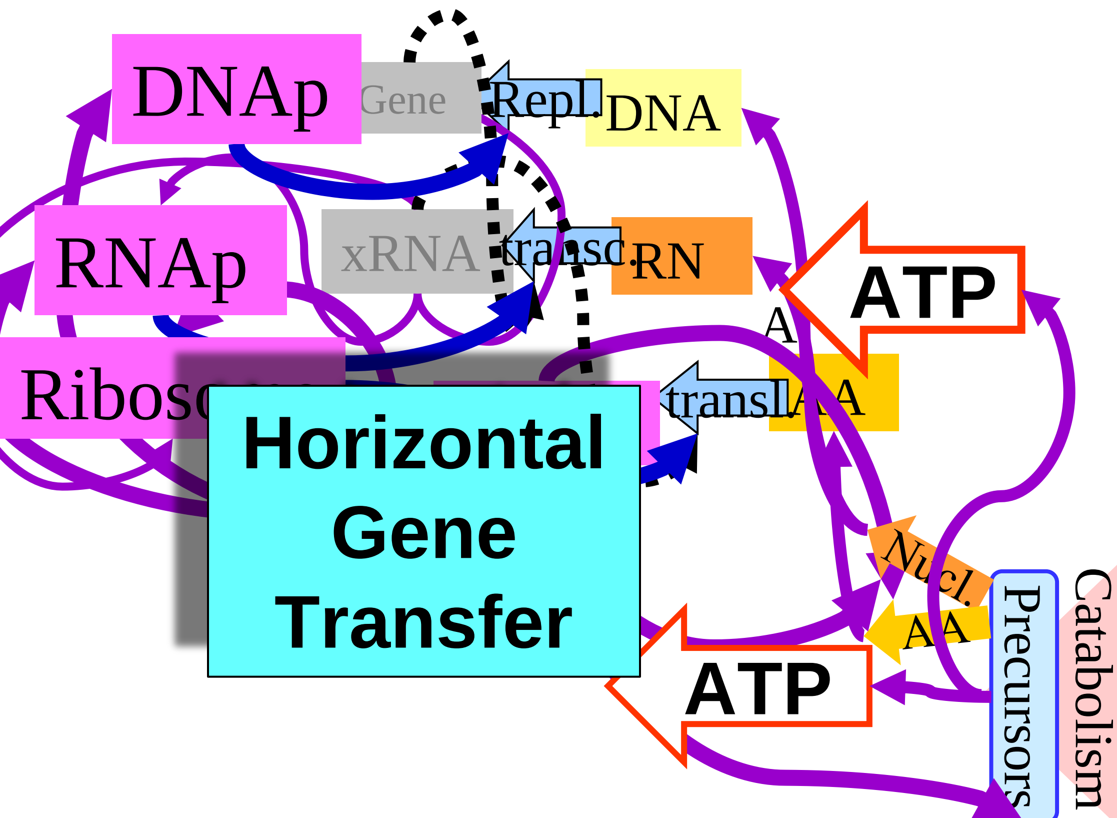
Need
- Details
- Theorems



Flexible/
Adaptable/
Evolvable
Horizontal
Meme
Transfer
frontal
Sensory
arning
Striatu
Software
Hardware
Reflex
Horizontal
App
Transfer
Digital
Analog
DNAp
Gene
Repl.
RNAp
xRNA
transc.
RN
ATP
Ribos
transl.
AA
Horizontal
Gene
Transfer
Nucl.
AA
Precursors
Catabolism
ATP
Depends
crucially on
layered
architecture

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

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



See slides on bacterial biosphere

Mechanisms in molecular biology

0. HGT (Horizontal Gene Transfer)
1. DNA replication
2. DNA repair
3. Mutation
4. Transcription
5. Translation
6. Metabolism
7. Signal transduction
8. …

Think of this as a “protocol stack”

Control 1.0

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

Highly controlled

Think of this as a “protocol stack”

Control 2.0

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

Highly controlled ?!? (0–3)

Highly controlled (4–8)

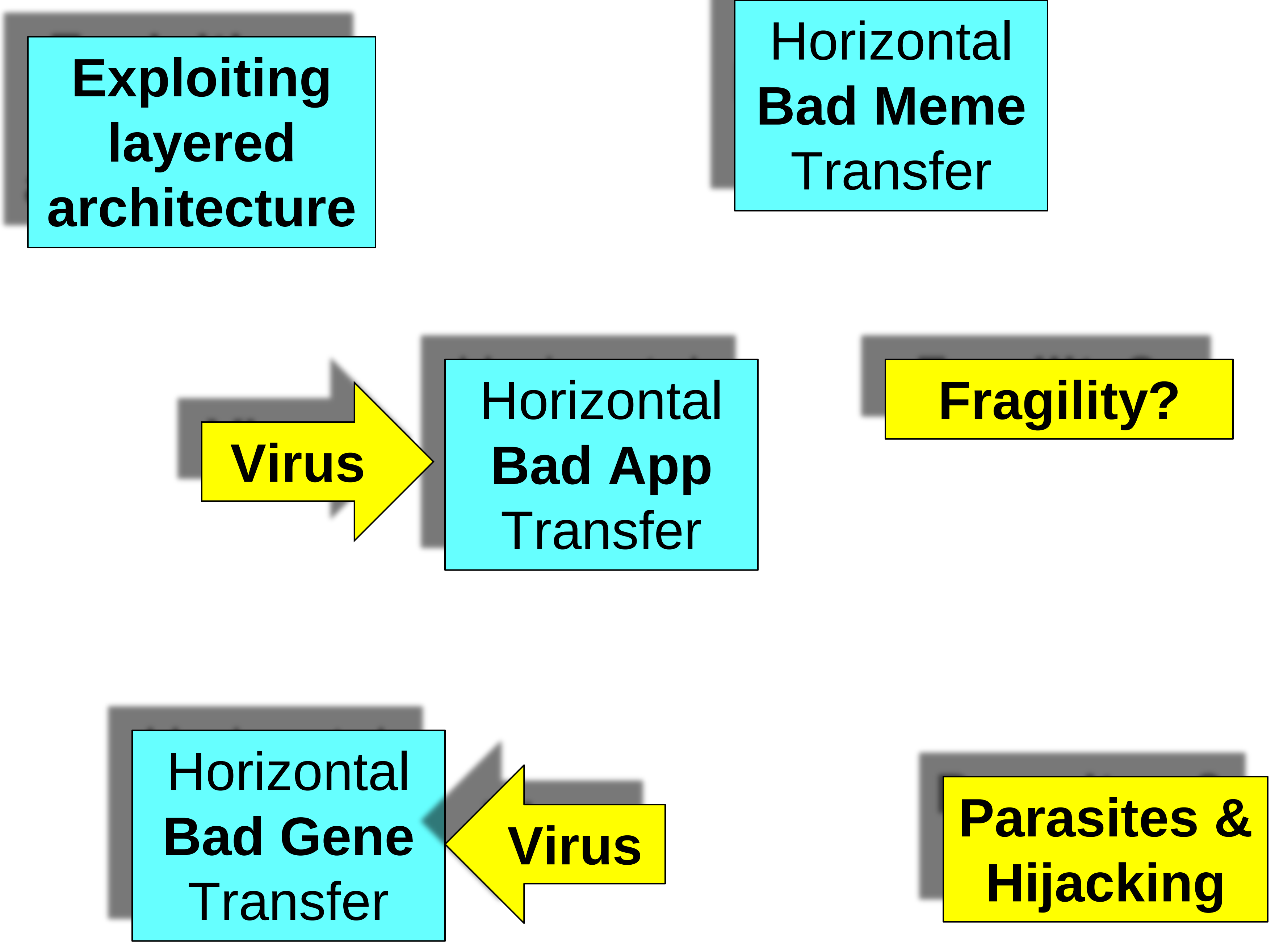
Think of this as a "protocol stack"

CNS "stack"

- Central nervous system
  - Brain
    - Prosencephalon
      - Telencephalon
        - Rhinencephalon, Amygdala, Hippocampus, Neocortex, Basal ganglia, Lateral ventricles
      - Diencephalon
        - Epithalamus, Thalamus, Hypothalamus, Subthalamus, Pituitary gland, Pineal gland, Third ventricle
    - Brain stem
      - Mesencephalon
        - Tectum, Cerebral peduncle, Pretectum, Mesencephalic duct
      - Rhombencephalon
        - Metencephalon
          - Pons, Cerebellum
        - Myelencephalon
          - Medulla oblongata
  - Spinal cord

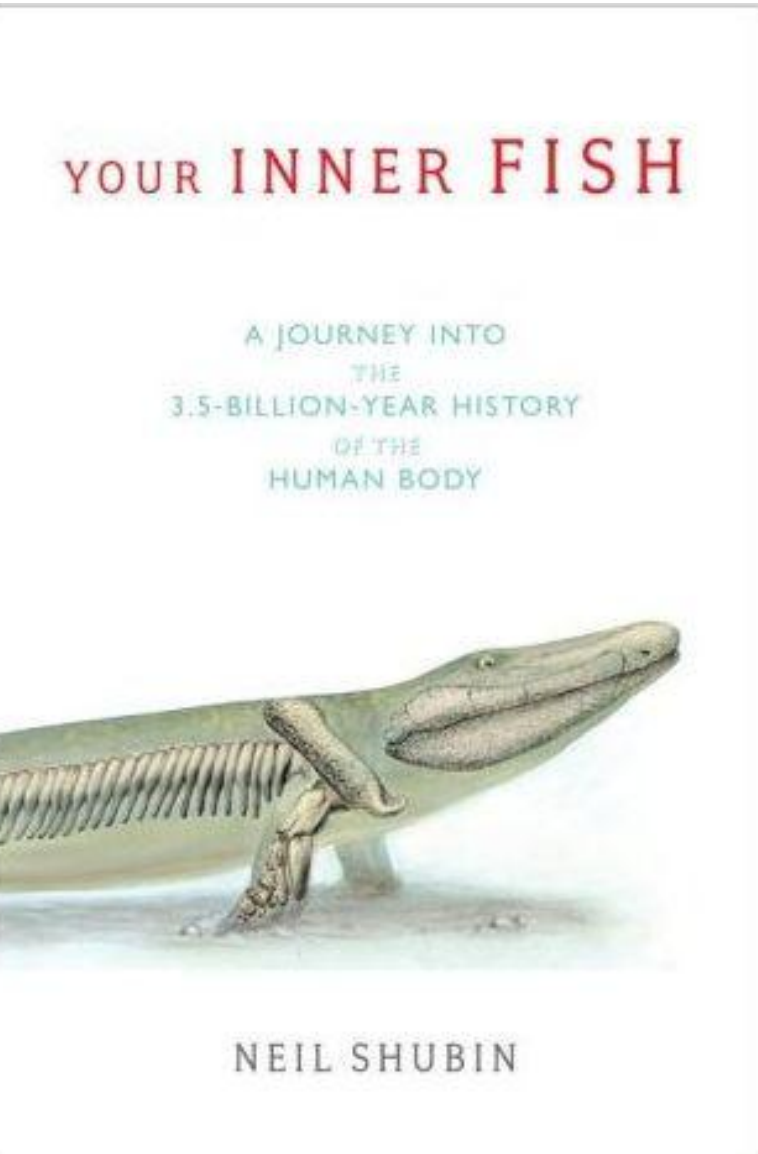
Universal architectures

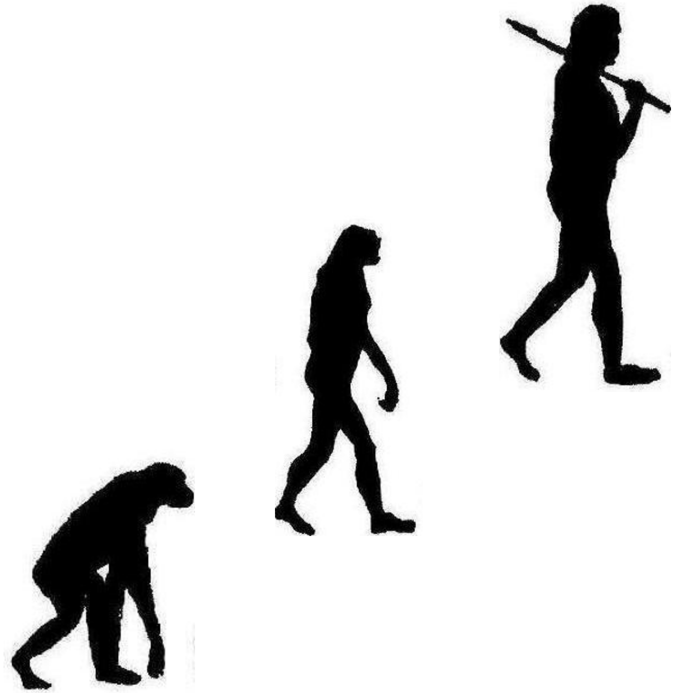
What can go wrong?



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

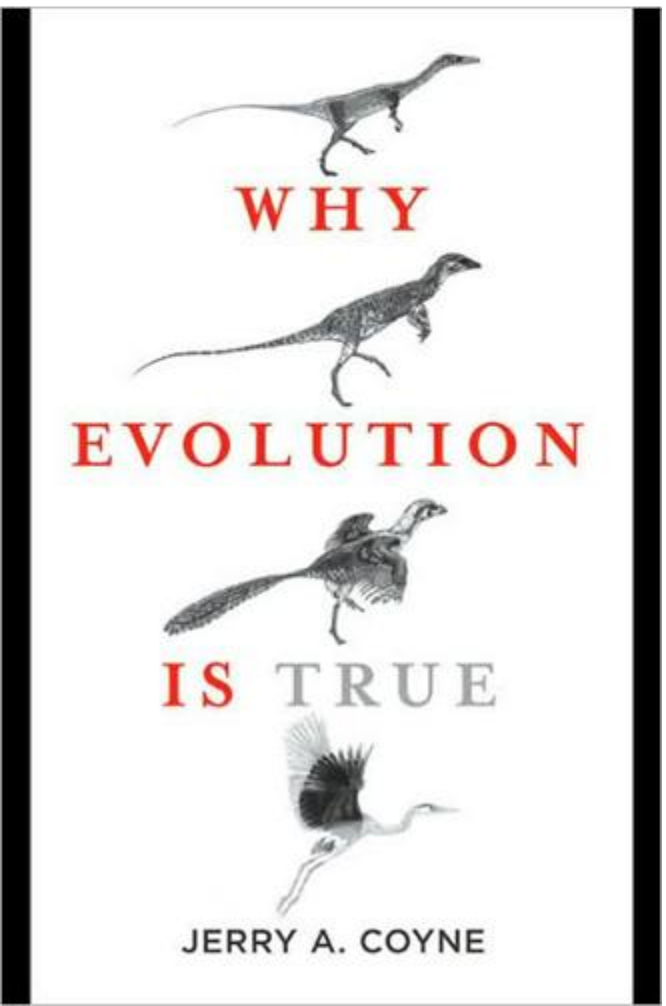
Unfortunately, not intelligent design

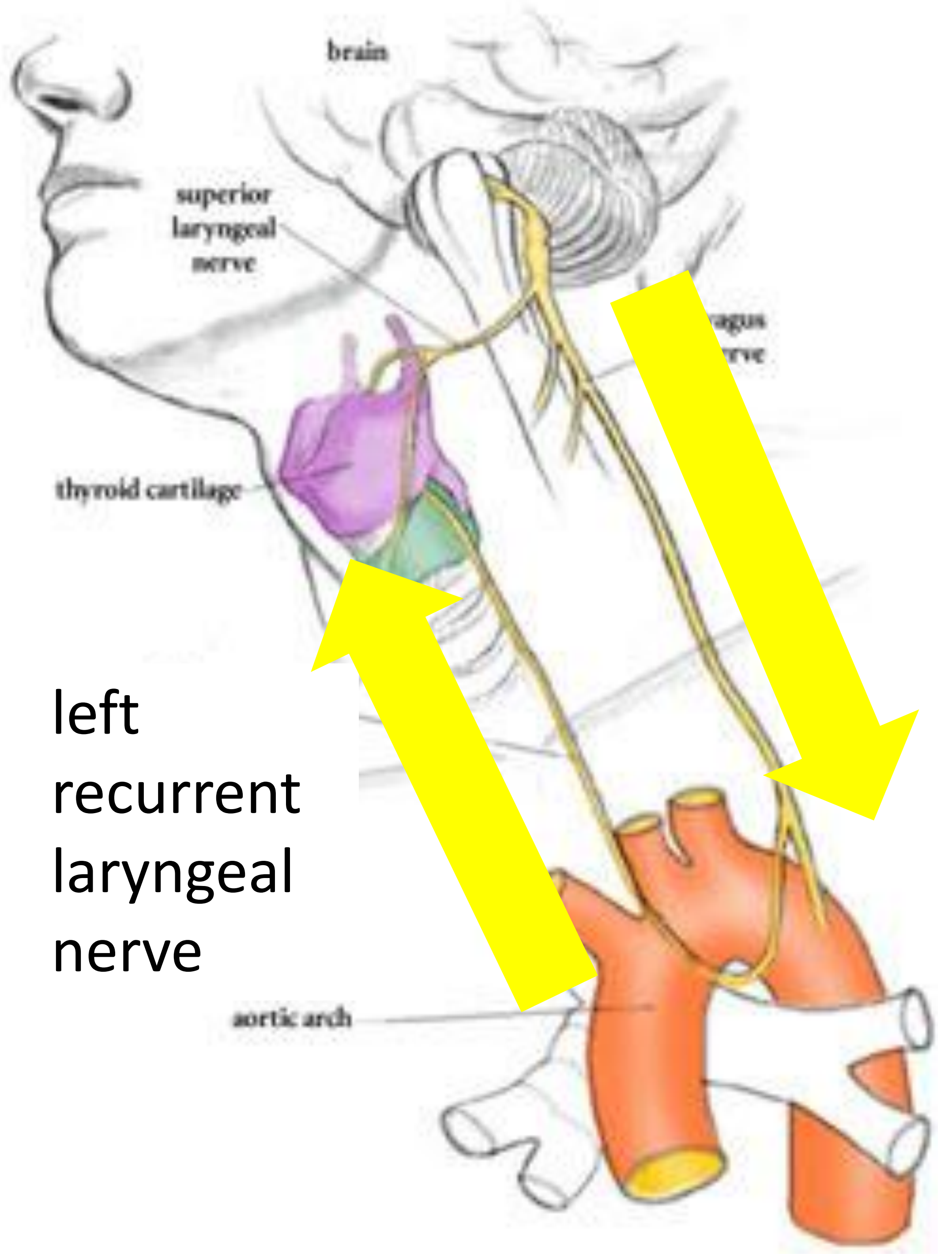




Ouch.

Why?





left
recurrent
laryngeal
nerve

Why? Building humans from fish parts.

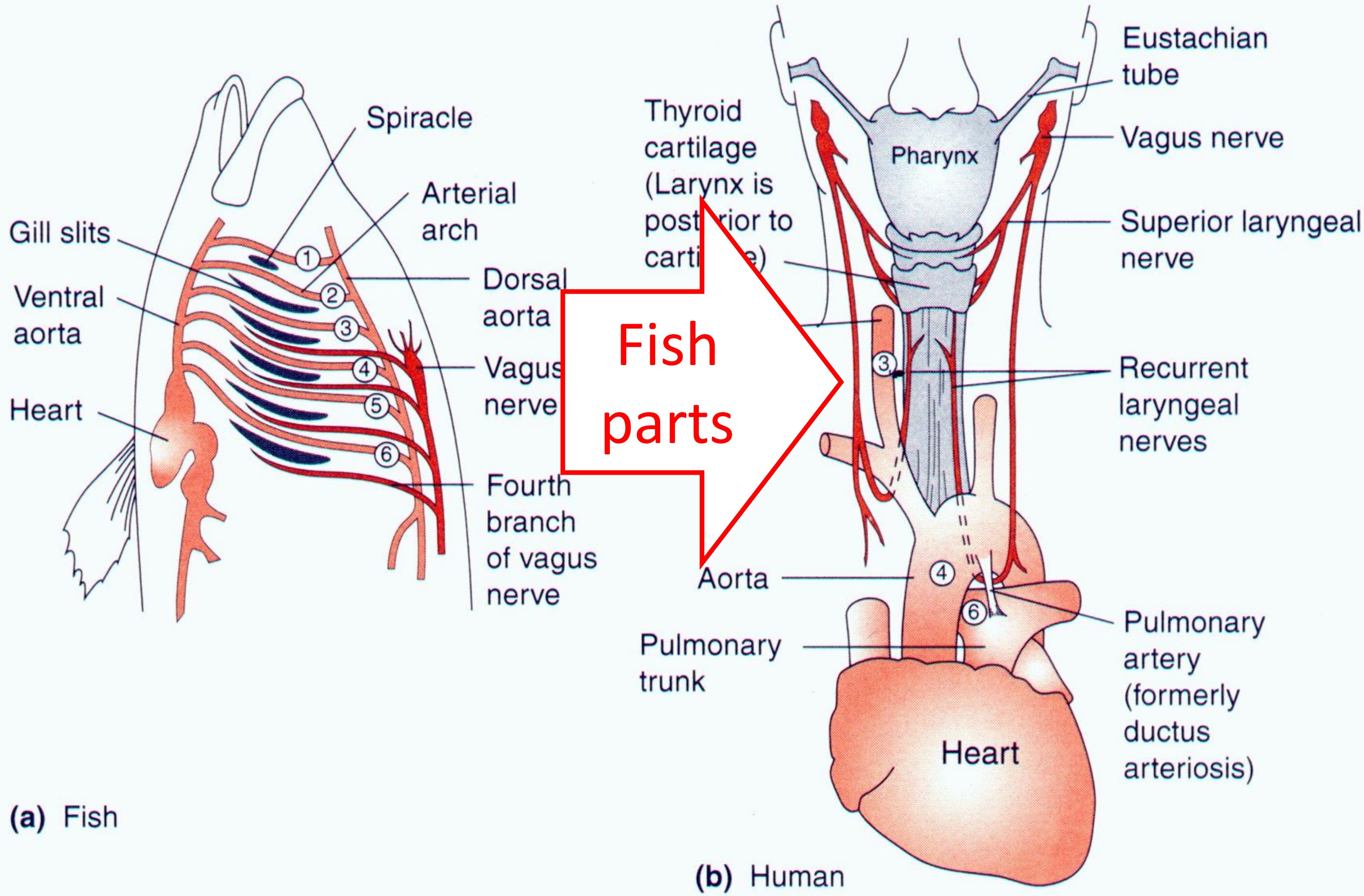
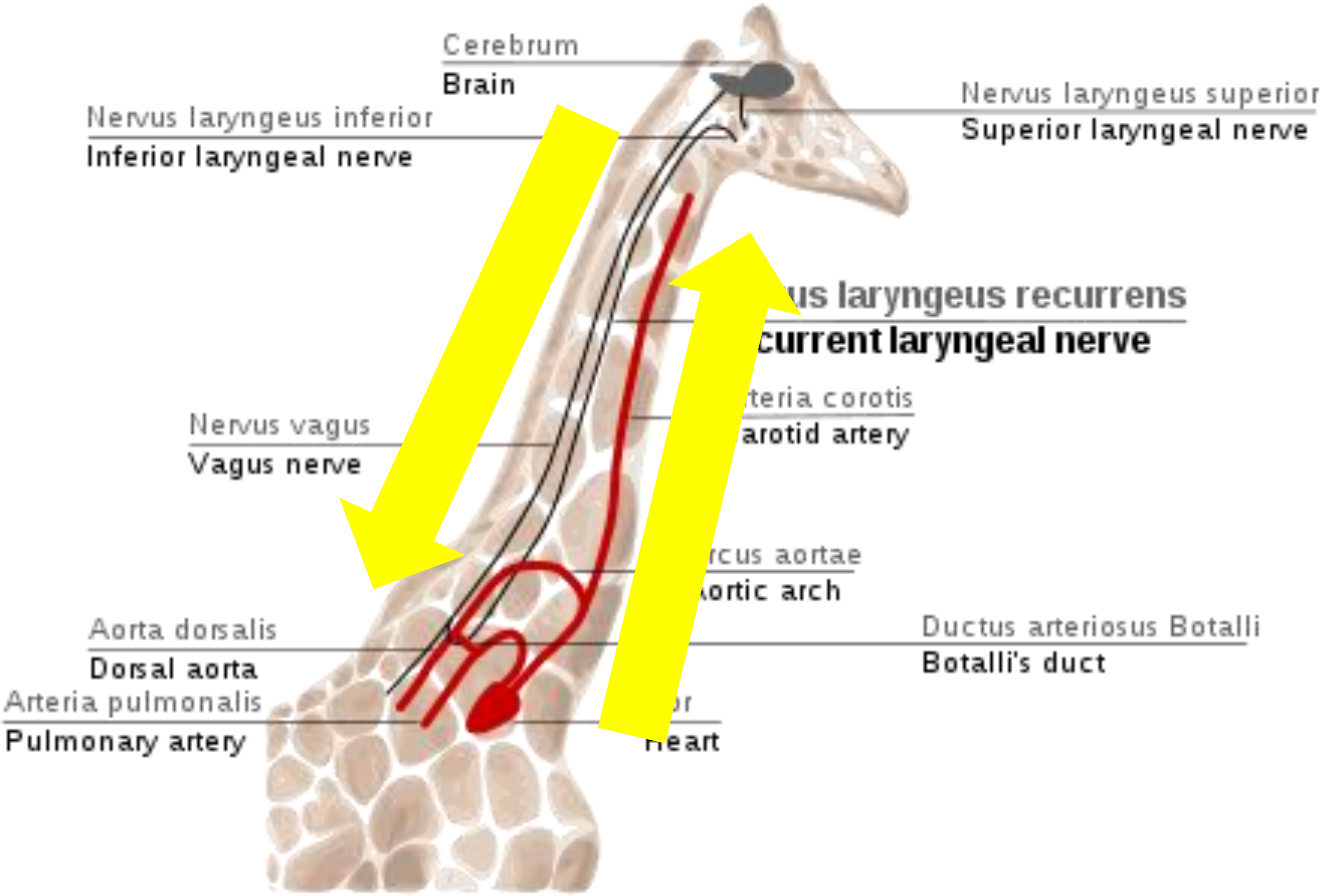
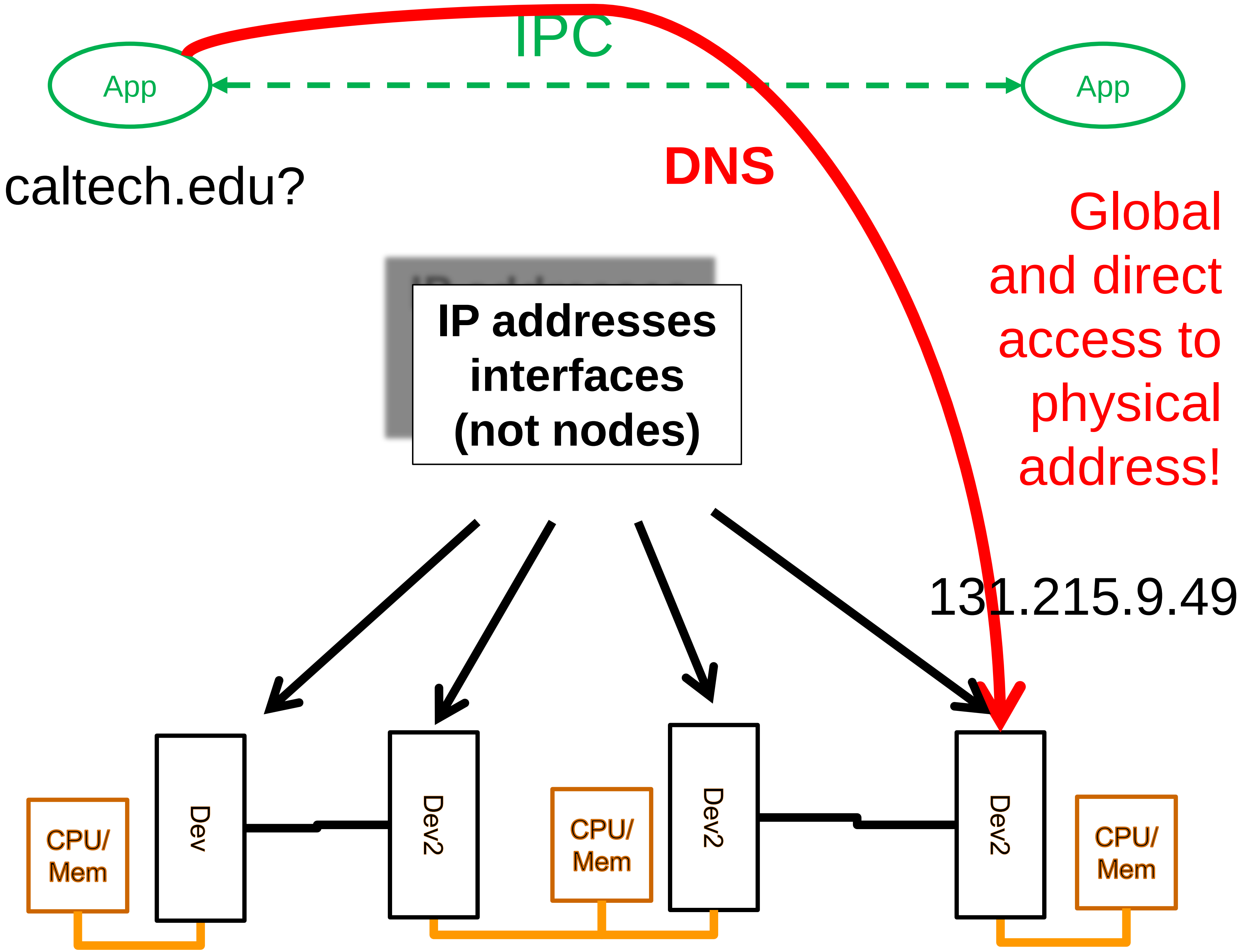


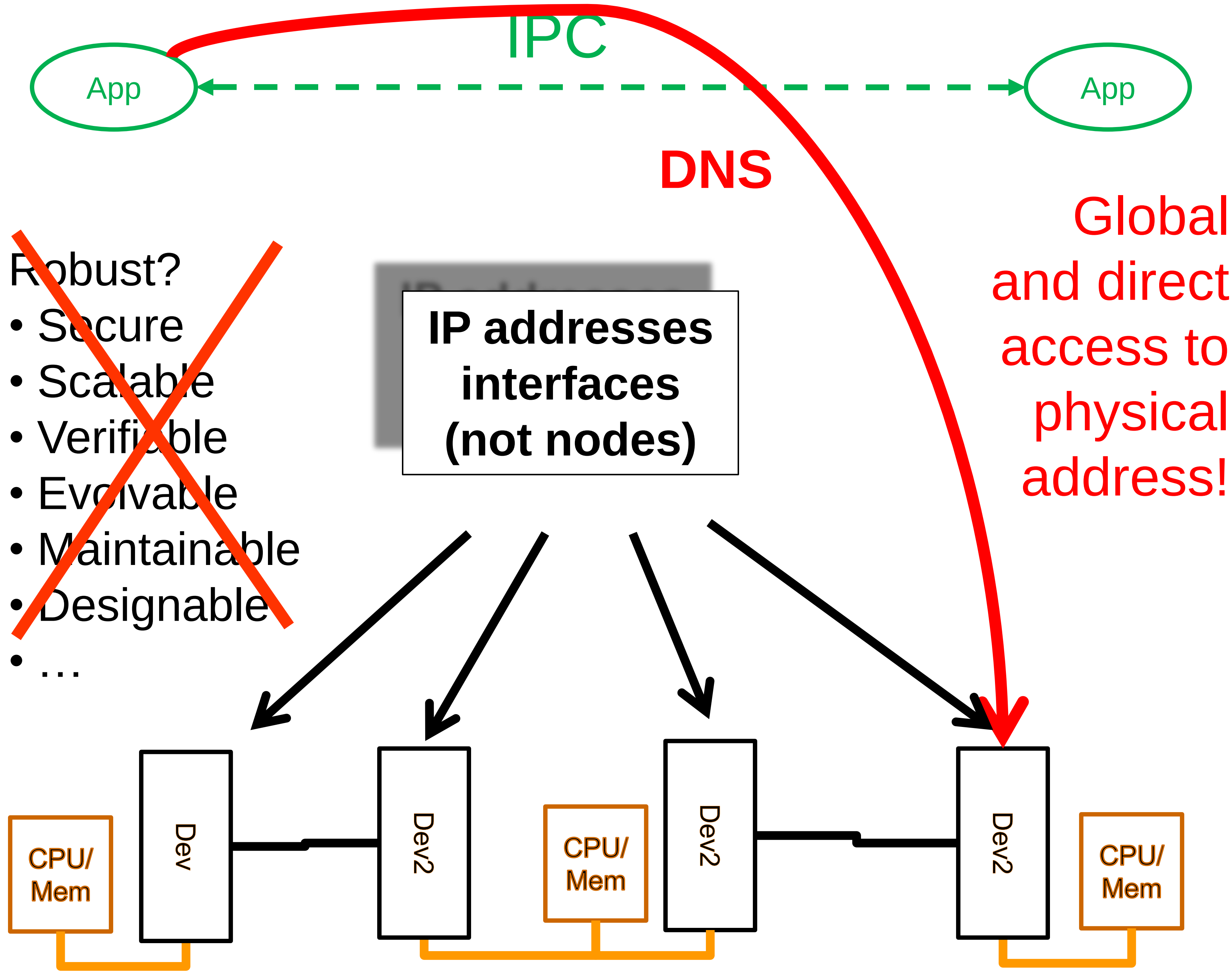
FIGURE 3–11 Schematic diagram showing the relationship between the vagus cranial nerve and the arterial arches in fish (*a*) and human (*b*). Only the third, fourth, and part of the sixth arterial arches remain in placental mammals, the sixth acting only during fetal development to carry blood to the placenta. The fourth vagal nerve in mammals (the recurrent laryngeal nerve) loops around the sixth arterial arch just as it did in the original fishlike ancestor, but must now travel a greater distance since the remnant of the sixth arch is in the thorax.

It could be worse.





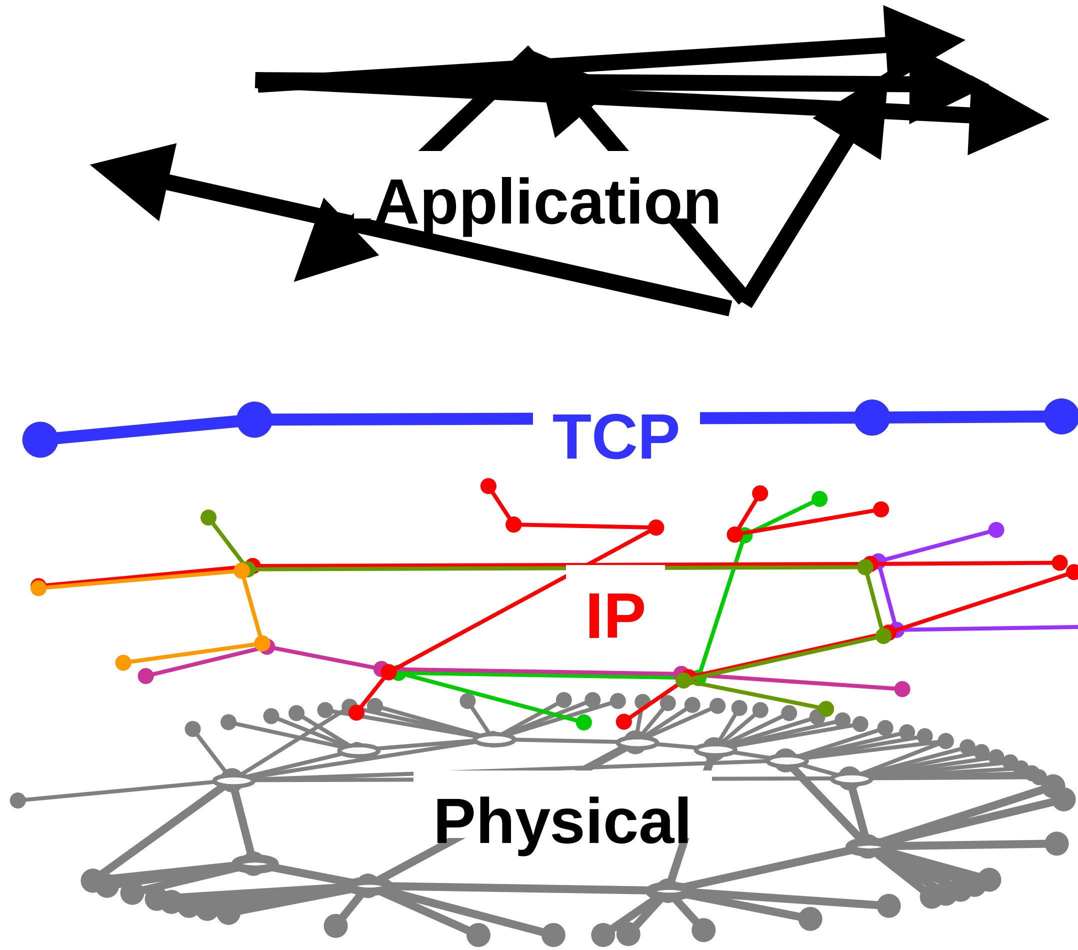
IPC
App
App
caltech.edu?
DNS
Global and direct access to physical address!
IP addresses interfaces (not nodes)
131.215.9.49
CPU/ Mem
Dev
Dev2
CPU/ Mem
Dev2
Dev2
CPU/ Mem

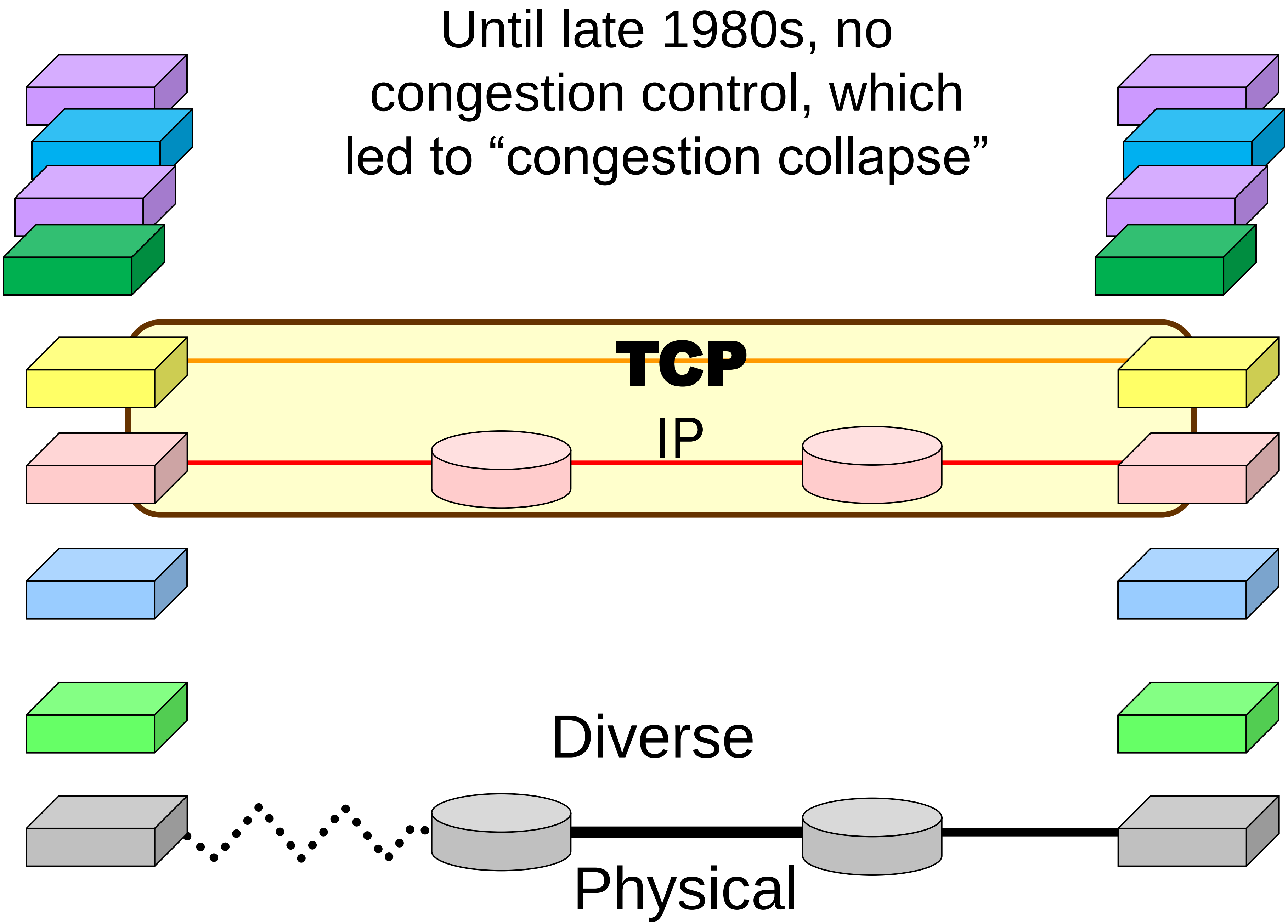


IPC
App
App
DNS
Global and direct access to physical address!
Robust?
• Secure
• Scalable
• Verifiable
• Evolvable
• Maintainable
• Designable
• …
IP addresses interfaces (not nodes)
CPU/ Mem
Dev
Dev2
CPU/ Mem
Dev2
Dev2
CPU/ Mem

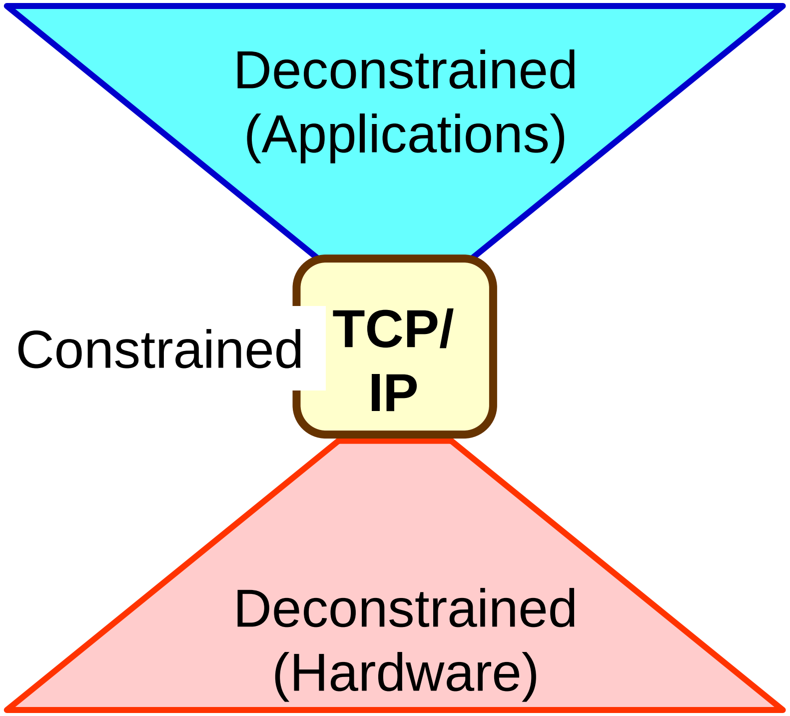
Naming and addressing need to have ***scope*** and
- resolved within layer
- translated between layers
- not exposed outside of layer

Related "issues"
- VPNs
- NATS
- Firewalls
- Multihoming
- Mobility
- Routing table size
- Overlays
- …




Until late 1980s, no
congestion control, which
led to “congestion collapse”
TCP
IP
Diverse
Physical

Original design challenge?



Networked OS

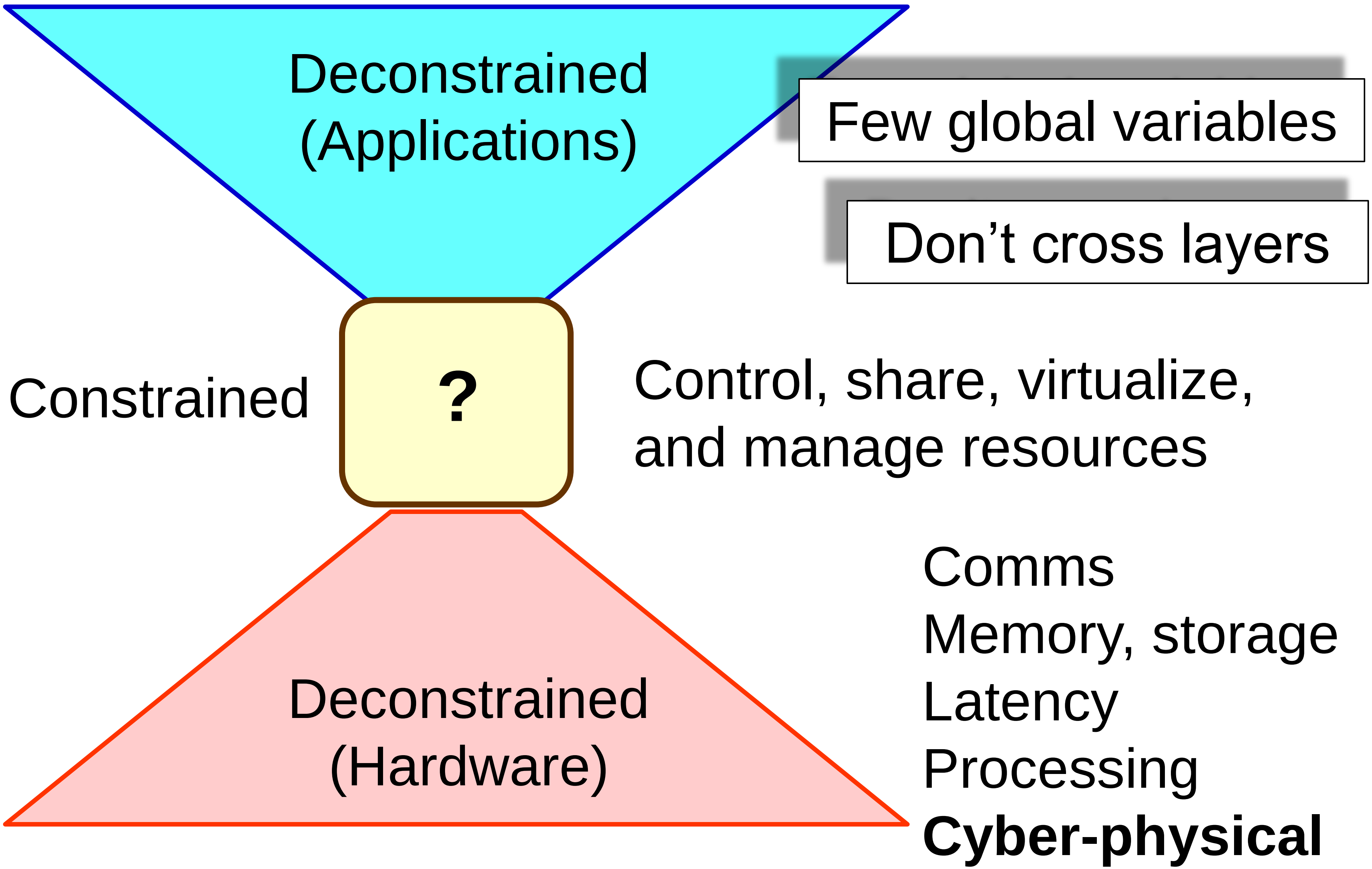
- Expensive mainframes
- Trusted end systems
- Homogeneous
- Sender centric
- Unreliable comms

Facilitated wild evolution

Created

- whole new ecosystem
- completely opposite

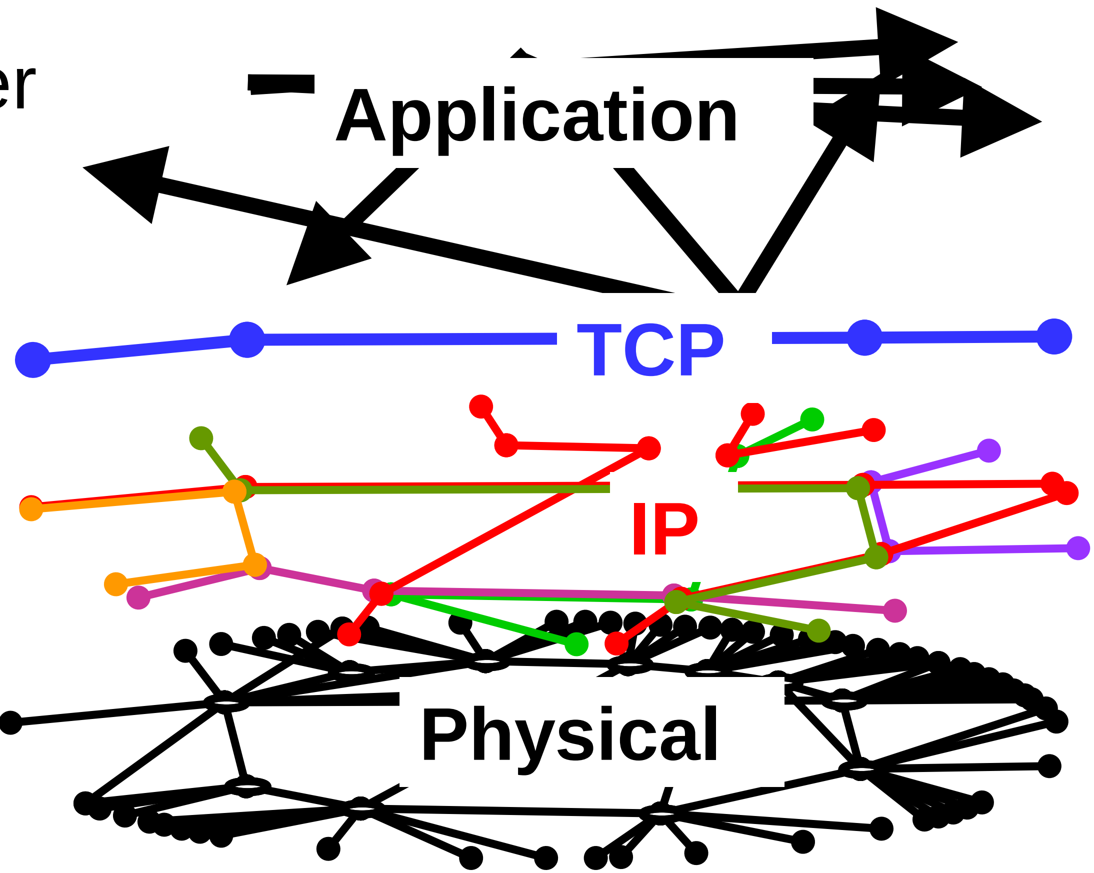
Next layered architectures



Persistent errors and confusion ("network science")

Architecture is ***least*** graph topology.

Every layer has different diverse graphs.



Architecture facilitates arbitrary graphs.

The "robust yet fragile" nature of the Internet

John C. Doyle*†, David L. Alderson*, Lun Li*, Steven Low*, Matthew Roughan‡, Stanislav Shalunov§, Reiko Tanaka¶, and Walter Willinger‖

*Engineering and Applied Sciences Division, California Institute of Technology, Pasadena, CA 91125; ‡Applied Mathematics, University of Adelaide, South Australia 5005, Australia; §Internet2, 3025 Boardwalk Drive, Suite 200, Ann Arbor, MI 48108; ¶Bio-Mimetic Control Research Center, Institute of Physical and Chemical Research, Nagoya 463-0003, Japan; and ‖AT&T Labs–Research, Florham Park, NJ 07932

Edited by Robert M. May, University of Oxford, Oxford, United Kingdom, and approved August 29, 2005 (received for review February 18, 2005)

The search for unifying properties of complex networks is popular, challenging, and important. For modeling approaches that focus on

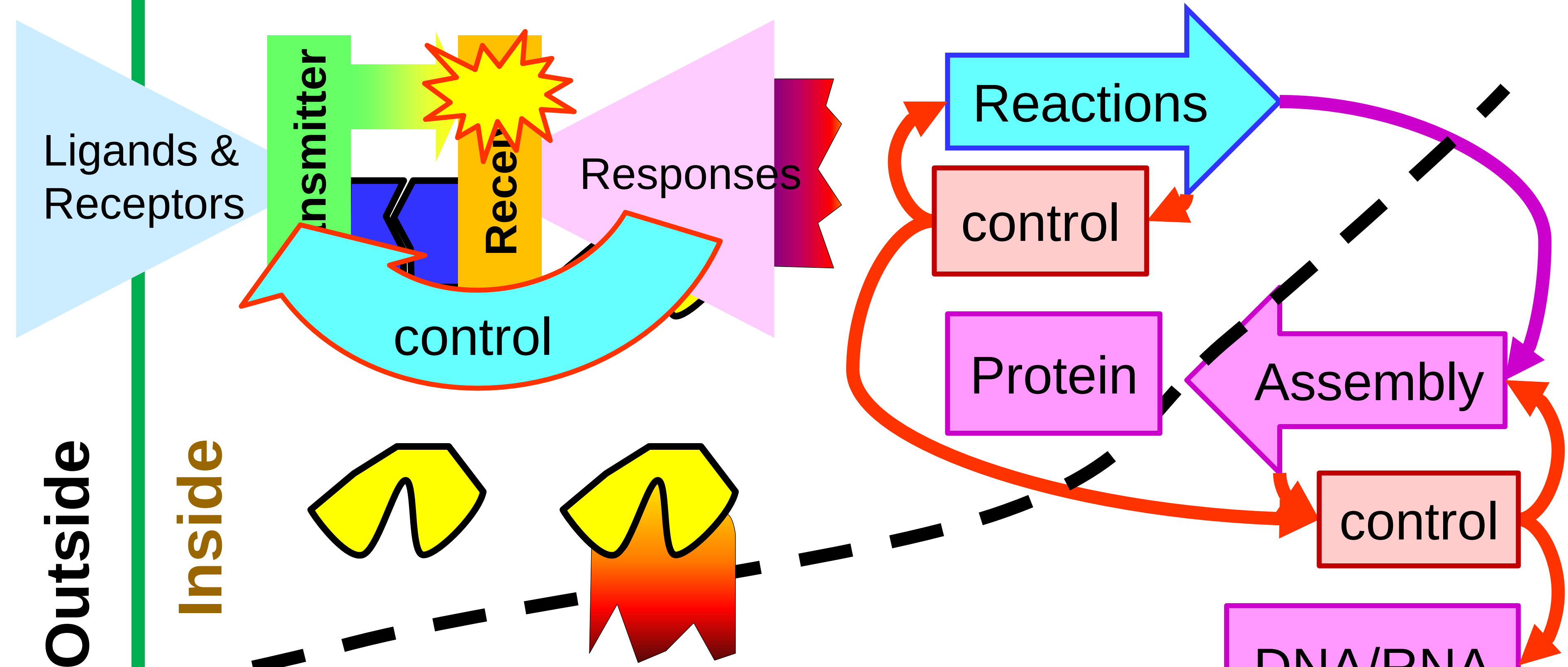
no self-loops or parallel edges) having the same graph degree
We will say that graphs $g \in G(D)$ have scaling-degree sequen

PNAS | October 11, 2005 | vol. 102 | no. 41 | 14497–14502

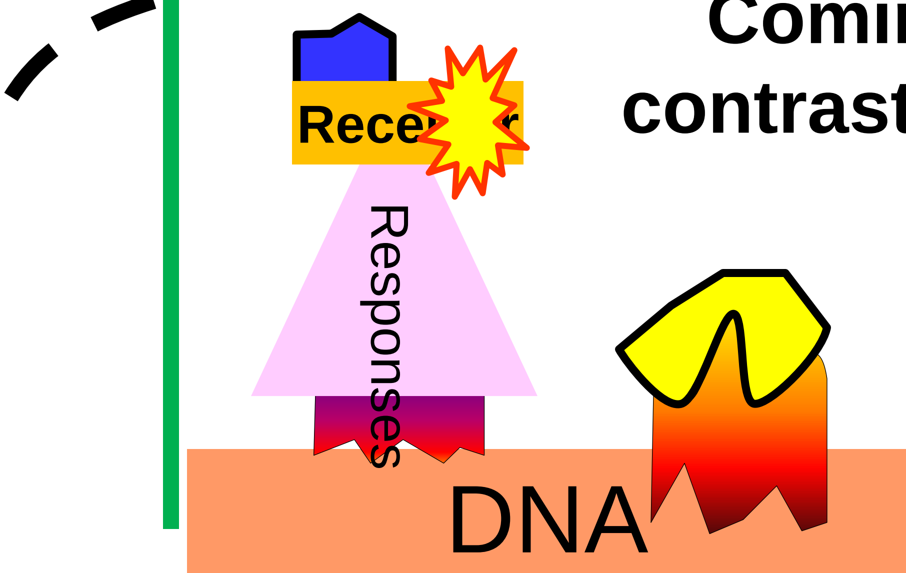
Notices of the AMS, 2009

Mathematics and the Internet: A Source of Enormous Confusion and Great Potential

Walter Willinger, David Alderson, and John C. Doyle

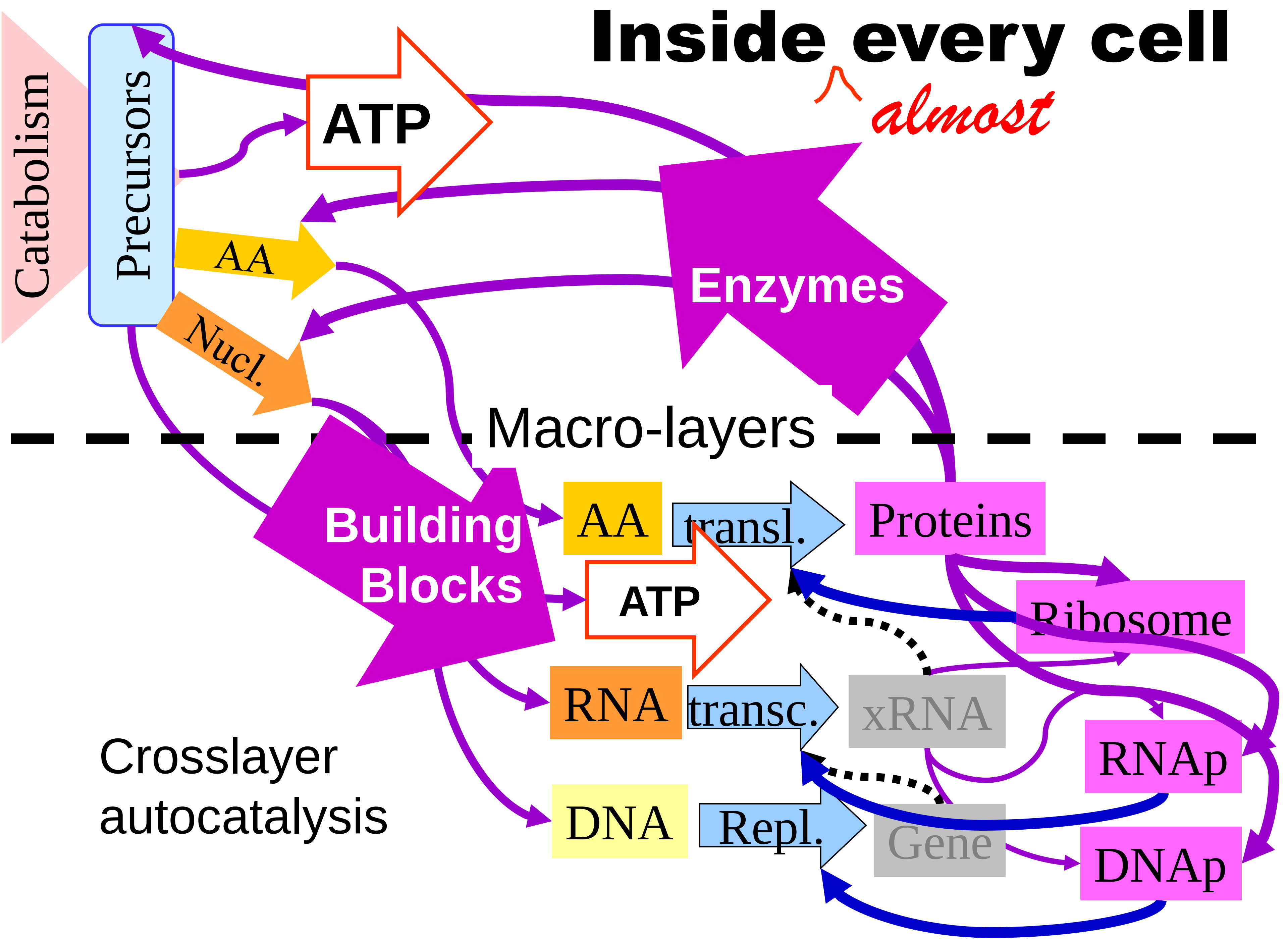


Coming later: contrast with cells



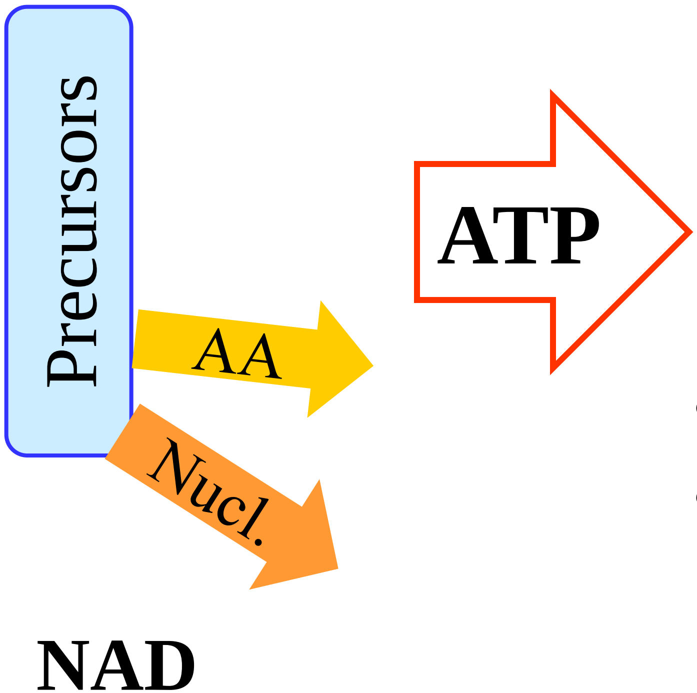
Cross-layer control

- Highly organized
- Naming and addressing

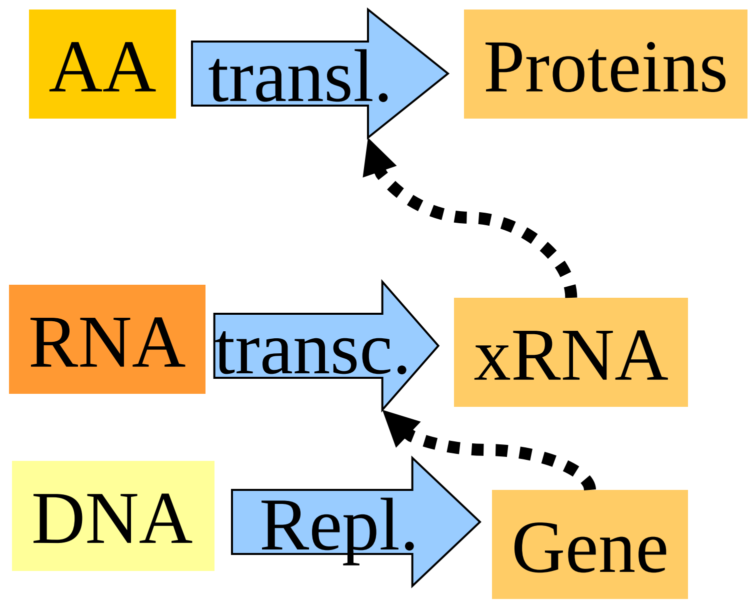


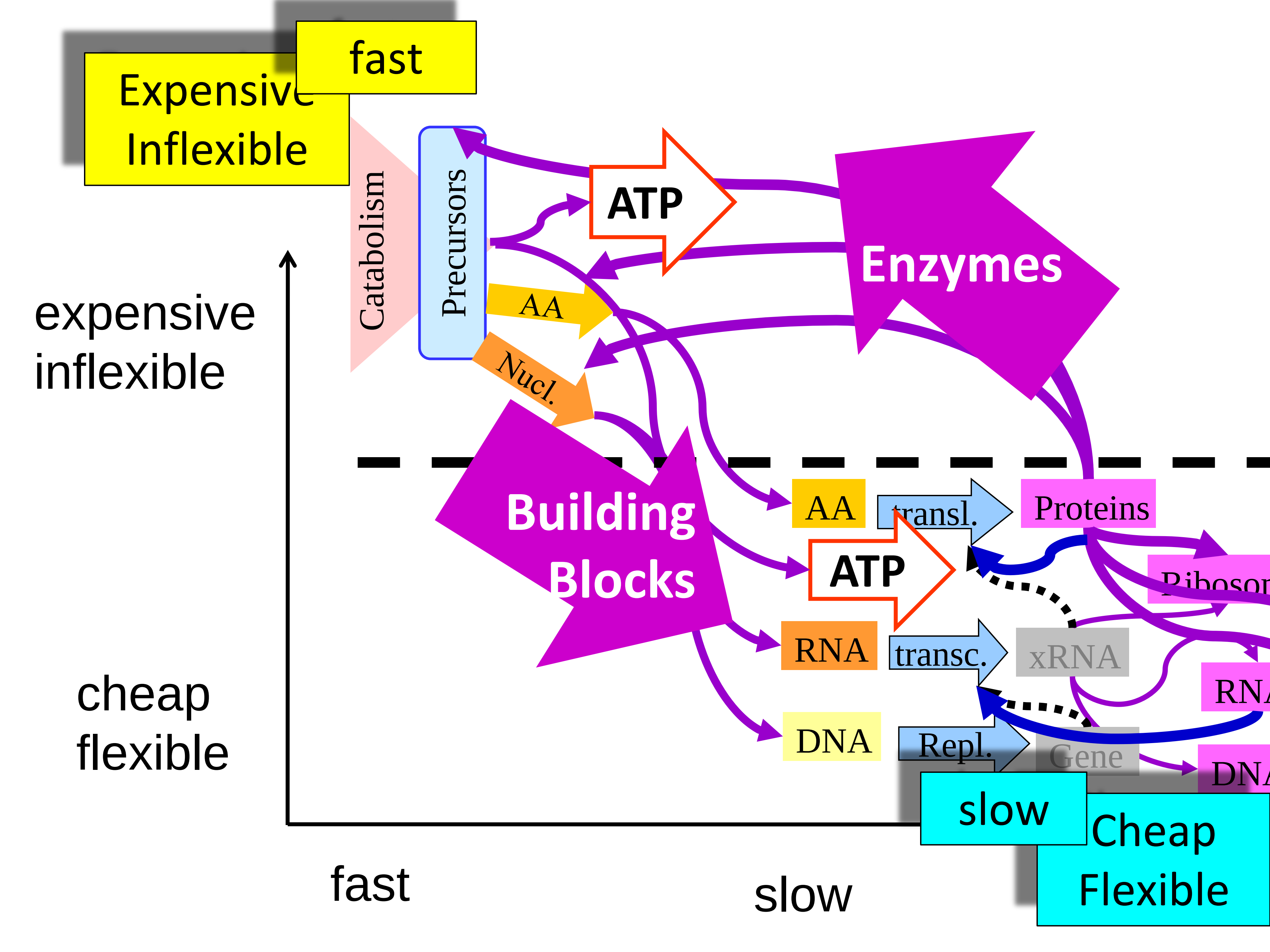
Inside every cell
almost
Catabolism
Precursors
ATP
AA
Nucl.
Enzymes
Macro-layers
Building Blocks
AA
transl.
Proteins
ATP
Ribosome
RNA
transc.
xRNA
RNAp
DNA
Repl.
Gene
DNAp
Crosslayer autocatalysis

Shared protocols

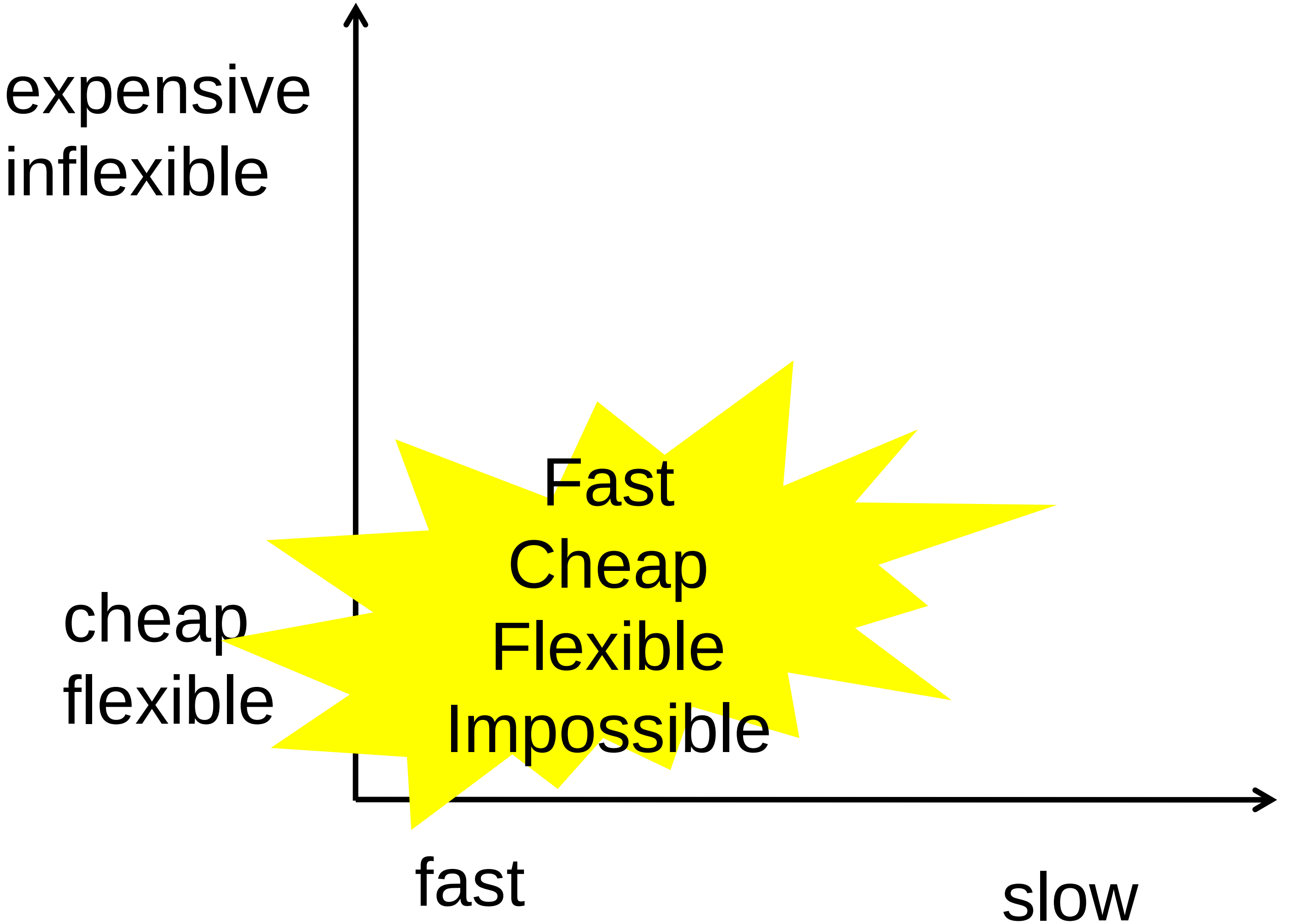


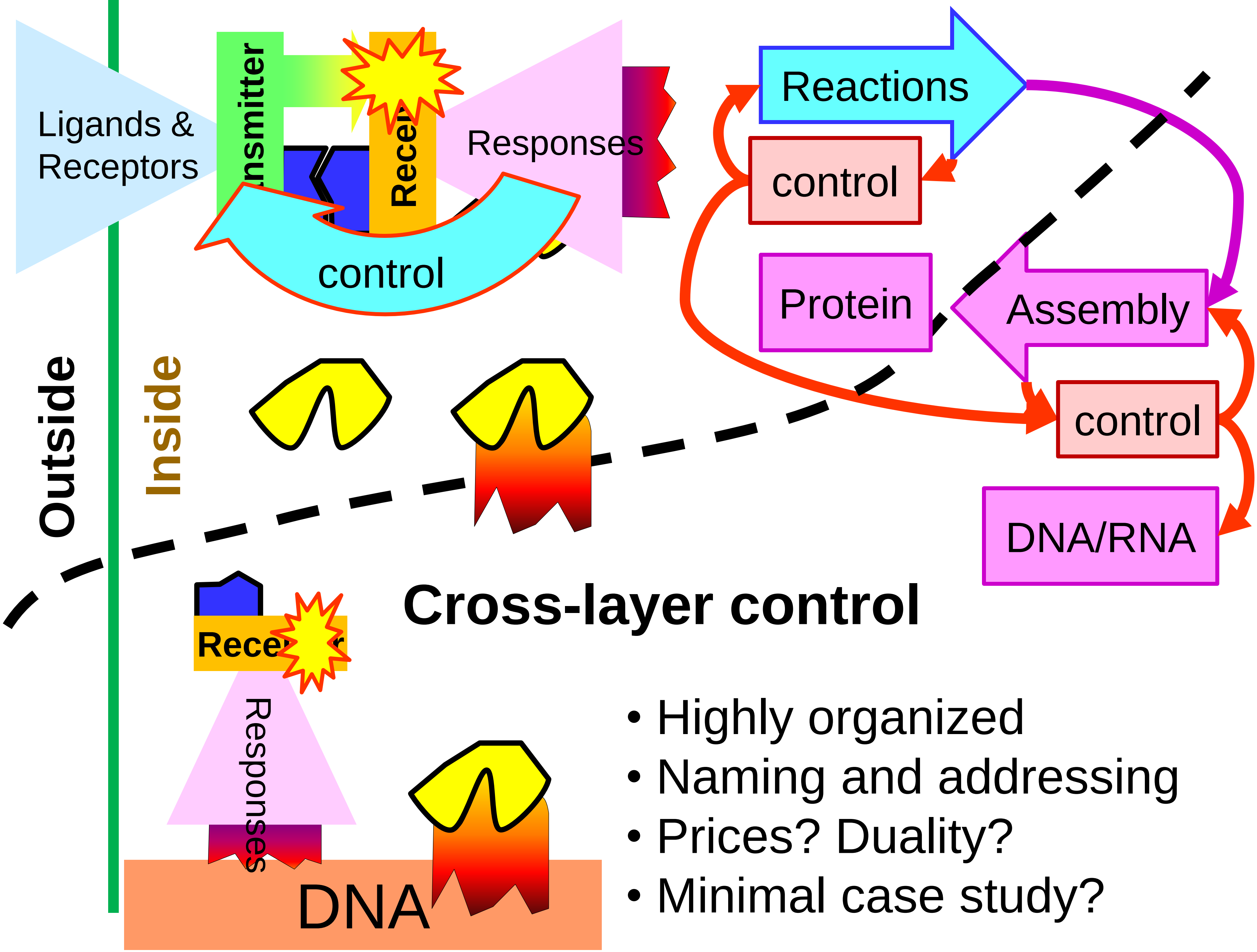
- Universal core constraints
- “virtual machines”



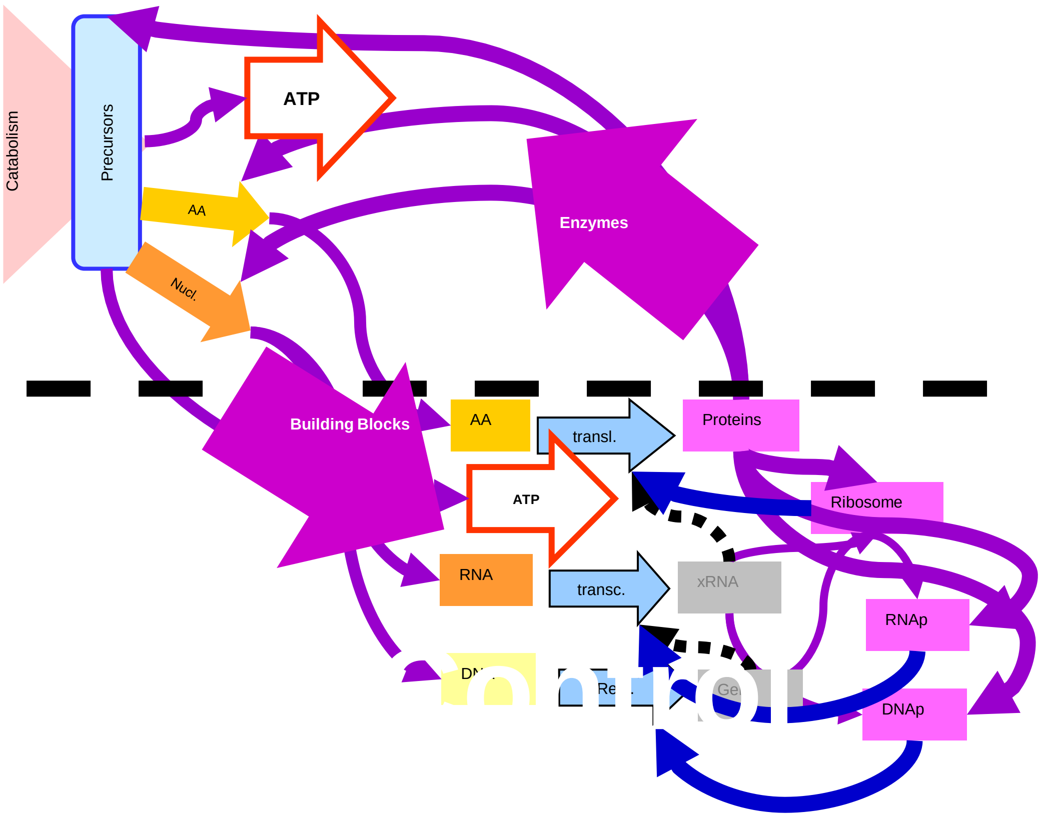


fast
Expensive
Inflexible
Catabolism
Precursors
ATP
Enzymes
AA
Nucl.
expensive
inflexible
Building
Blocks
AA
transl.
Proteins
ATP
RNA
transc.
xRNA
DNA
Repl.
Gene
cheap
flexible
slow
Cheap
Flexible
fast
slow


expensive
inflexible
cheap
flexible
Fast
Cheap
Flexible
Impossible
fast
slow


Ligands & Receptors
Transmitter
Receptor
Responses
control
Outside
Inside
Reactions
control
Protein
Assembly
control
DNA/RNA
Cross-layer control
Receptor
Responses
DNA
• Highly organized
• Naming and addressing
• Prices? Duality?
• Minimal case study?

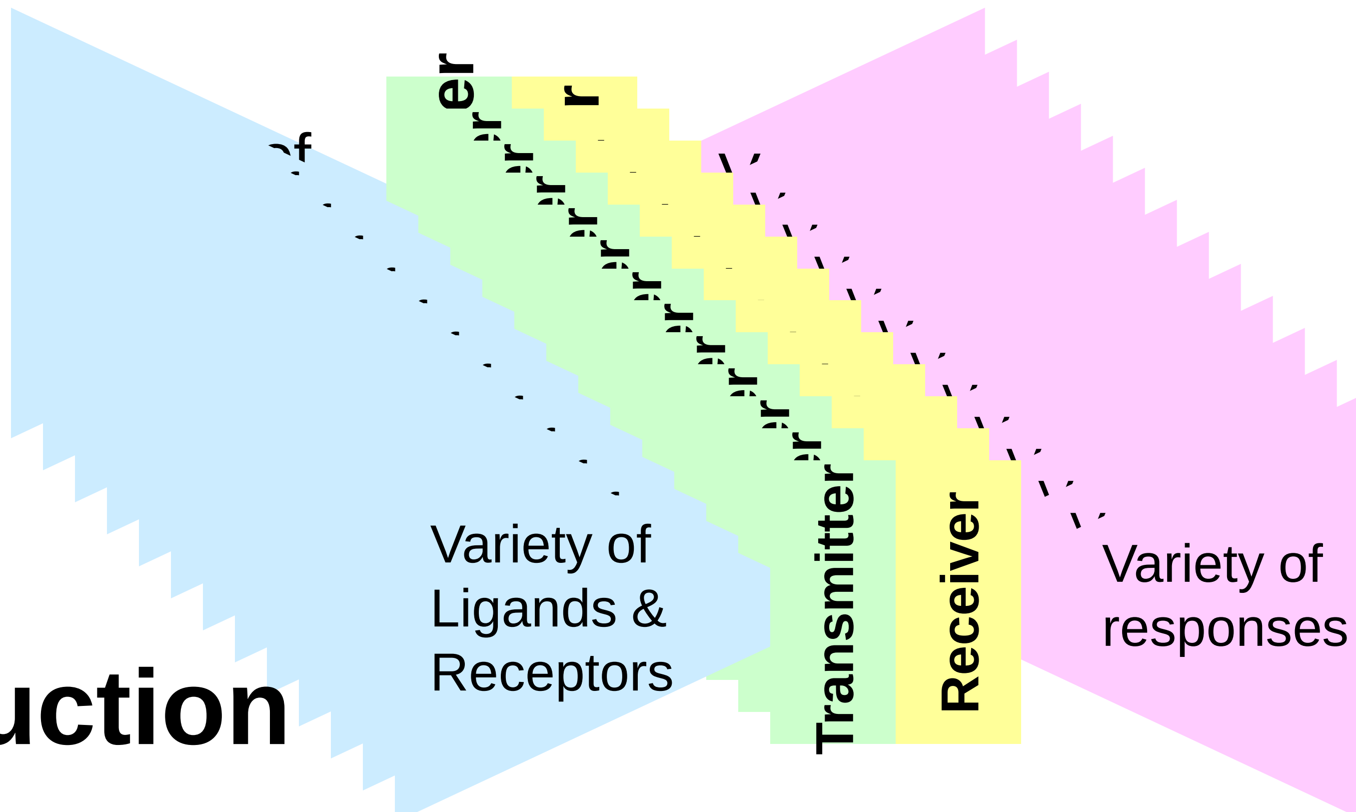
Upper megalayer/metalayer performs all cell functions, behaviors, scope is functional, distributed



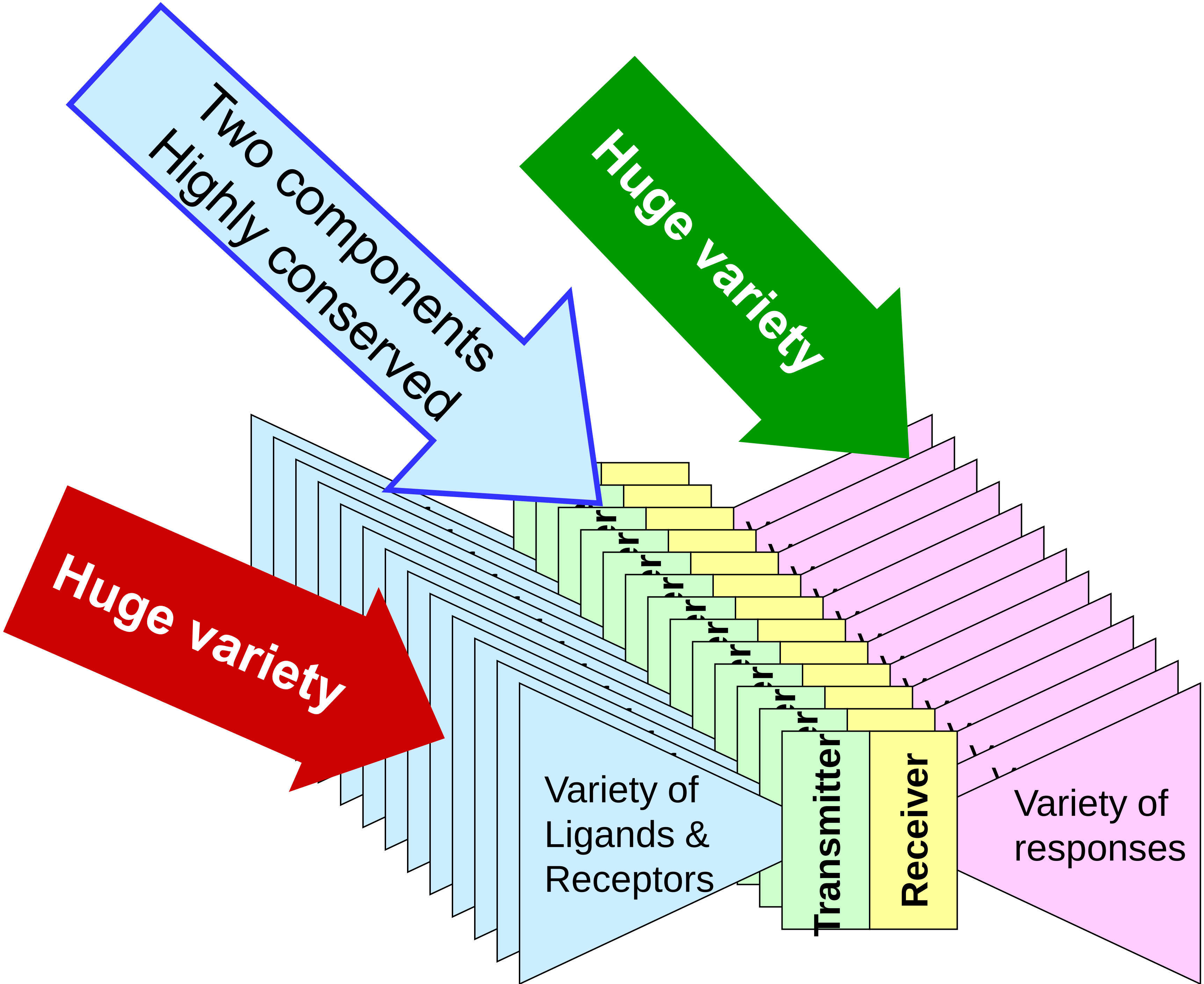
Signal transduction and transcription factors do name/address translation

Genome is physical, scope is location

- ≈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

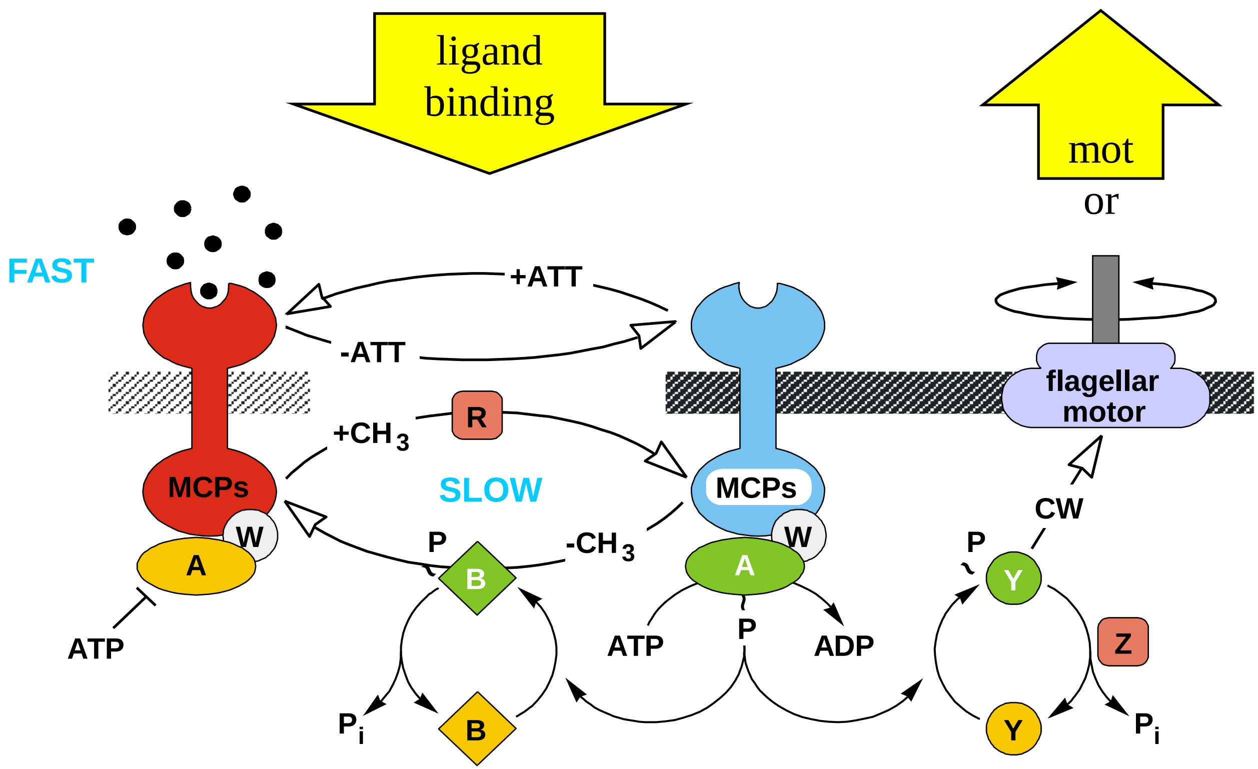


Signal transduction

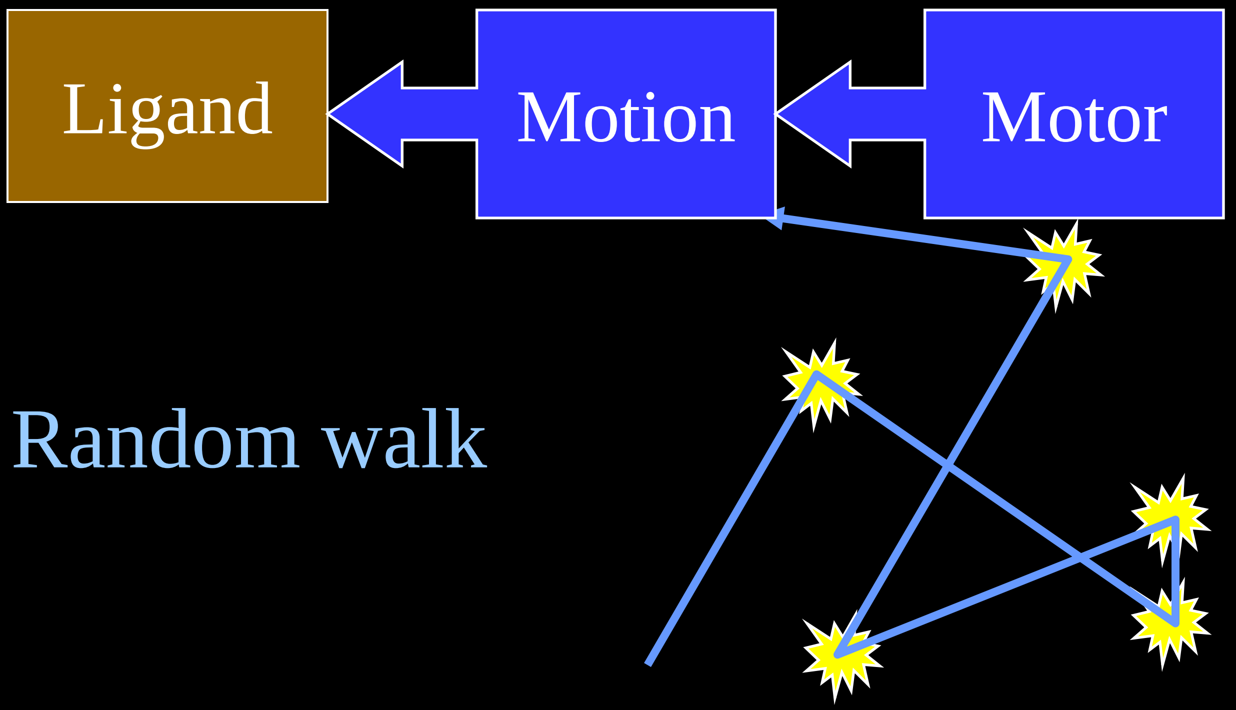

Two components
Highly conserved
Huge variety
Huge variety
Variety of
Ligands &
Receptors
Transmitter
Receiver
Variety of
responses

More necessity and robustness

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



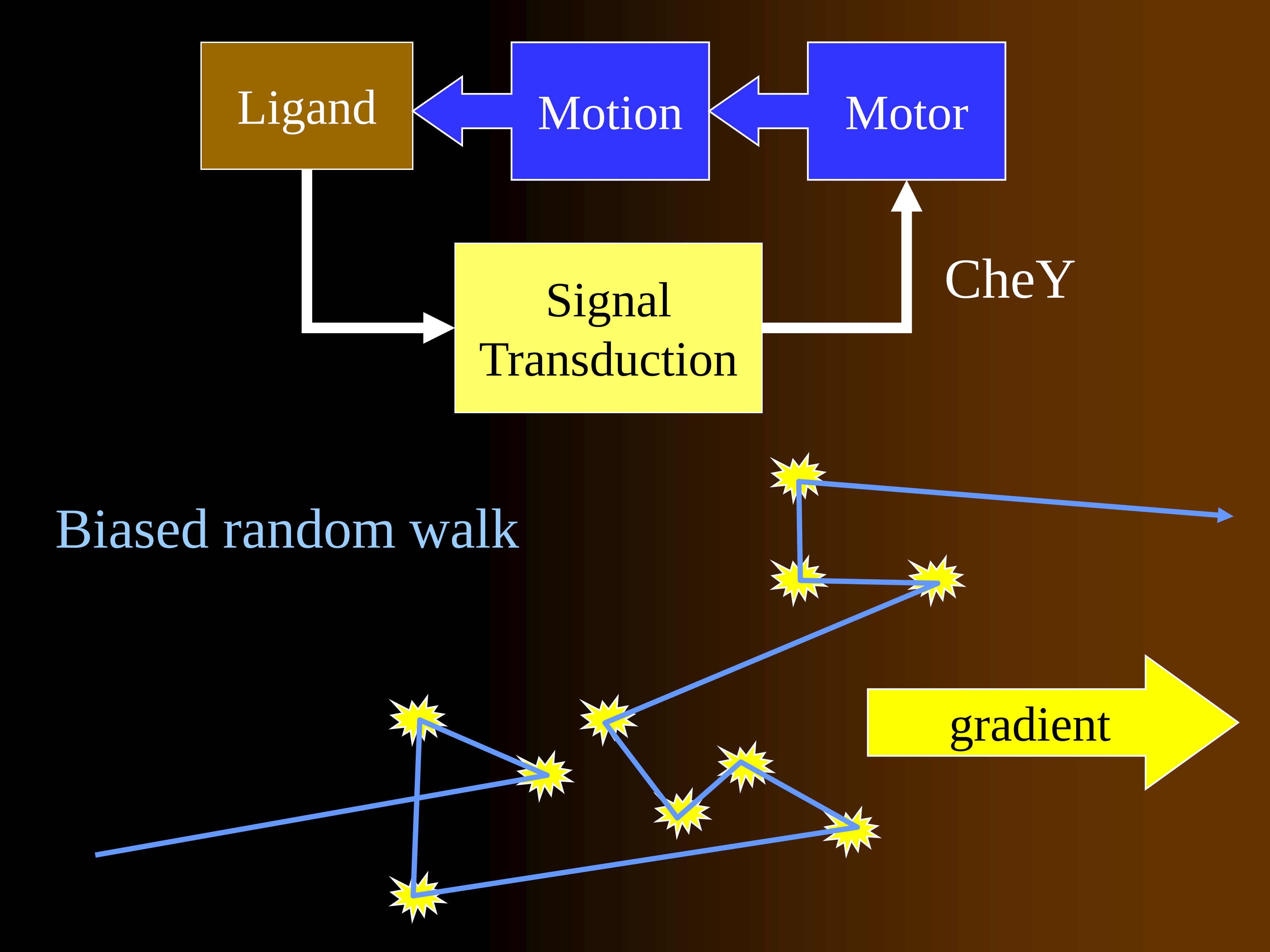
Bacterial chemotaxis

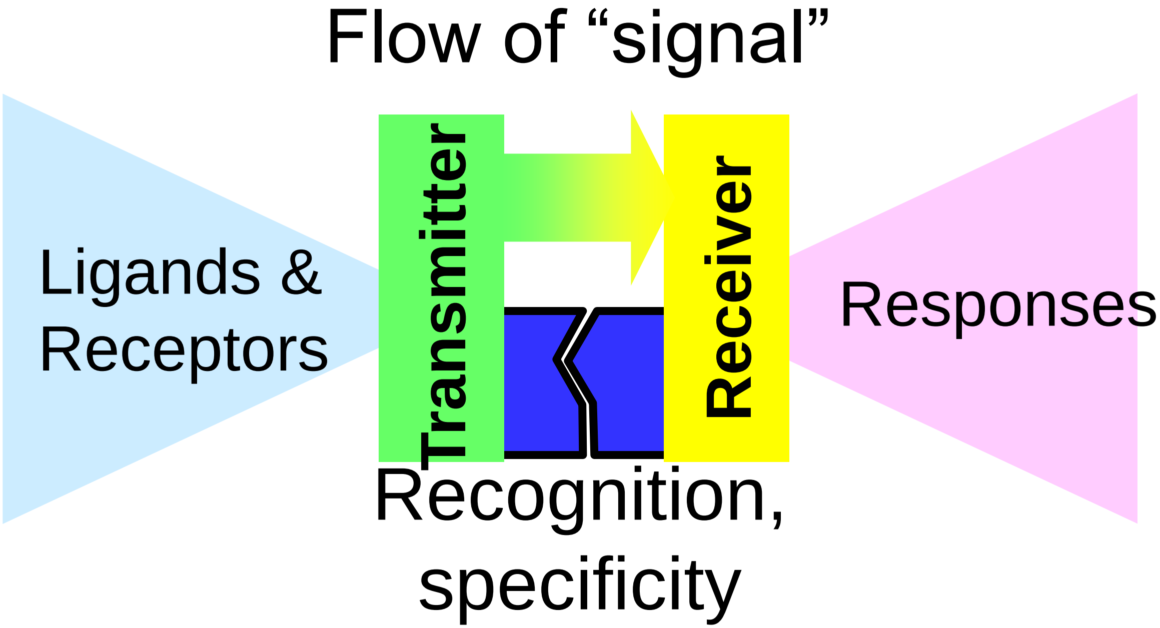


Robust perfect adaptation in bacterial chemotaxis through integral feedback control

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

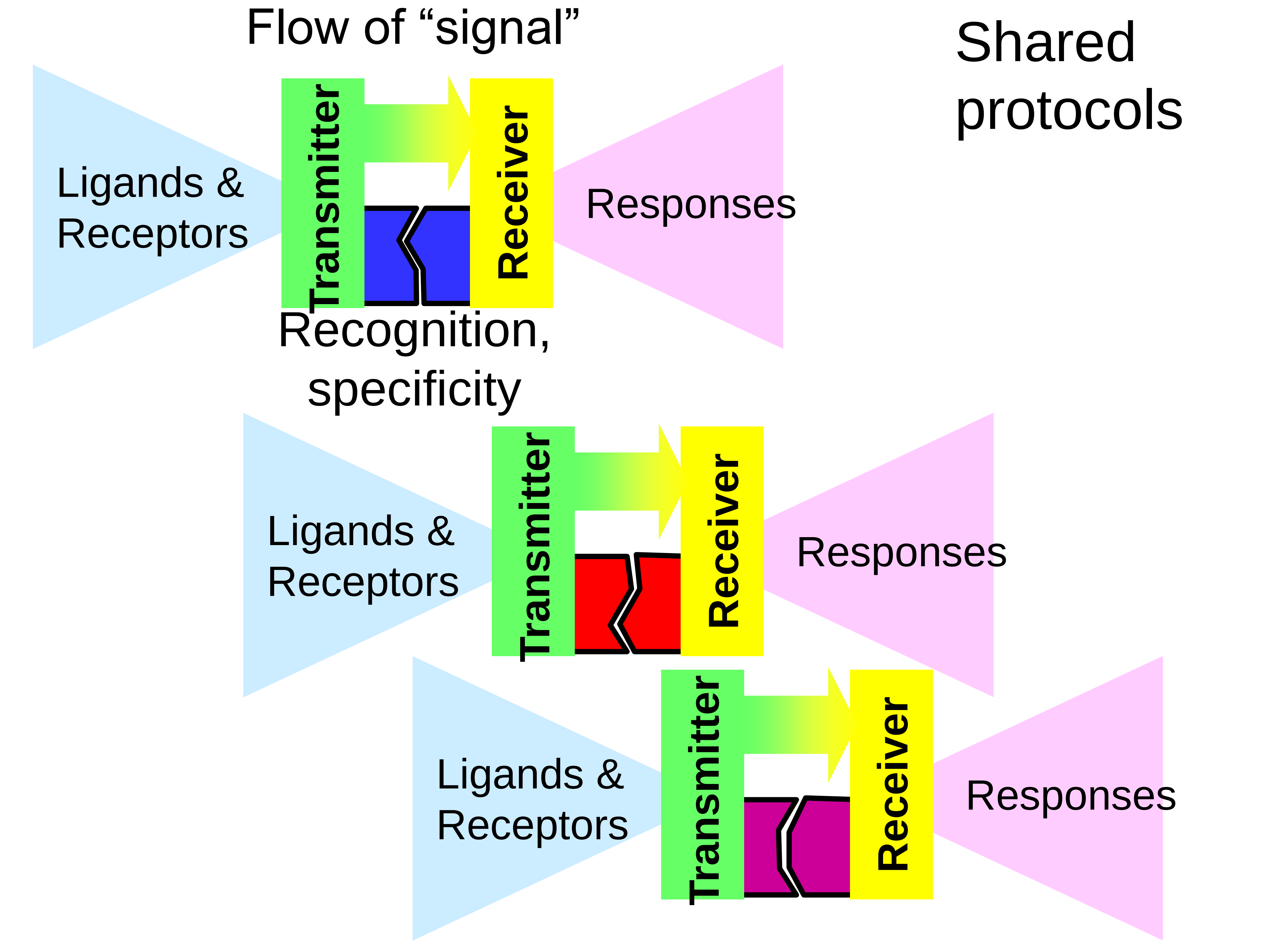
PNAS | **April 25, 2000** | vol. 97 | no. 9 | **4649–4653**


Ligand
Motion
Motor
Signal Transduction
CheY
Biased random walk
gradient

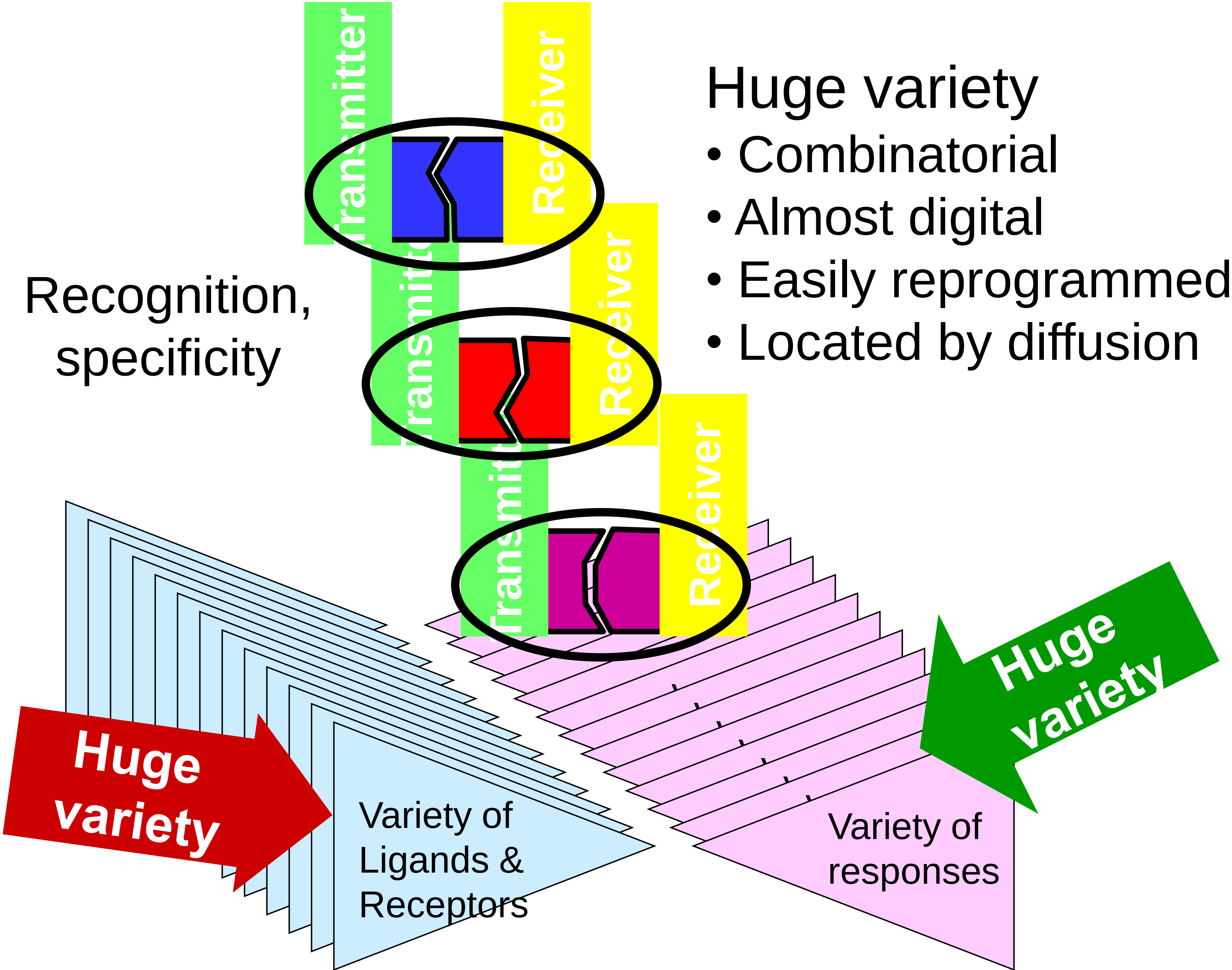


Shared protocols

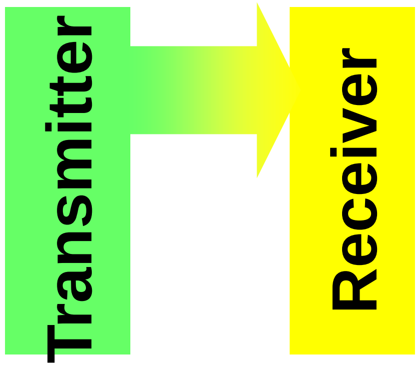
- “Name resolution” within signal transduction
- Transmitter must locate “cognate” receiver and avoid non-cognate receivers
- Global search by rapid, local diffusion
- Limited to very small volumes



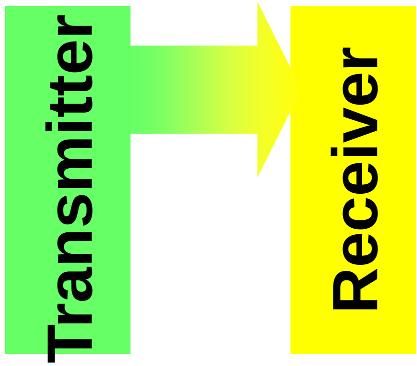
Flow of "signal"
Shared protocols
Ligands &
Receptors
Transmitter
Receiver
Responses
Recognition,
specificity
Ligands &
Receptors
Transmitter
Receiver
Responses
Ligands &
Receptors
Transmitter
Receiver
Responses


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

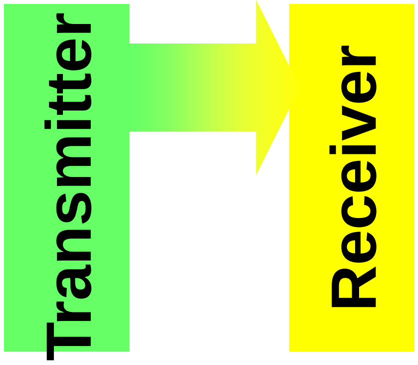
Flow of "signal"



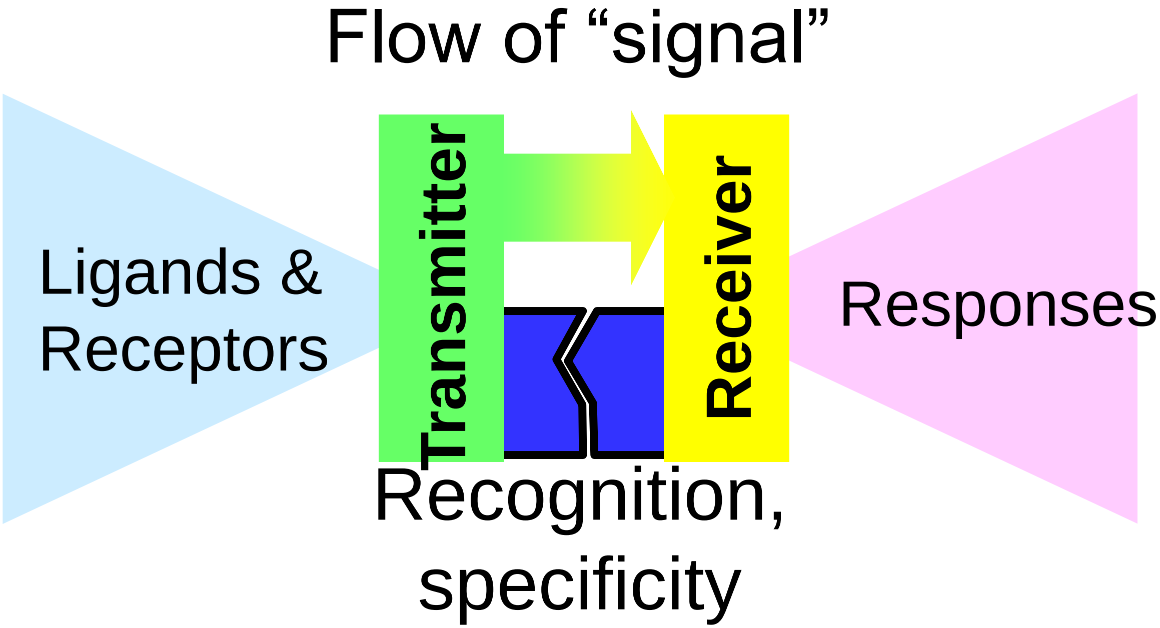
Limited variety
- Fast, analog (via #)
- Hard to change



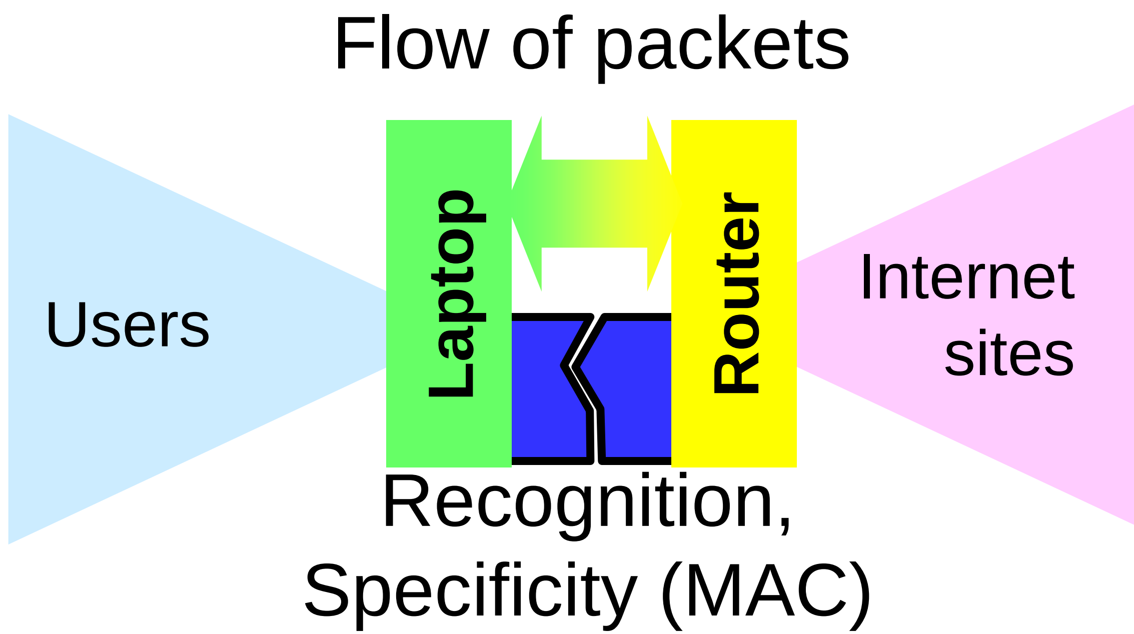
Reusable in different pathways



Shared protocols



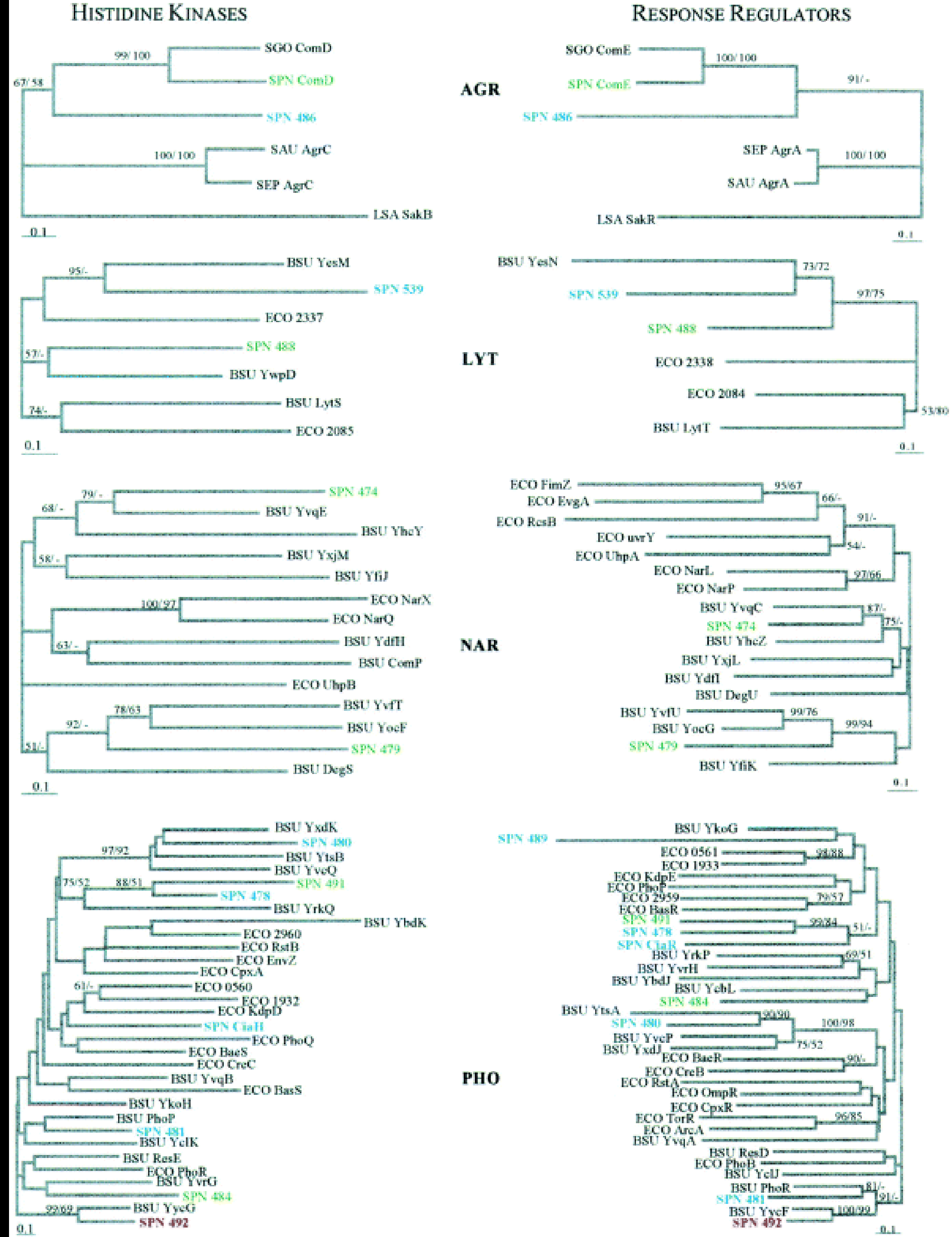
Note: Any wireless system and the Internet to which it is connected work the same way.

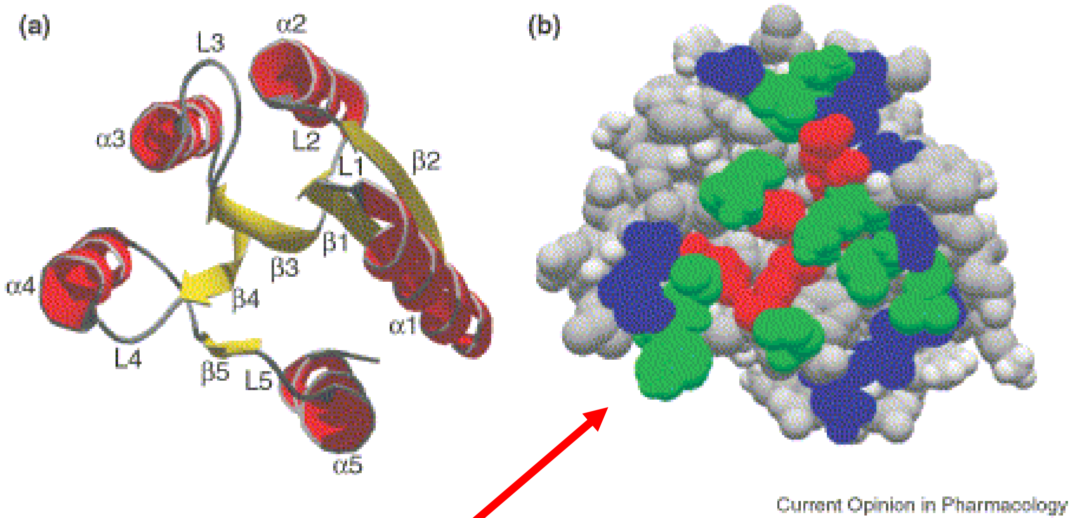


Molecular phylogenies show evolvability of this bowtie architecture.

“Name” recognition is almost digital.

Response regulators can translate these names to DNA addresses with another DNA-binding domain (also digital).

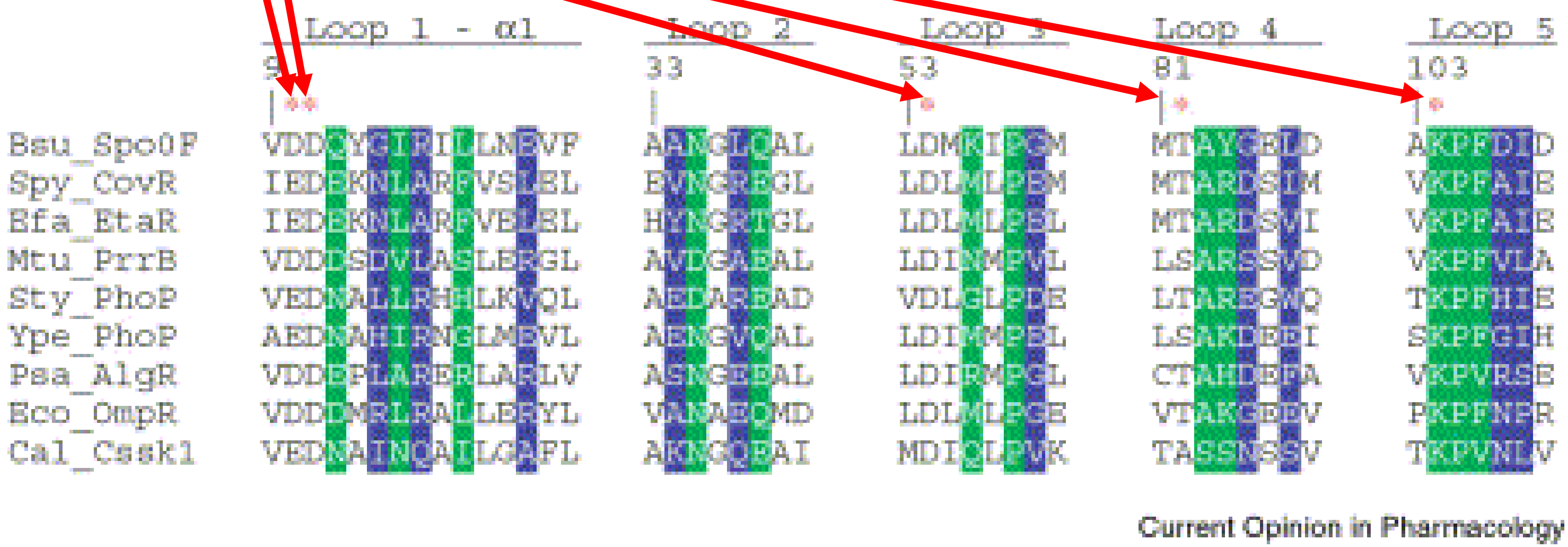


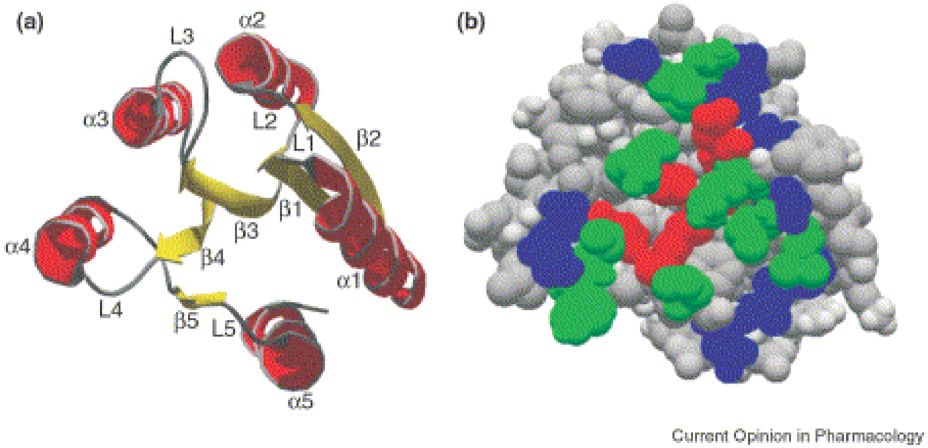


conserved residues of interaction surface with phosphotransferase domains

highly variable amino acids of the interaction surface that are responsible for specificity of the interaction

invariant active-site residues



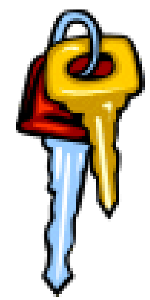


conserved functional domains

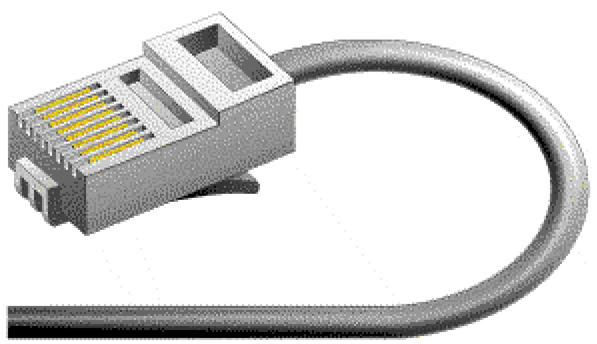
invariant active-site residues

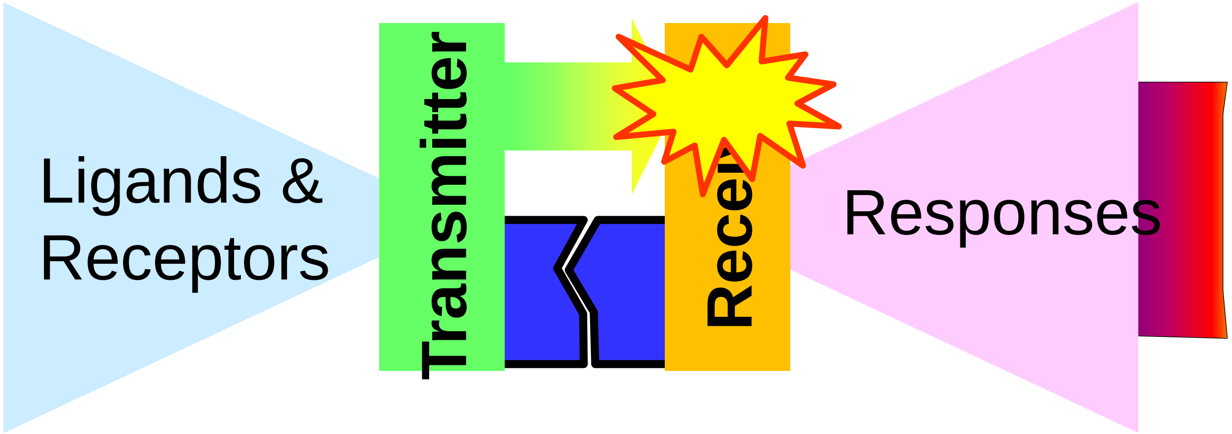
highly variability for specificity of the interaction

- **Automobiles**: Keys provide specificity but no other function. Other function conserved, driver/vehicle interface protocol is "universal."
- **Ethernet cables**: Specificity via MAC addresses, function via standardized protocols.



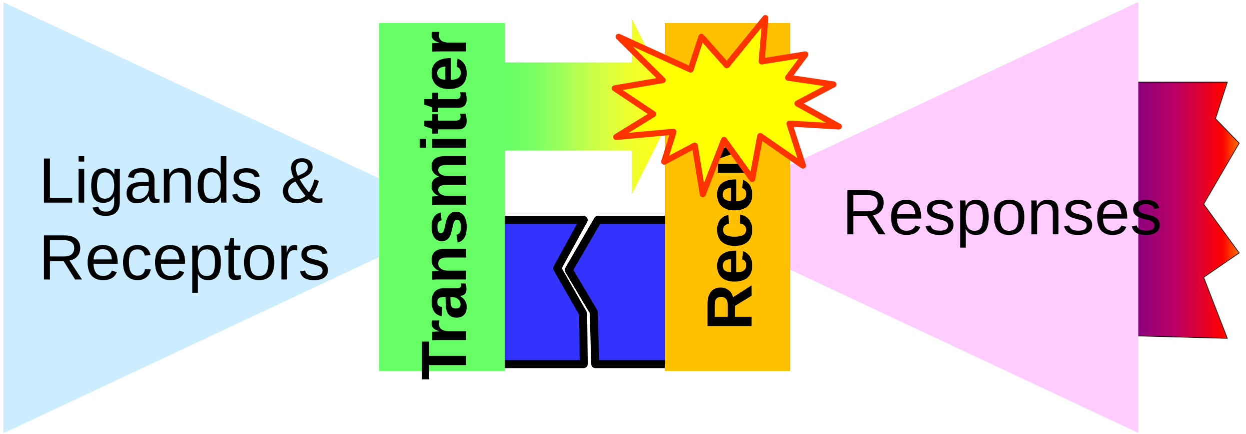
MAC





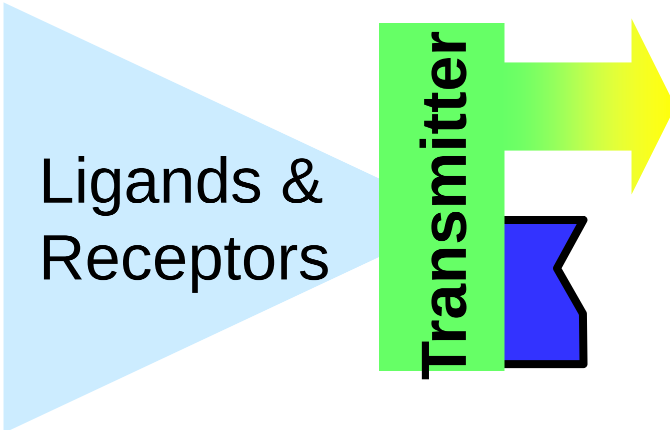
“Name” recognition
= molecular recognition
= localized functionally
= global spatially

Transcription factors do “name” to “address” translation



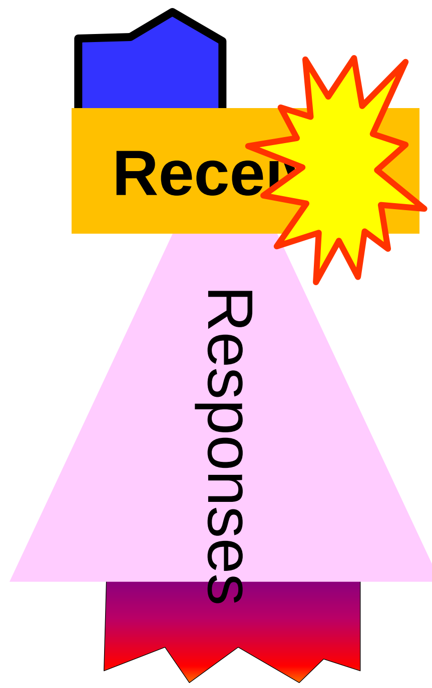
“Name” recognition
= molecular recognition
= localized functionally

Transcription factors
do “name” to “address”
translation



"Name" recognition
= molecular recognition
= localized functionally

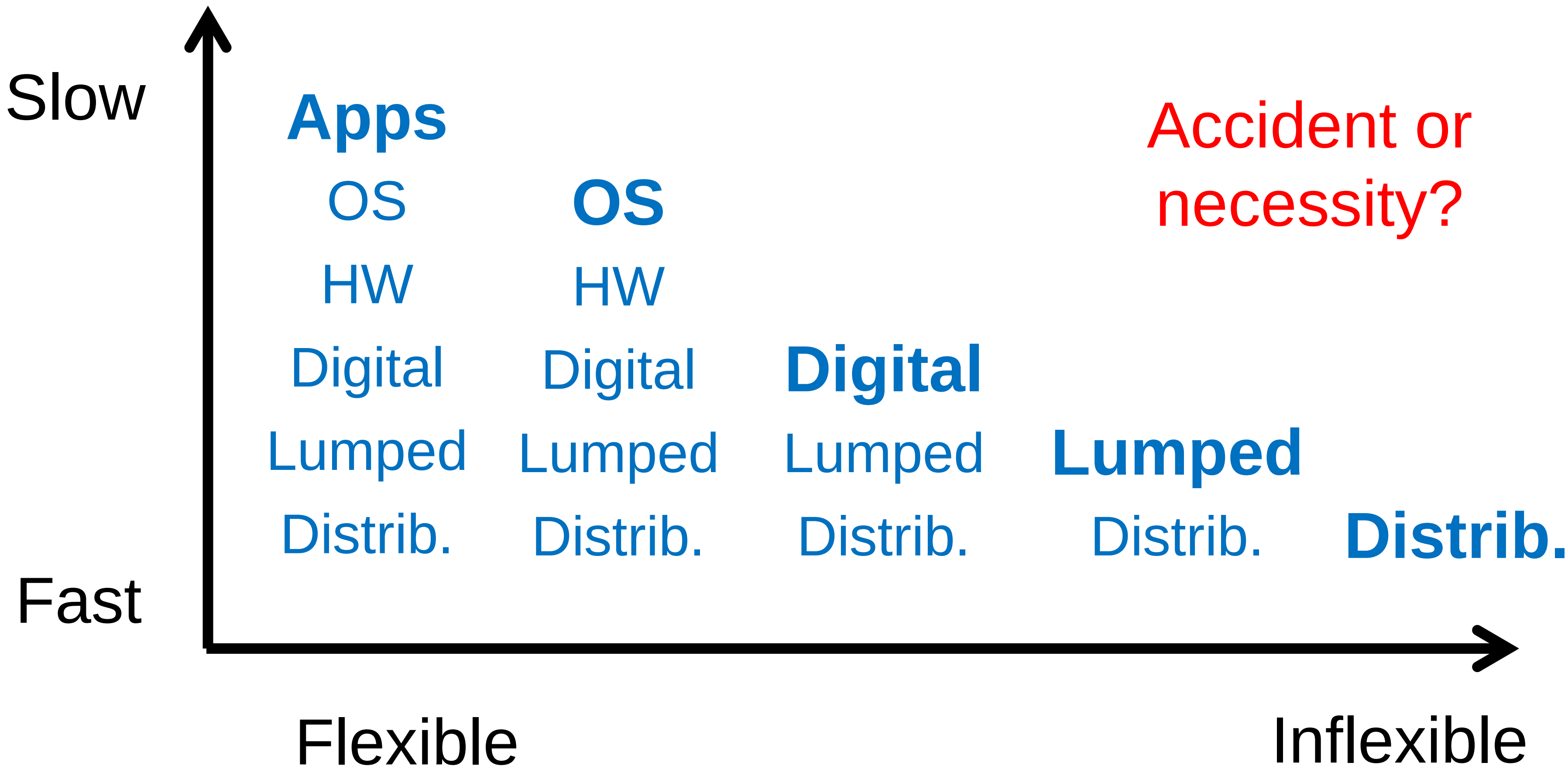
Transcription factors do "name" to "address" translation



"Addressing"
= molecular recognition
= localized spatially

Both are
• Almost digital
• Highly programmable

Tradeoffs:
PC, smartphone, router, etc



Control 2.0

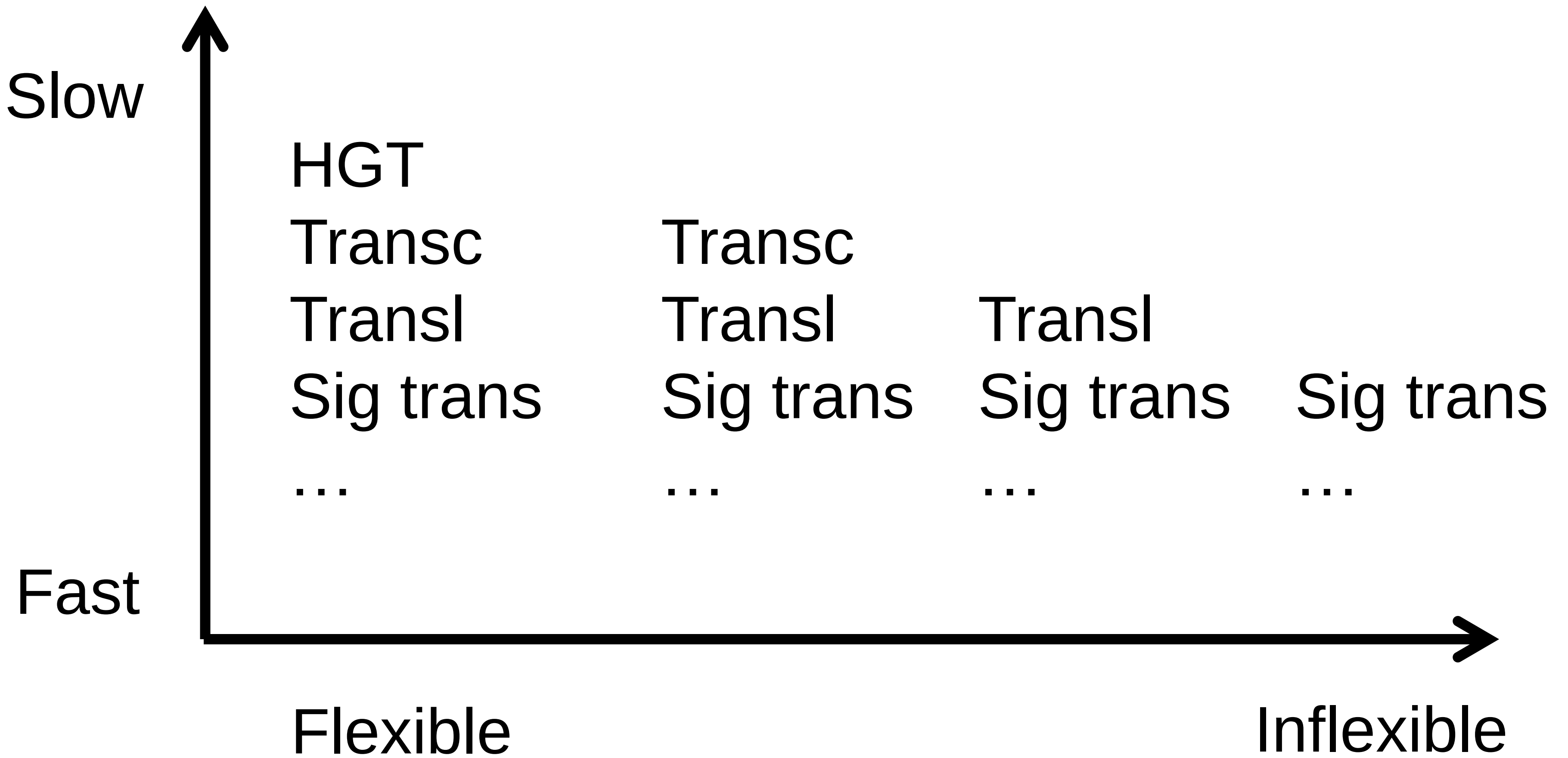
0. HGT
1. DNA replication
2. DNA repair
3. Mutation
4. Transcription
5. Translation
6. Metabolism
7. Signal transduction
8. …

Highly controlled ?!? (items 0–3)

Highly controlled (items 4–8)

Think of this as a “protocol stack”

Control 3.0


Slow
HGT
Transc
Transl
Sig trans
…
Transc
Transl
Sig trans
…
Transl
Sig trans
…
Sig trans
…
Fast
Flexible
Inflexible

Reverse Engineering of Biological Complexity

Marie E. Csete[1] and John C. Doyle[2]*

1 MARCH 2002 VOL 295 SCIENCE

More (old, background) reading

ELSEVIER

Opinion

TRENDS in Biotechnology Vol.22 No.9 September 2004

Bow ties, metabolism and disease

Marie Csete[1] and John Doyle[2]

Surviving heat shock: Control strategies for robustness and performance

H. El-Samad[*,†], H. Kurata[*,‡], J. C. Doyle[§], C. A. Gross[¶], and M. Khammash[*,‖]

*Department of Mechanical and Environmental Engineering, University of California, Santa Barbara, CA 93106; ‡Department of Engineering, Kyushu Institute of Technology, Izuka, 820-8502, Japan; §Department of Control and Dynamical Systems, California Pasadena, CA 91125; and ¶Departments of Stomatology and Microbiology and Immunology, University of California, San Francis

Edited by Melvin I. Simon, California Institute of Technology, Pasadena, CA, and approved December 16, 2004 (received for revi

Molecular biology studies the cause-and-effect relationships **The hsr**

Robustness of Cellular Functions

Cell, Vol. 118, 675–685, September 17, 2004

Jörg Stelling,[1,*] Uwe Sauer,[2] Zoltan Szallasi,[3]
Francis J. Doyle, III,[4] and John Doyle[5]

Other fun stuff not for today

Not enough time

Wildfire ecosystem as ideal example

- Cycles on years to decades timescale
- Regime shifts: grass vs shrub vs tree
- Fire= keystone “specie”
  - Metabolism: consumes vegetation
  - Doesn’t (co-)evolve
  - Simplifies co-evolution spirals and metabolisms
- 4 ecosystems globally with convergent evo
  - So Cal, Australia, S Africa, E Mediterranean
  - Similar vegetation mix
  - Invasive species

Fire in the Earth System

I'm interested in fire…

David M. J. S. Bowman,[1*] Jennifer K. Balch,[2,3,4*†] Paulo Artaxo,[5] William J. Bond,[6] Jean M. Carlson,[7] Mark A. Cochrane,[8] Carla M. D'Antonio,[9] Ruth S. DeFries,[10] John C. Doyle,[11] Sandy P. Harrison,[12] Fay H. Johnston,[13] Jon E. Keeley,[14,15] Meg A. Krawchuk,[16] Christian A. Kull,[17] J. Brad Marston,[18] Max A. Moritz,[16] I. Colin Prentice,[19] Christopher I. Roos,[20] Andrew C. Scott,[21] Thomas W. Swetnam,[22] Guido R. van der Werf,[23] Stephen J. Pyne[24]

Fire is a worldwide phenomenon that appears in the geological record soon after the appearance of terrestrial plants. Fire influences global ecosystem patterns and processes, including vegetation distribution and structure, the carbon cycle, and climate. Although humans and fire have always coexisted, our capacity to manage fire remains imperfect and may become more difficult in the future as climate change alters fire regimes. This risk is difficult to assess, however, because fires are still poorly represented in global models. Here, we discuss some of the most important issues involved in developing a better understanding of the role of fire in the Earth system.

Very accessible
No math

Science AAAS

www.sciencemag.org SCIENCE VOL 324 24 APRIL 2009

Wildfires, complexity, and highly optimized tolerance

Max A. Moritz*, Marco E. Morais[†], Lora A. Summerell[‡], J. M. Carlson[§¶], and John Doyle[‖]

*Department of Environmental Science, Policy, and Management, University of California, Berkeley, CA 94720; Departments of [†]Geography and [§]Physics, University of California, Santa Barbara, CA 93106; [‡]Department of Earth Sciences, California Polytechnic State University, San Luis Obispo, CA 93407; and [‖]Department of Control and Dynamical Systems, California Institute of Technology, Pasadena, CA 91125

Communicated by James S. Langer, University of California, Santa Barbara, CA, October 19, 2005 (received for review July 26, 2004)

Recent, large fires in the western United States have rekindled debates about fire management and the role of natural fire regimes in the resilience of terrestrial ecosystems. This real-world experience parallels debates involving abstract models of forest fires, a central metaphor in complex systems theory. Both real and modeled fire-prone landscapes exhibit roughly power law statistics in fire size versus frequency. Here, we examine historical fire catalogs and a detailed fire simulation model; both are in agreement with a highly optimized tolerance model. Highly optimized tolerance suggests robustness tradeoffs underlie resilience in different fire-prone ecosystems. Understanding these mechanisms may provide new insights into the structure of ecological systems and be key in evaluating fire management strategies and sensitivities to climate change.

Highly optimized tolerance (HOT) is a conceptual framewo
for examining organization and structure in complex system
(18). Theoretically, HOT builds on models and mathemati
from physics and engineering, and identifies robustness tradeof
as a principle underlying mechanism for complexity and pow
law statistics. HOT has been discussed in the context of a varie
of technological and natural systems, including wildfires (18, 22
A quantitative prediction for the distribution of fire sizes h
come from an extremely simple analytical HOT model, referre
to as the PLR (probability–loss–resource) model (22). As
precursor to results presented later in this article, Fig. 2 dem
onstrates the PLR prediction and truncated power law statisti
(23) for several fire history catalogs. This plot represents the ra
data as rank or cumulative frequency of fires $P(l)$ greater tha

Accessible ecology
UG math

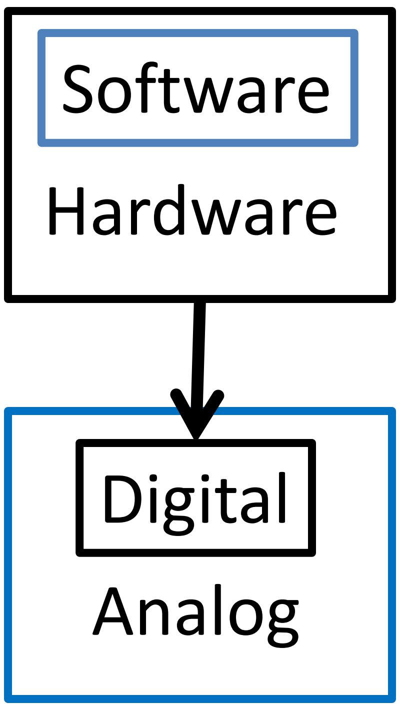
17912–17917 | PNAS | December 13, 2005 | vol. 102 | no. 50

Universal "laws" (constraints)

- Some constraints on bio & tech rise "bottom up" from physics/chemistry
  - Gravity
  - Speed of light
  - Small moieties (energy, redox, …)… more later

- ***But***, the most universal laws for bio&tech are largely ***independent*** of physics
- Most scientists and many engineers don't understand and/or believe this is even possible
- So skepticism is warranted

Turing as “new” starting point?



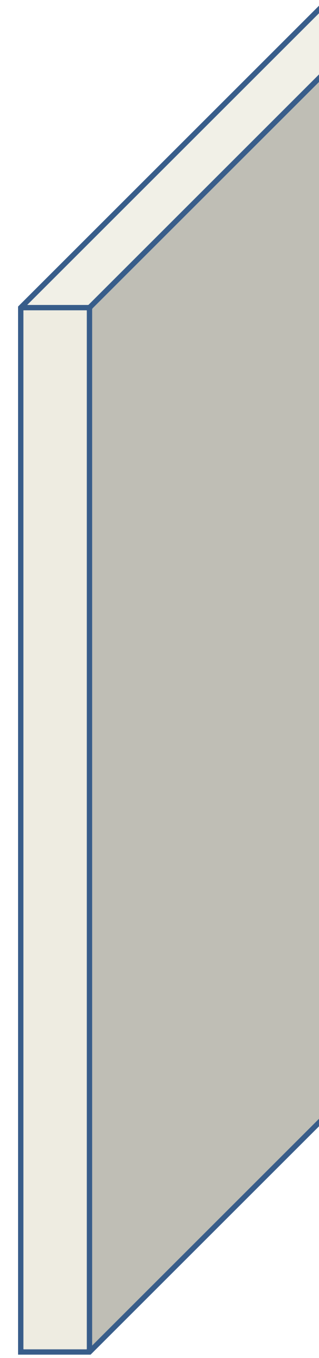
Compute

Turing

Delay is *most* important

Bode

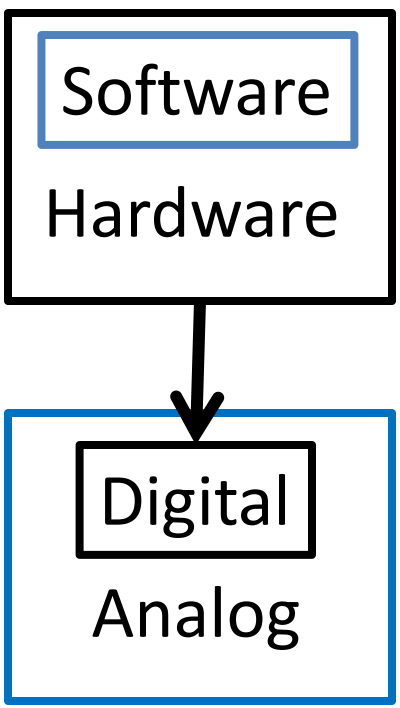
Control, OR



Turing as "new" starting point?

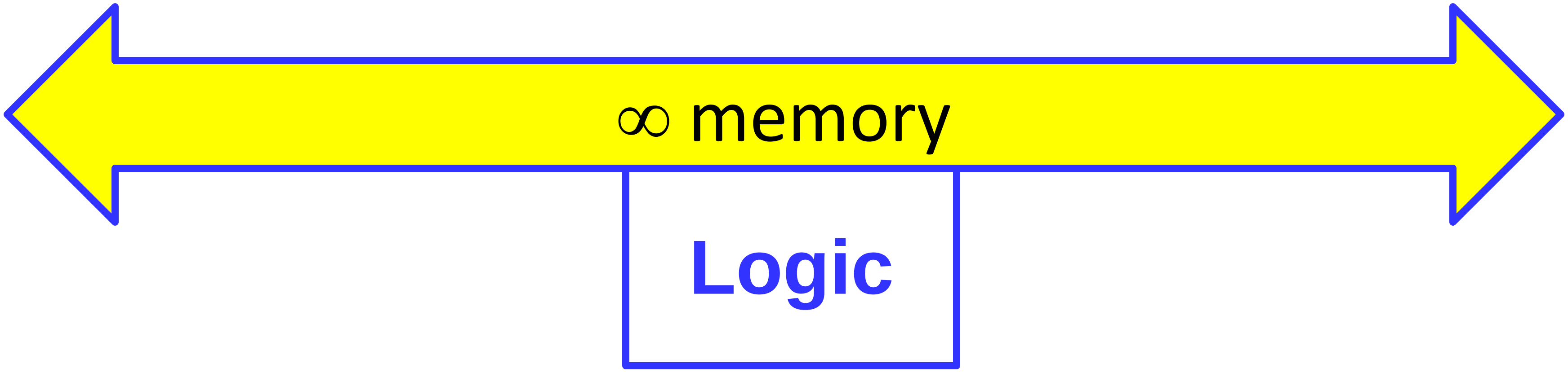
Essentials:

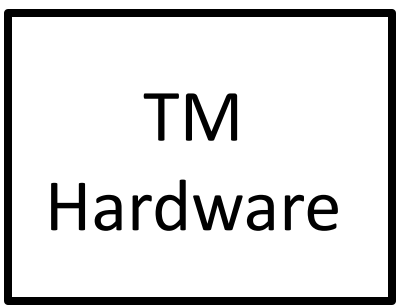
0. **Model**
1. **Universal laws**
2. **Universal architecture**
3. **Practical implementation**



Turing's 3 step research:

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





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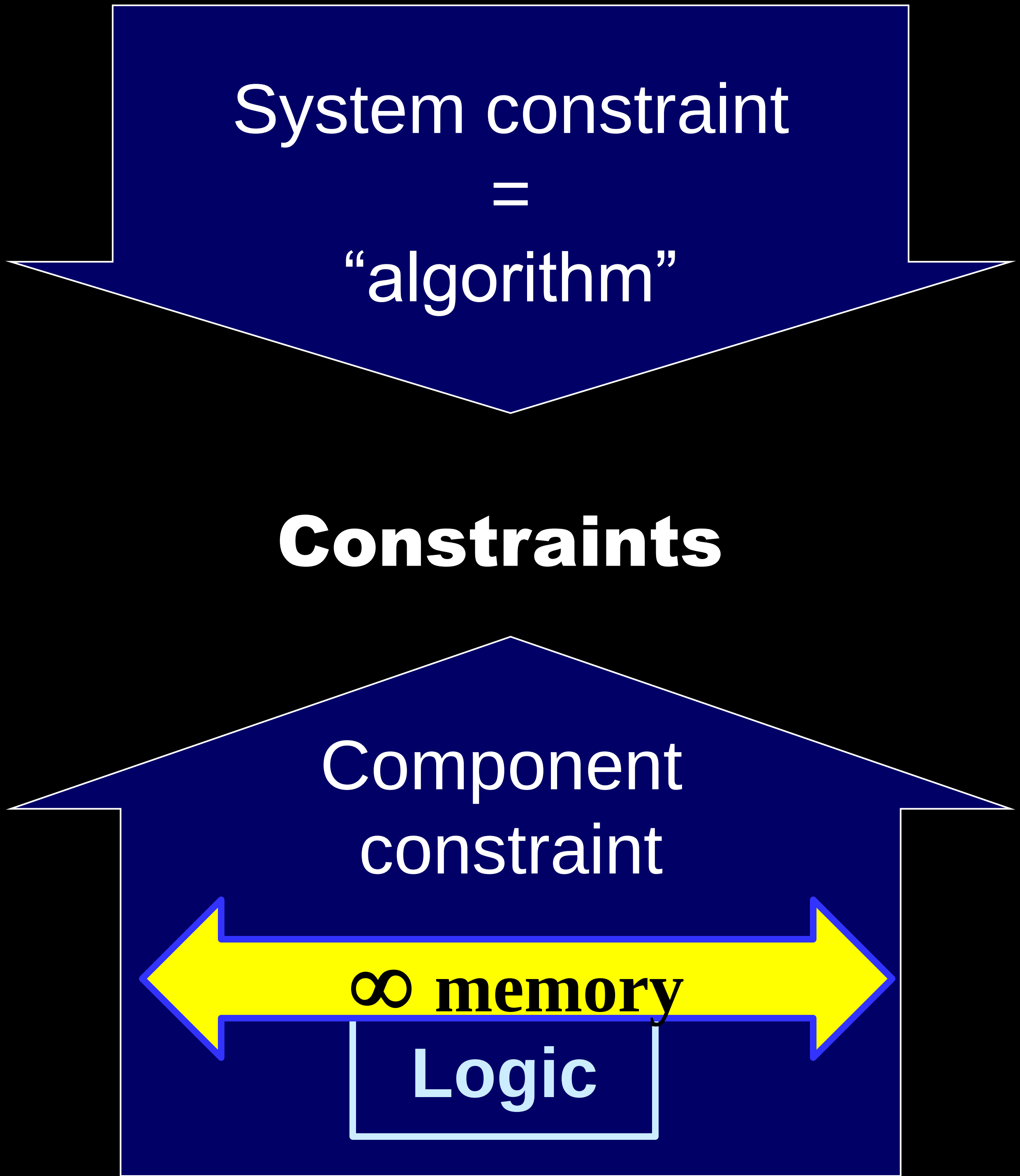
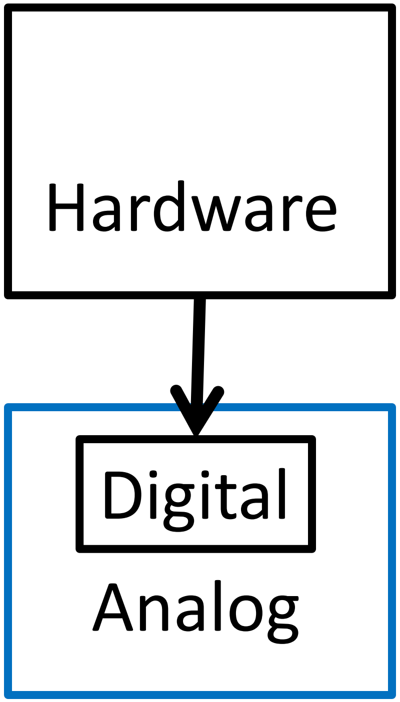
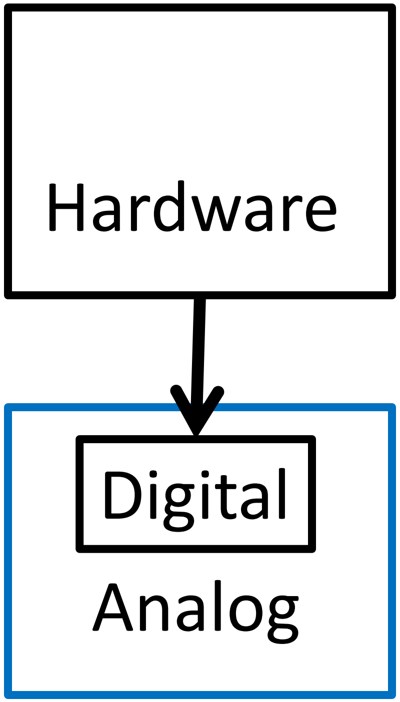


System constraint
=
“algorithm”
Constraints
Component
constraint
∞ memory
Logic



- …**being digital** should be of **greater interest than** that of being **electronic**. That it is electronic is certainly important because these machines owe their high speed to this… But this is virtually all that there is to be said on that subject.
- That the machine is digital however has more subtle significance. … One can therefore **work to any desired degree of accuracy**.

1947 Lecture to LMS

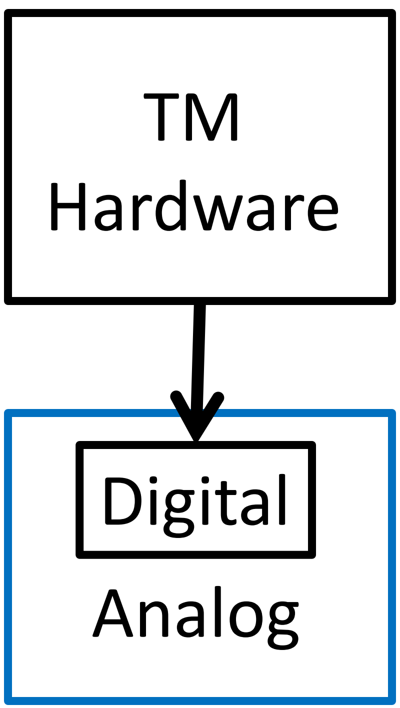


- … digital … of greater interest than that of being electronic …
- …any desired degree of accuracy…
- This accuracy is not obtained by more careful machining of parts, control of temperature variations, and such means, but by **a slight increase in the amount of equipment** in the machine.

1947 Lecture to LMS

Summarizing Turing:

- Digital more important than electronic…
- Robustness: accuracy and repeatability.
- Achieved more by internal hidden complexity than precise components or environments.



Turing Machine (TM)

- Digital
- Symbolic
- Logical
- Repeatable

avalanche

The ~~butterfly~~ effect

- … quite **small errors in the initial conditions** can have an overwhelming effect at a later time. The displacement of a single electron by a billionth of a centimetre at one moment might make the difference between a man being killed by an avalanche a year later, or escaping.

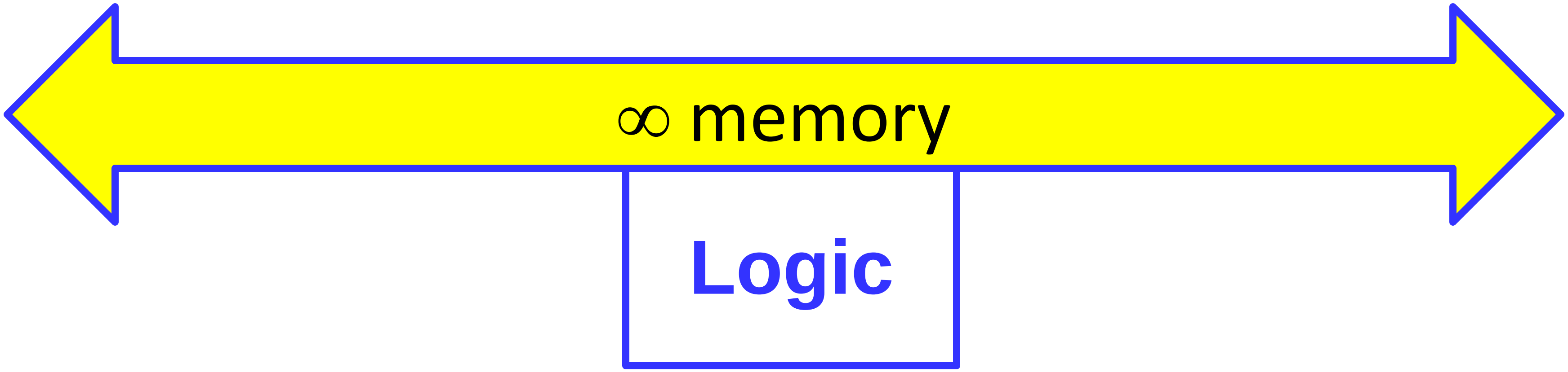
1950, Computing Machinery and Intelligence, *Mind*

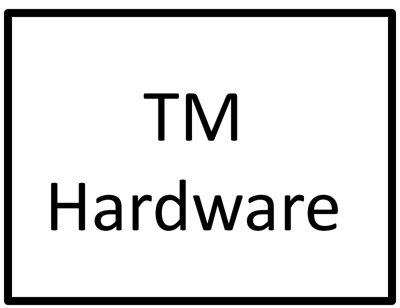
• … small errors in the initial conditions can have an overwhelming effect at a later time….

• It is an **essential** property of the mechanical systems which we have called 'discrete state machines' **that this phenomenon does not occur**.

• Even when we consider the actual physical machines instead of the idealised machines, reasonably accurate knowledge of the state at one moment yields reasonably accurate knowledge any number of steps later.

1950, Computing Machinery and Intelligence, *Mind*





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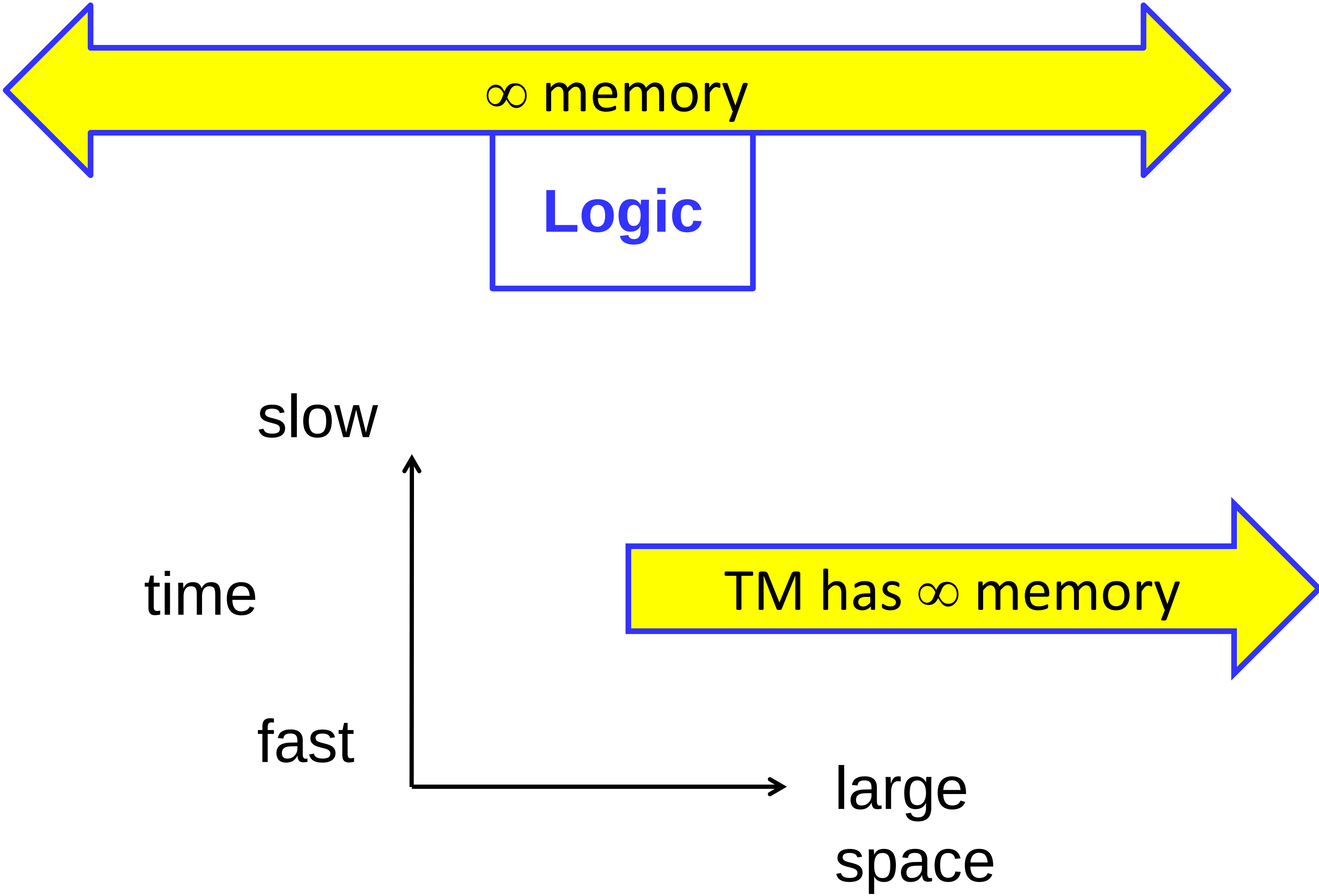
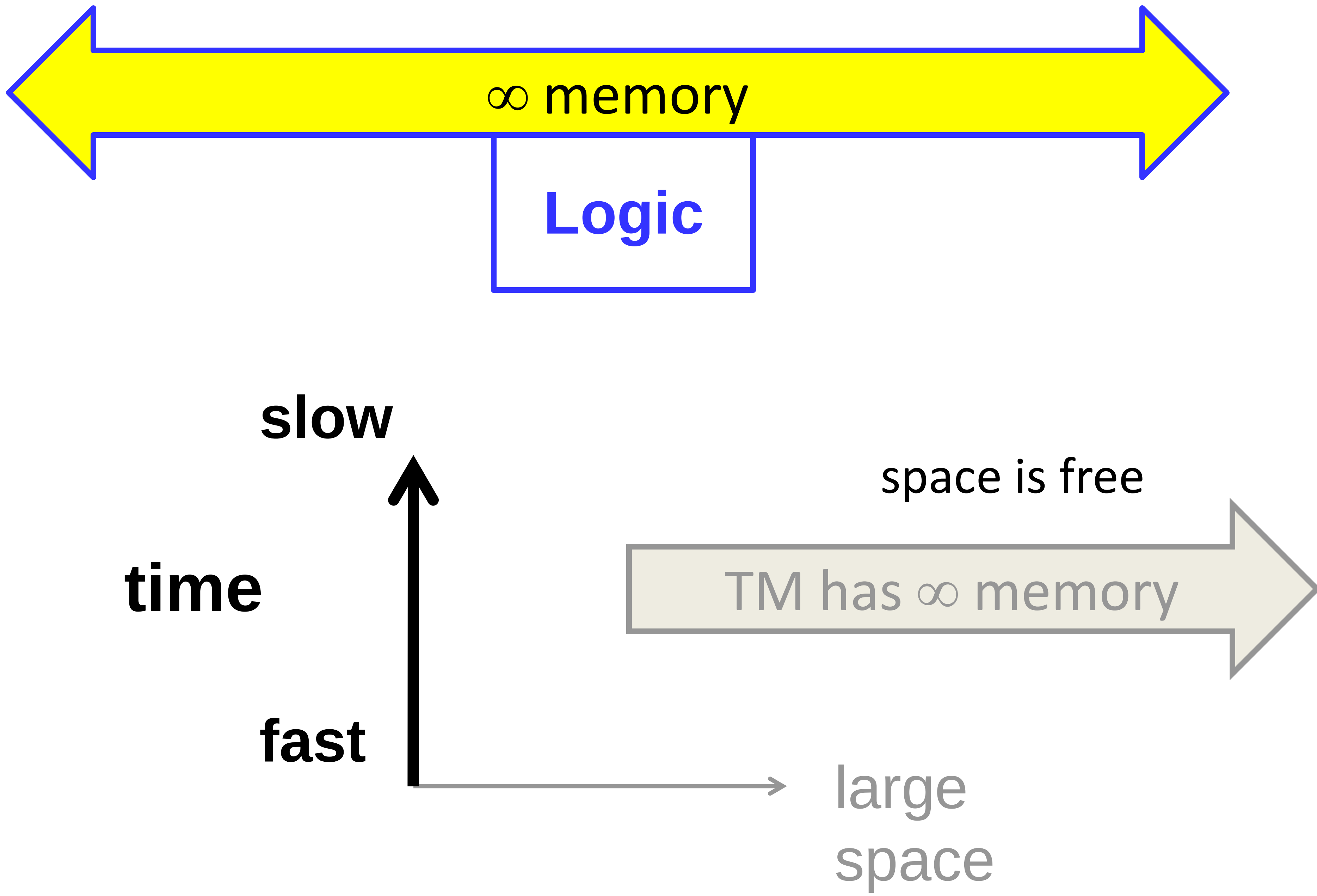
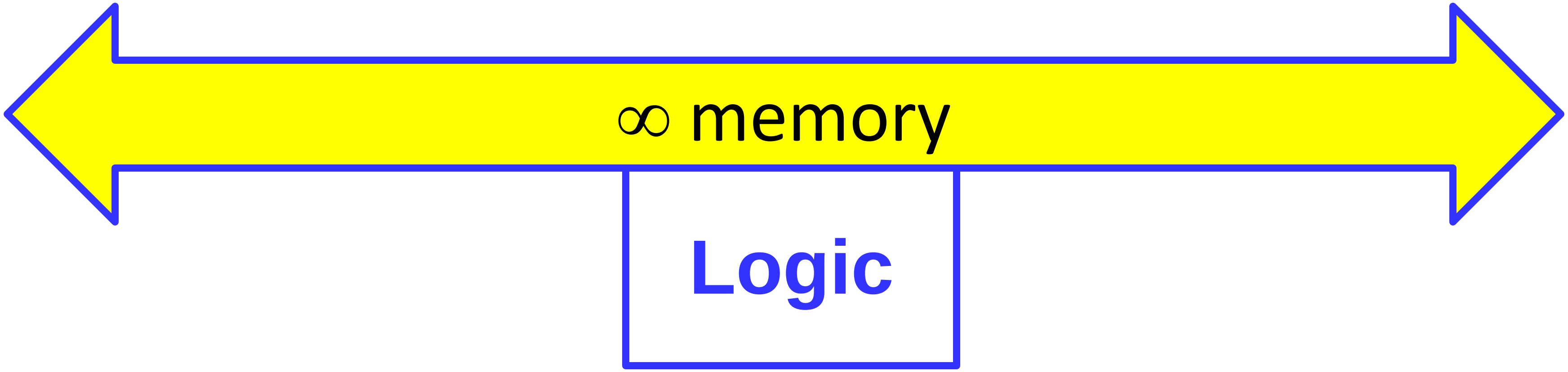

∞ memory
Logic
slow
time
fast
TM has ∞ memory
large
space



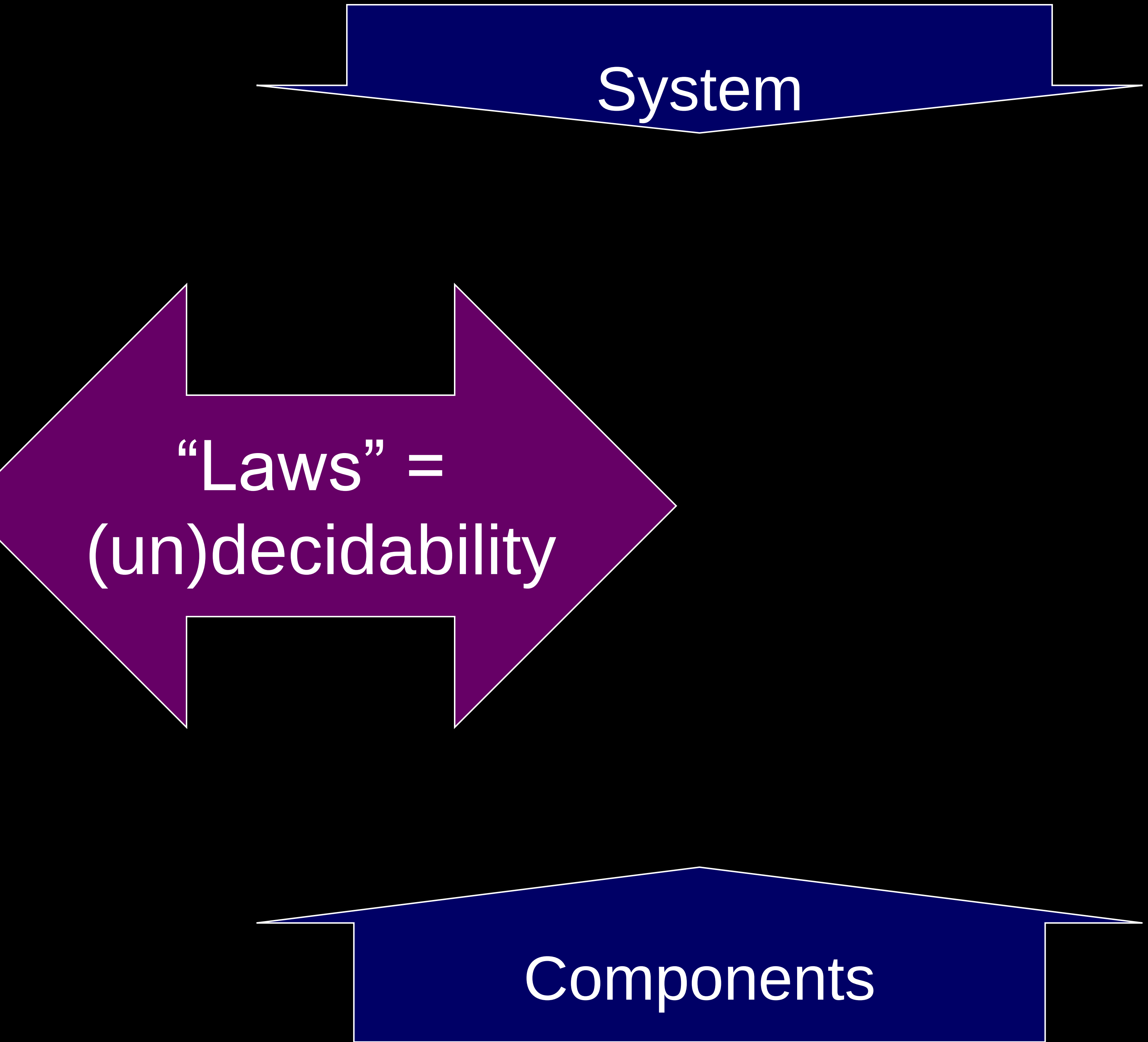
∞ memory
Logic
slow
time
fast
space is free
TM has ∞ memory
large
space

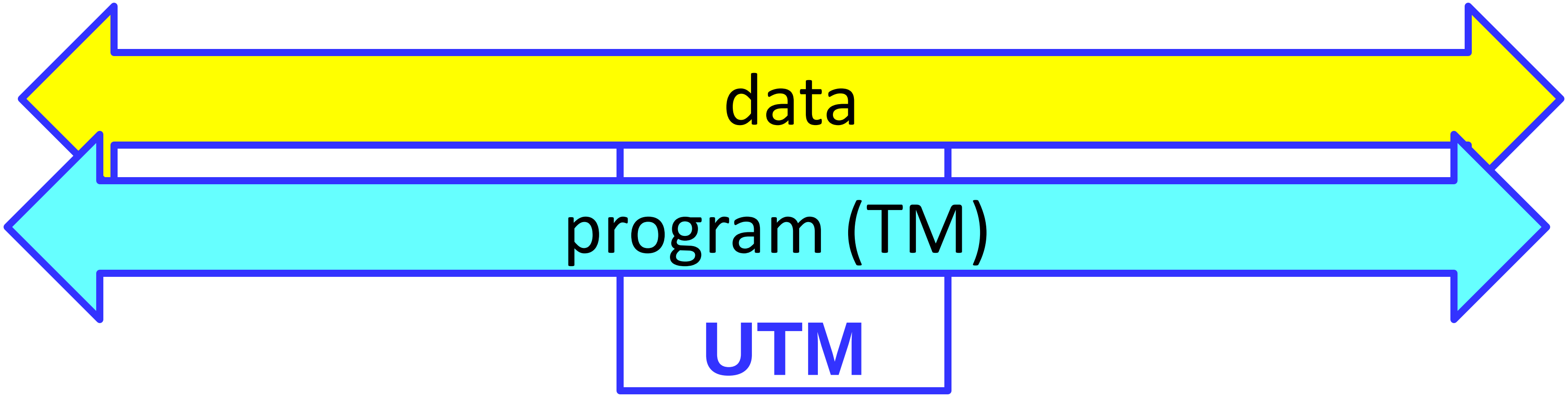


time?

Decidable problem = ∃ algorithm that solves it

Most naively posed problems are undecidable.


System
"Laws" =
(un)decidability
Components



Turing’s 3 step research:

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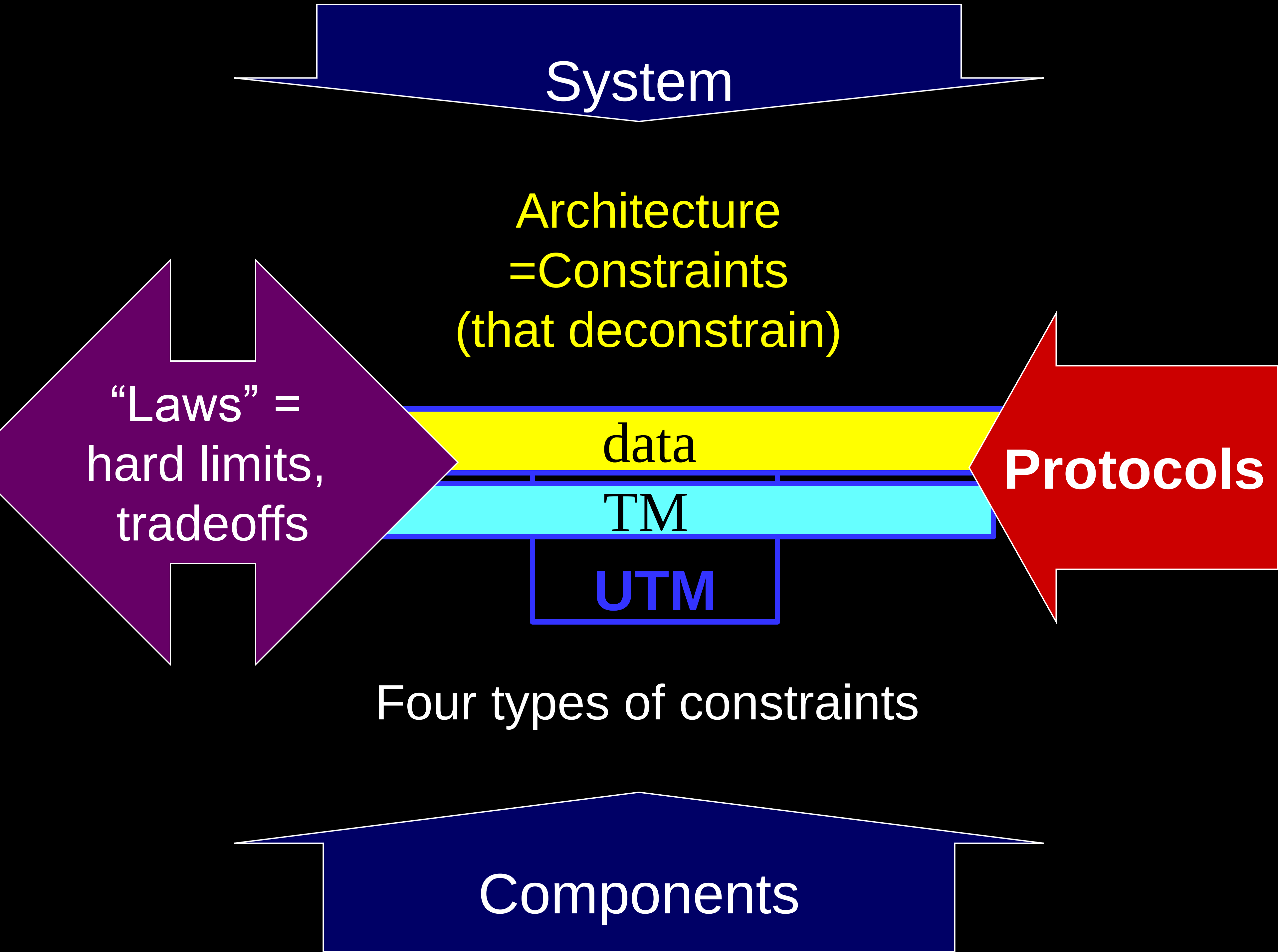
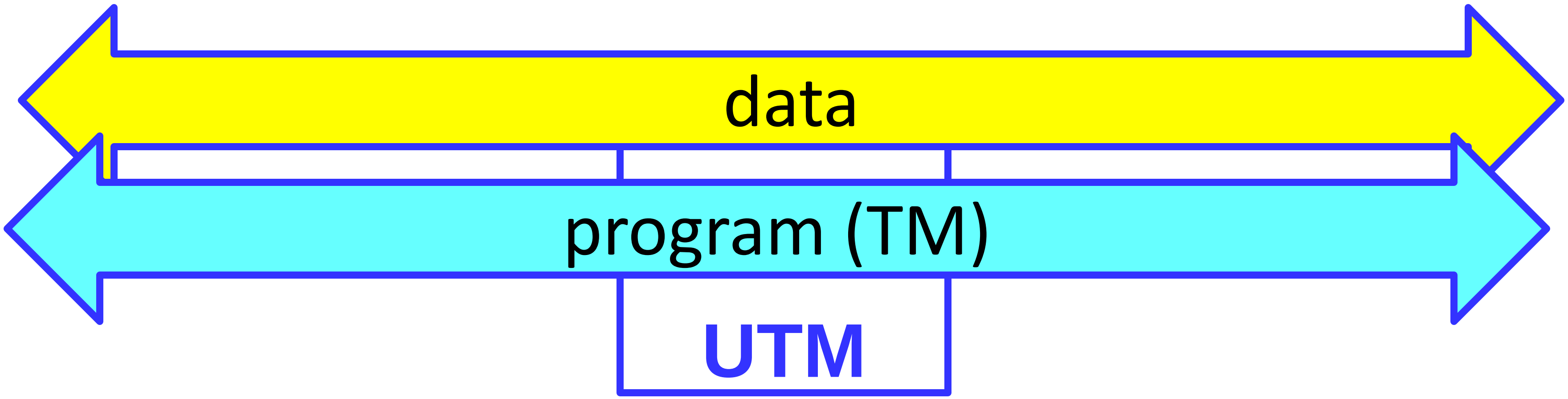
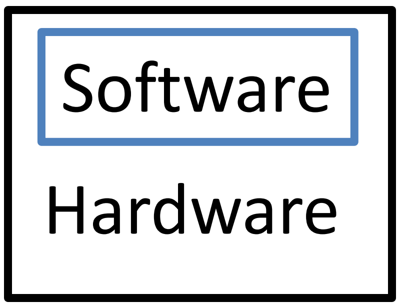
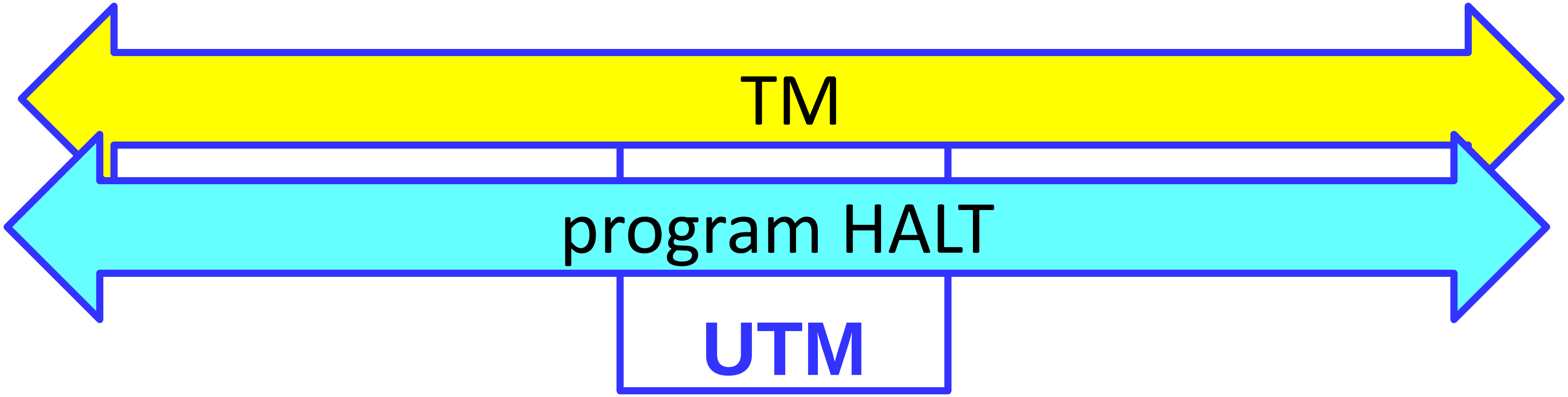

System
Architecture
=Constraints
(that deconstrain)
"Laws" =
hard limits,
tradeoffs
data
TM
UTM
Protocols
Four types of constraints
Components





2. Universal architecture achieving hard limits (UTM)

- Software: A Turing machine (TM) can be data for another Turing machine
- A Universal Turing Machine can run any TM
- A UTM is a virtual machine.
- There are lots of UTMs, differ only (but greatly) in speed and programmability (space assumed free)



The halting problem

- Given a TM (i.e. a computer program)
- Does it halt (or run forever)?
- Or do more or less anything in particular.
- Undecidable! There does not exist a special TM that can tell if any other TM halts.
- i.e. the program HALT does not exist. ☹

Thm: TM H=HALT does not exist.

That is, there does not exist a program like this:

$$H(TM, input) \triangleq \begin{cases} 1 \text{ if } TM\left(input\right) \text{ halts} \\ 0 \text{ otherwise} \end{cases}$$

Proof is by contradiction. Sorry, don't know any alternative. And Turing is a god.

$$H(TM, input) \triangleq \begin{cases} 1 \text{ if } TM(input) \text{ halts} \\ 0 \text{ otherwise} \end{cases}$$

Thm: No such H exists.

Proof: Suppose it does. Then define 2 more programs:

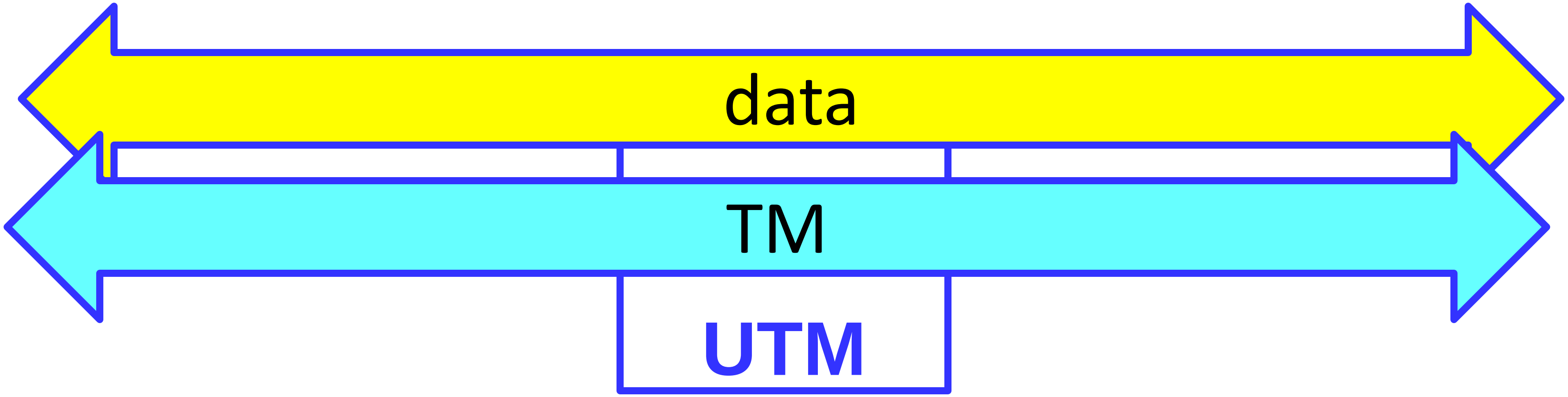
$$H'(TM, input) \triangleq \begin{cases} 1 \text{ if } H(TM, input) = 0 \\ \text{loop forever otherwise} \end{cases}$$

$$H^*(TM) \triangleq H'(TM, TM)$$

$$\text{Run } H^*(H^*) = H'(H^*, H^*)$$

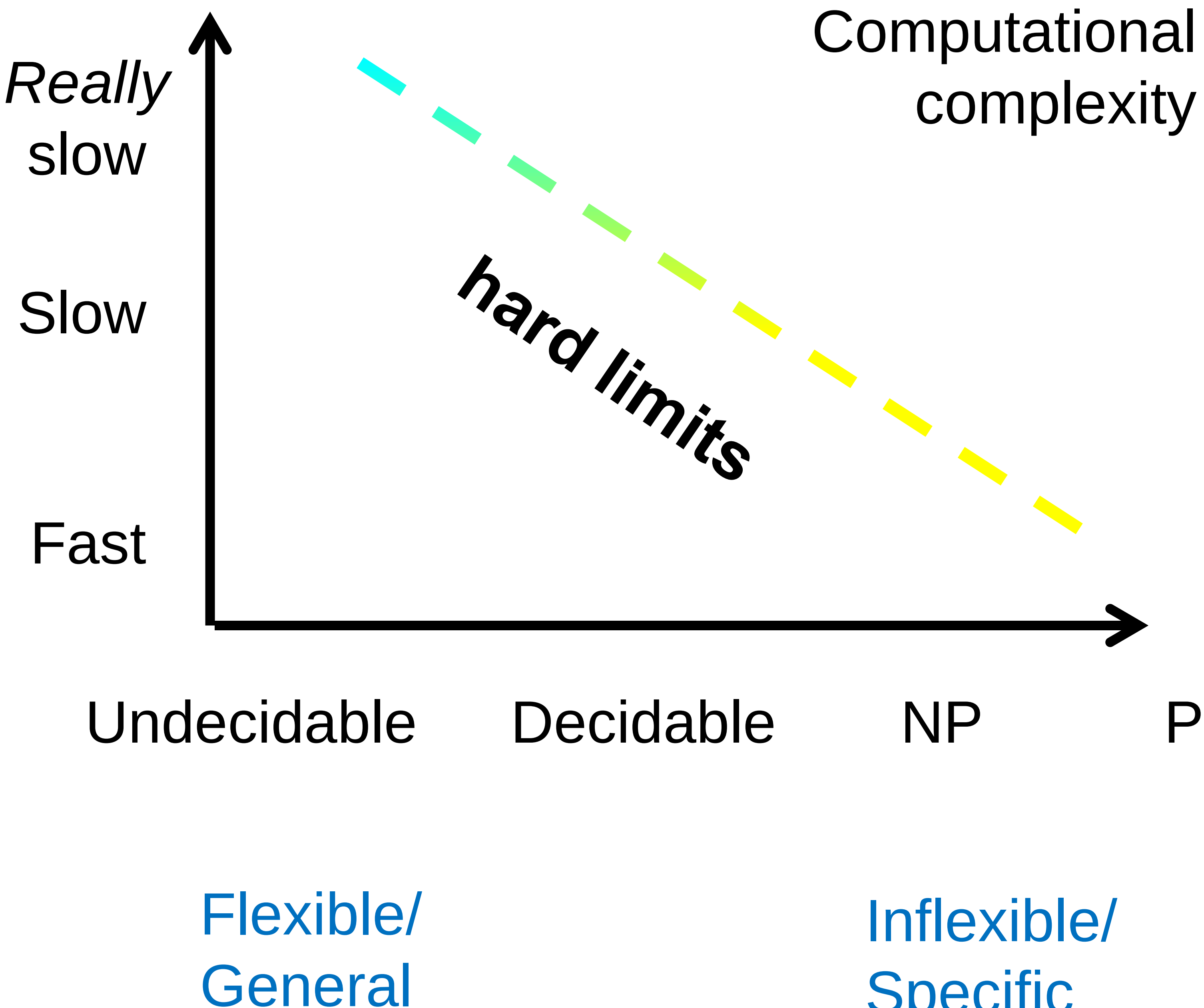
$$= \begin{cases} \text{halt if } H^*(H^*) \text{ loops forever} \\ \text{loop forever otherwise} \end{cases}$$

Contradiction!



Implications

- Large, thin, nonconvex everywhere…
- TMs and UTMs are perfectly repeatable
- But perfectly unpredictable
- Undecidable: Will a TM halt? Is a TM a UTM? Does a TM do X (for almost any X)?
- Easy to make UTMs, but hard to recognize them.
- Is anything decidable? Yes, questions NOT about TMs.



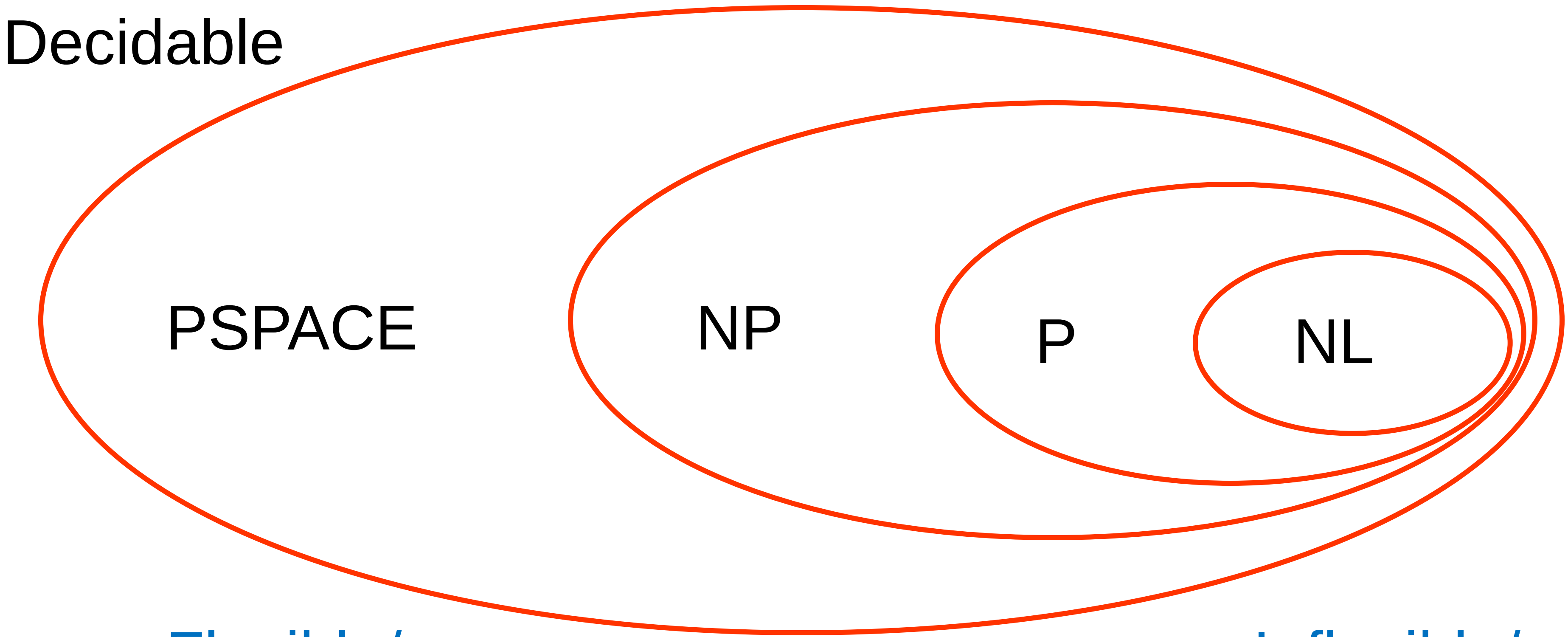
Computational complexity
Really slow
Slow
Fast
hard limits
Undecidable
Decidable
NP
P
Flexible/ General
Inflexible/ Specific

Computational complexity

$PSPACE \subset NP \subset P \subset NL$

$PSPACE \neq NL$

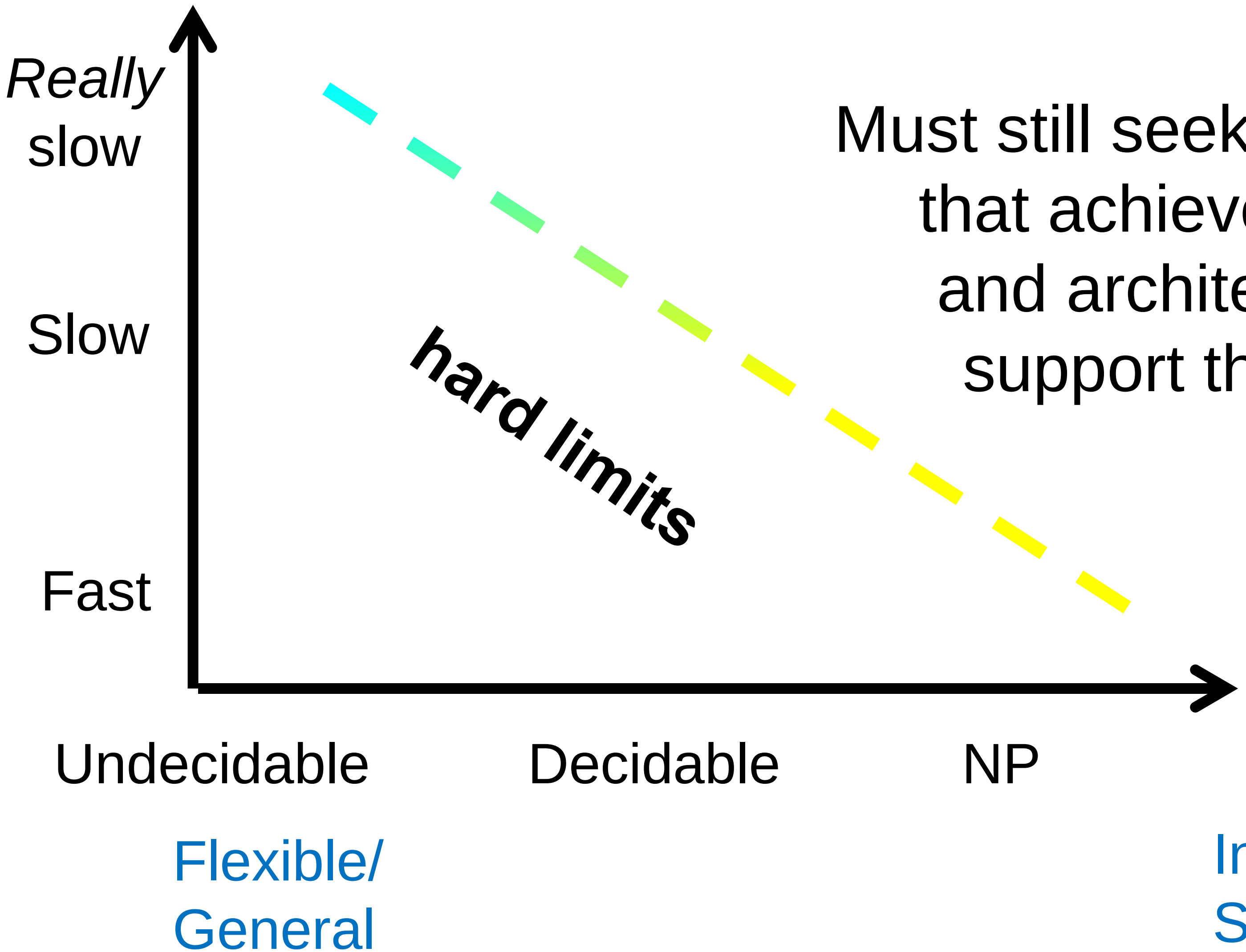
Space is powerful and/or cheap.



Flexible/
General

Inflexible/
Specific

These are hard limits on the ***intrinsic*** computational complexity of ***problems***.



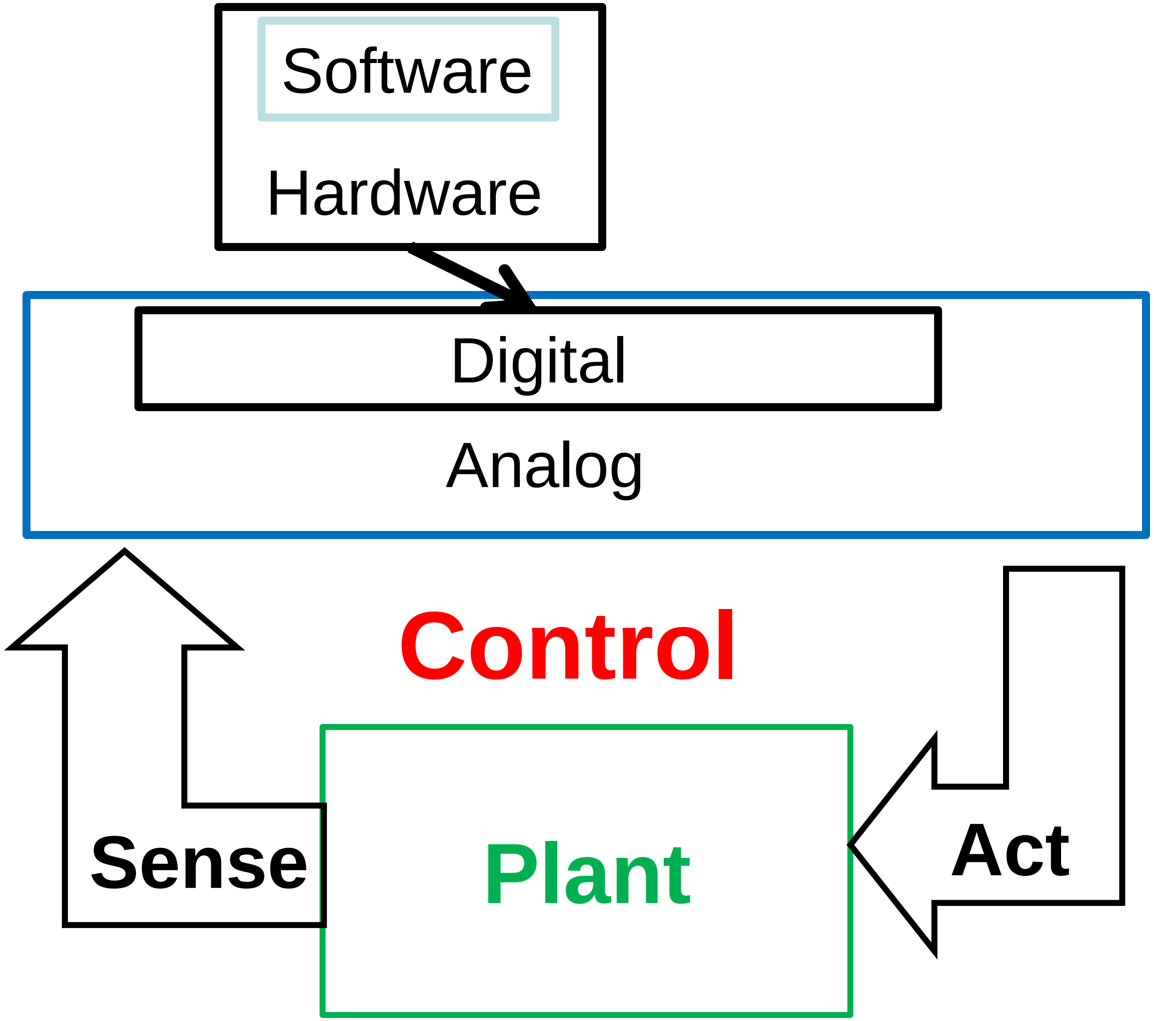
Must still seek algorithms that achieve the limits, and architectures that support this process.

Compute

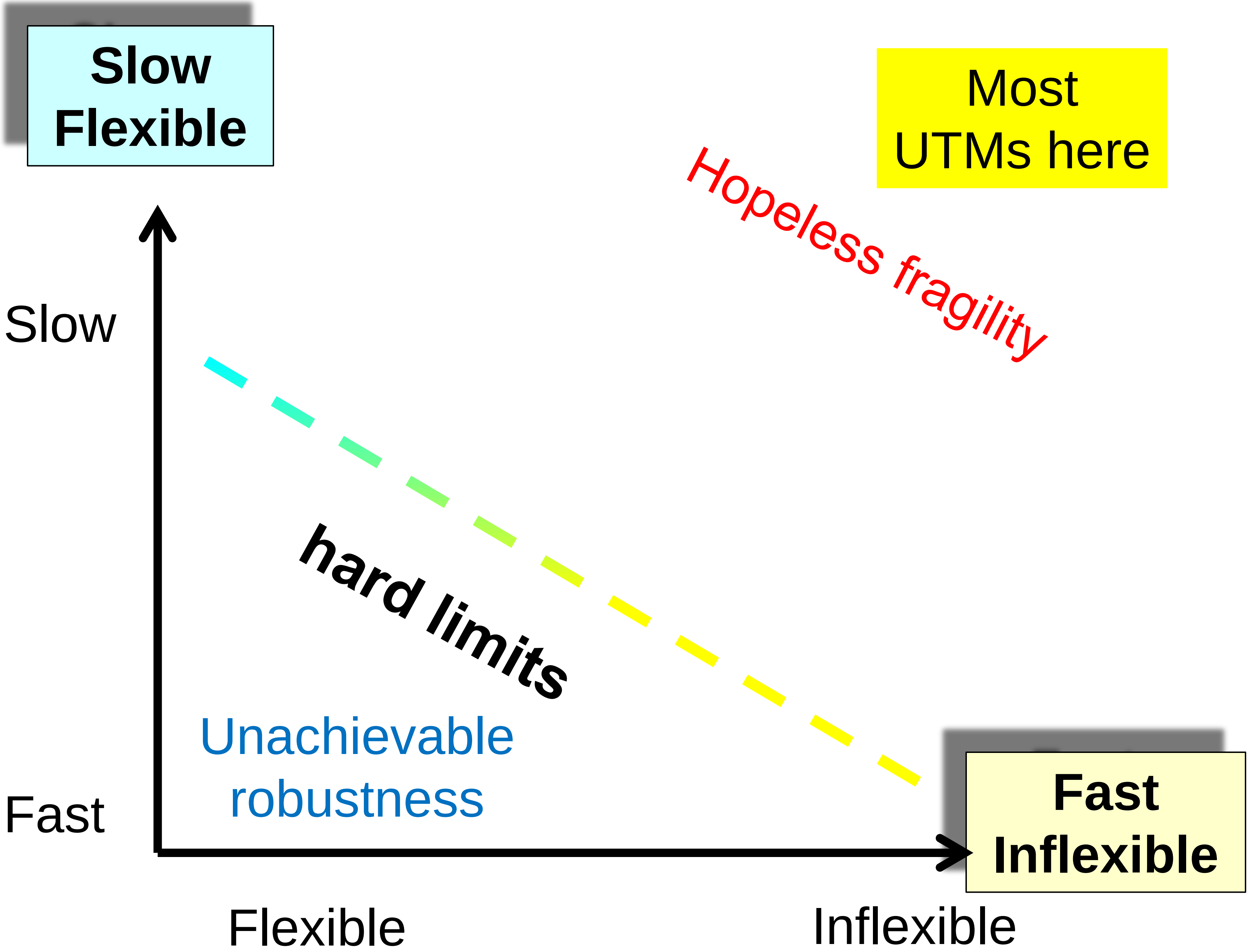
Computational complexity of

- ***Designing*** control algorithms
- ***Implementing*** control algorithms

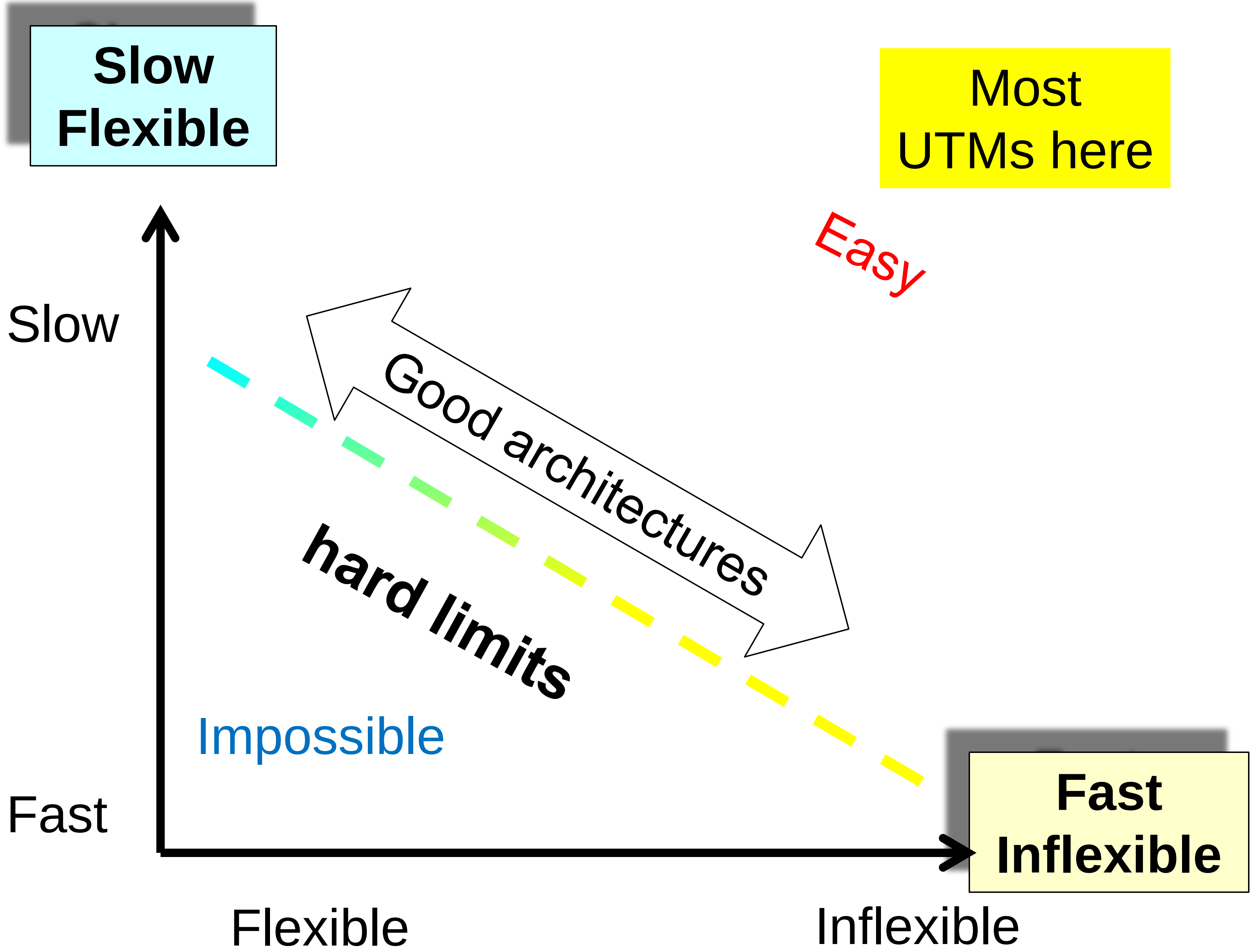
Delay is *even more* important in control



Control



Slow
Flexible
Most
UTMs here
Hopeless fragility
Slow
hard limits
Unachievable
robustness
Fast
Fast
Inflexible
Flexible
Inflexible


Slow
Flexible
Most
UTMs here
Easy
Slow
Good architectures
hard limits
Impossible
Fast
Fast
Inflexible
Flexible
Inflexible

Issues for engineering

- Turing remarkably relevant for 76 years
- UTMs are ≈ implementable
  - Differ only (but greatly) in speed and programmability
  - Time/speed/delay is most critical resource
  - Space (memory) almost free for most purposes
- Read/write random access memory hierarchies
- Further gradations of decidable (P/NP/coNP)
- **Most crucial:**
  - UTMs differ vastly in speed, usability, and programmability
  - You can fix bugs but it is hard to automate finding/avoiding them

Issues for engineering

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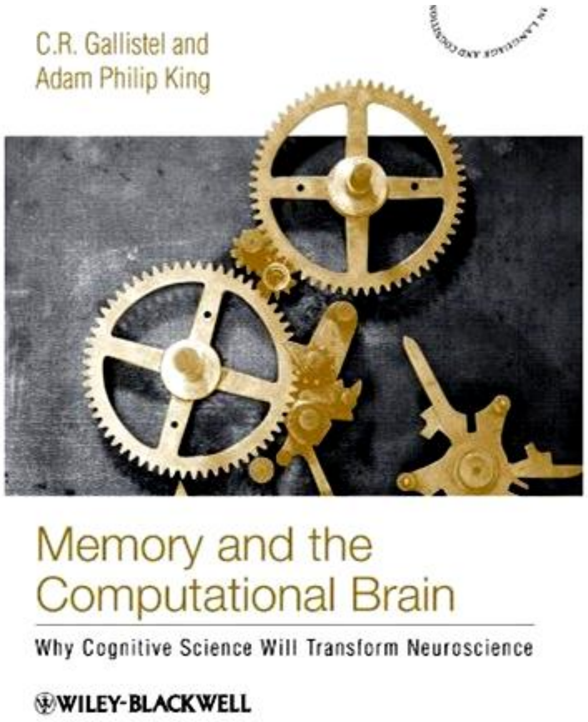
Conjectures, biology

Gallistel and King

- Memory potential $\approx \infty$
- Examples
  - Insects
  - Scrub jays
  - Autistic Savants



- But why so rare and/or accidental?
- Large memory, computation of limited value?
- Selection favors fast robust ***action***?
- Brains are distributed (not studied by Gallistel)

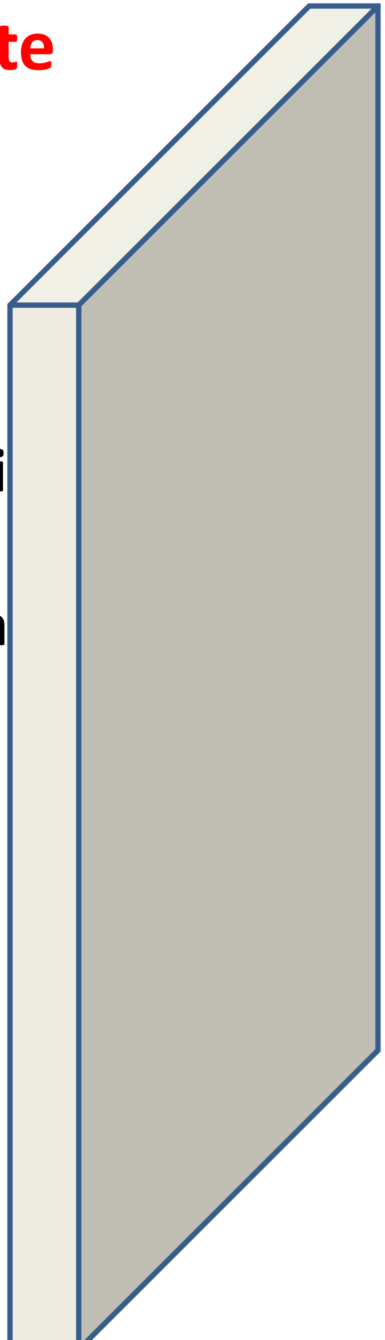
Compute

Turing

Delay i
most
importa

Bode

Control,



Communicate

Shannon

Delay is
least
important

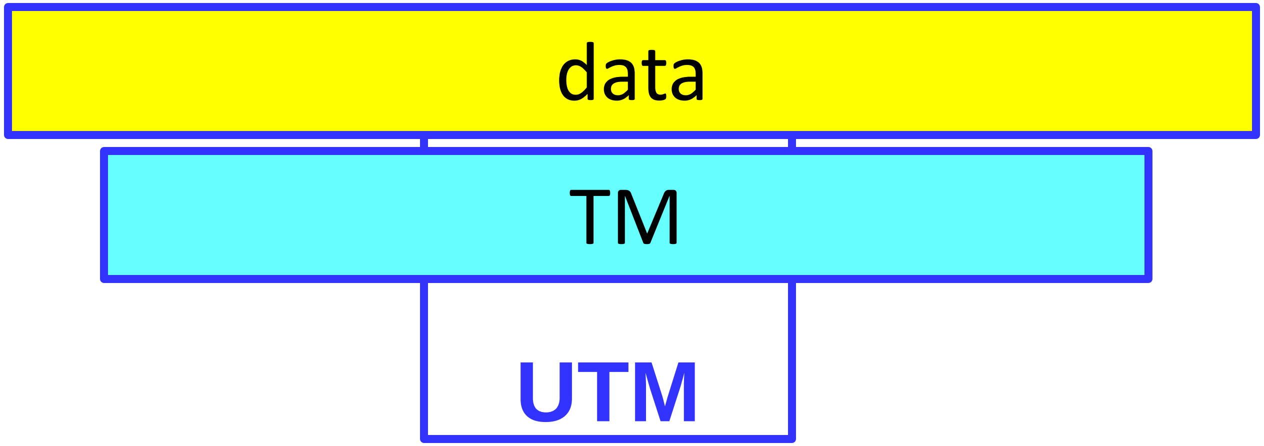
Carnot

Boltzmann

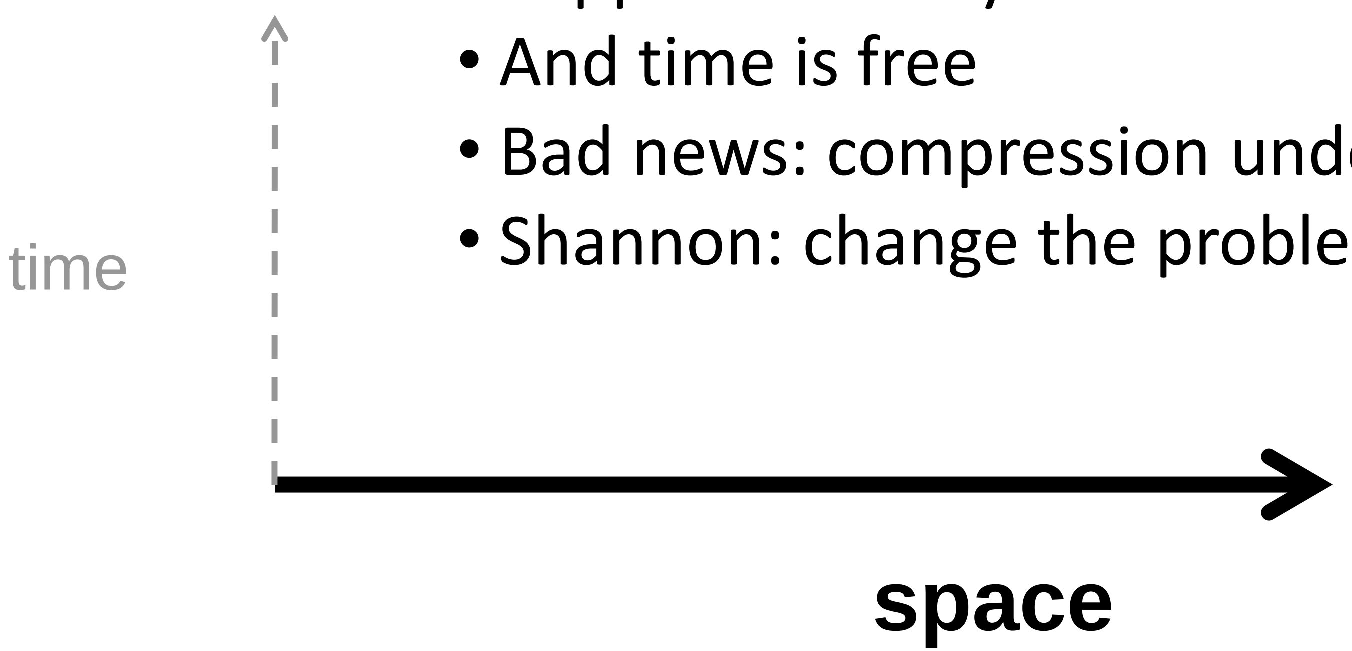
Heisenberg

Physics

Einstein



- Suppose we only care about space?
- And time is free
- Bad news: compression undecidable.
- Shannon: change the problem!



Communications

Shannon

Shannon's brilliant insight

- Forget time
- Forget files, use ***infinite random ensembles***

Good news

- Laws and architecture!
- Info theory most popular and accessible topic in systems engineering
- ***Fantastic*** for some engineering problems

Communications

Shannon

Shannon's brilliant insight

- Forget time
- Forget files, use ***infinite random ensembles***

***Bad* news**

- Laws and architecture very brittle

- Less than zero impact on internet architecture
- Almost useless for biology (But see Lestas et al, 2010)
- Misled, distracted generations of biologists (and neuroscientists)

Compute

Communicate

Turing

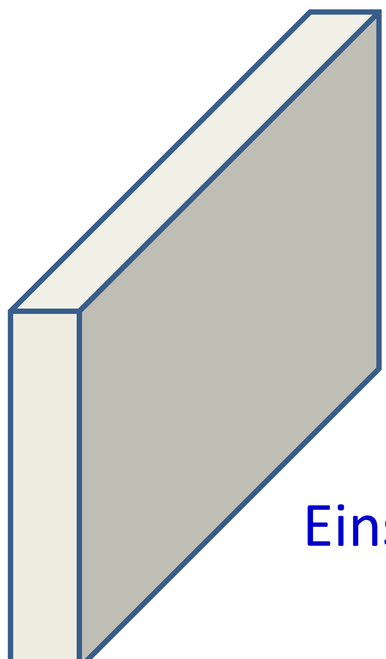
Lowering the barrier

Shannon

Delay is *most* important

New progress!

Delay is ~~*least*~~ important



Carnot

Boltzmann

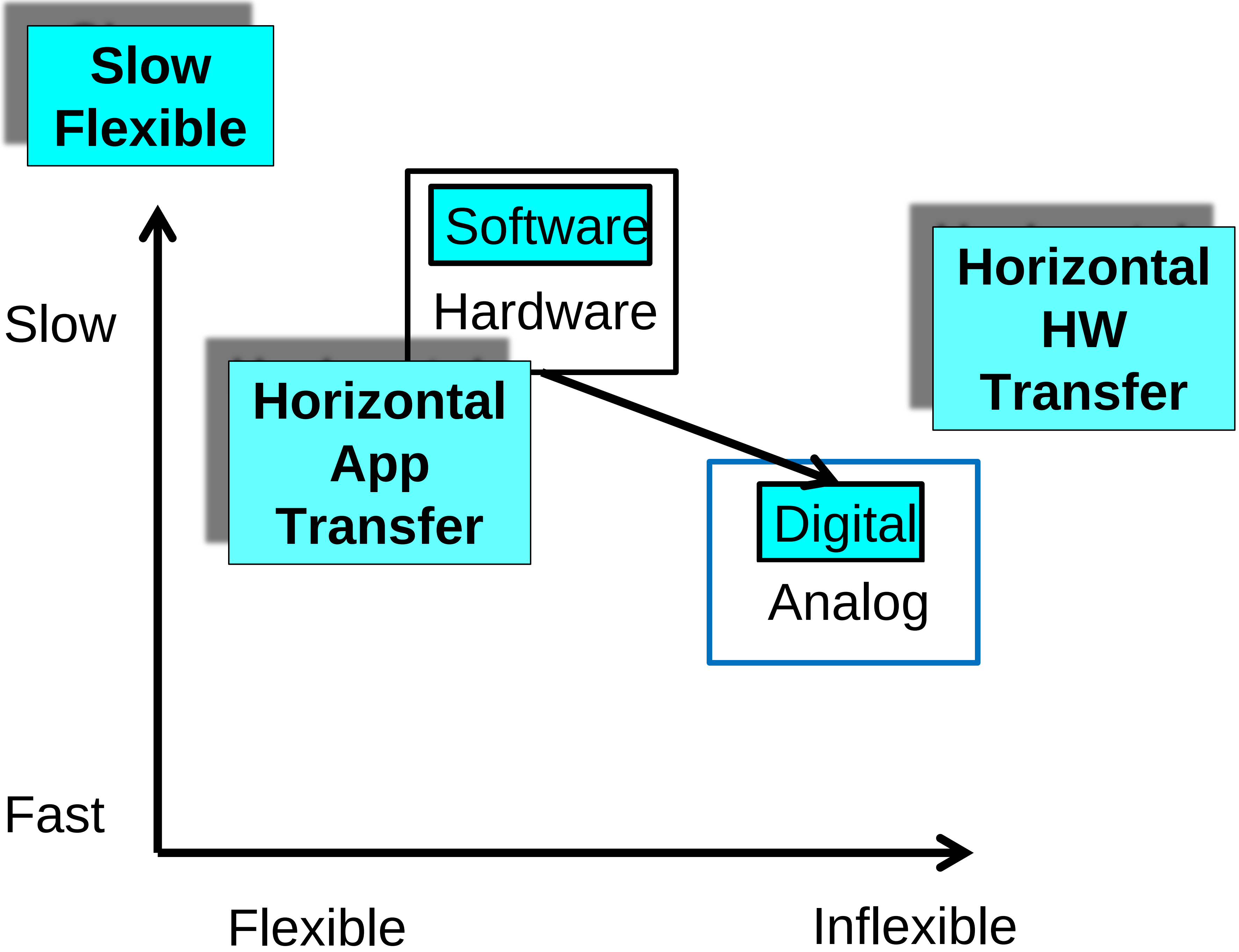
Bode

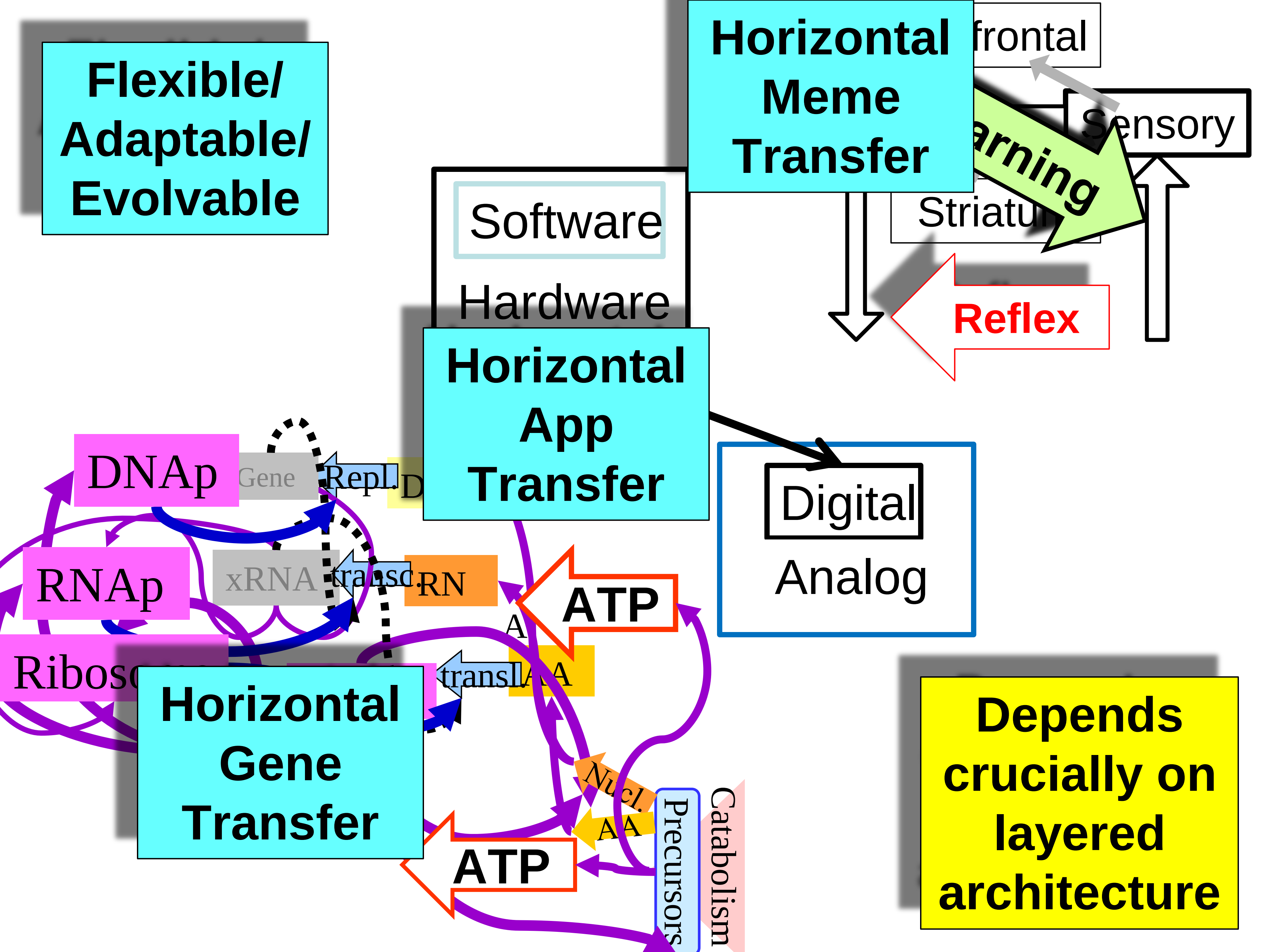
Heisenberg

Control, OR

Einstein

Physics


Slow
Flexible
Software
Hardware
Horizontal
HW
Transfer
Slow
Horizontal
App
Transfer
Digital
Analog
Fast
Flexible
Inflexible


Flexible/ Adaptable/ Evolvable
Horizontal Meme Transfer
frontal
Sensory
arning
Striatu
Software
Hardware
Reflex
Horizontal App Transfer
Digital
Analog
DNAp
Gene
Repl.
D
RNAp
xRNA
transc.
RN
ATP
A
Ribos
Horizontal Gene Transfer
transl.
AA
Nucl.
AA
Precursors
Catabolism
ATP
Depends crucially on layered architecture

Human complexity

Robust	Fragile
☺ Metabolism	☹ Obesity, diabetes
☺ Regeneration & repair	☹ Cancer
☺ Healing wound /infect	☹ AutoImmune/Inflame

Start with physiology

Lots of triage

Benefits

Robust

- ☺ Metabolism
- ☺ Regeneration & repair
- ☺ Healing wound /infect

  - ☺ Efficient
  - ☺ Mobility
  - ☺ Survive uncertain food supply
  - ☺ Recover from moderate trauma and infection

Mechanism?

Robust

- ☺ Metabolism
- ☺ Regeneration & repair
- ☺ Healing wound /infect
  - ☹ Fat accumulation
  - ☹ Insulin resistance
  - ☹ Proliferation
  - ☹ Inflammation

Fragile

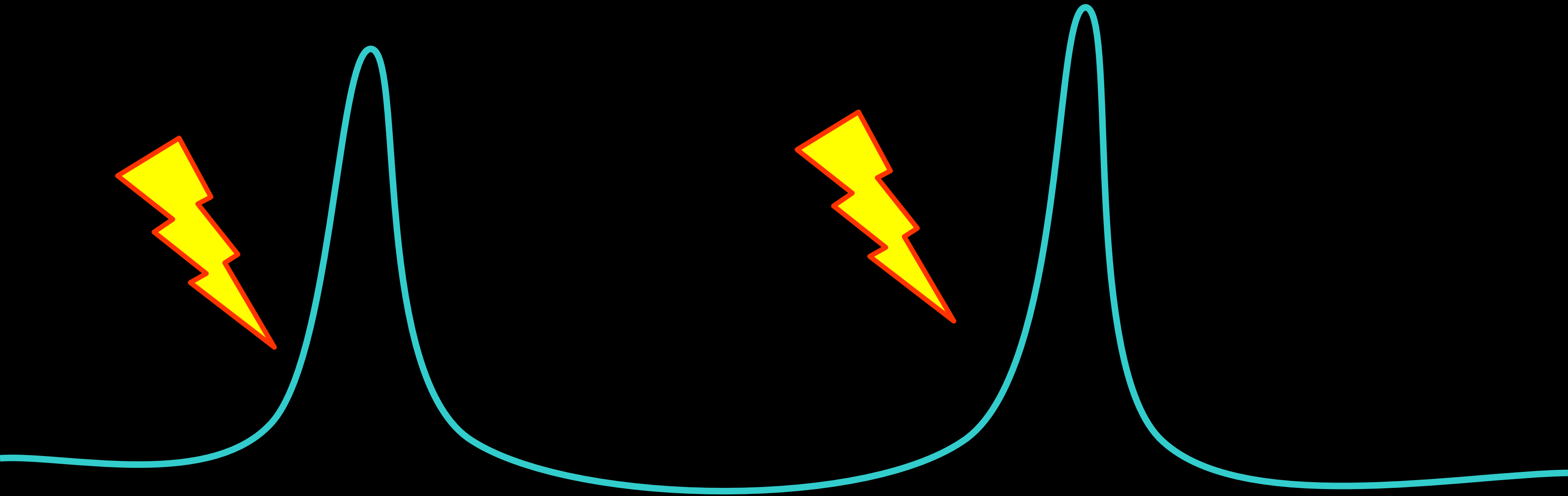
- ☹ Obesity, diabetes
- ☹ Cancer
- ☹ AutoImmune/Inflame
  - ☹ Fat accumulation
  - ☹ Insulin resistance
  - ☹ Proliferation
  - ☹ Inflammation

What's the difference?

Robust	Fragile
☺ Metabolism	☹ Obesity, diabetes
☺ Regeneration & repair	☹ Cancer
☺ Healing wound /infect	☹ AutoImmune/Inflame

☹ Fat accumulation
☹ Insulin resistance
☹ Proliferation
☹ Inflammation

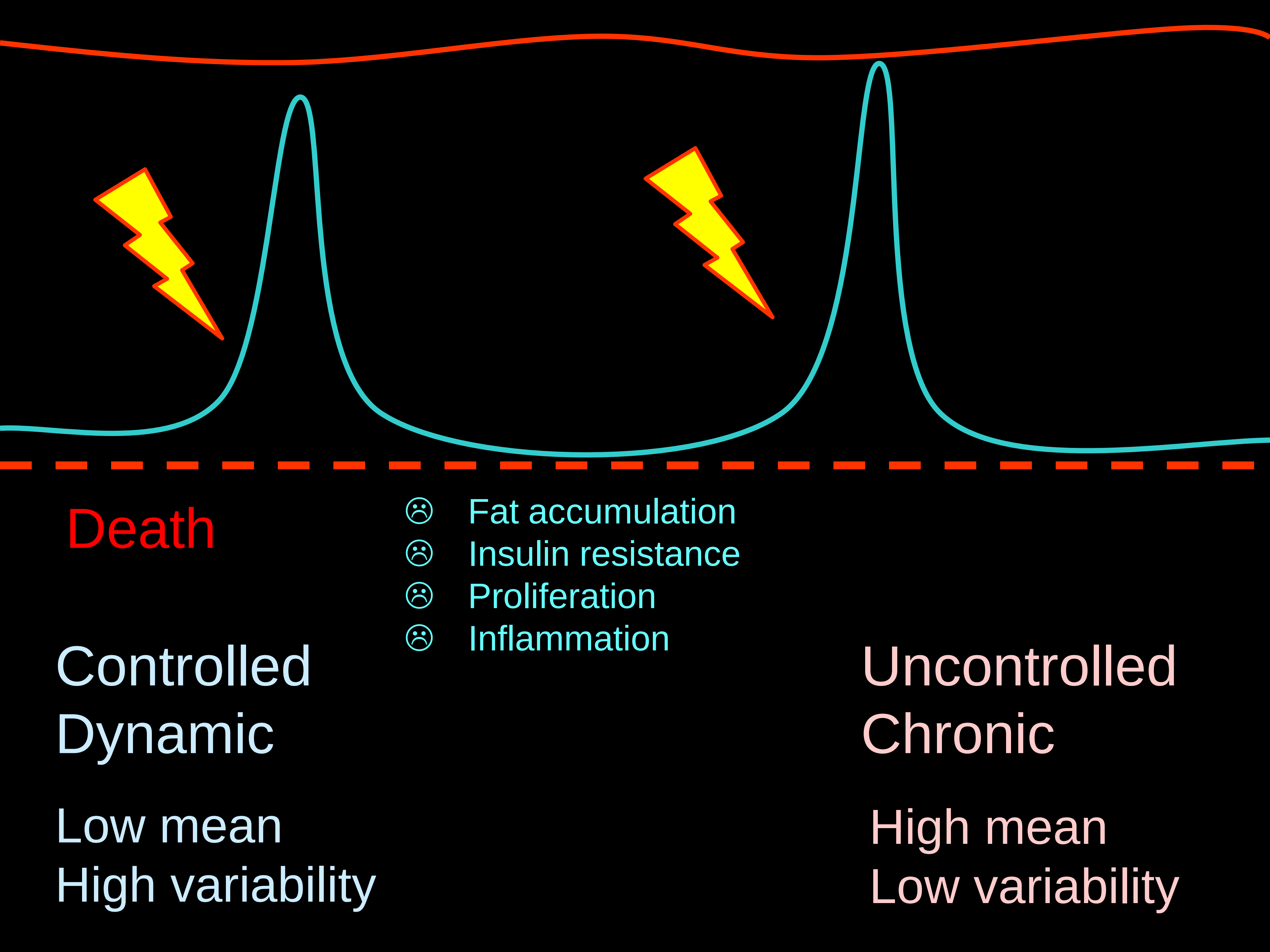
Controlled	Uncontrolled
Dynamic	Chronic



☹ Fat accumulation
☹ Insulin resistance
☹ Proliferation
☹ Inflammation

Controlled
Dynamic

Low mean
High variability



Death
☹ Fat accumulation
☹ Insulin resistance
☹ Proliferation
☹ Inflammation
Controlled
Dynamic
Low mean
High variability
Uncontrolled
Chronic
High mean
Low variability

Restoring robustness?

Robust

☺ Metabolism
☺ Regeneration & repair
☺ Healing wound /infect

☹ Fat accumulation
☹ Insulin resistance
☹ Proliferation
☹ Inflammation

Controlled
Dynamic

Low mean
High variability

Fragile

☹ Obesity, diabetes
☹ Cancer
☹ AutoImmune/Inflame

☹ Fat accumulation
☹ Insulin resistance
☹ Proliferation
☹ Inflammation

Uncontrolled
Chronic

High mean
Low variability

Human complexity

Robust	Yet Fragile
☺ Metabolism	☹ Obesity, diabetes
☺ Regeneration & repair	☹ Cancer
☺ Immune/inflammation	☹ AutoImmune/Inflame
☺ Microbe symbionts	☹ Parasites, infection
☺ Neuro-endocrine	☹ Addiction, psychosis,…
🗐 Complex societies	☠ Epidemics, war,…
🗐 Advanced technologies	💣 Disasters, global &!%$#
🗐 Risk "management"	💣 Obfuscate, amplify,…

Accident or necessity?

Robust

- ☺ Metabolism
- ☺ Regenerati
- ☺ Healing wo

Fragile

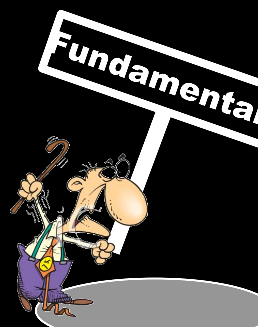
- ☹ Obesity, diabetes
- une/Inflame

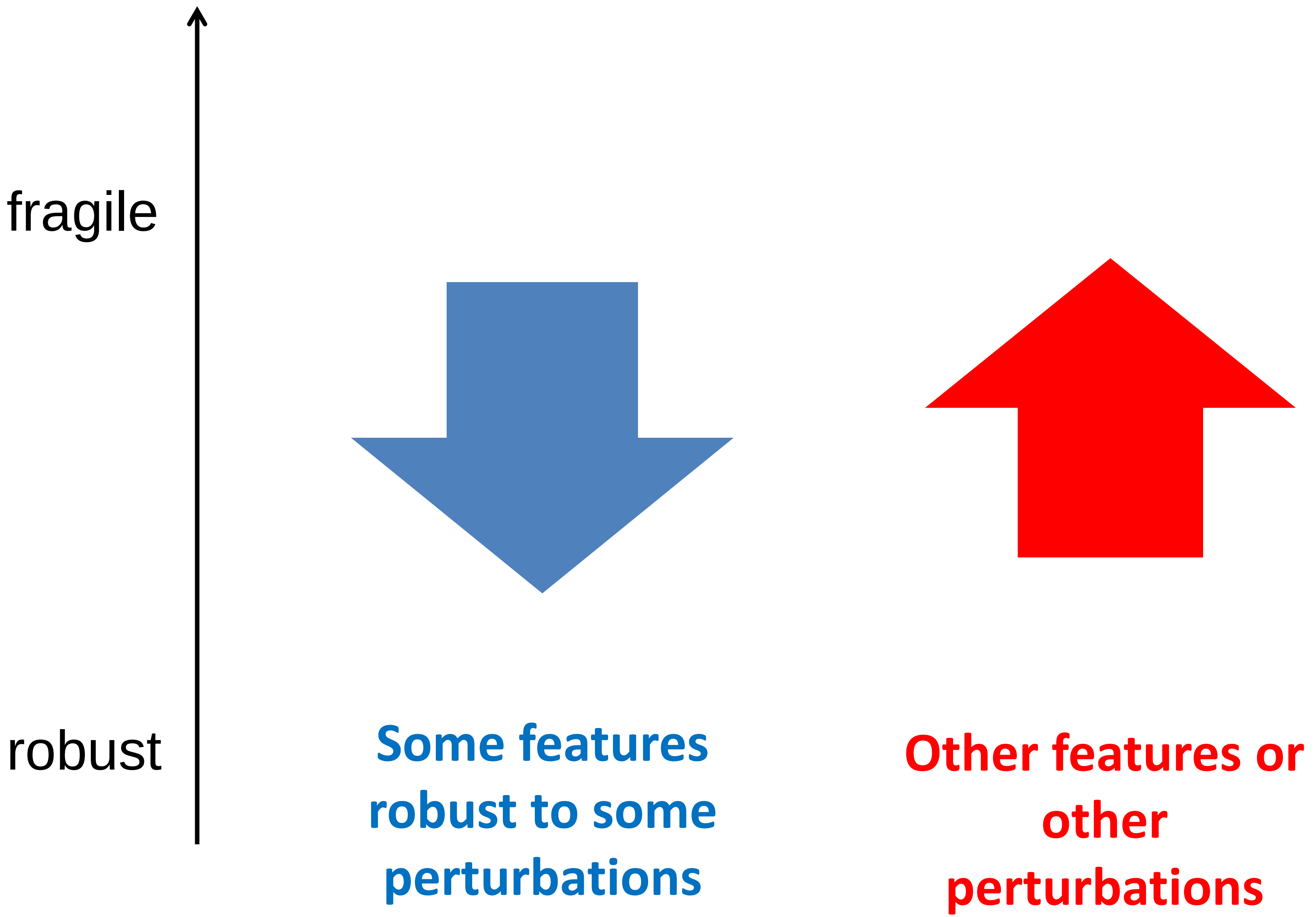
- ☹ Fat accumulation
- ☹ Insulin resistance
- ☹ Proliferation
- ☹ Inflammation

- Fragility ← Hijacking, side effects, unintended…
- Of mechanisms evolved for robustness
- Complexity ← control, robust/fragile tradeoffs
- Math: robust/fragile constraints ("conservation laws")

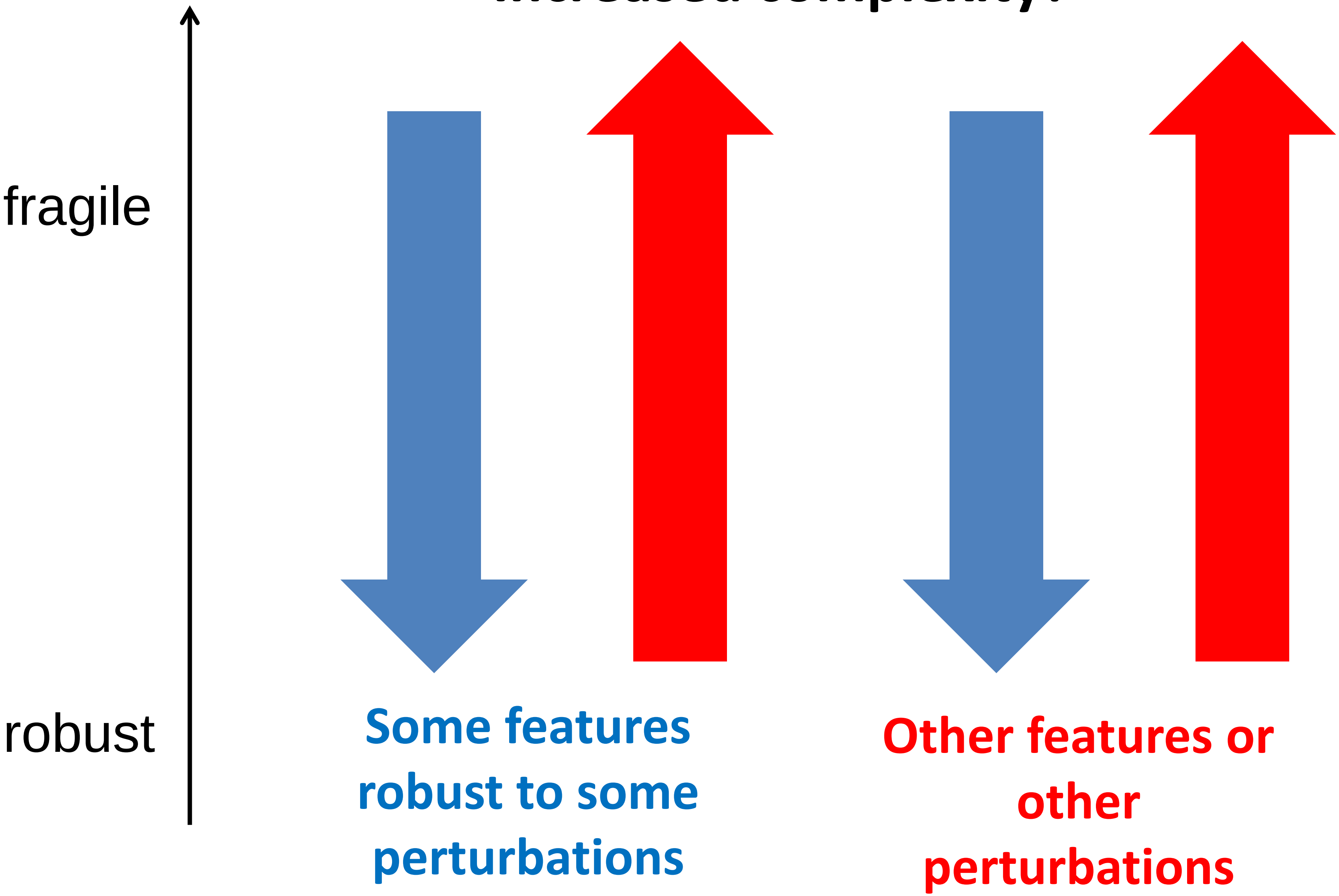
Both

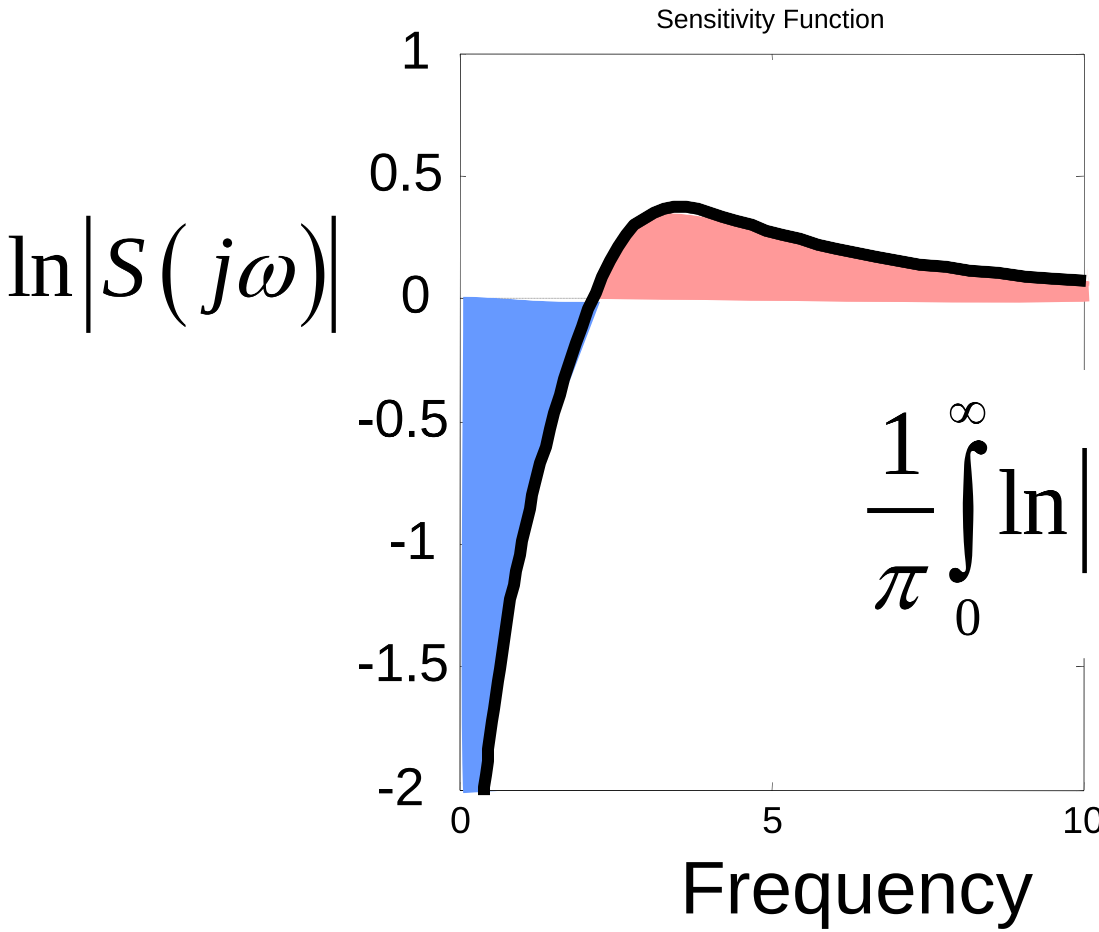
Accident or necessity?



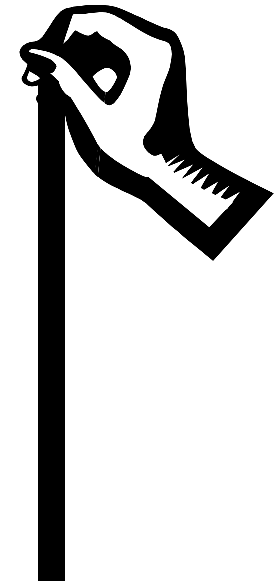

fragile
robust
Some features robust to some perturbations
Other features or other perturbations

Increased complexity?





$$\frac{1}{\pi}\int_0^\infty \ln\left|S(j\omega)\right| d\omega = 0$$



Compute

Turing

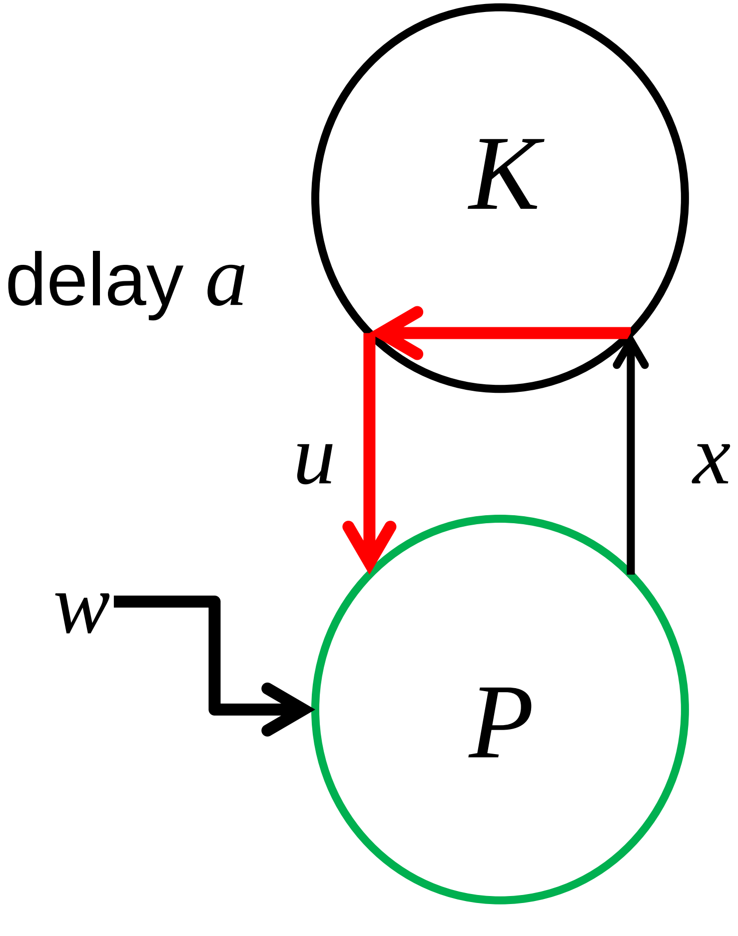
Delay is *most* important

Why

Necessity

Bode

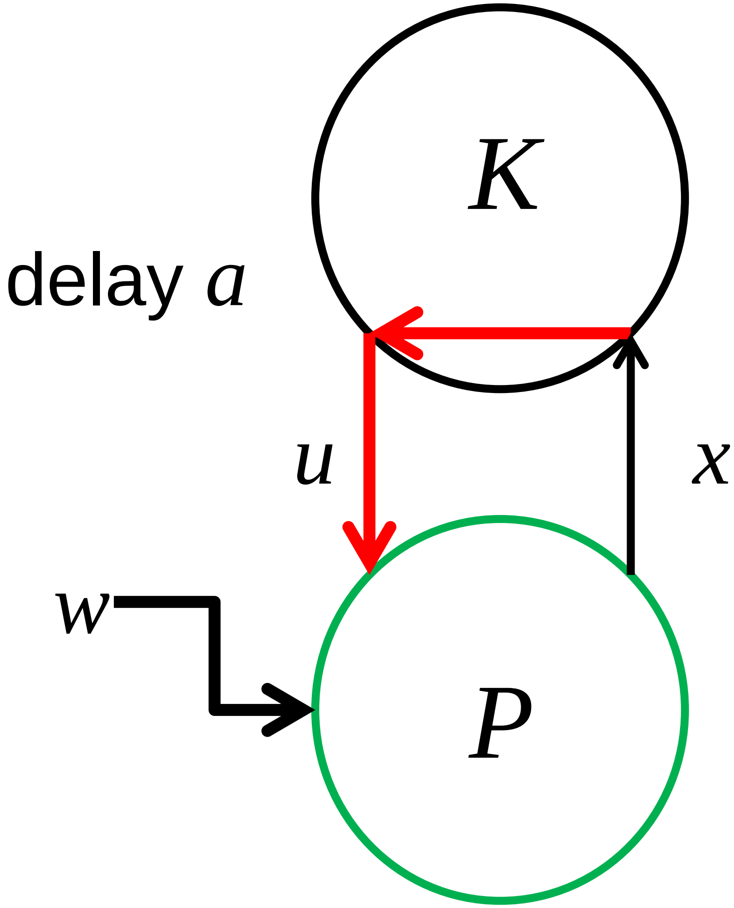
Control, OR



$$x_{t+1} = px_t + w_t + u_{t-a}$$

delay a

$$p > 1$$



No delay or
no uncertainty

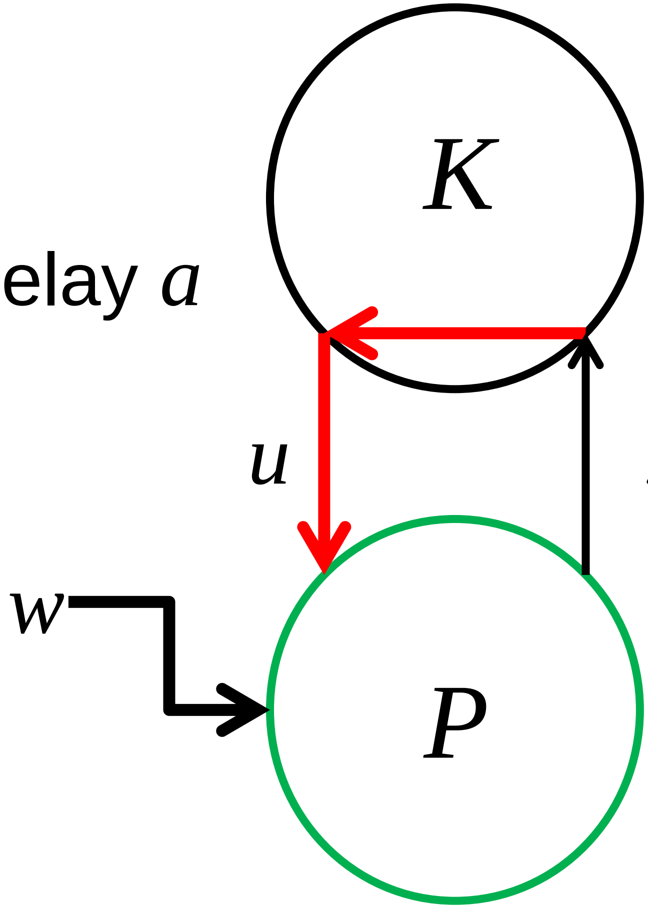
$$u_{t-a} = -\left(px_t + w_t \right)$$

$$\Rightarrow \|x\| \approx 0 \quad \|u\| \approx \|w\|$$

$$x_{t+1} = px_t + w_t + u_{t-a}$$

$$p > 1$$

delay a



No delay or
no uncertainty

$$u_{t-a} = -\left(px_t + w_t\right)$$

$$\Rightarrow \|x\| \approx 0 \quad \|u\| \approx \|w\|$$

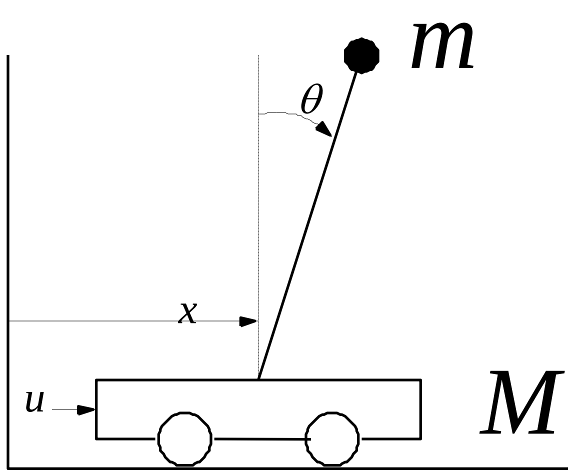
With delay ***and***
uncertainty

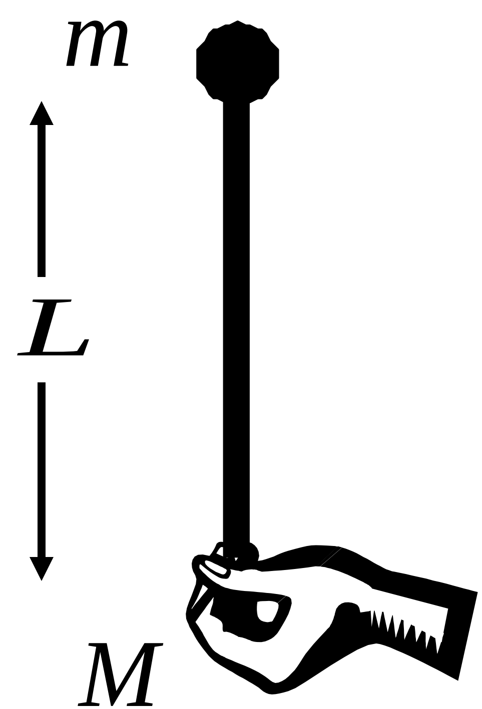
$$x_{t+1} = px_t + w_t + u_{t-a}$$

$$p > 1$$

$$\Rightarrow \|x\| \approx \|u\| \approx p^a \|w\|$$

Linearized pendulum on a cart





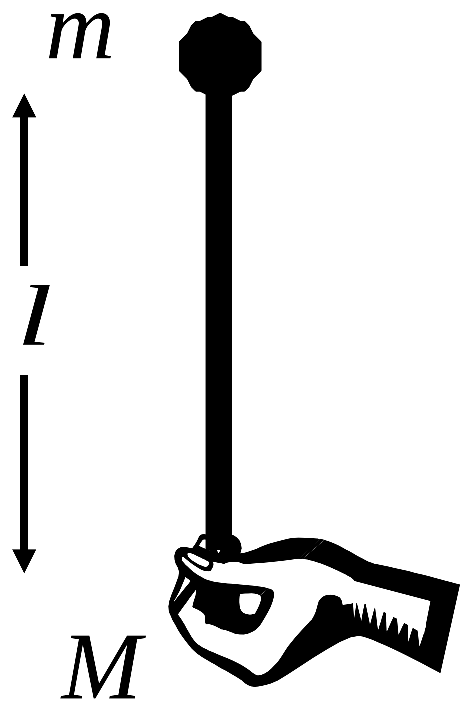
$$\frac{d}{dt}\begin{bmatrix} x \\ \theta \\ \dot{x} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & \dfrac{m^2gl^2}{q} & \dfrac{-(J+ml^2)b}{q} & 0 \\ 0 & \dfrac{mgl(M+m)}{q} & \dfrac{-mlb}{q} & 0 \end{bmatrix} x + \begin{bmatrix} 0 \\ 0 \\ \dfrac{J+ml^2}{q} \\ \dfrac{ml}{q} \end{bmatrix} u$$

$$q = J(M+m) + Mml^2$$

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

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

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



linearize

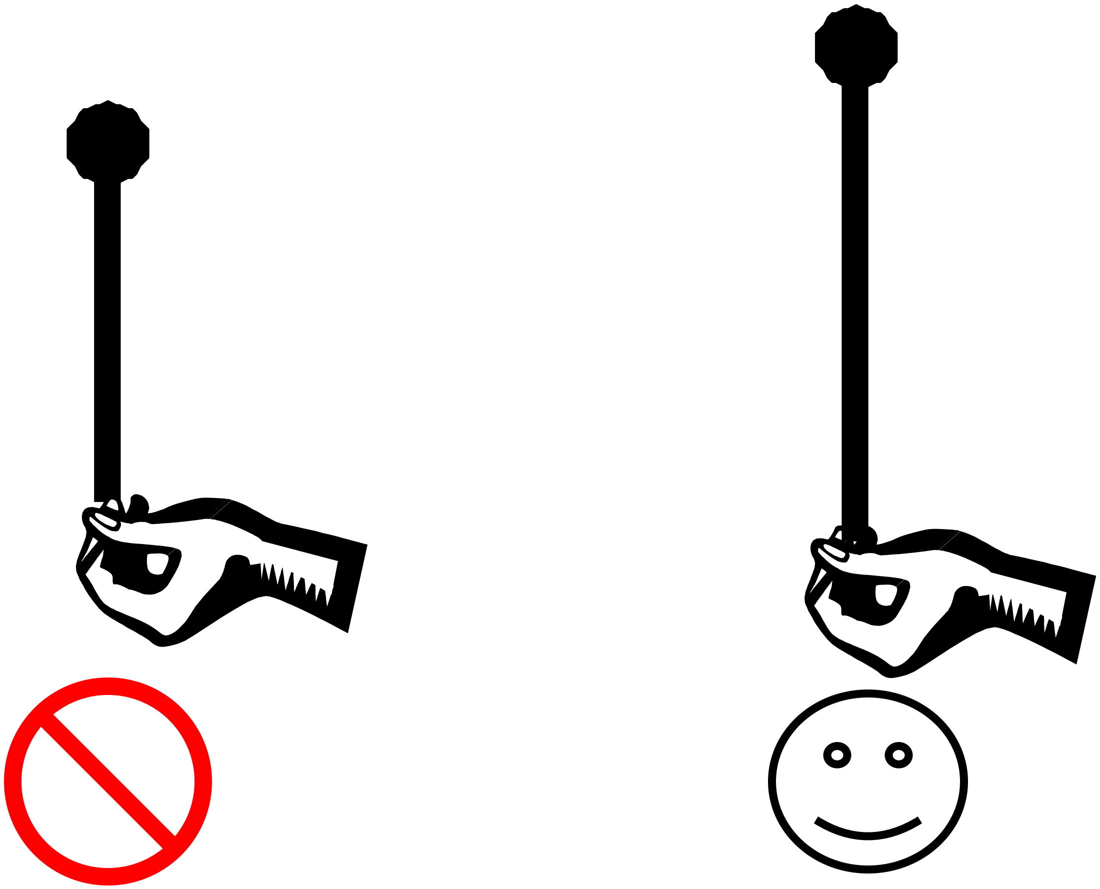
$$(M+m)\ddot{x} + ml\ddot{\theta} = u$$

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

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

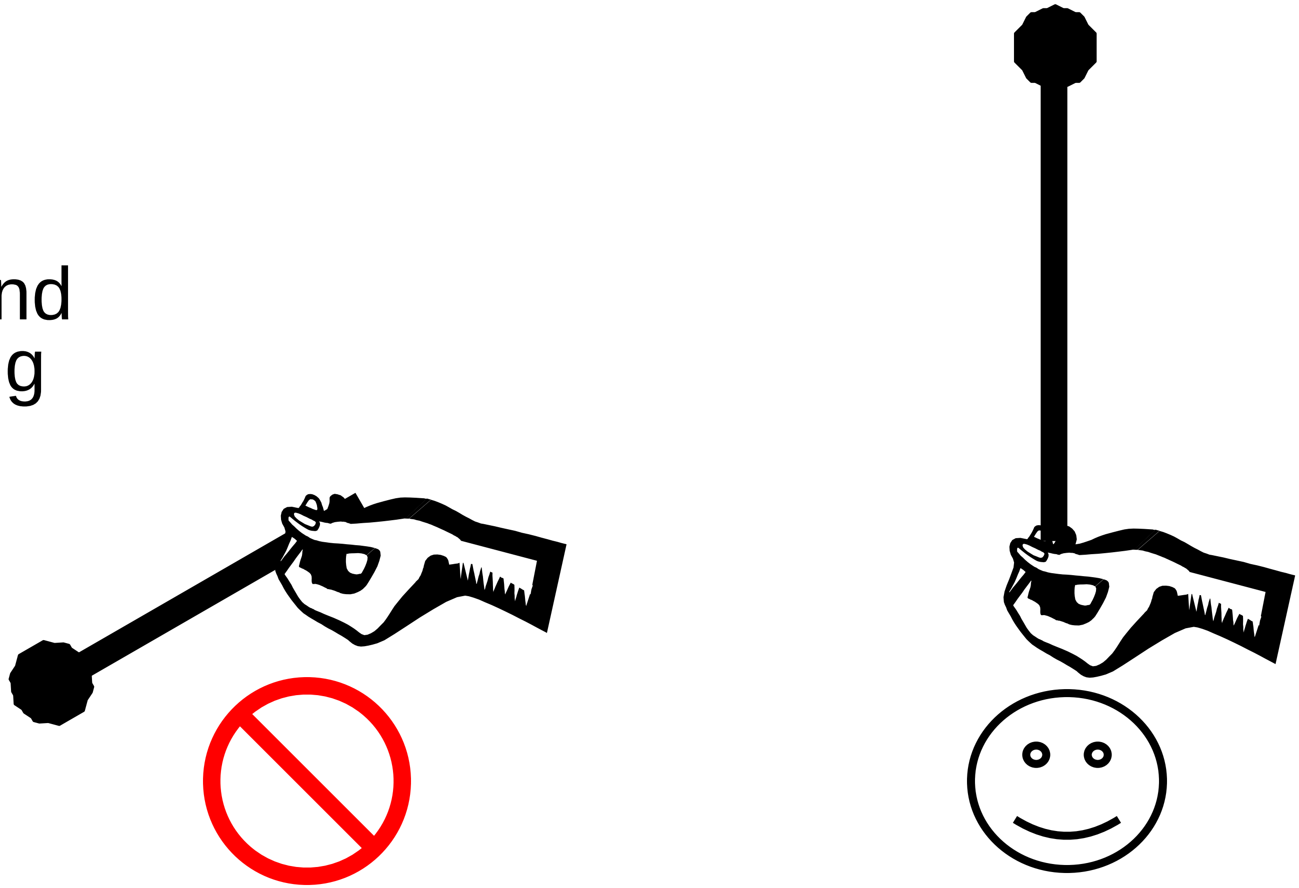
Robust

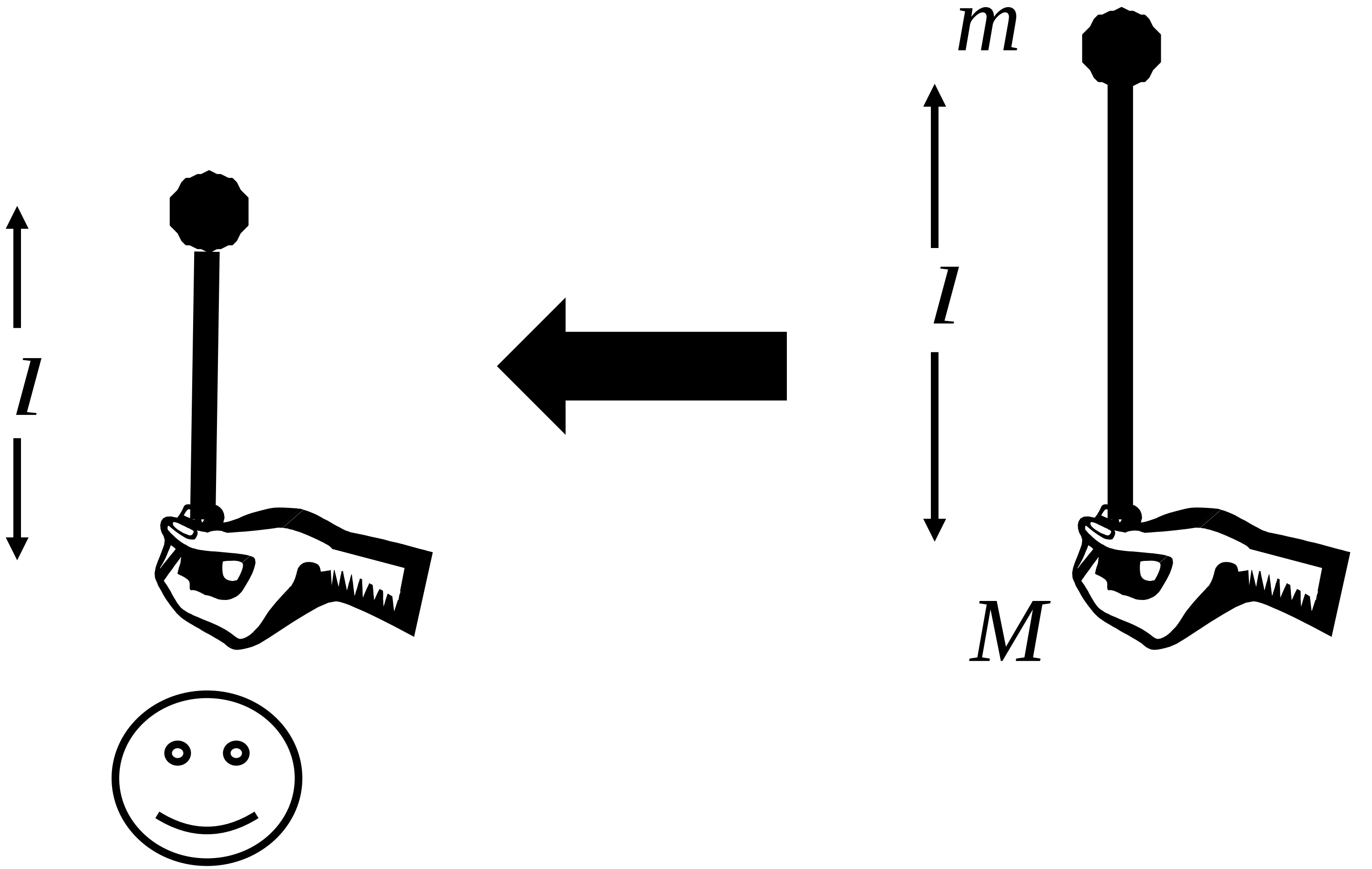
=agile and balancing



Robust

=agile and balancing





Efficient=length of pendulum (artificial)

$$\begin{bmatrix} x \\ \theta \end{bmatrix} = \frac{1}{D(s)} \begin{bmatrix} ls^2 \pm g \\ -s^2 \end{bmatrix} u \qquad D(s) = s^2\left(Mls^2 \pm (M+m)g\right)$$

$$y = x + \alpha l\theta = \frac{\varepsilon ls^2 \pm g}{D(s)} \qquad \varepsilon = 1 - \alpha$$

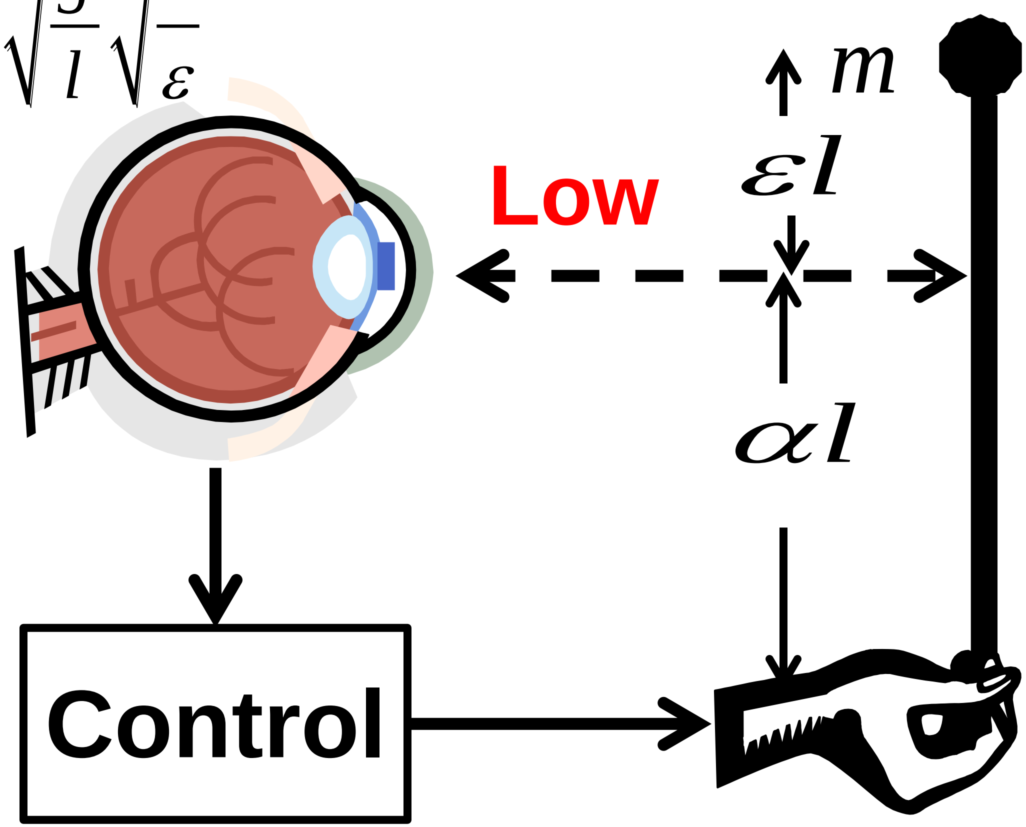
$$p = \sqrt{\frac{g}{l}}\sqrt{1+r} \quad r = \frac{m}{M} \quad z = \sqrt{\frac{g}{l}}\sqrt{\frac{1}{\varepsilon}}$$

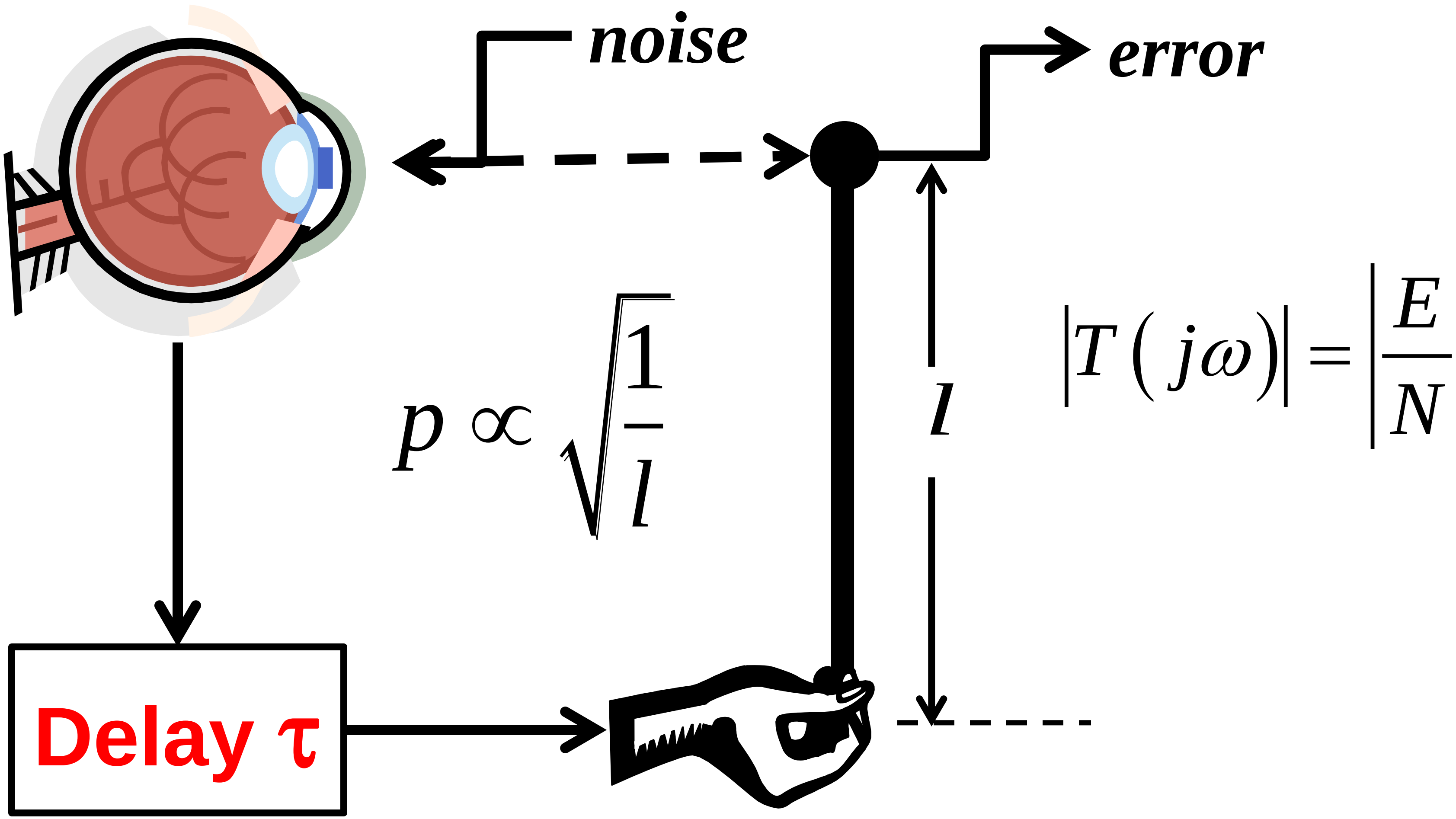
transform+
algebra

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

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

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

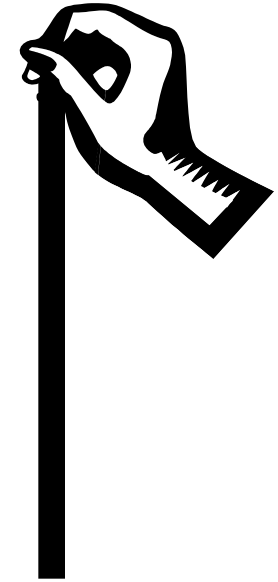




noise
error
$p \propto \sqrt{\frac{1}{l}}$
l
$\left|T(j\omega)\right| = \left|\frac{E}{N}\right|$
Delay τ

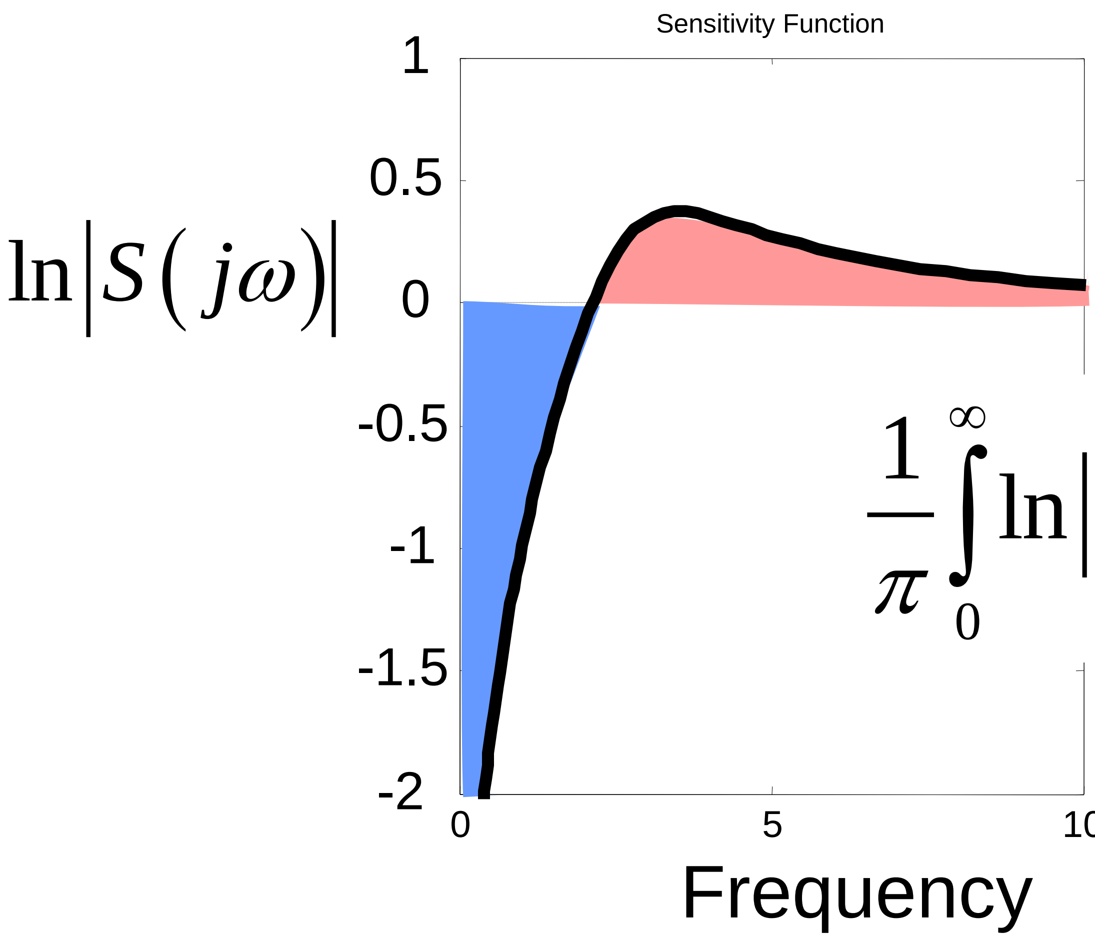
$$\frac{1}{\pi}\int_0^\infty \ln\left|T(j\omega)\right| d\omega \geq 0$$

$$\frac{1}{\pi}\int_0^\infty \ln\left|S(j\omega)\right| d\omega \geq 0$$

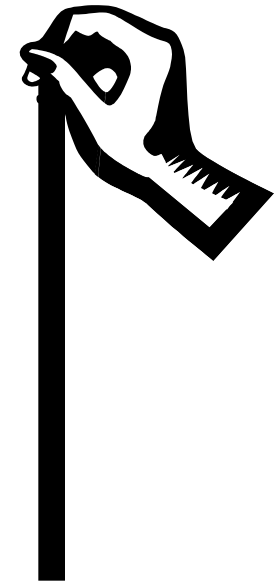


Easy, even with eyes closed
No matter what the length

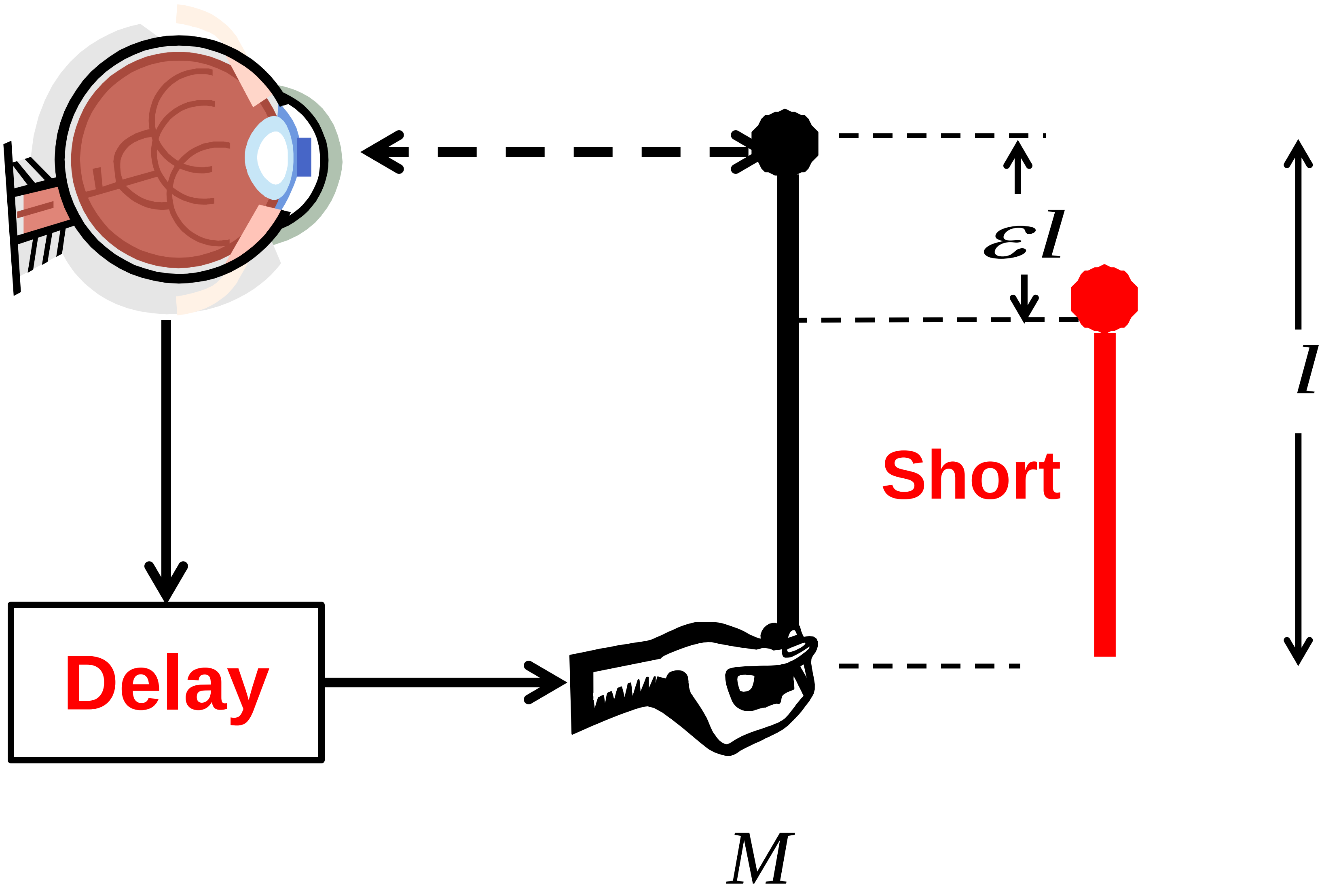
Proof: Standard UG control theory:
Easy calculus, easier contour integral,
easiest Poisson Integral formula



$$\frac{1}{\pi}\int_0^{\infty} \ln\left|S(j\omega)\right| d\omega = 0$$

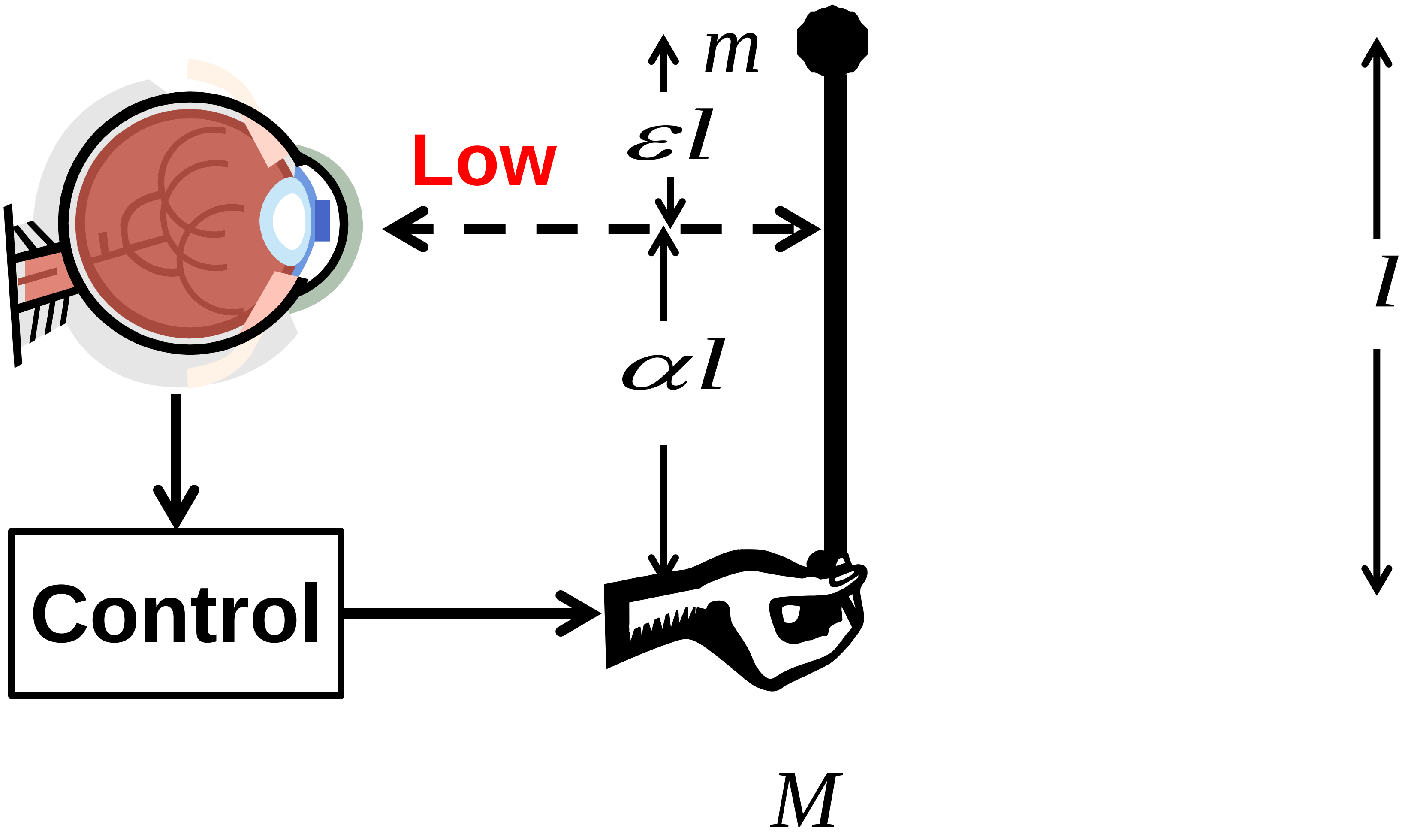


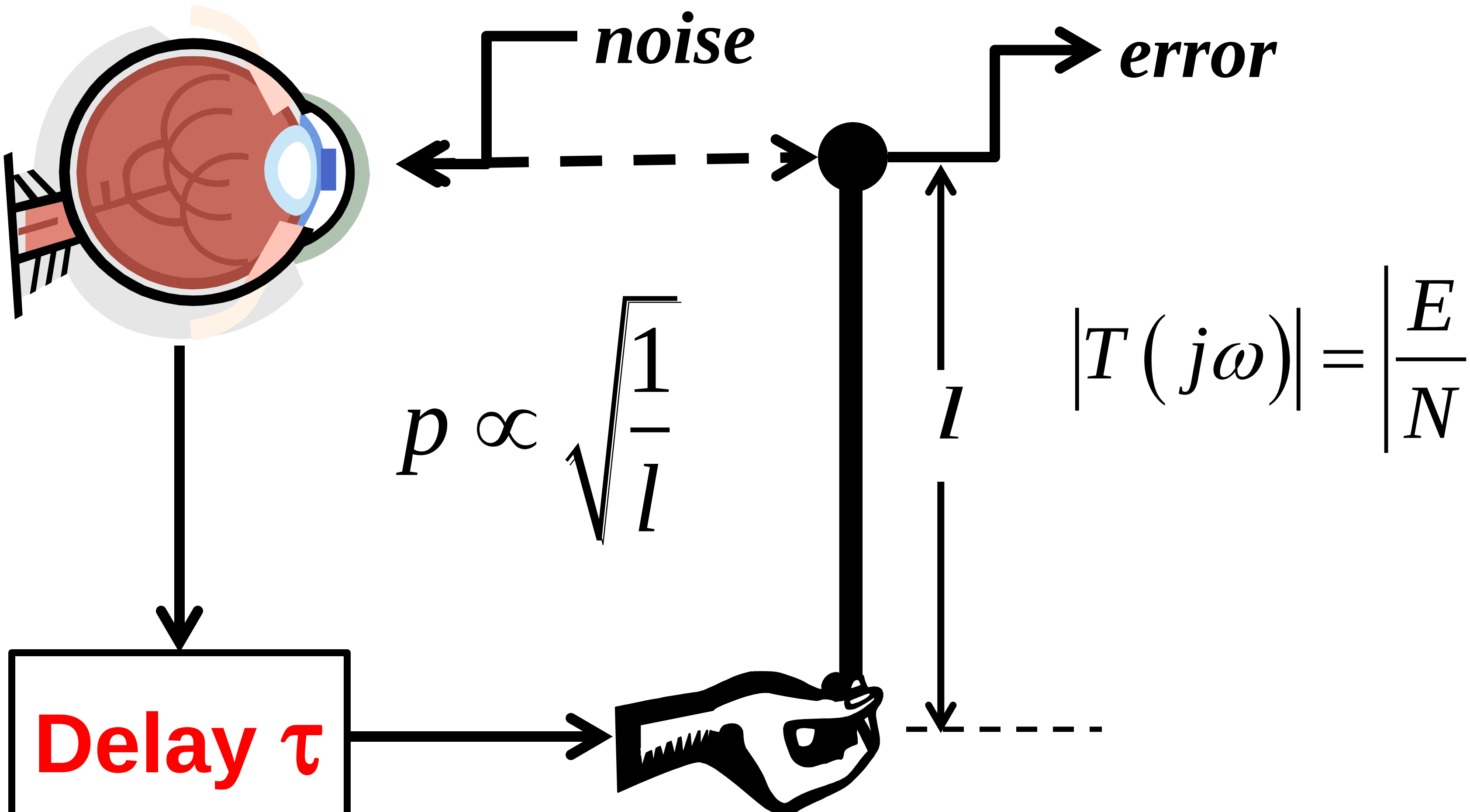
Harder if delayed or short

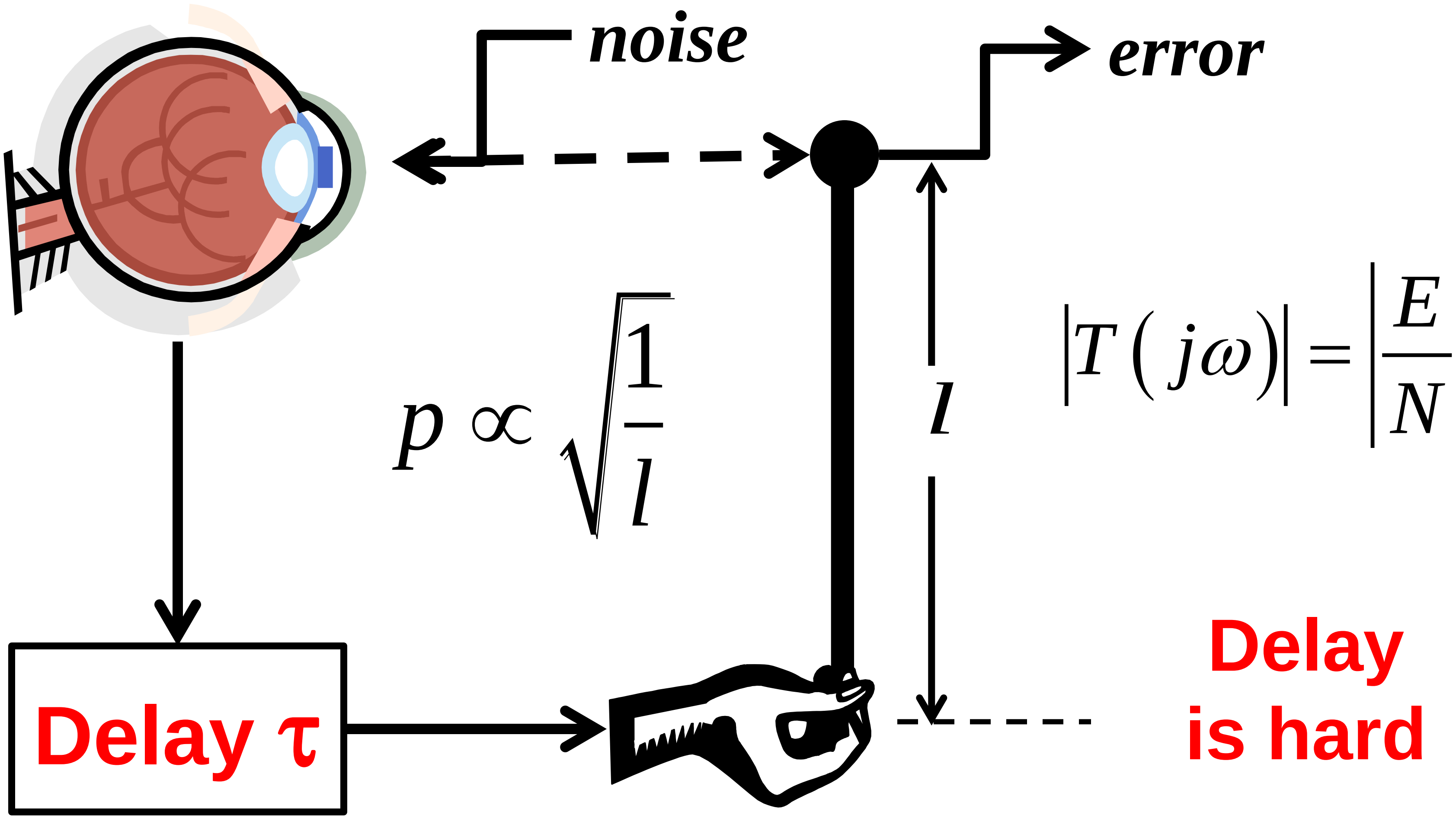


Also harder if sensed low (details later)

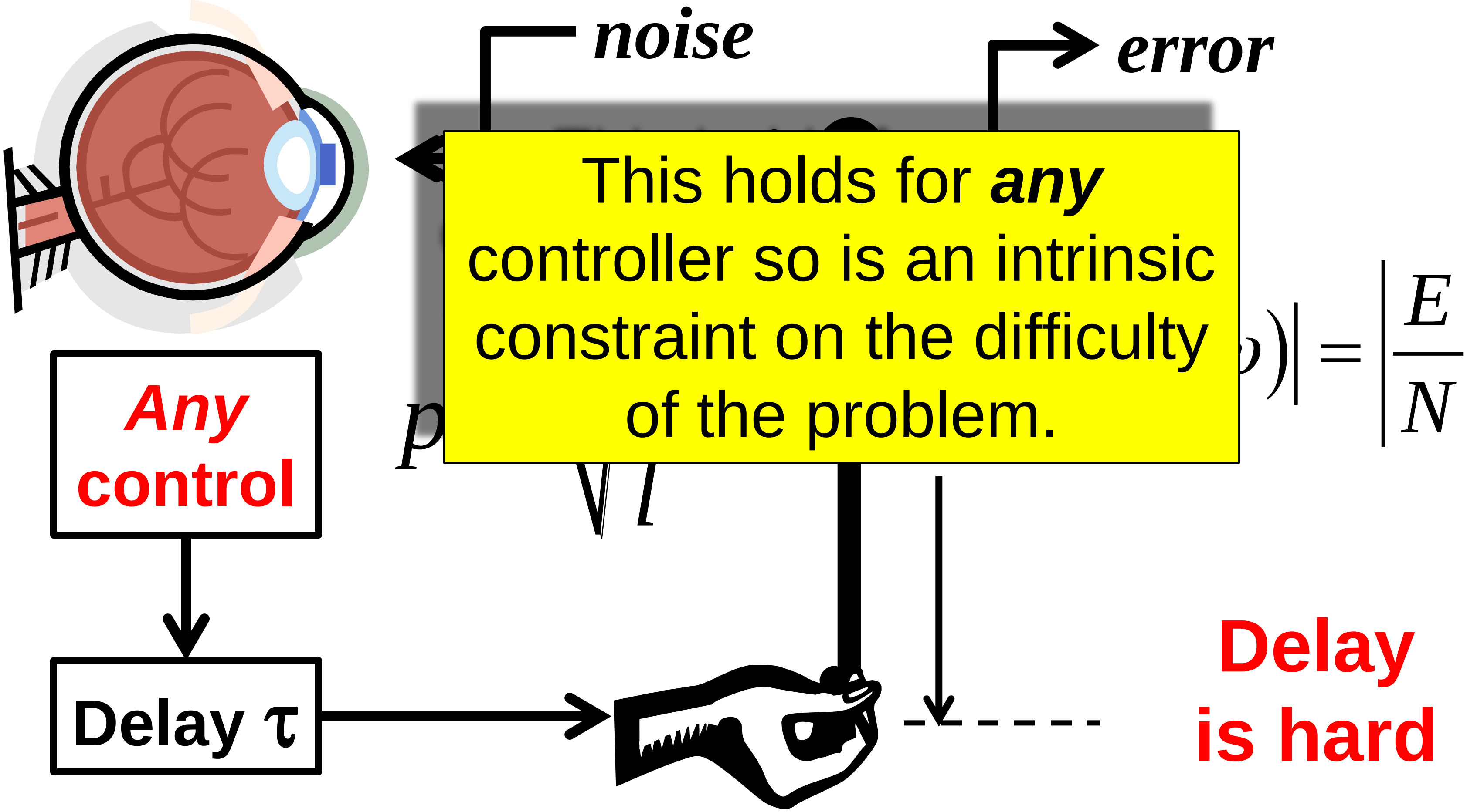
$$r = \frac{m}{M}$$




noise
error
$p \propto \sqrt{\frac{1}{l}}$
l
$\left|T(j\omega)\right| = \left|\frac{E}{N}\right|$
Delay τ



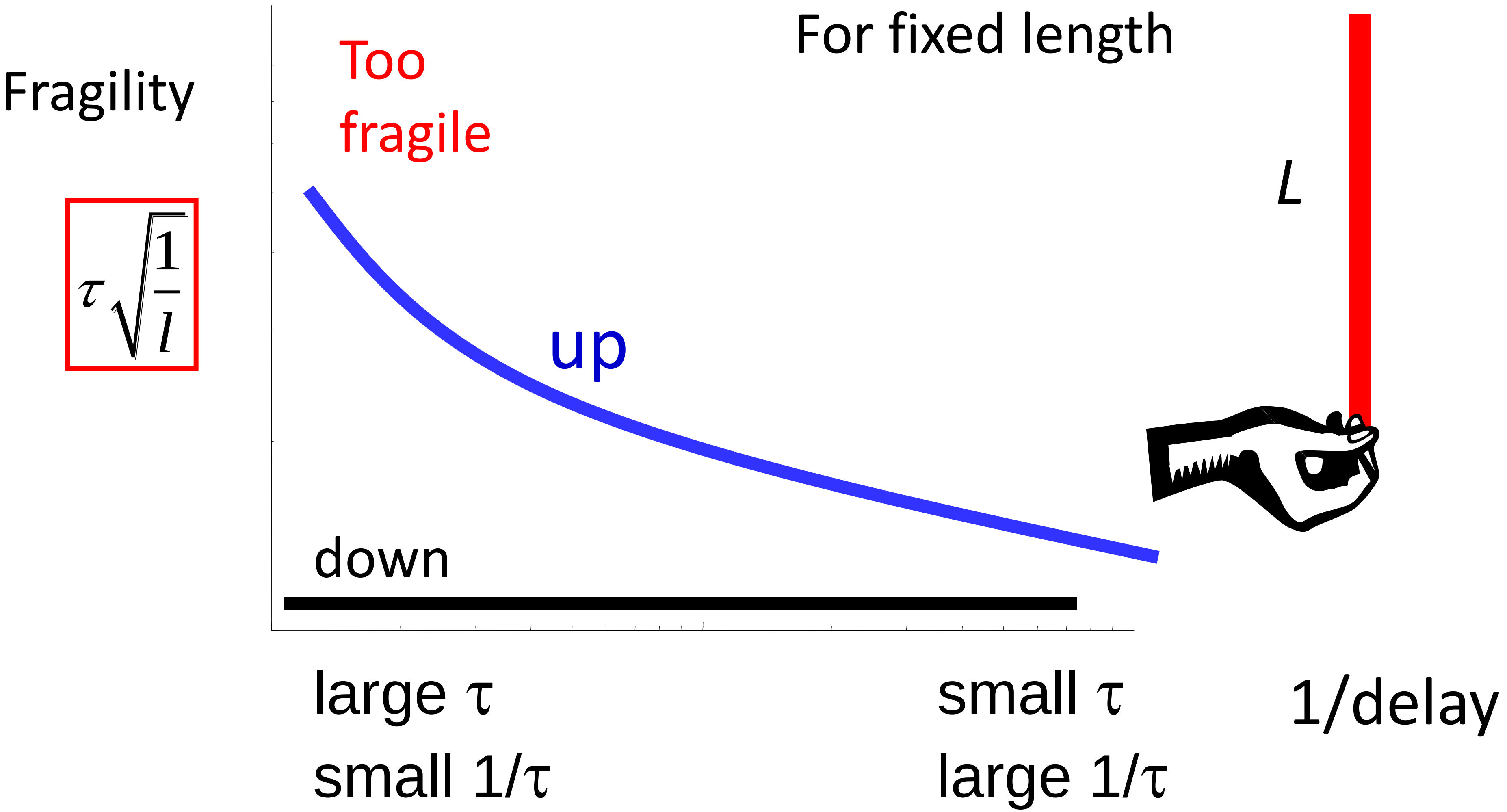
$$\frac{1}{\pi}\int_0^\infty \ln\left|T(j\omega)\right| \frac{2p}{p^2+\omega^2} d\omega \geq \ln\left|T_{mp}(p)\right| = p\tau \propto \tau\sqrt{\frac{1}{l}}$$



This holds for ***any*** controller so is an intrinsic constraint on the difficulty of the problem.

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

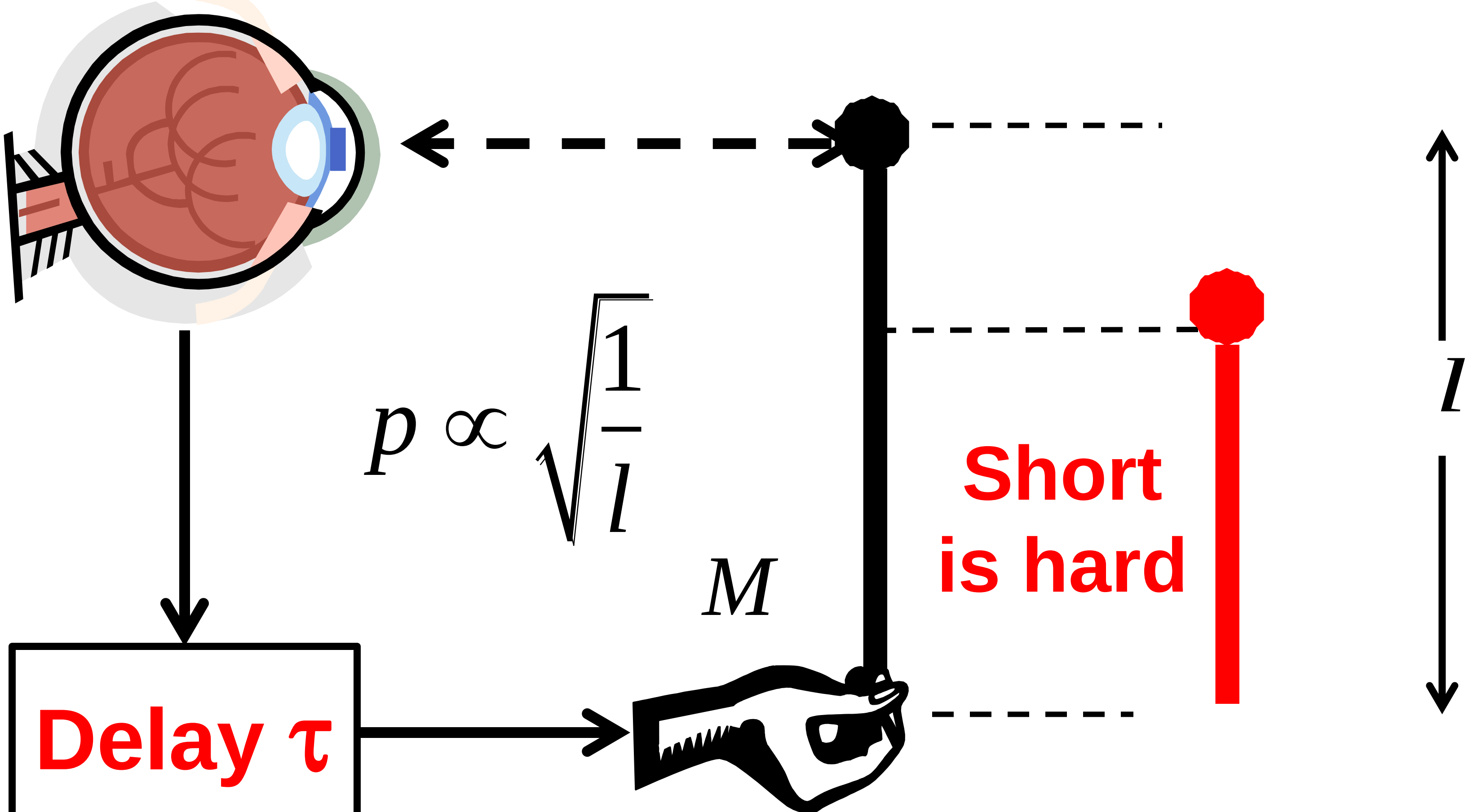
$$\frac{1}{\pi}\int_0^{\infty} \ln\left|T(j\omega)\right| \frac{2p}{p^2+\omega^2} d\omega \geq p\tau \propto \tau\sqrt{\frac{1}{l}}$$



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

We would like to tolerate large delays (and small lengths), but large delays severely constrain the achievable robustness.

large τ | small τ
small $1/\tau$ | large $1/\tau$



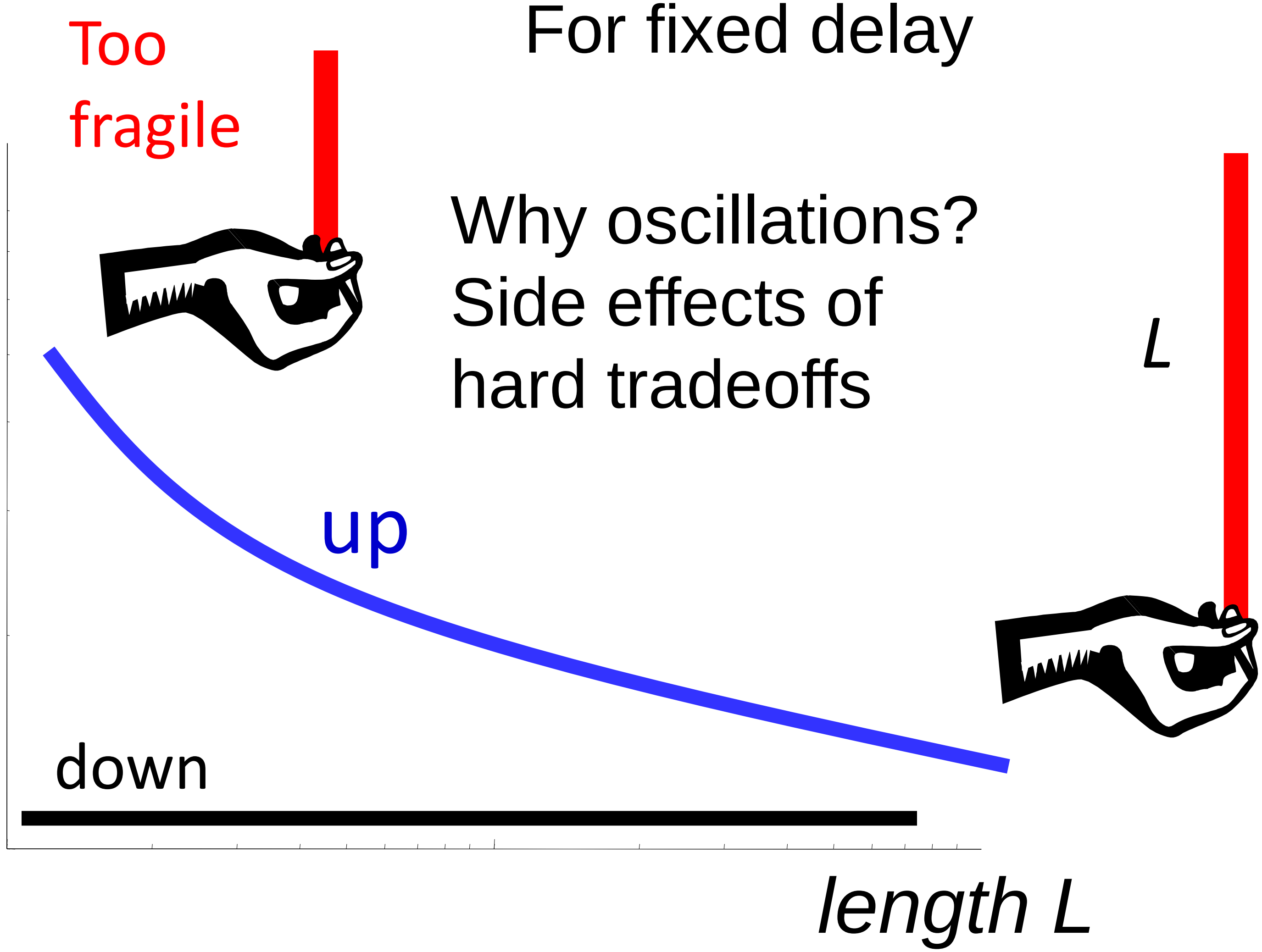
$$\frac{1}{\pi}\int_0^\infty \ln\left|T(j\omega)\right| \frac{2p}{p^2+\omega^2} d\omega \ge \ln\left|T_{mp}(p)\right| = p\tau \propto \tau\sqrt{\frac{1}{l}}$$

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

For fixed delay

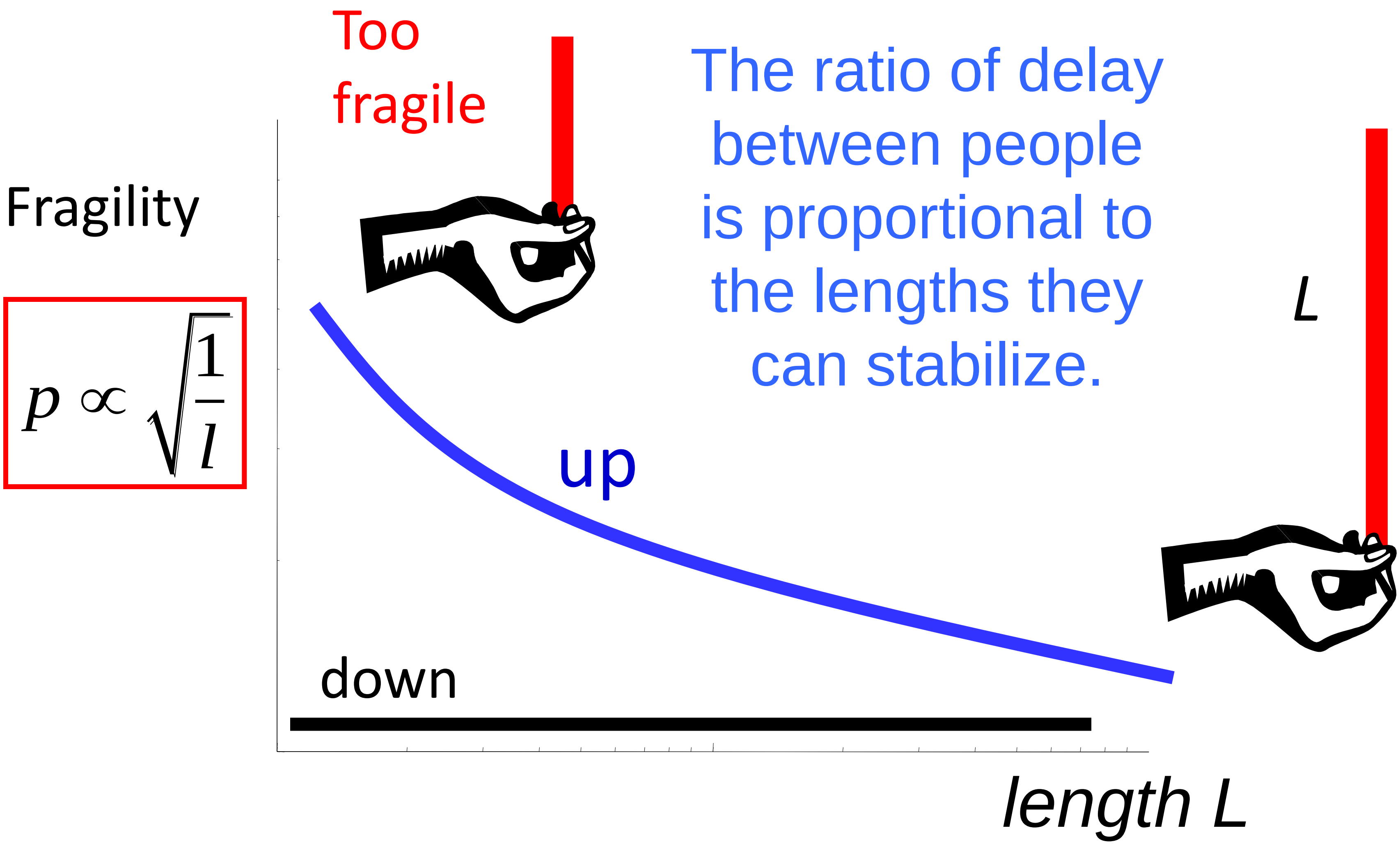
Fragility

$$p \propto \sqrt{\frac{1}{l}}$$

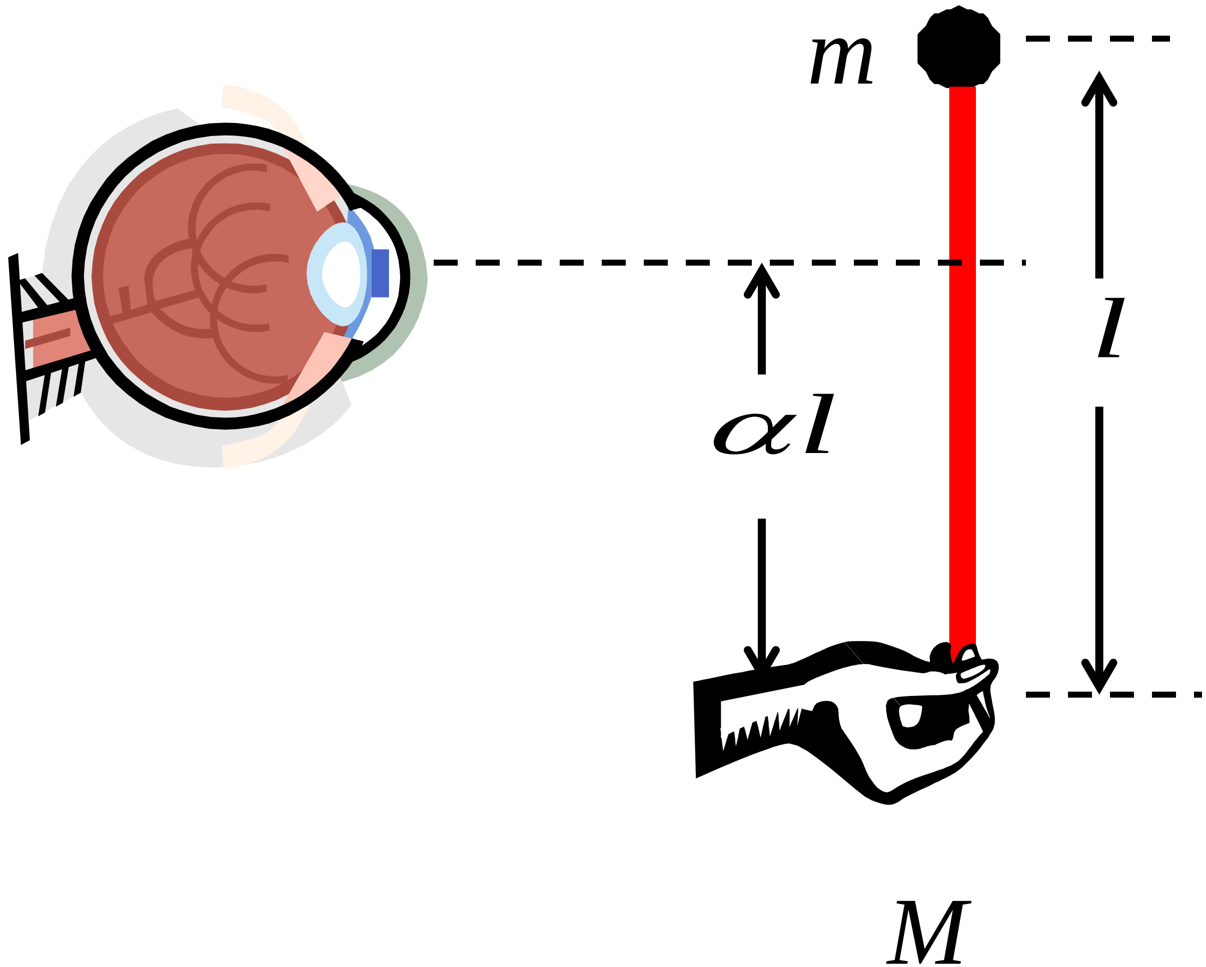


Why oscillations?
Side effects of
hard tradeoffs

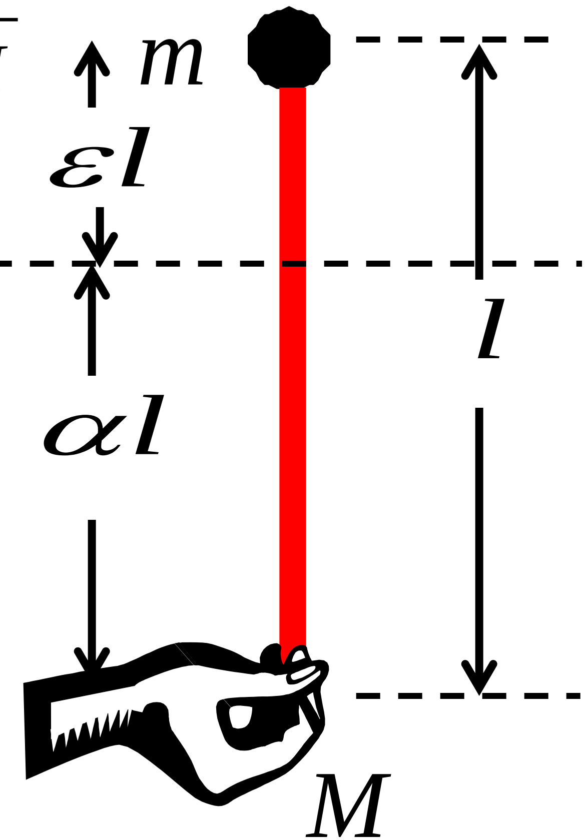
$$\frac{1}{\pi}\int_0^\infty \ln\left|T(j\omega)\right|\frac{2p}{p^2+\omega^2}d\omega \geq \ln\left|T_{mp}(p)\right| = p\tau \propto \tau\sqrt{\frac{1}{l}}$$



Eyes moved down is harder
(RHP zero)
Similar to delay

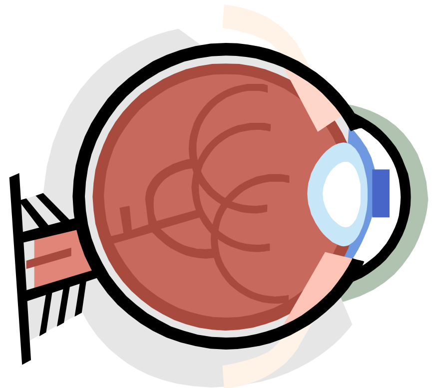


$$r = \frac{m}{M}$$



Suppose $r = \dfrac{m}{M} << 1$

Units $\Rightarrow M = g = 1$



$$y = x + \alpha l \theta = \frac{\varepsilon l s^2 \pm g}{s^2 \left(l s^2 \pm g \right)} \qquad \varepsilon = 1 - \alpha$$

$$p \approx \sqrt{\frac{g}{l}} \qquad z = \sqrt{\frac{g}{l}} \sqrt{\frac{1}{\varepsilon}} \Rightarrow \frac{z+p}{z-p} = \frac{1+\sqrt{\varepsilon}}{1-\sqrt{\varepsilon}}$$

Compare

$$p=\sqrt{\frac{g}{l(1-\varepsilon)}}\sqrt{1+r}=p_0\sqrt{\frac{1}{(1-\varepsilon)}}\approx p_0\left(1+\frac{\varepsilon}{2}\right)$$

Move eyes

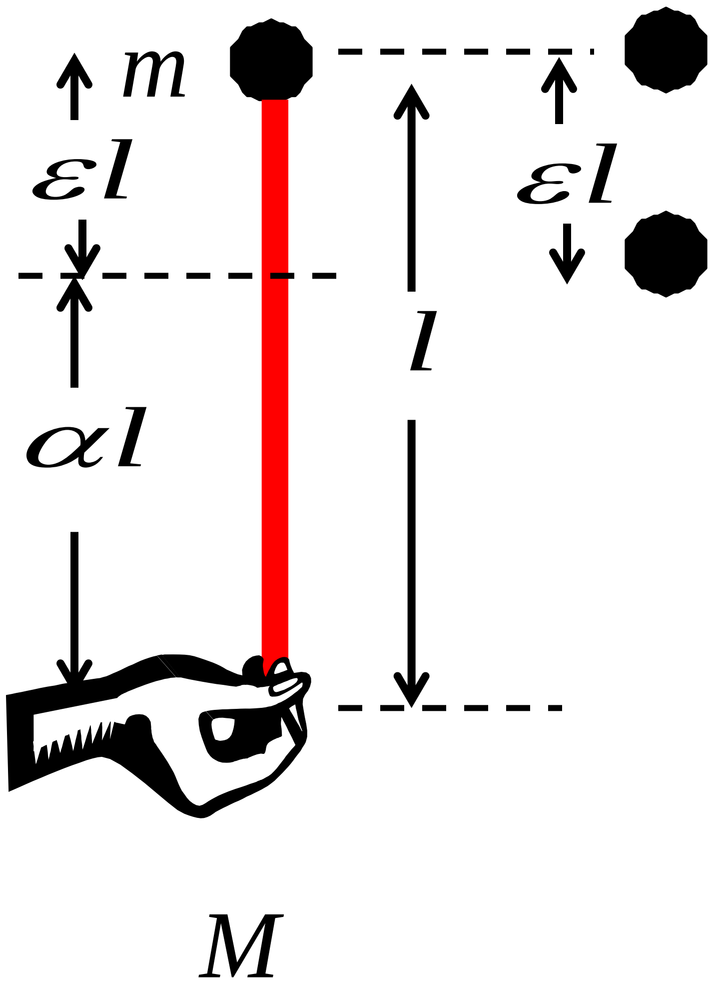
$$p=\sqrt{\frac{g}{l}}\sqrt{1+r}\qquad r=\frac{m}{M}\qquad z=\sqrt{\frac{g}{l}}\sqrt{\frac{1}{\varepsilon}}$$

$$p=z\Rightarrow 1+r=\frac{1}{\varepsilon}\Rightarrow \varepsilon=\frac{1}{1+r}$$

$$p\left(1+\frac{1}{3}\frac{p^2}{z^2}\right)=\sqrt{\frac{g}{l}}\sqrt{1+r}\left(1+\frac{1}{3}\varepsilon\right)=p\left(1+\frac{\varepsilon}{3}\right)$$

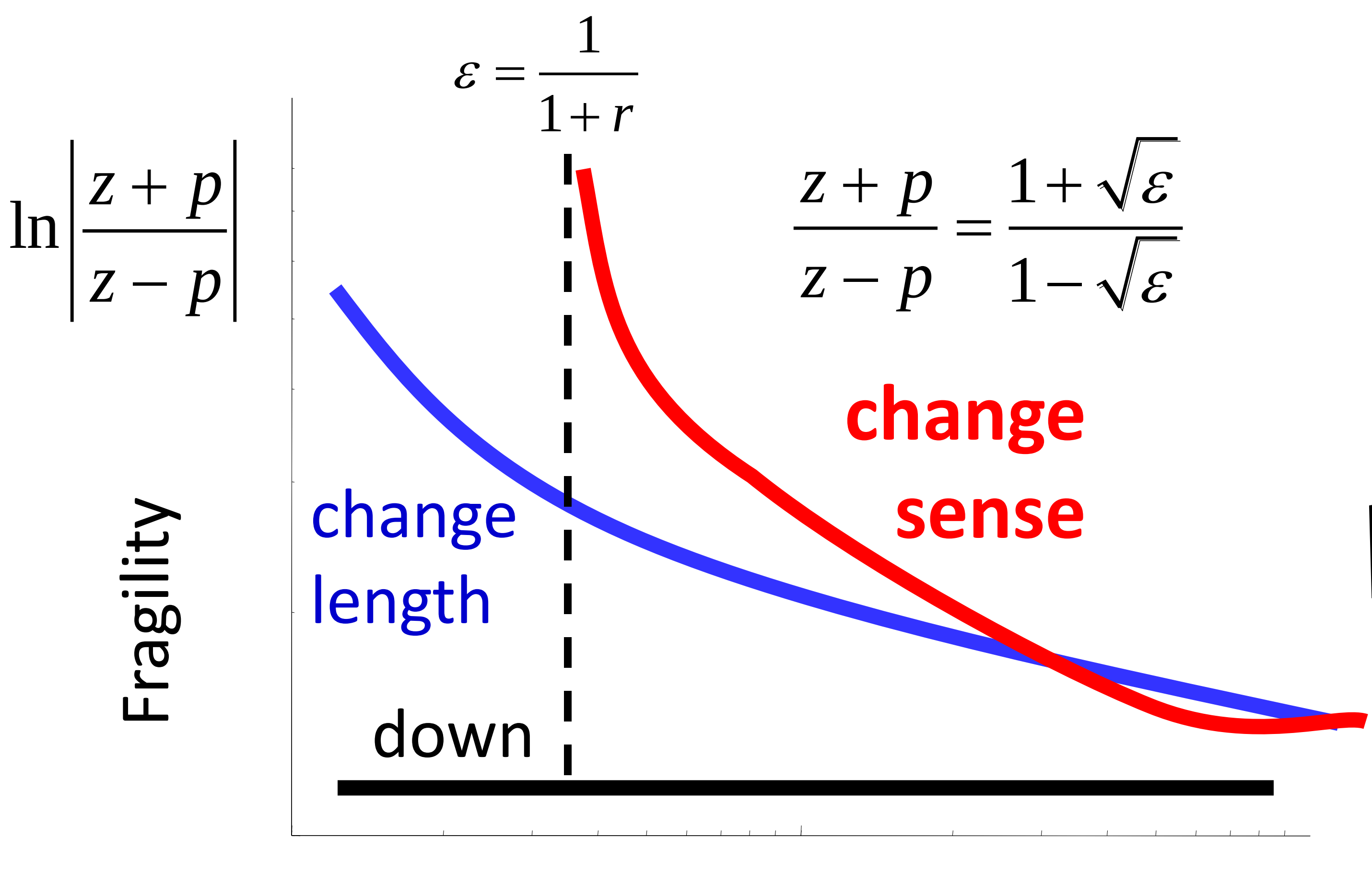
$$=p\left(1+\frac{1-\alpha}{3}\right)$$

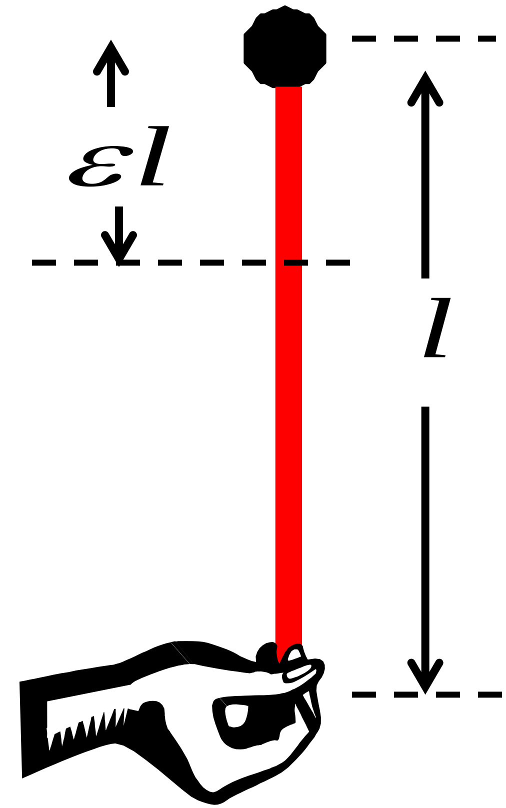
$$r=\frac{m}{M}$$



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

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

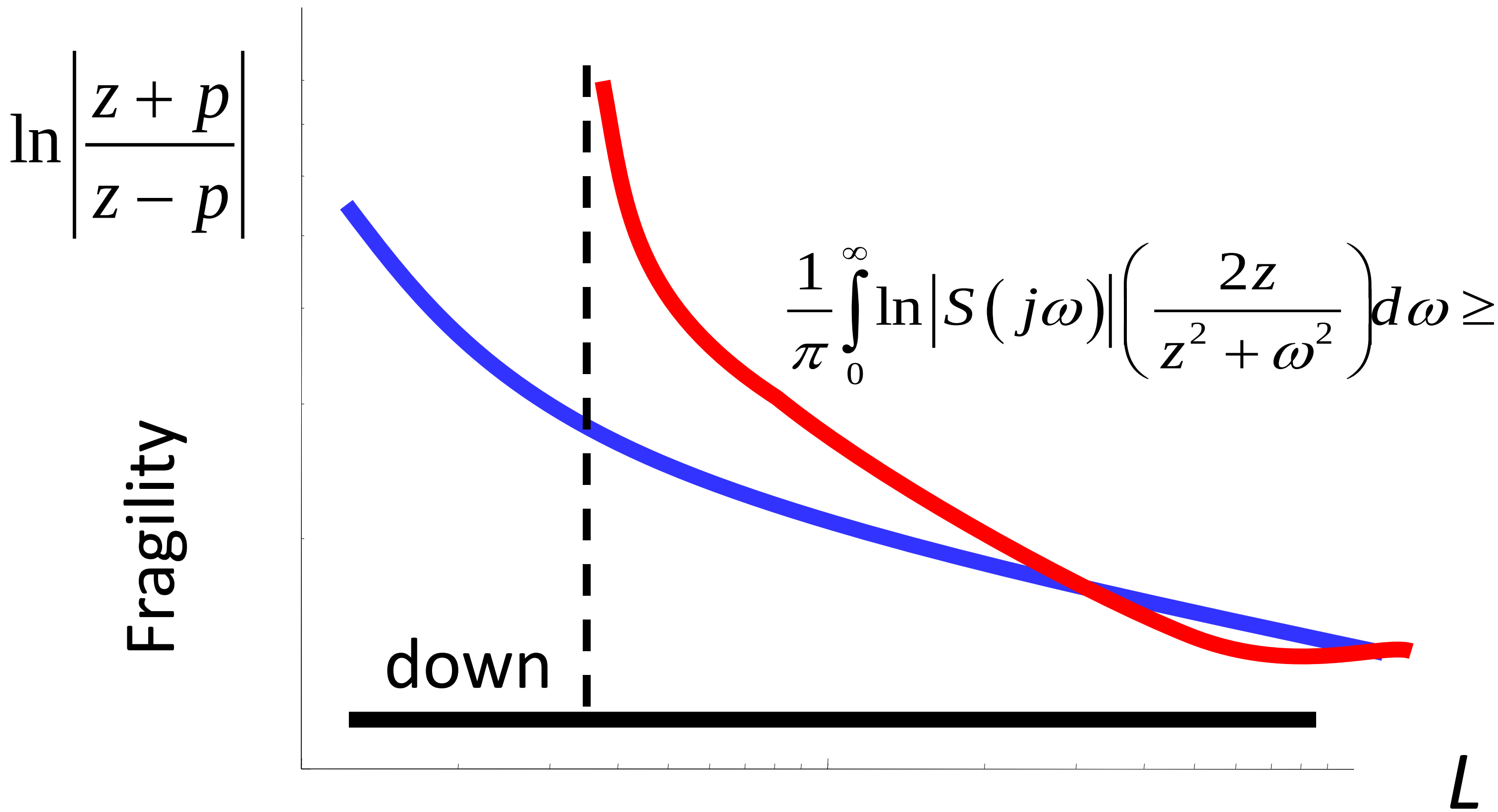




This is a cartoon, but can be made precise.

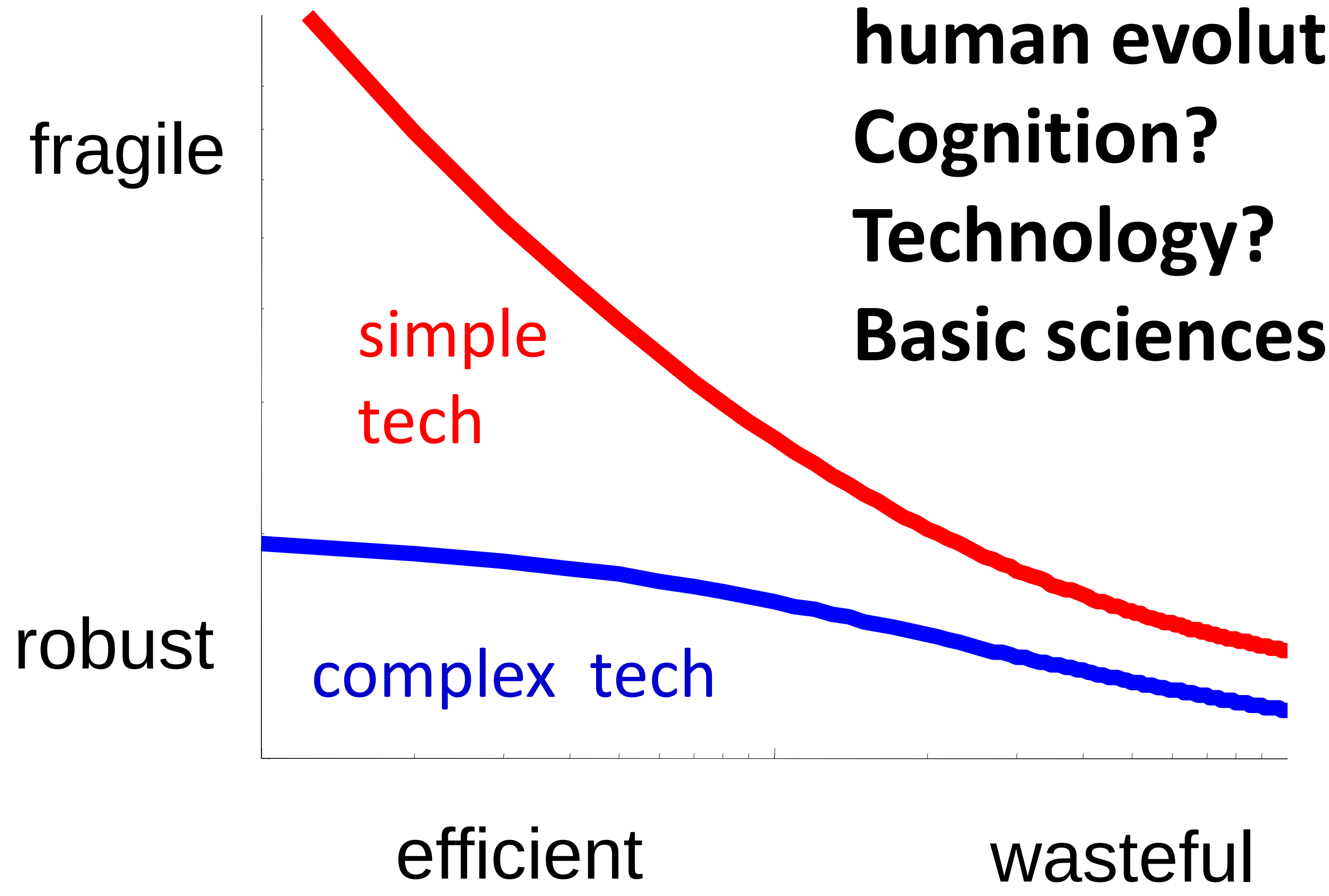
Hard limits on the ***intrinsic*** robustness of control ***problems***.

Must (and do) have algorithms that achieve the limits, and architectures that support this process.



This is a cartoon, but can be made precise.

How general is this picture?



Implications for human evolution?
Cognition?
Technology?
Basic sciences?

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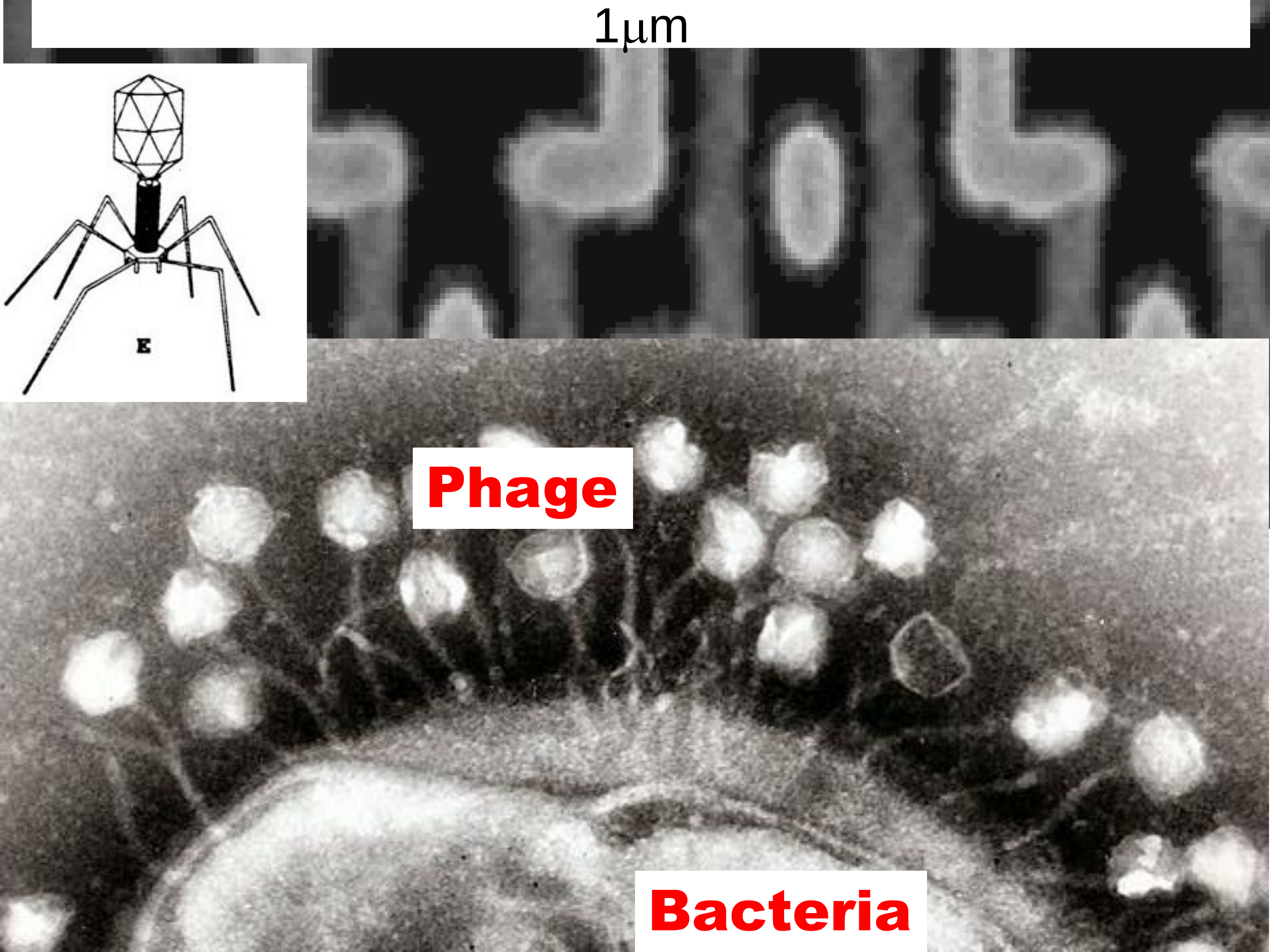
Viruses' Life History: Towards a Mechanistic Basis of a Trade-Off between Survival and Reproduction among Phages

Marianne De Paepe, François Taddei*

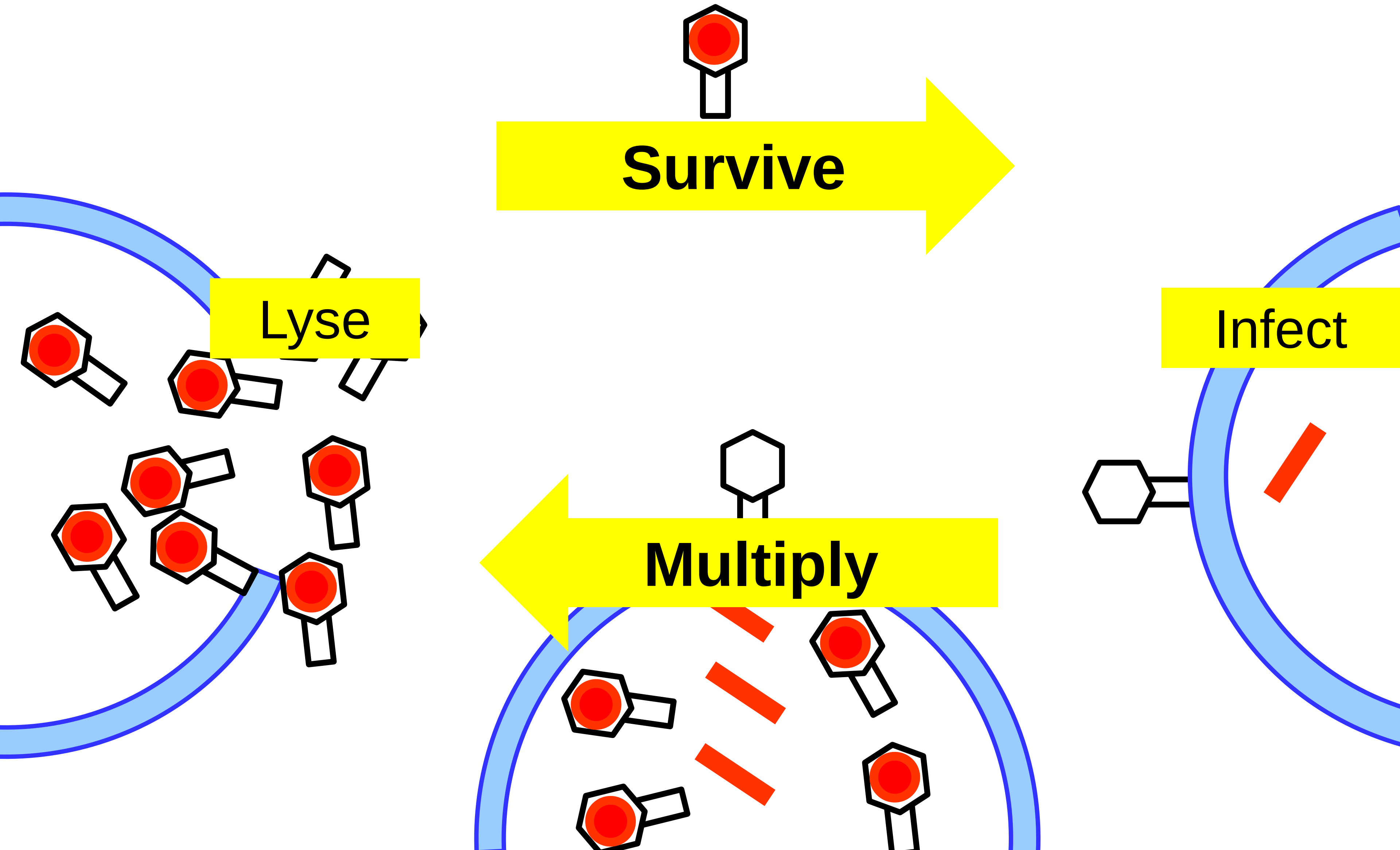
Laboratoire de Genetique Moleculaire, Evolutive et Medicale, University of Paris 5, INSERM, Paris, France

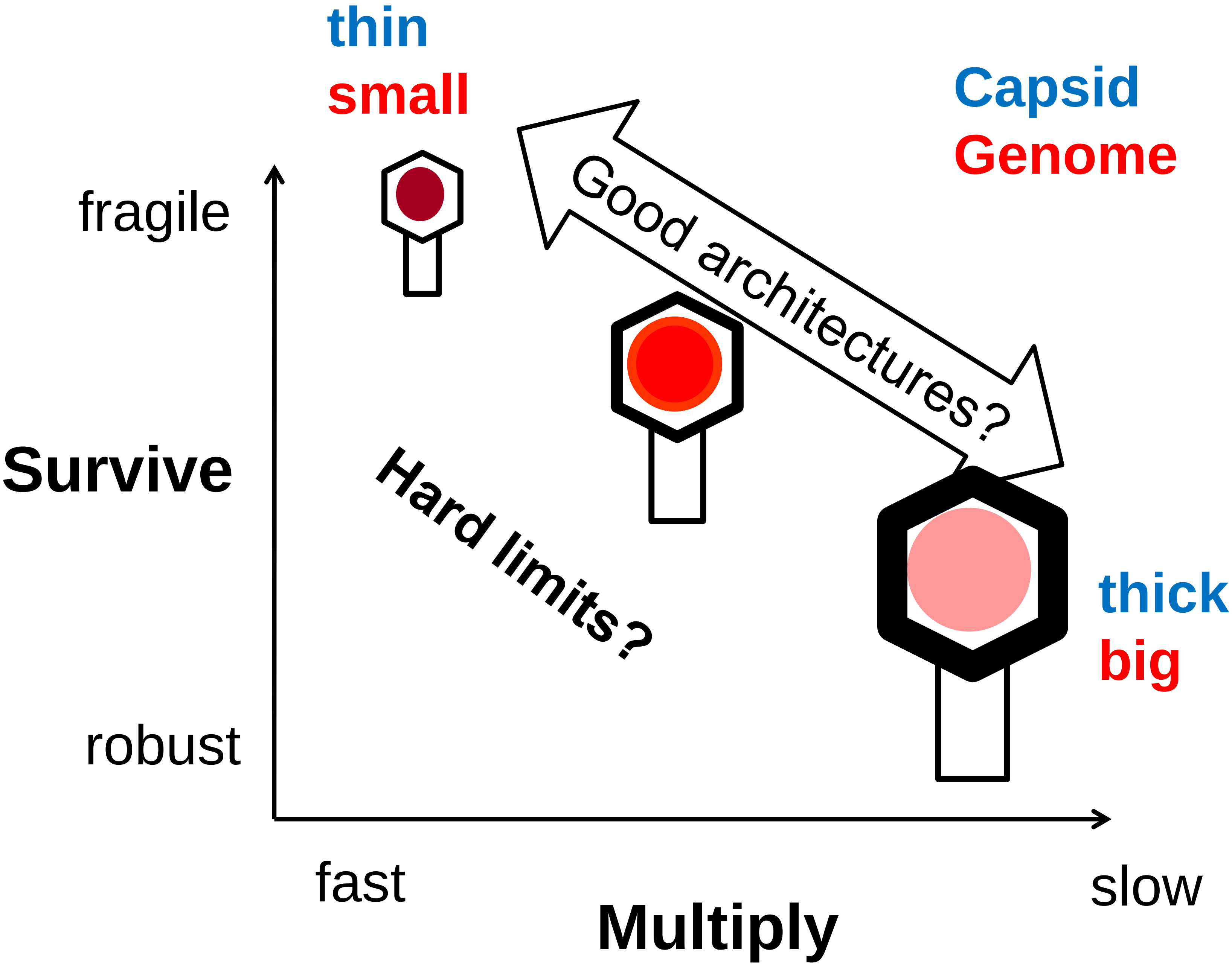
July 2006 | Volume 4 | Issue 7 | e193

I recently found this paper, a rare example of exploring an explicit tradeoff between robustness and efficiency. This seems like an important paper but it is rarely cited.


1μm
E
Phage
Bacteria

Phage lifecycle




thin
small
Capsid
Genome
fragile
Good architectures?
Survive
Hard limits?
thick
big
robust
fast
slow
Multiply

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.

the cell's use of ATP. In glycolysis, two ATP 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 as discussed below and in SOM, but the analysis

Chandra, Buzi, and Doyle

Most important paper so far.

Science
AAAS

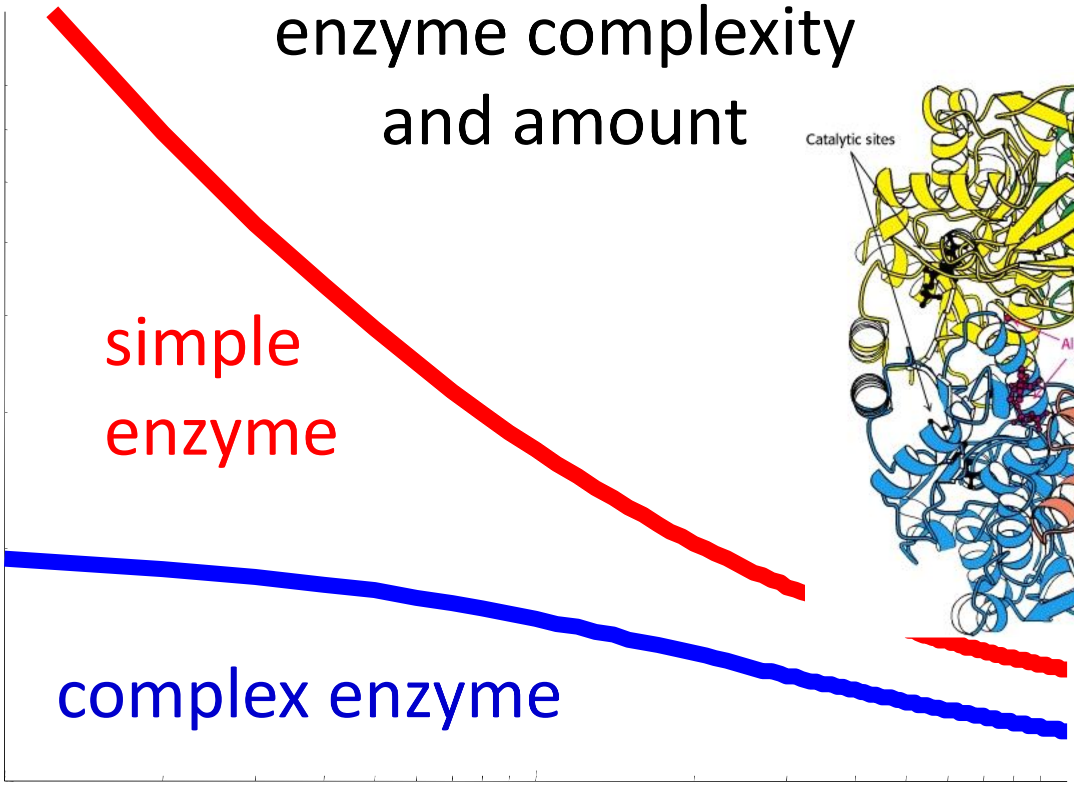
Theorem!

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

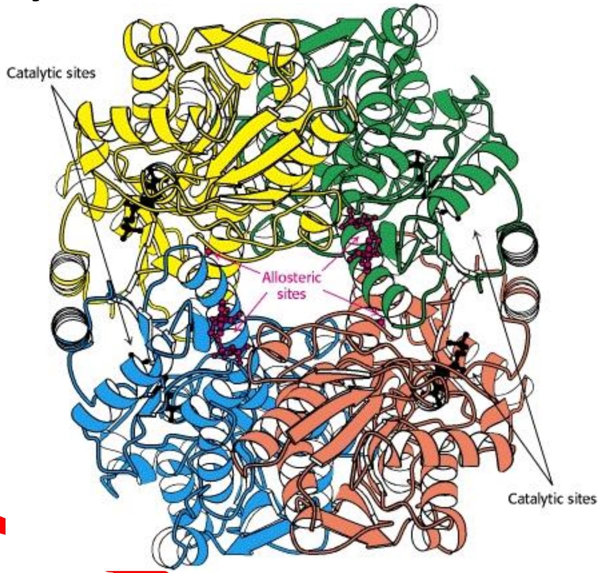
z and *p* functions of enzyme complexity and amount

Fragility

$$\ln\left|\frac{z+p}{z-p}\right|$$



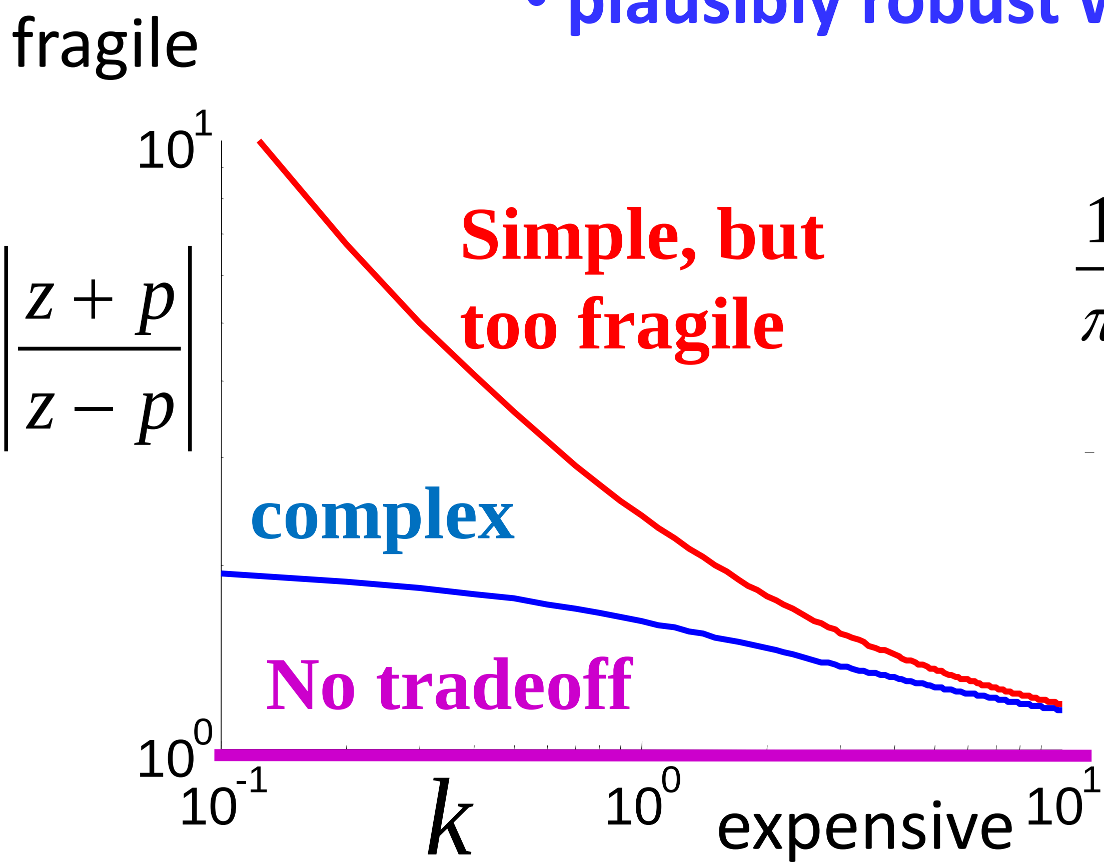
Enzyme amount



Savageaumics

Hard tradeoff in glycolysis is

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

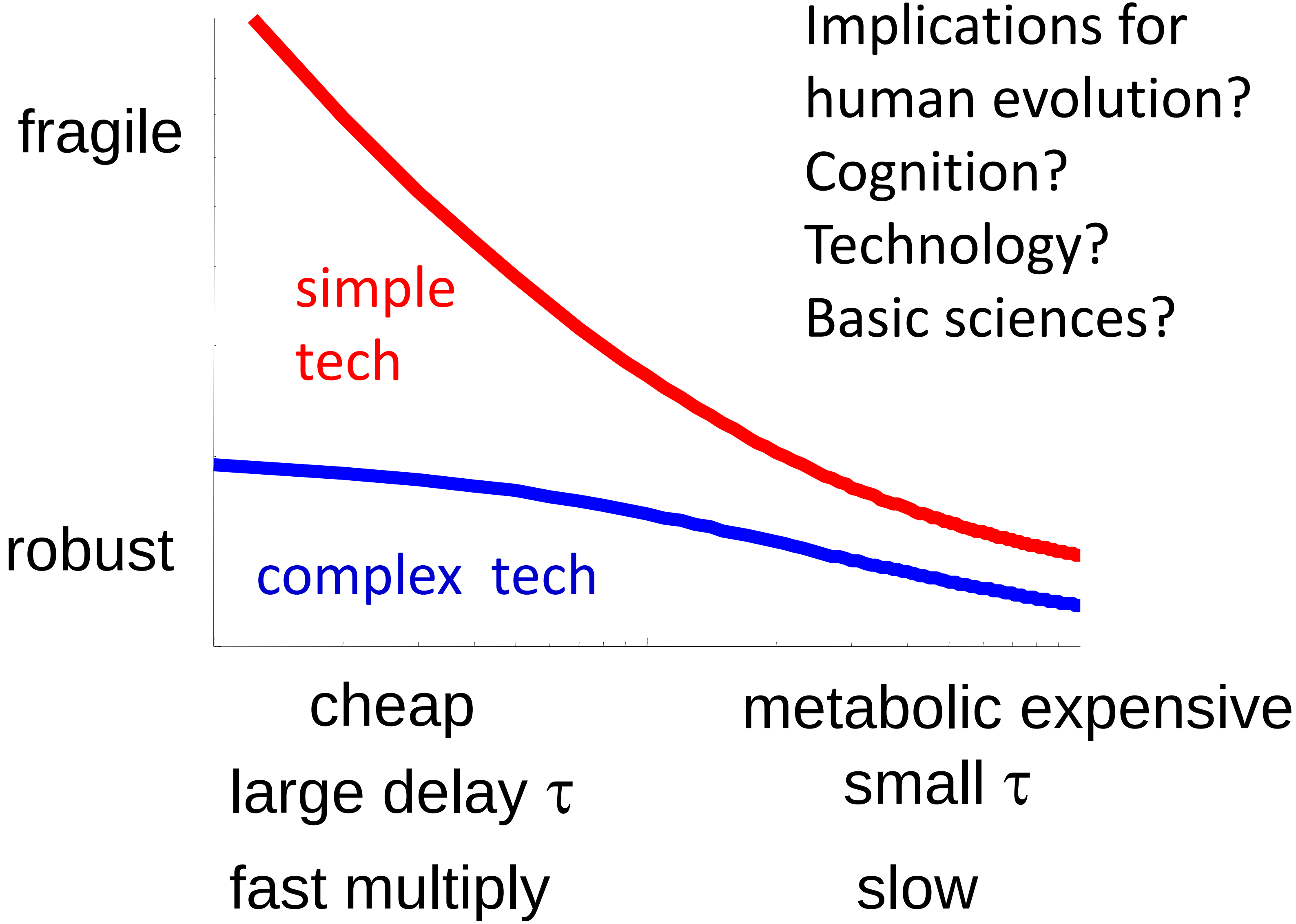


$$\frac{1}{\pi}\int_0^\infty \ln\left|S(j\omega)\right|\left(\frac{z}{z^2+\omega^2}\right)d\omega \ge \ln\left|\frac{z+p}{z-p}\right|$$

What (some) reviewers say

- "…to establish universality for all biological and physiological systems is **simply wrong**. It cannot be done…
- … a mathematical scheme **without any real connections to biological or medical**…
- …universality is well justified in physics… for biological and physiological systems …**a dream that will never be realized**, due to the vast diversity in such systems.
- …**does not seem to understand or appreciate** the vast diversity of biological and physiological systems…
- …a high degree of abstraction, which …make[s] **the model useless** …

This picture is very general



Implications for human evolution?

Cognition?

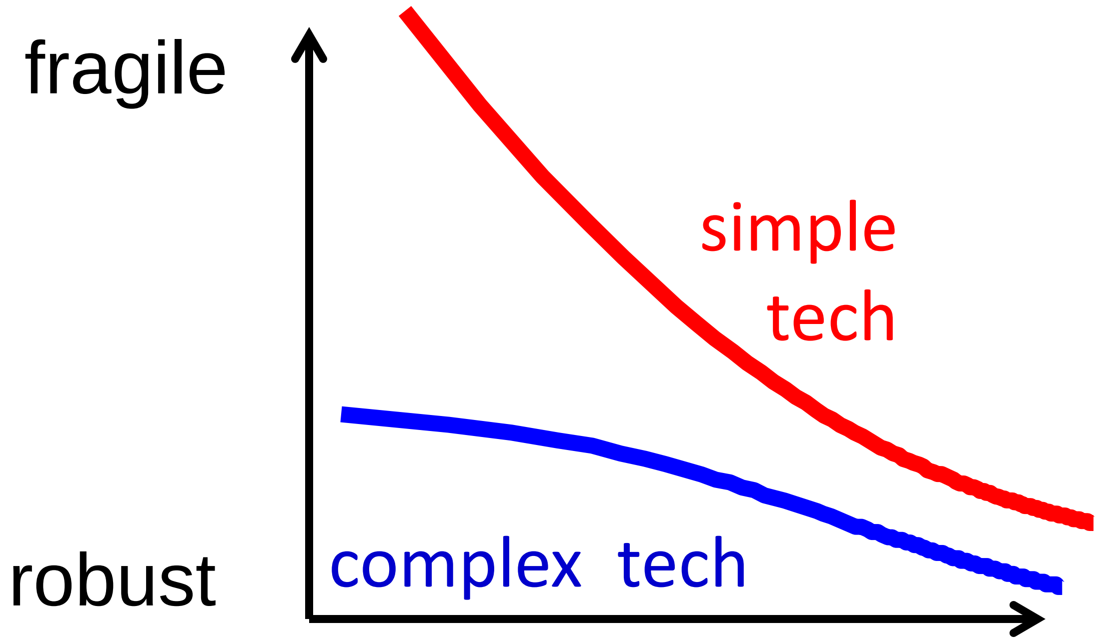
Technology?

Basic sciences?

This picture is very general

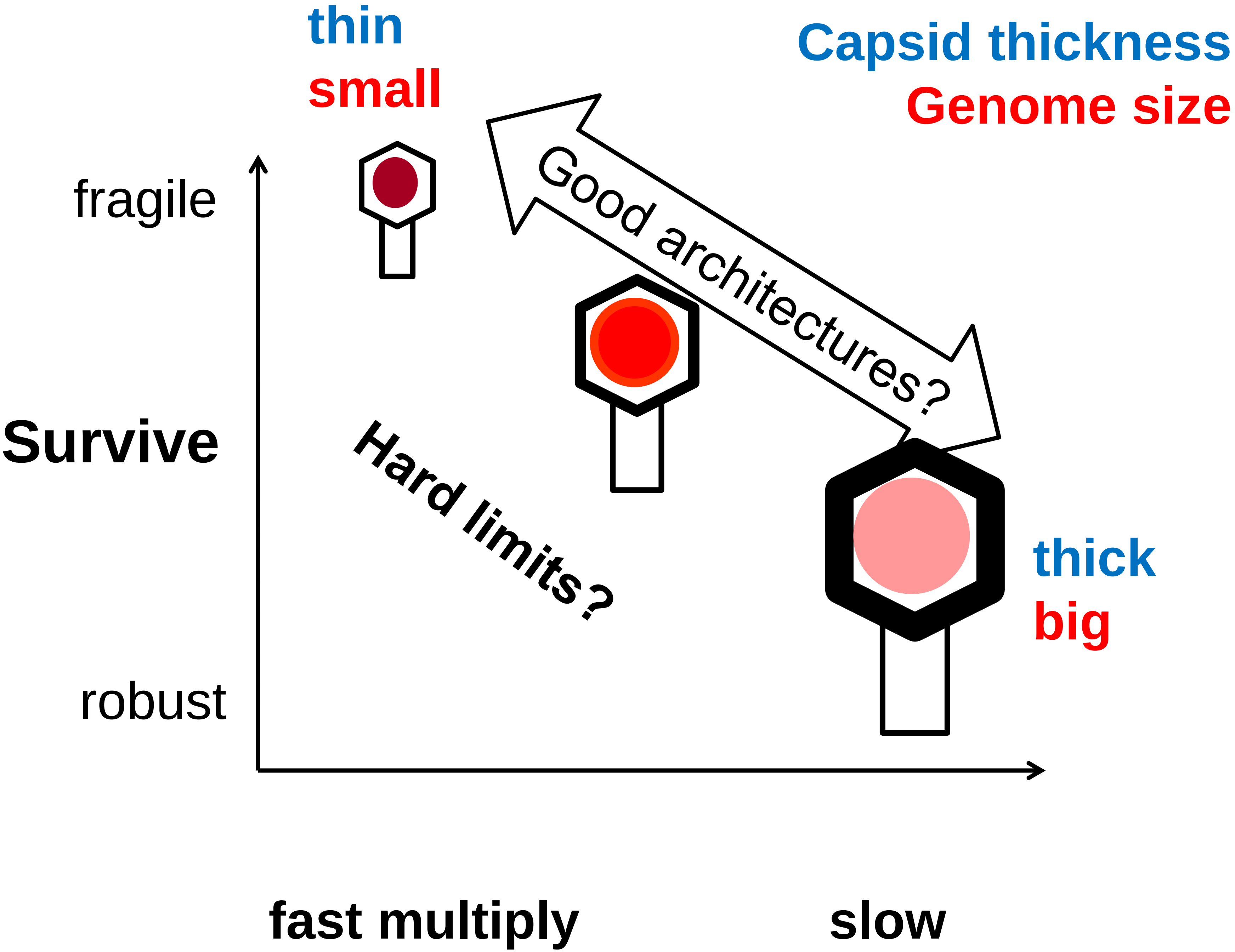
Domain specific costs/tradeoffs			
metabolic overhead	cheap	⟷	metabolic expensive
CNS reaction time τ (delay)	large τ	⟷	small τ
phage multiplication rate	fast multiply	⟷	slow

This picture is very general



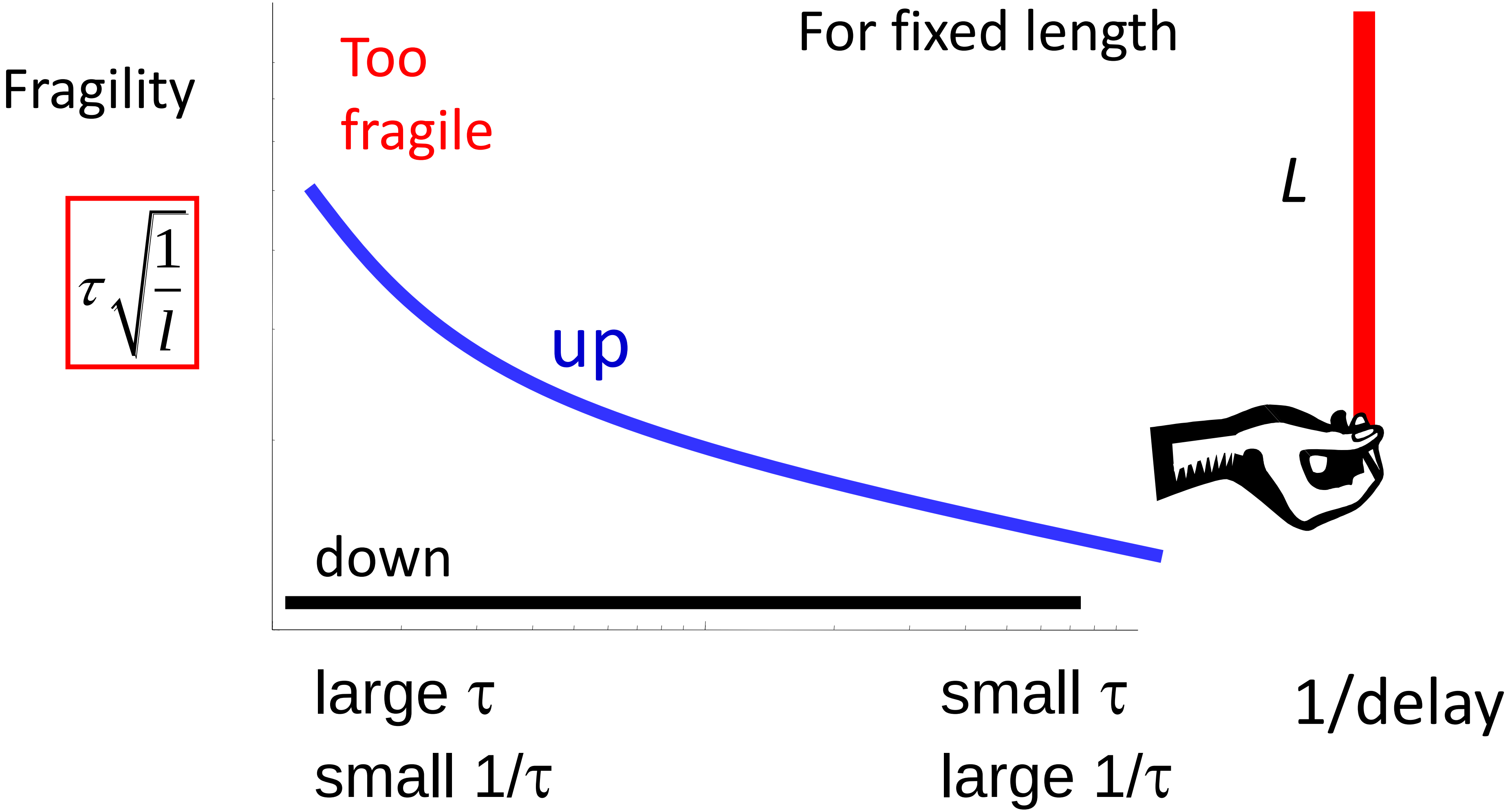
metabolic cost	cheap	⟷	expensive
reaction time τ	large τ	⟷	small τ
phage x rate	fast	⟷	slow

Domain specific costs/tradeoffs



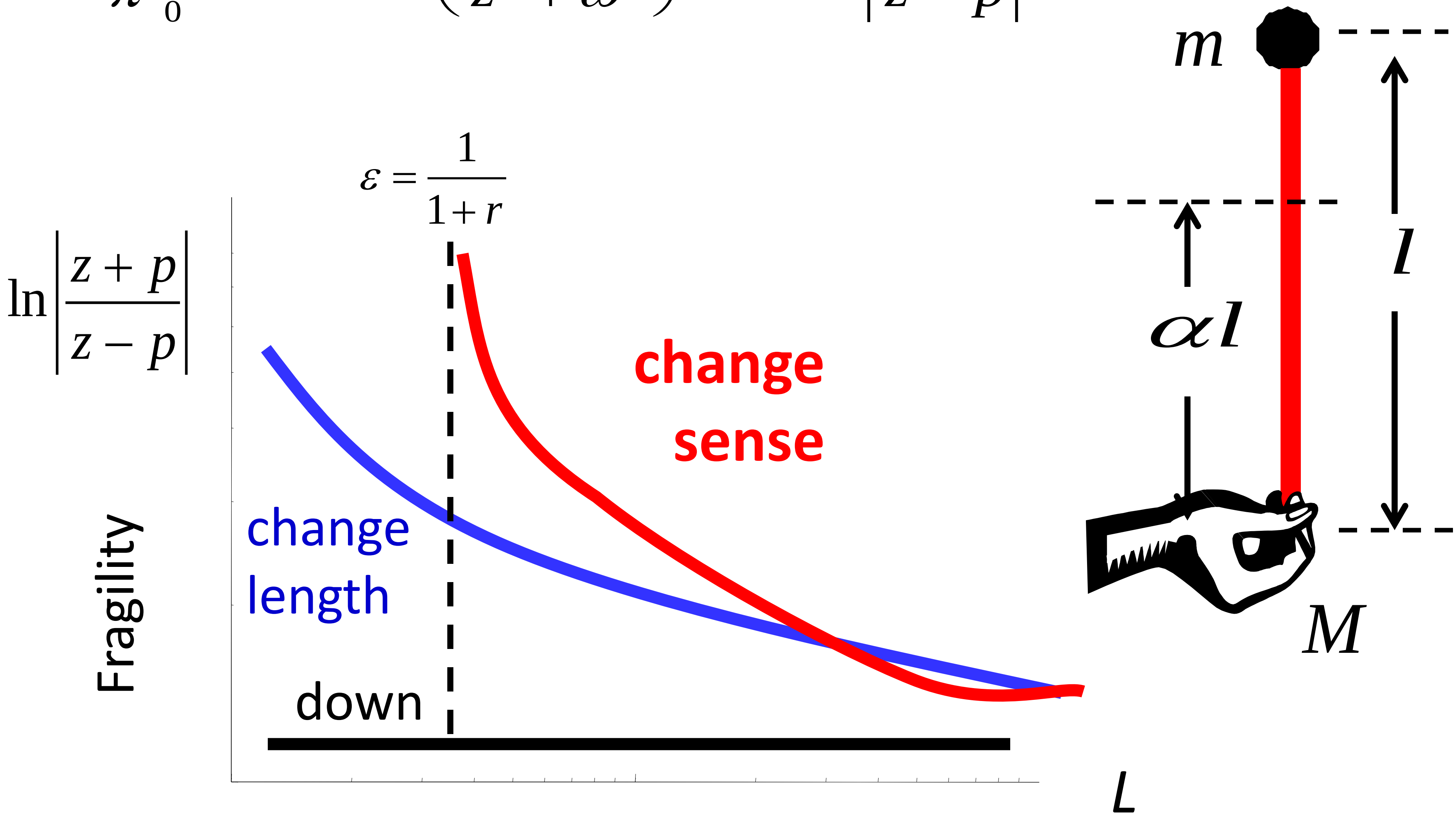
thin
small
Capsid thickness
Genome size
fragile
Good architectures?
Survive
Hard limits?
thick
big
robust
fast multiply
slow

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



$$r = \frac{m}{M}$$

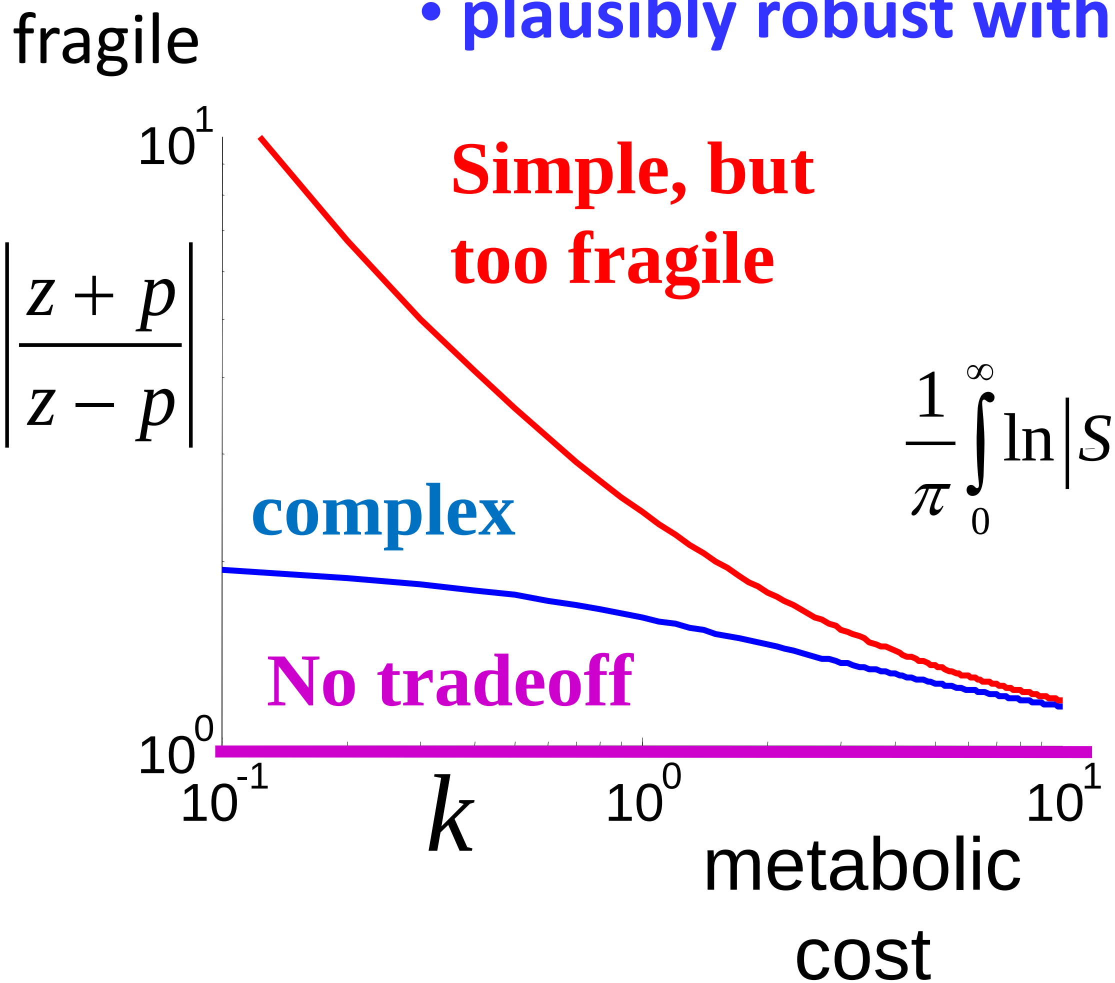
$$\frac{1}{\pi}\int_0^\infty \ln\left|S(j\omega)\right|\left(\frac{2z}{z^2+\omega^2}\right)d\omega \geq \ln\left|\frac{z+p}{z-p}\right|$$



This is a cartoon, but can be made precise.

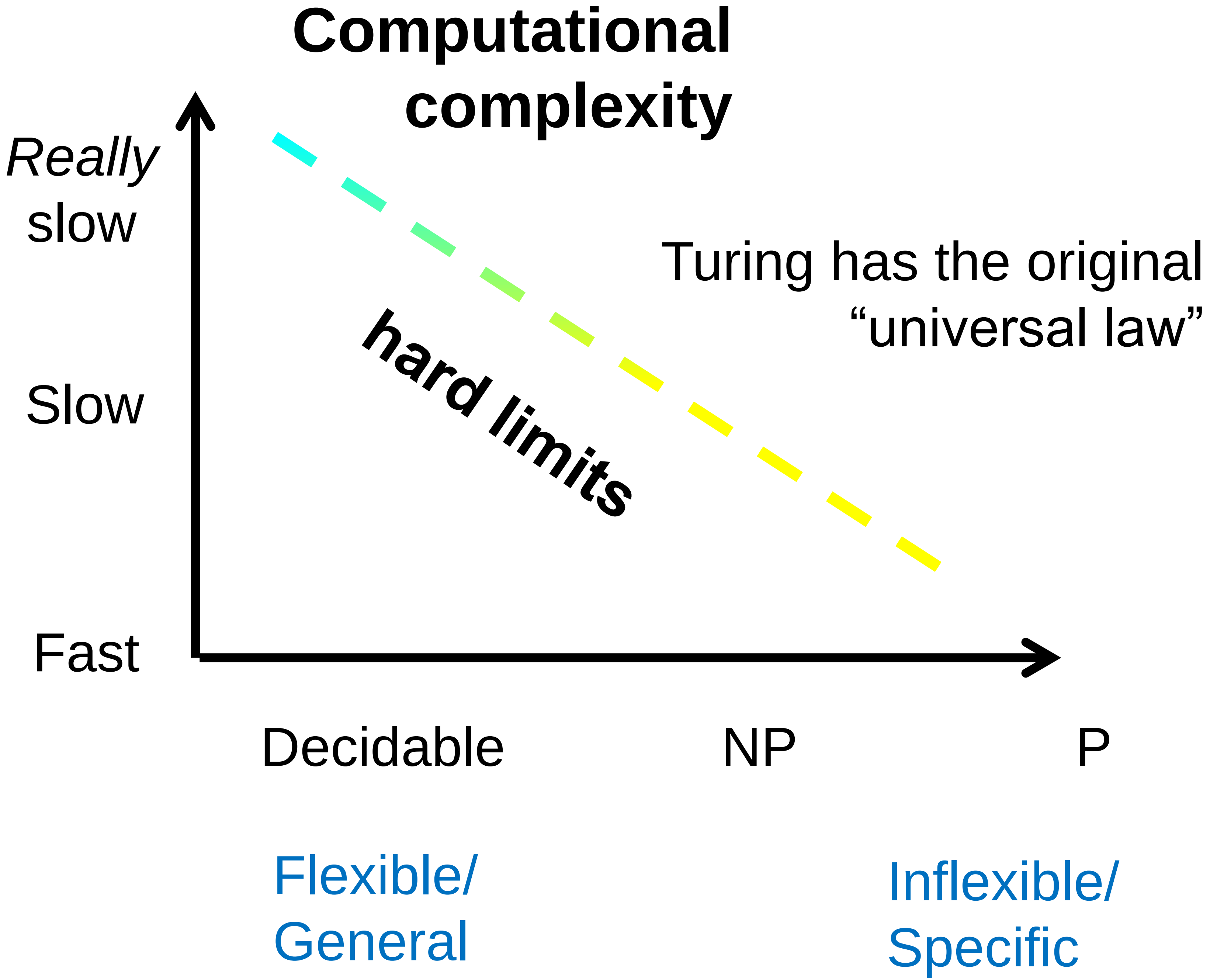
Hard tradeoff in glycolysis is

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

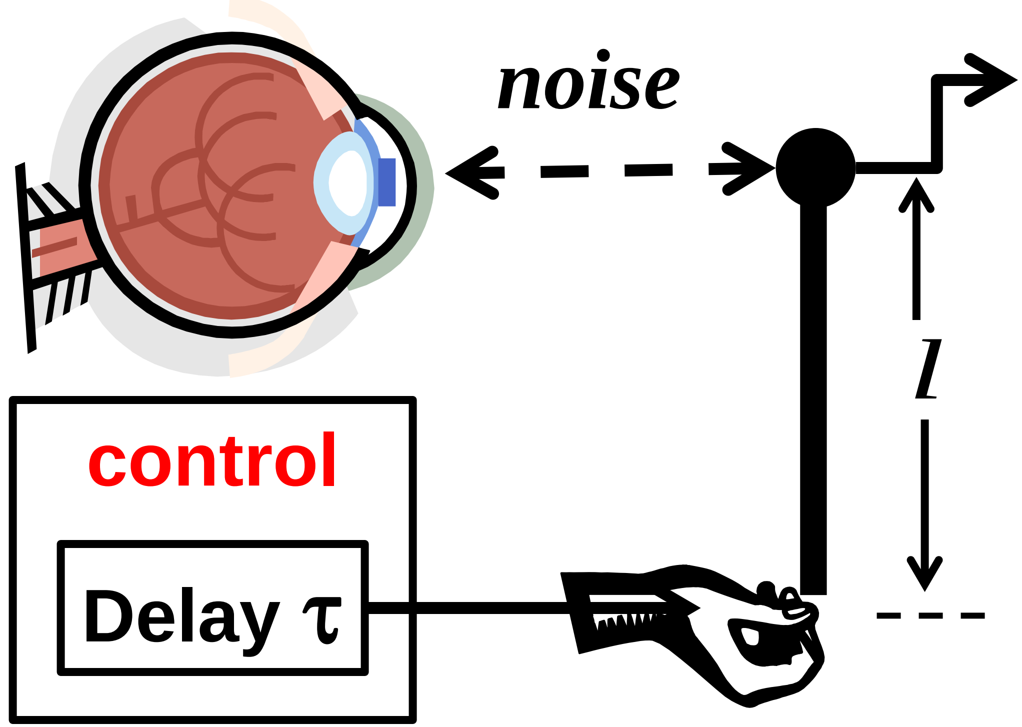


$$\frac{1}{\pi}\int_0^\infty \ln\left|S(j\omega)\right|\left(\frac{z}{z^2+\omega^2}\right)d\omega$$

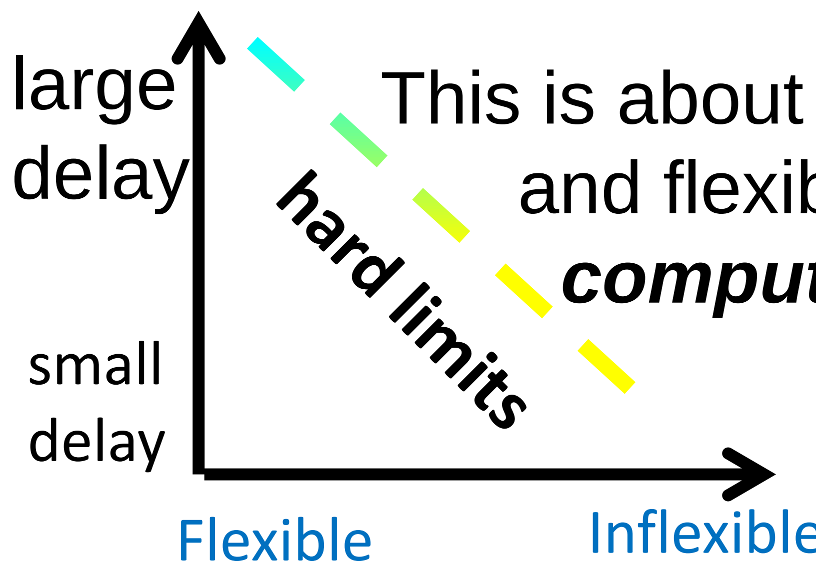
$$\geq \ln\left|\frac{z+p}{z-p}\right|$$


Computational complexity
Really slow
Slow
Fast
hard limits
Turing has the original “universal law”
Decidable
NP
P
Flexible/ General
Inflexible/ Specific

How do these two constraints (laws) relate?



Computation delay adds to total delay.

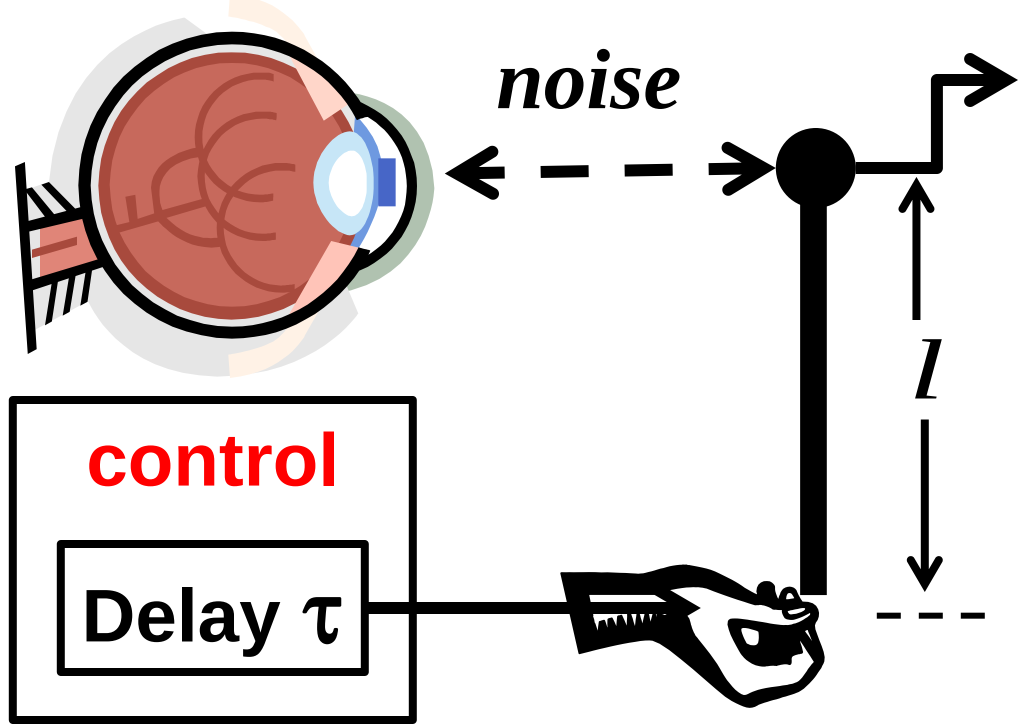


This is about speed and flexibility of ***computation***.

Computation is a component in control.

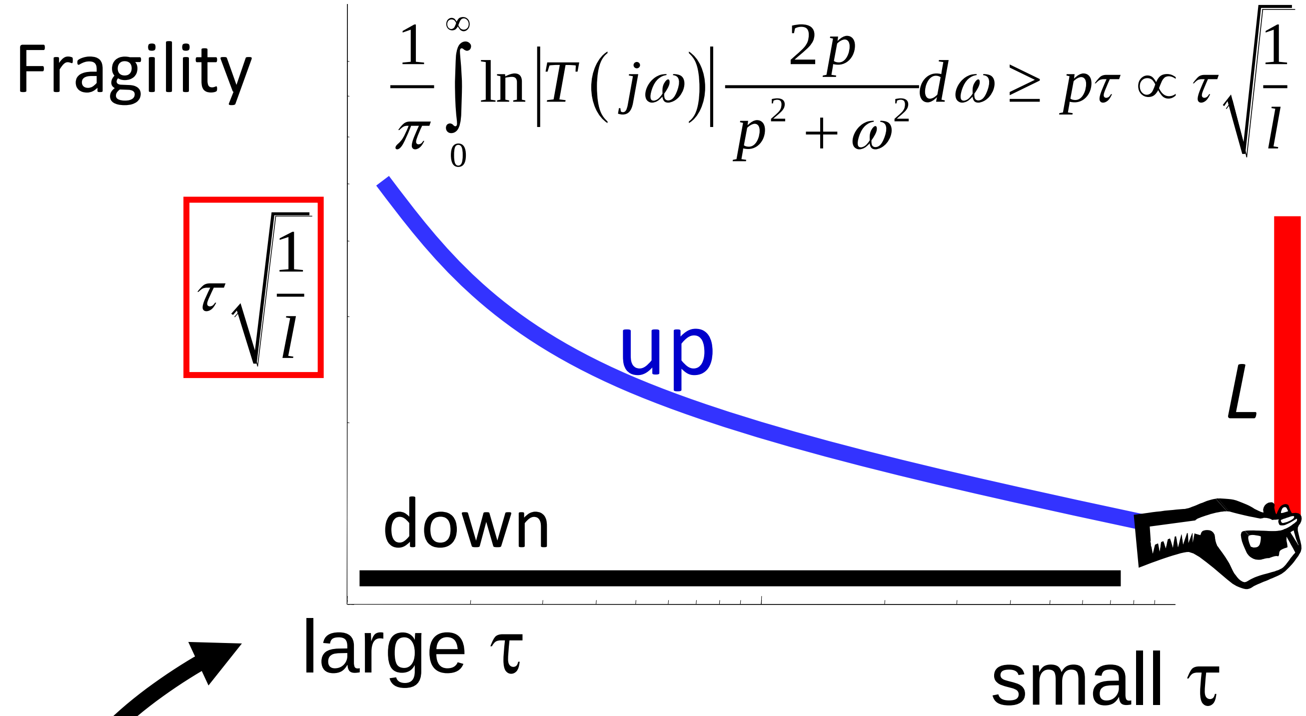
Delay comes from sensing, communications, computing, and actuation.

Delay limits robust performance.

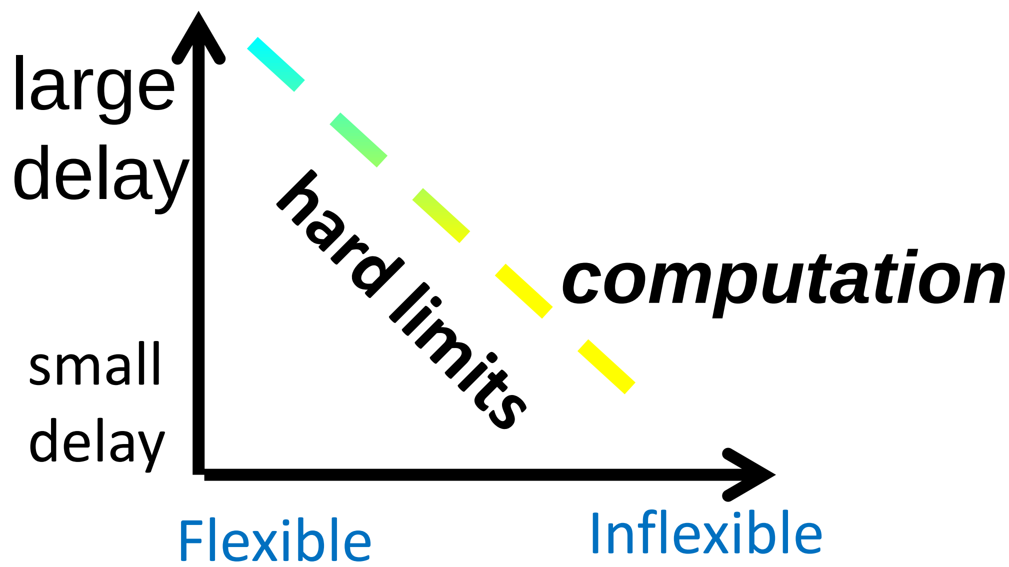


$$\frac{1}{\pi}\int_0^\infty \ln\left|T(j\omega)\right|\frac{2p}{p^2+\omega^2}d\omega \geq \ln\left|T_{mp}(p)\right| = p\tau \propto \tau\sqrt{\frac{1}{l}}$$

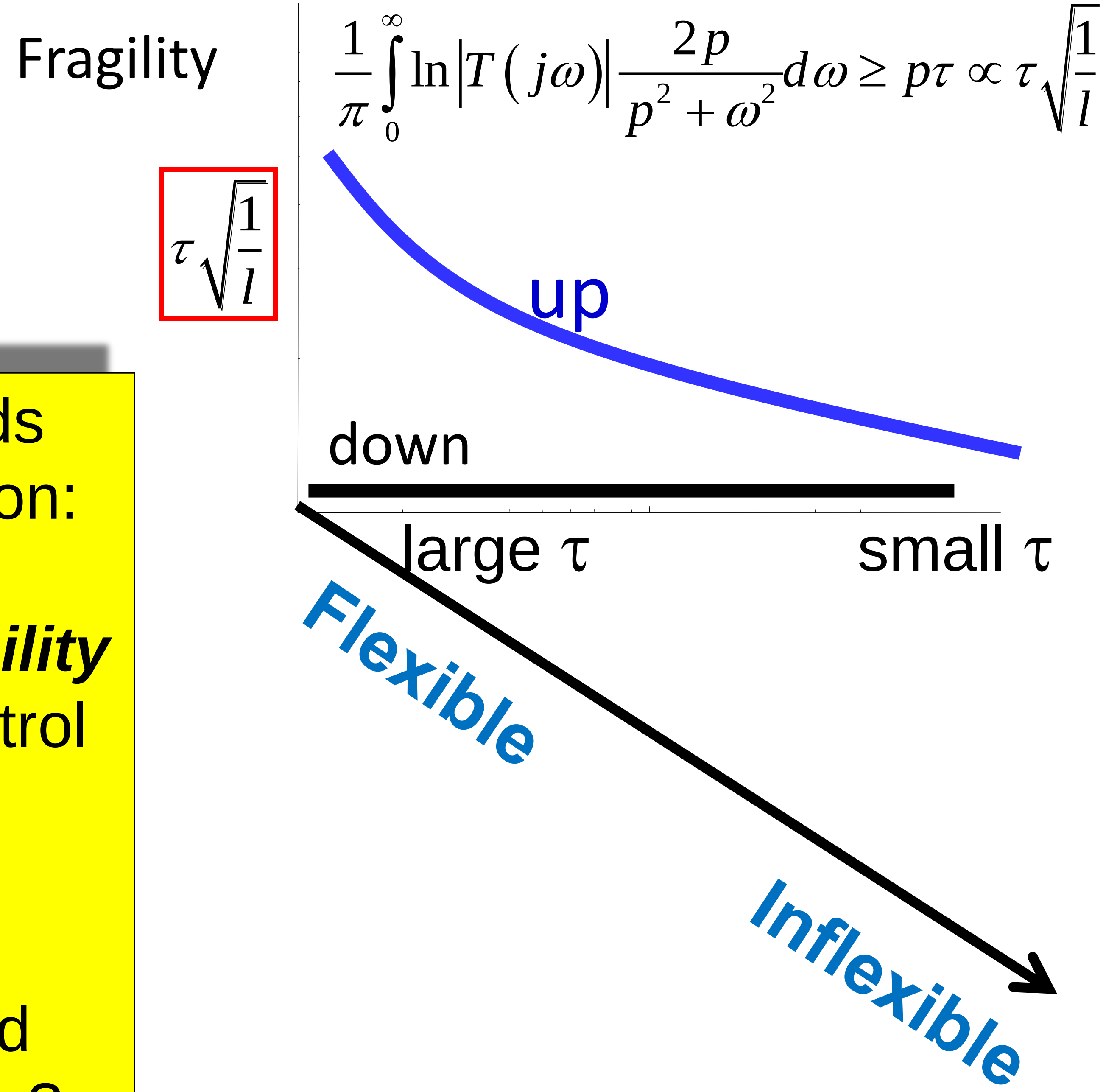
Delay makes control hard.



Computation delay adds to total delay.



Computation is a component in control.

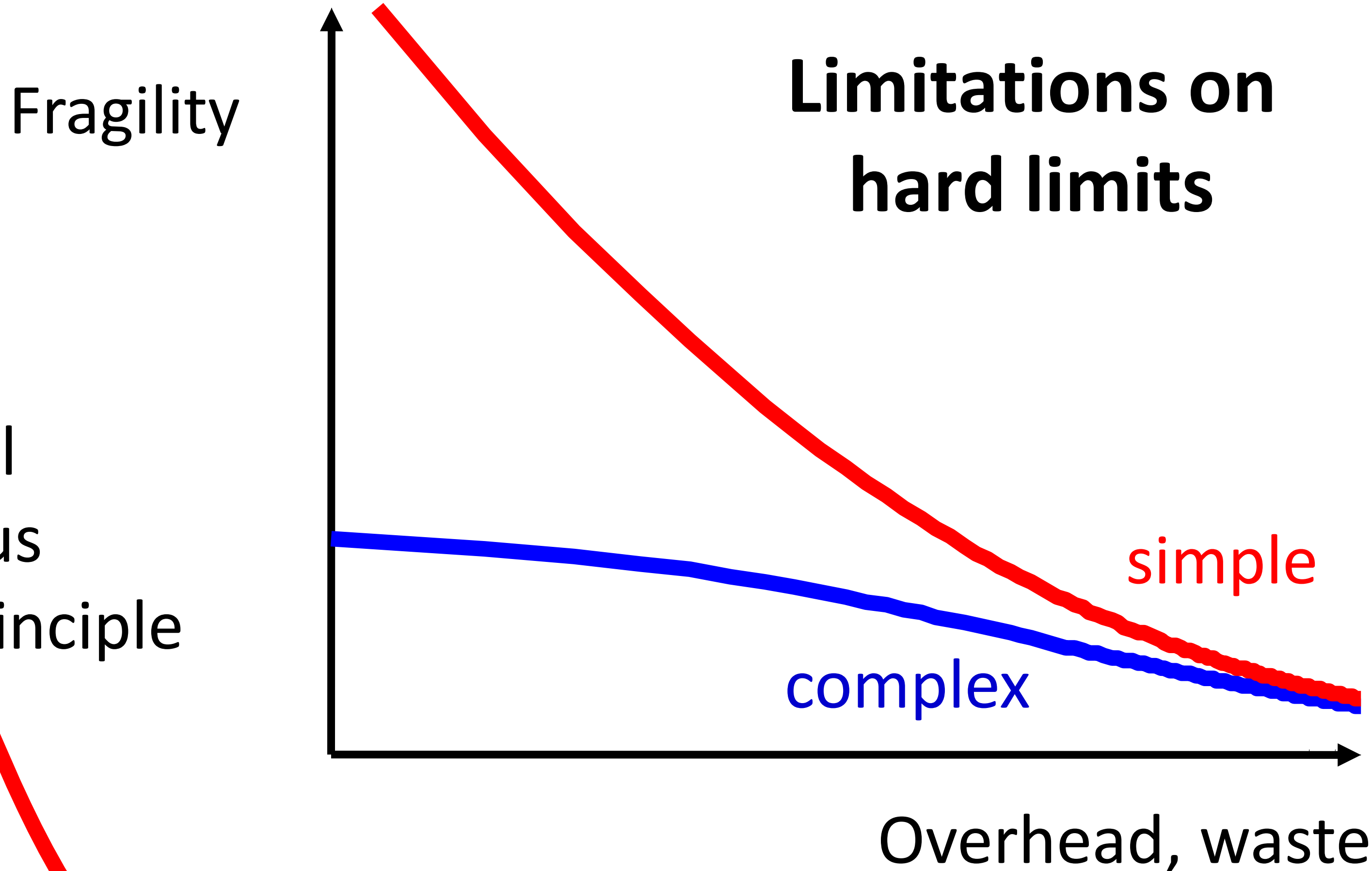


This needs formalization:

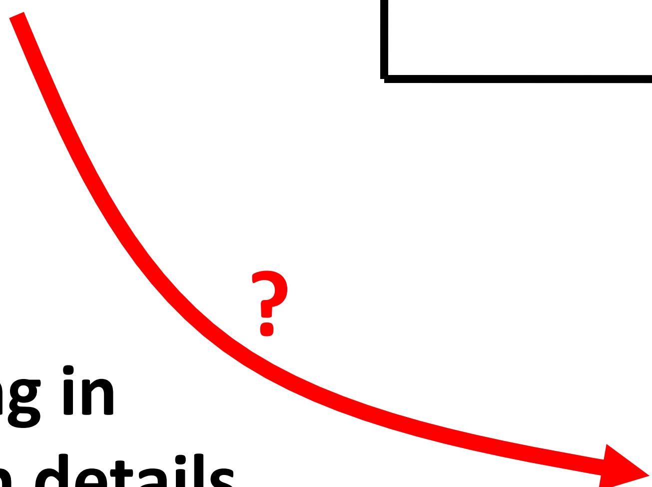
What ***flexibility*** makes control hard?

Large, structured uncertainty?

Limitations on hard limits



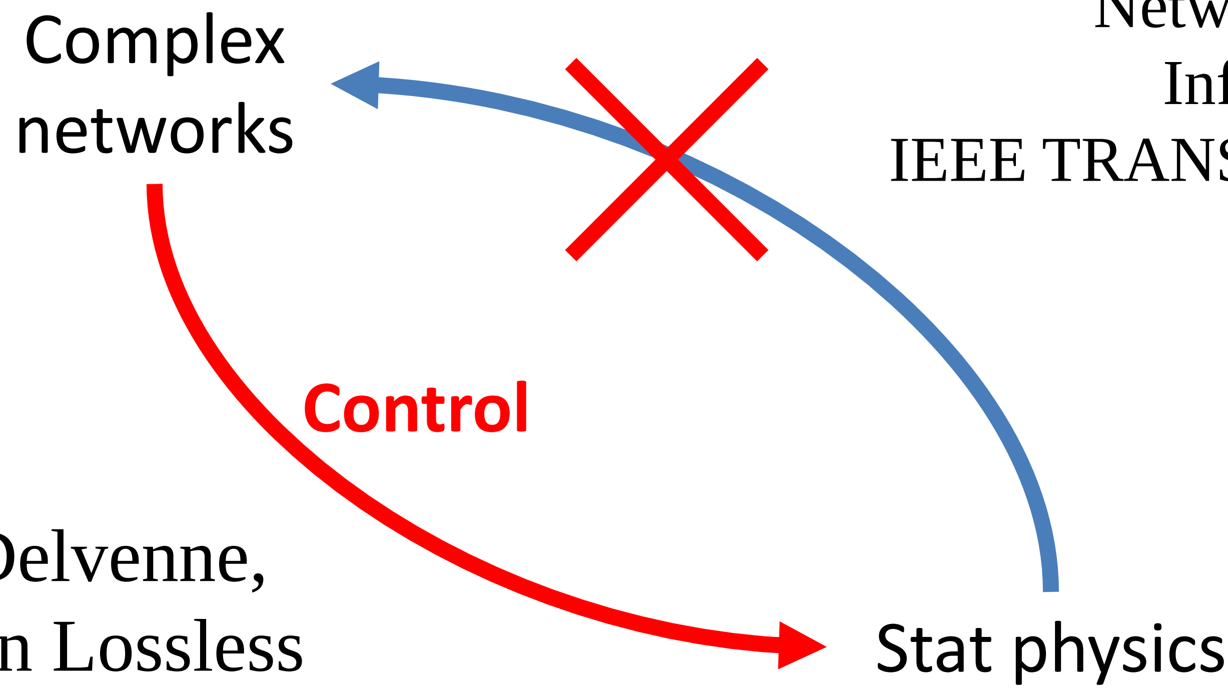
- General
- Rigorous
- First principle



Plugging in domain details

- Domain specific
- Ad hoc
- Phenomenological

Alderson &Doyle, Contrasting Views of Complexity and Their Implications for Network-Centric Infrastructure, IEEE TRANS ON SMC, JULY 2010



Sandberg, Delvenne, & Doyle, On Lossless Approximations, the Fluctuation-Dissipation Theorem, and Limitations of Measurement, IEEE TRANS ON AC, FEBRUARY, 2011

Carnot

Boltzmann

Heisenberg

Physics

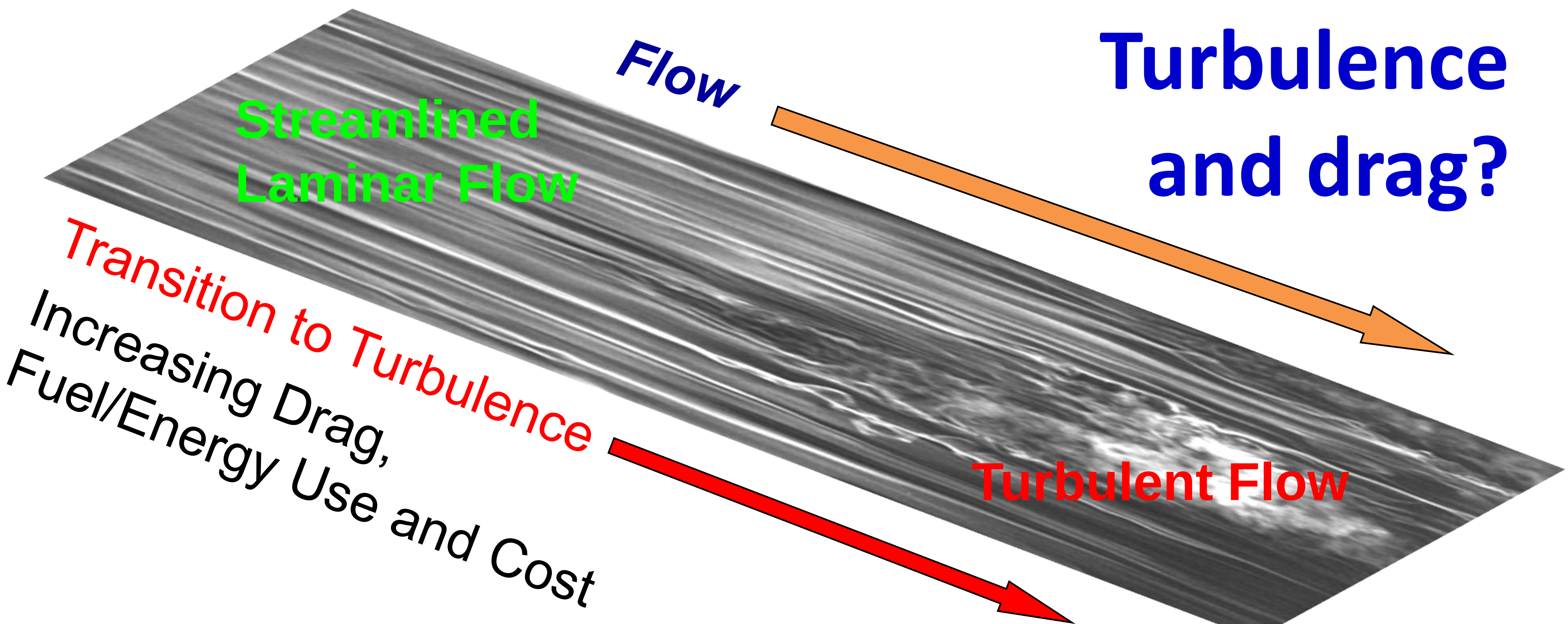
J. Fluid Mech. (2010), vol. 665, pp. 99–119.
doi:10.1017/S0022112010003861

J. Fluid Mech (2010)

A streamwise constant model of turbulence in plane Couette flow

D. F. GAYME[1]†, B. J. McKEON[1],
A. PAPACHRISTODOULOU[2], B. BAMIEH[3]
AND J. C. DOYLE[1]

Turbulence and drag?

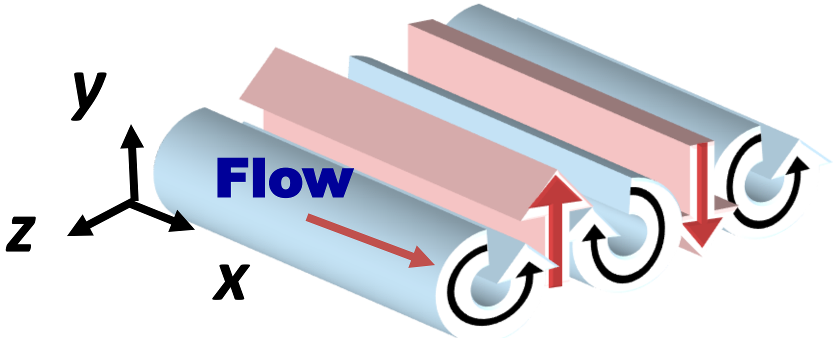


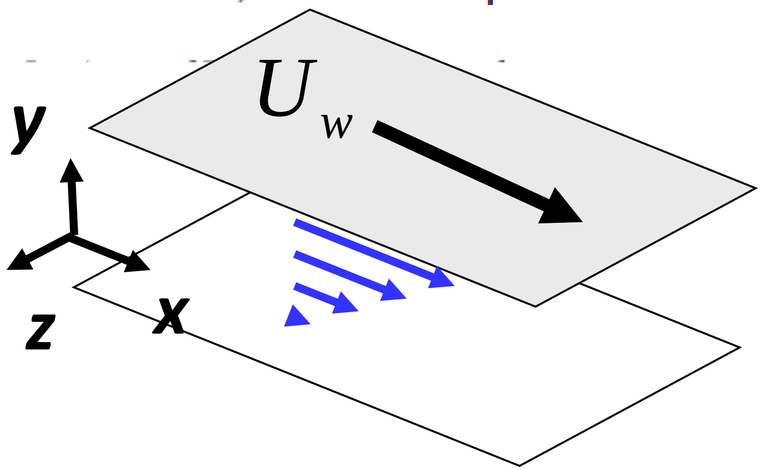
Physics of Fluids (2011)

PHYSICS OF FLUIDS 23, 065108 (2011)

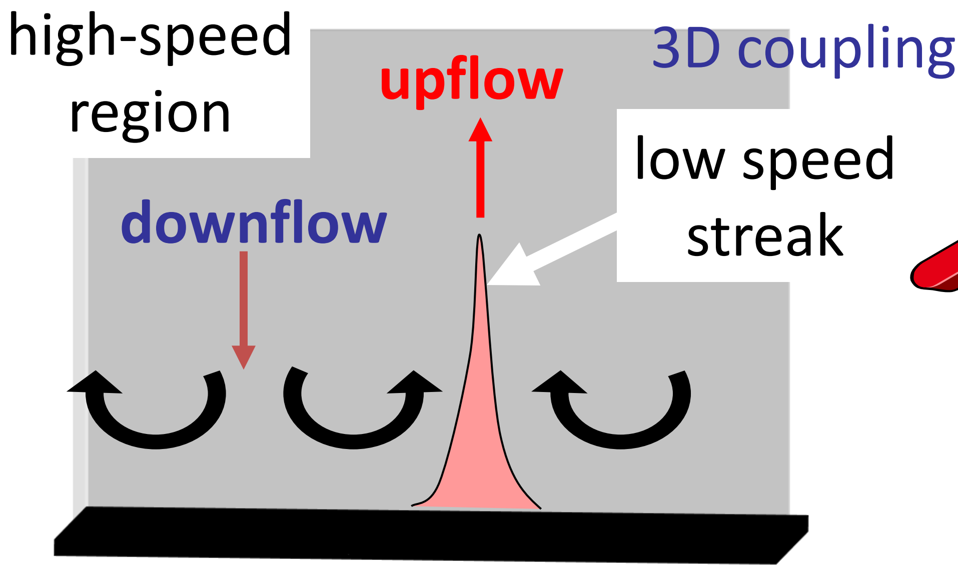
Amplification and nonlinear mechanisms in plane Couette flow

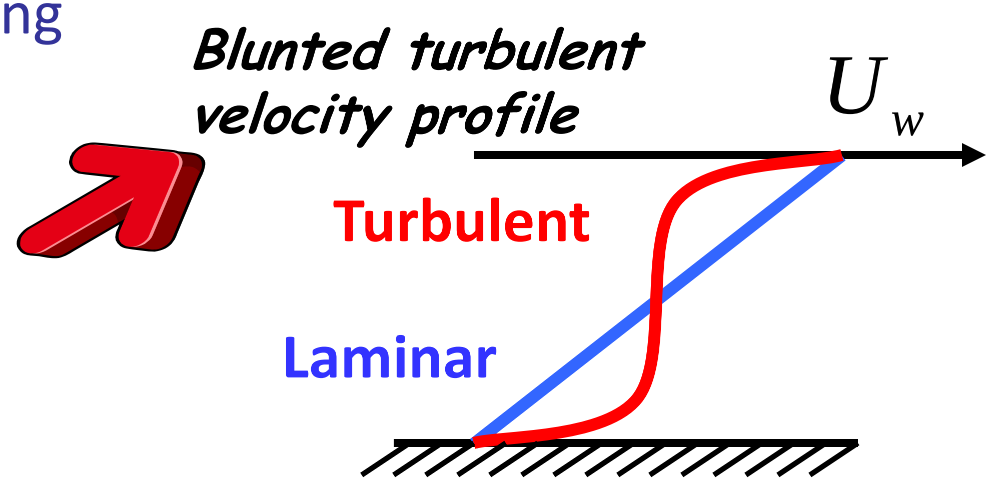
Dennice F. Gayme,[1] Beverley J. McKeon,[1] Bassam Bamieh,[2] Antonis Papachristodoulou,[3] and John C. Doyle[3]

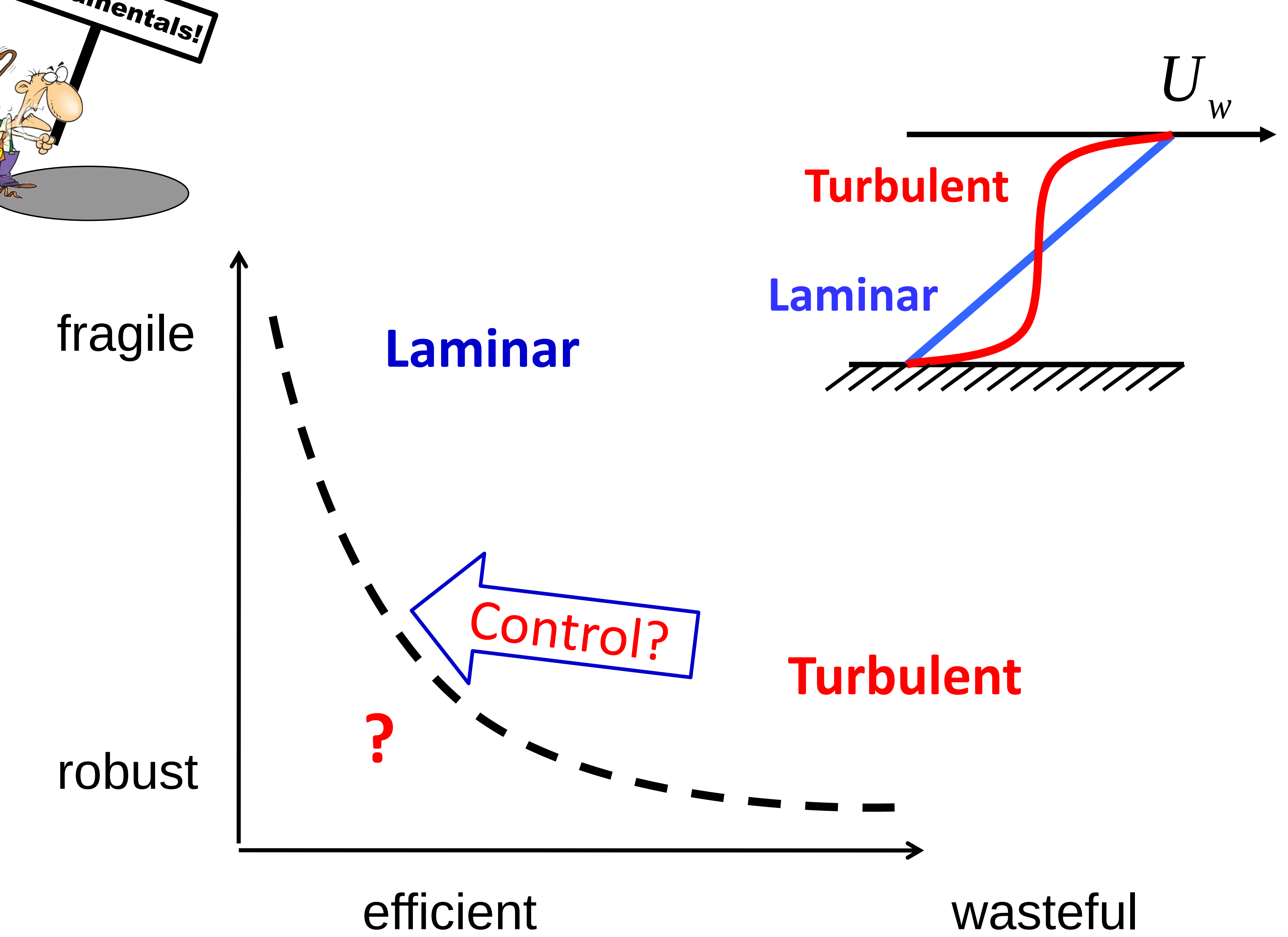




Coherent structures and turbulent drag





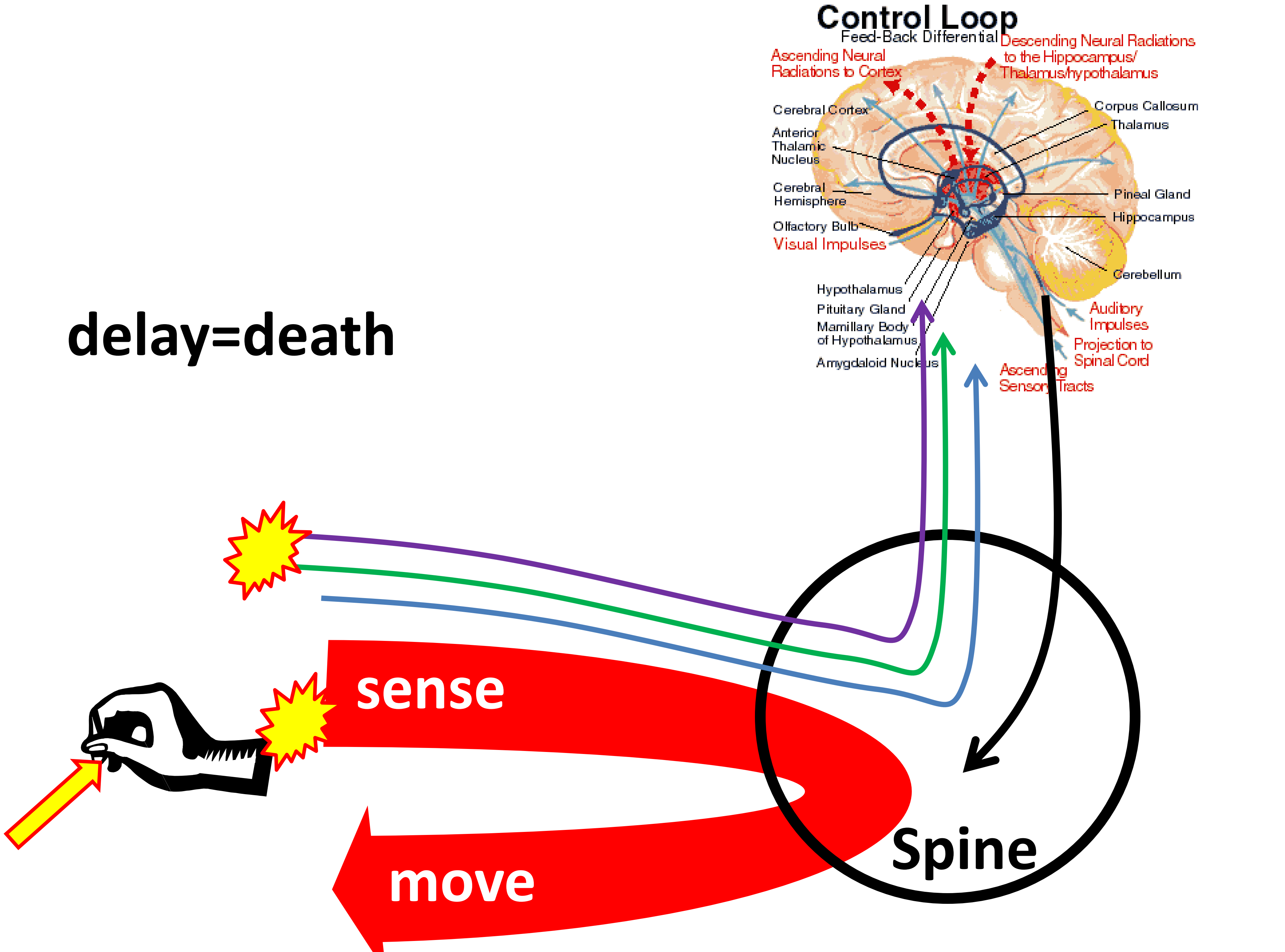


U_w
Turbulent
Laminar
fragile
Laminar
Control?
?
Turbulent
robust
efficient
wasteful

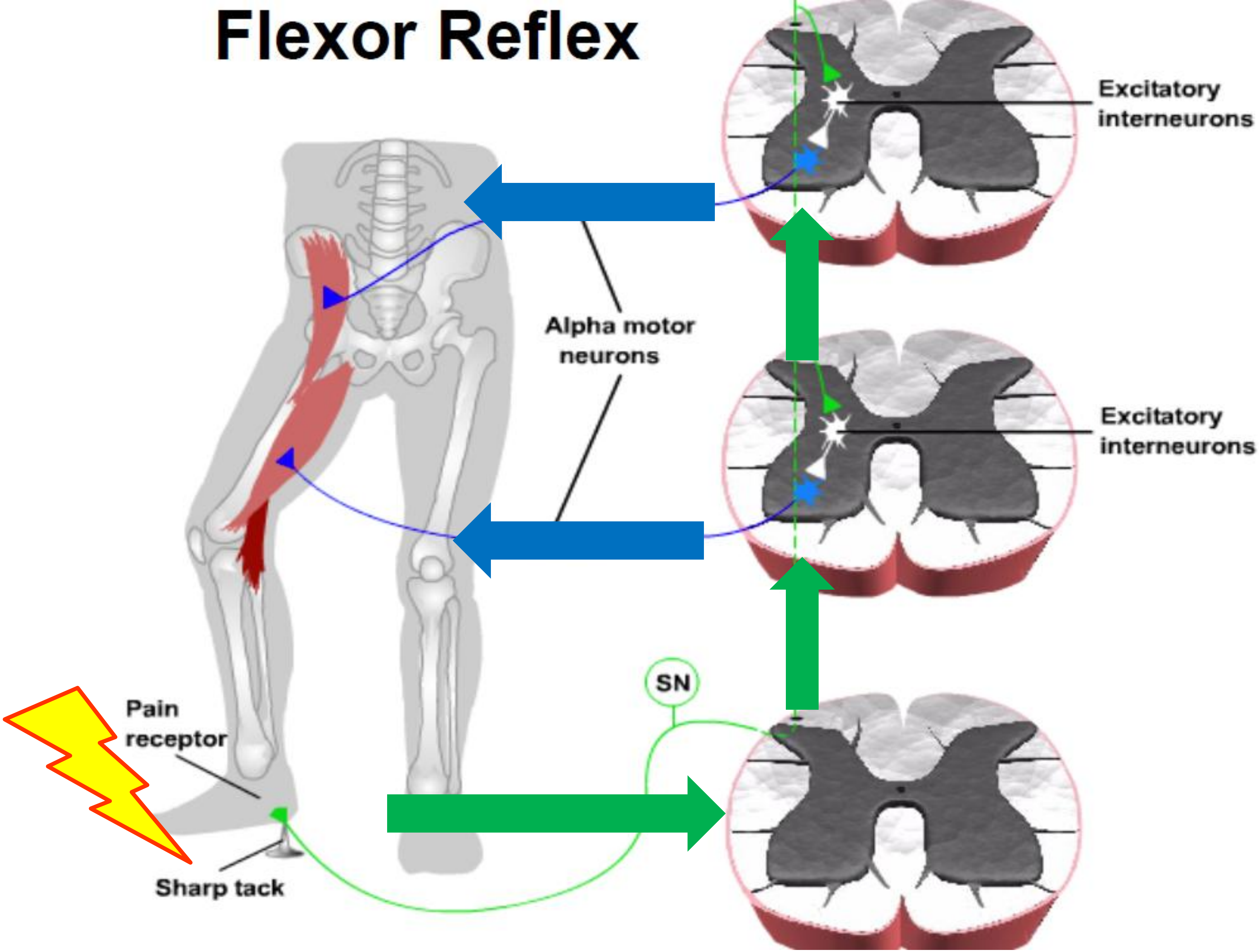
Delays and layering

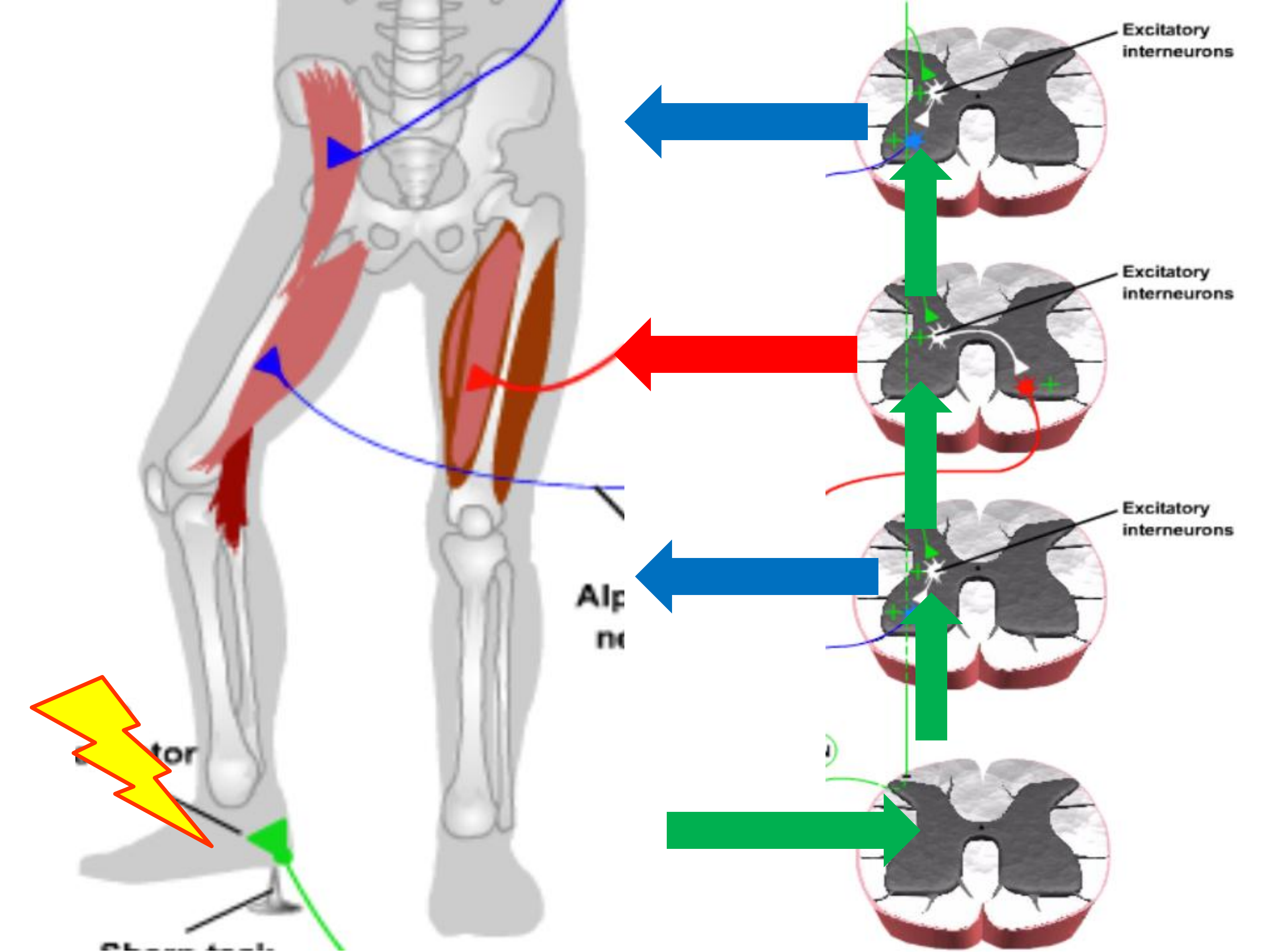
Demos and cartoons

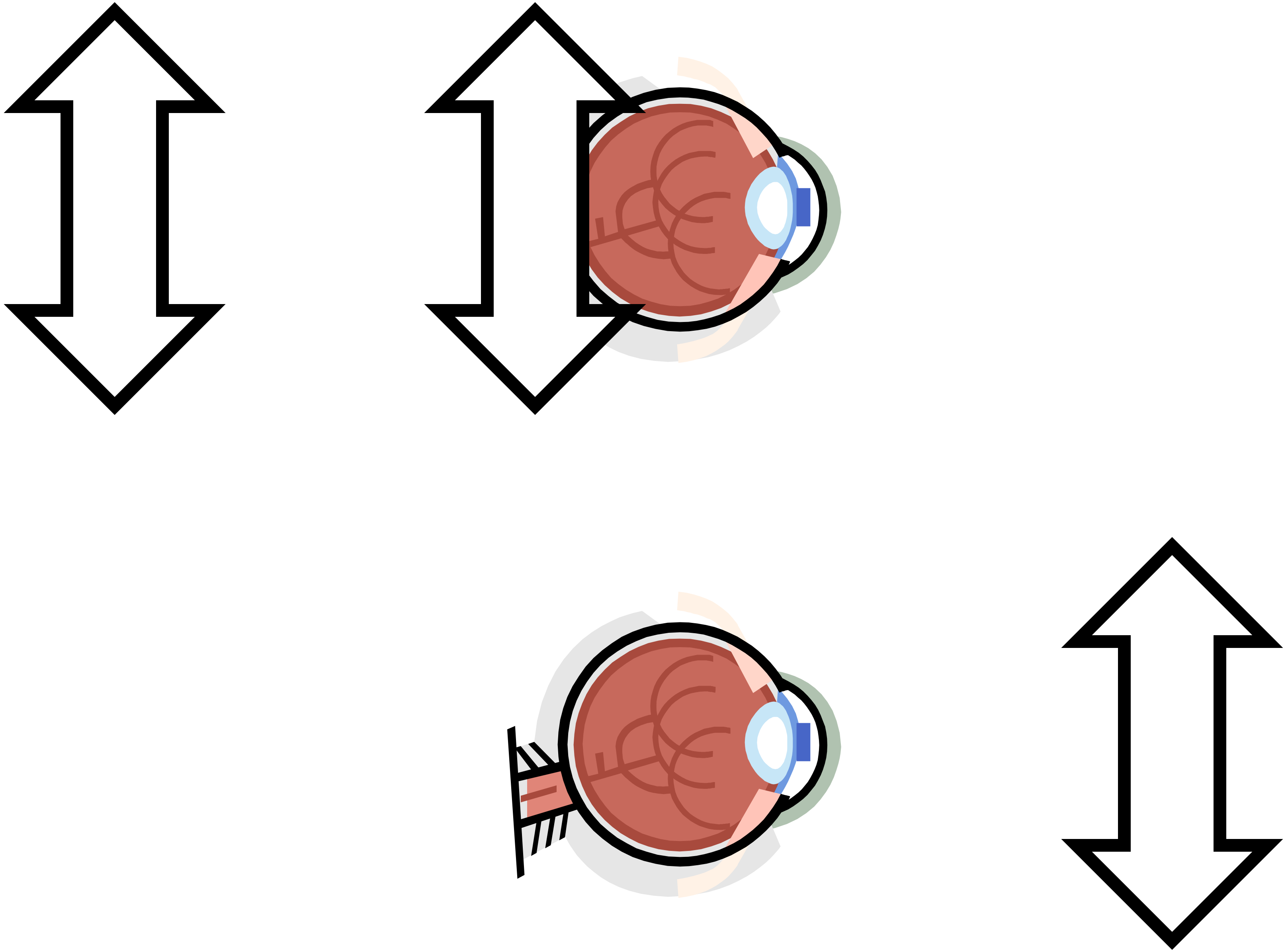
delay=death

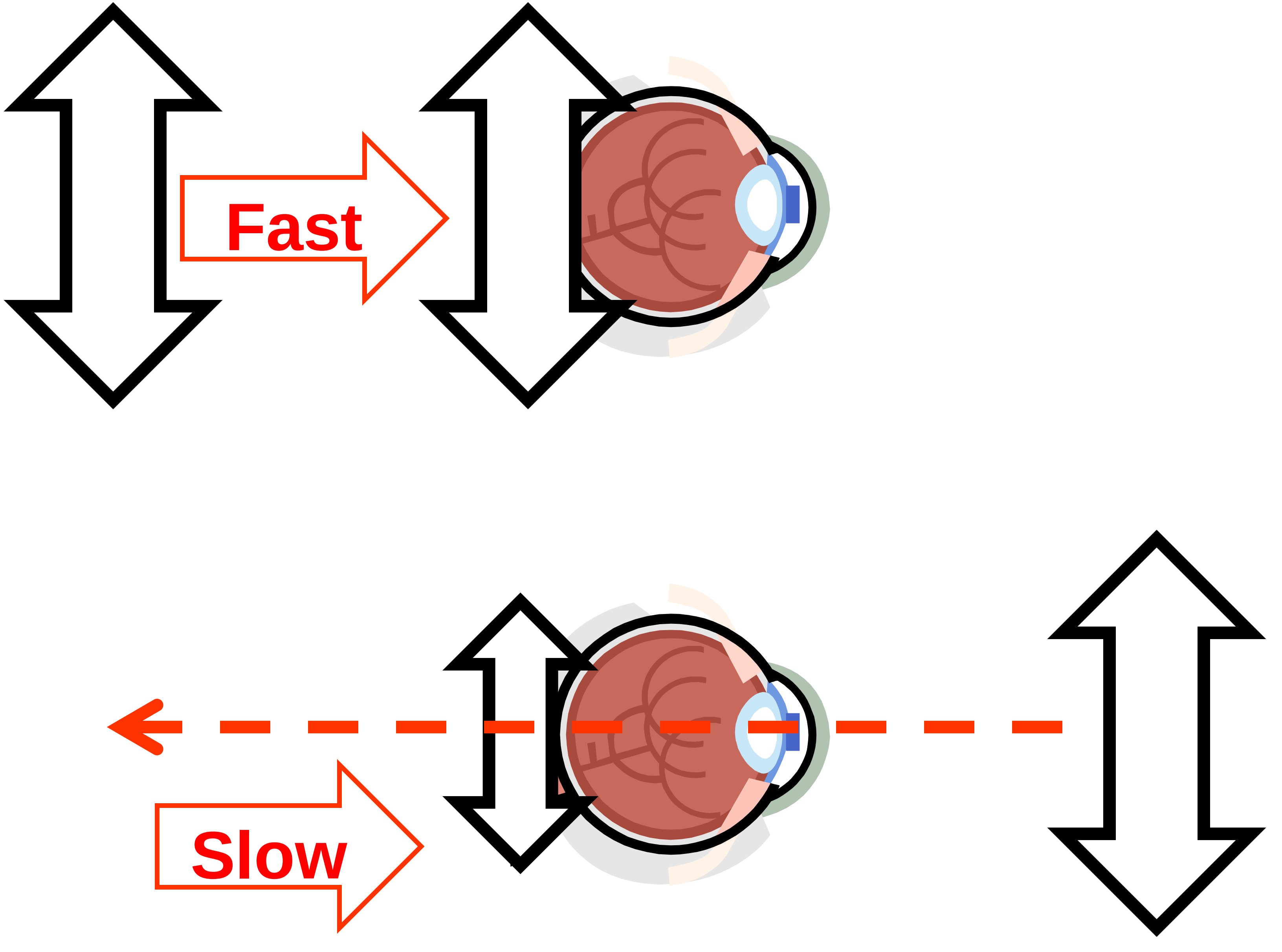

Control Loop
Feed-Back Differential
Ascending Neural Radiations to Cortex
Descending Neural Radiations to the Hippocampus/ Thalamus/hypothalamus
Cerebral Cortex
Anterior Thalamic Nucleus
Cerebral Hemisphere
Olfactory Bulb
Visual Impulses
Corpus Callosum
Thalamus
Pineal Gland
Hippocampus
Cerebellum
Hypothalamus
Pituitary Gland
Mamillary Body of Hypothalamus
Amygdaloid Nucleus
Auditory Impulses
Projection to Spinal Cord
Ascending Sensory Tracts
sense
move
Spine

Flexor Reflex

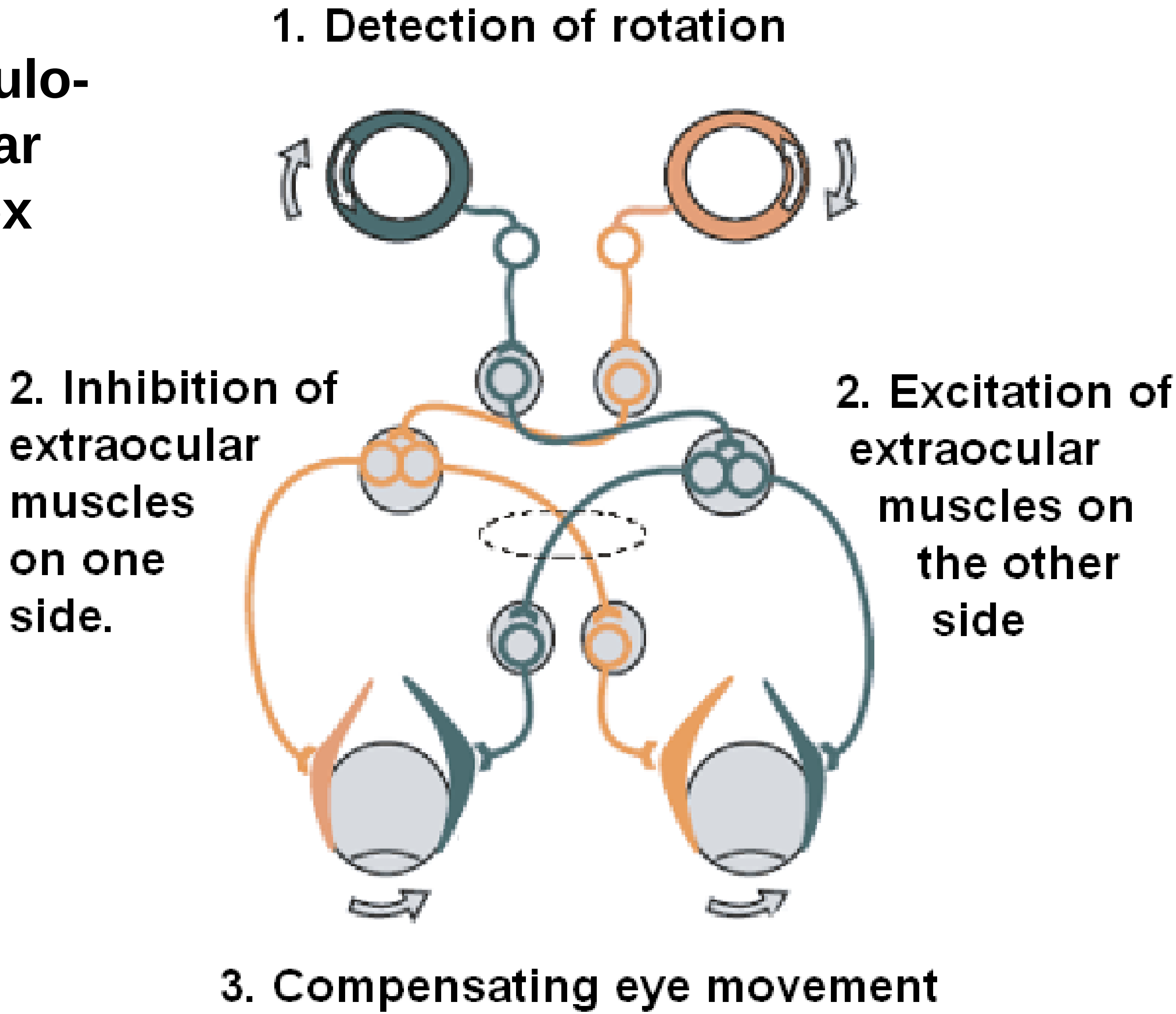


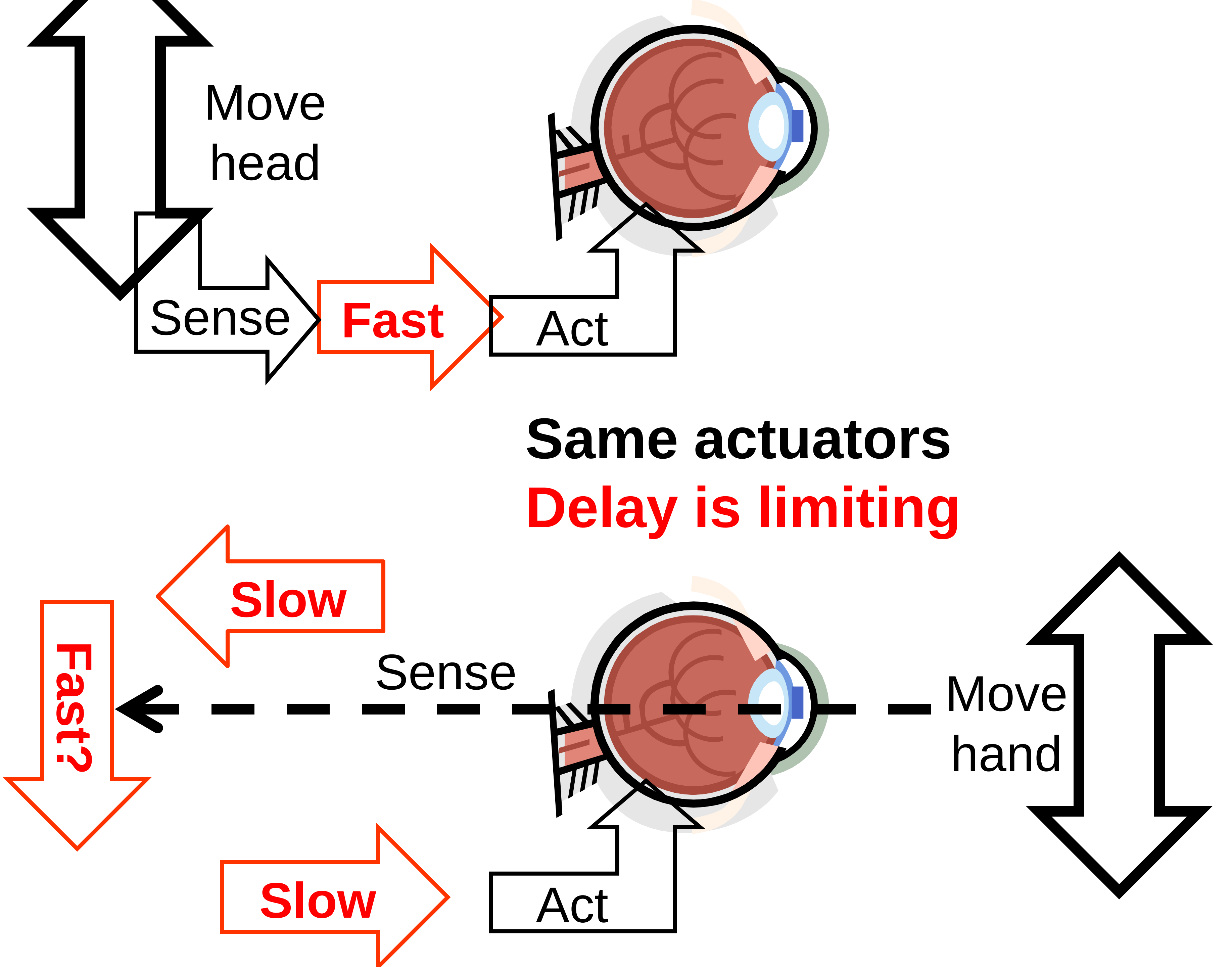

Excitatory interneurons
Excitatory interneurons
Excitatory interneurons




Fast
Slow

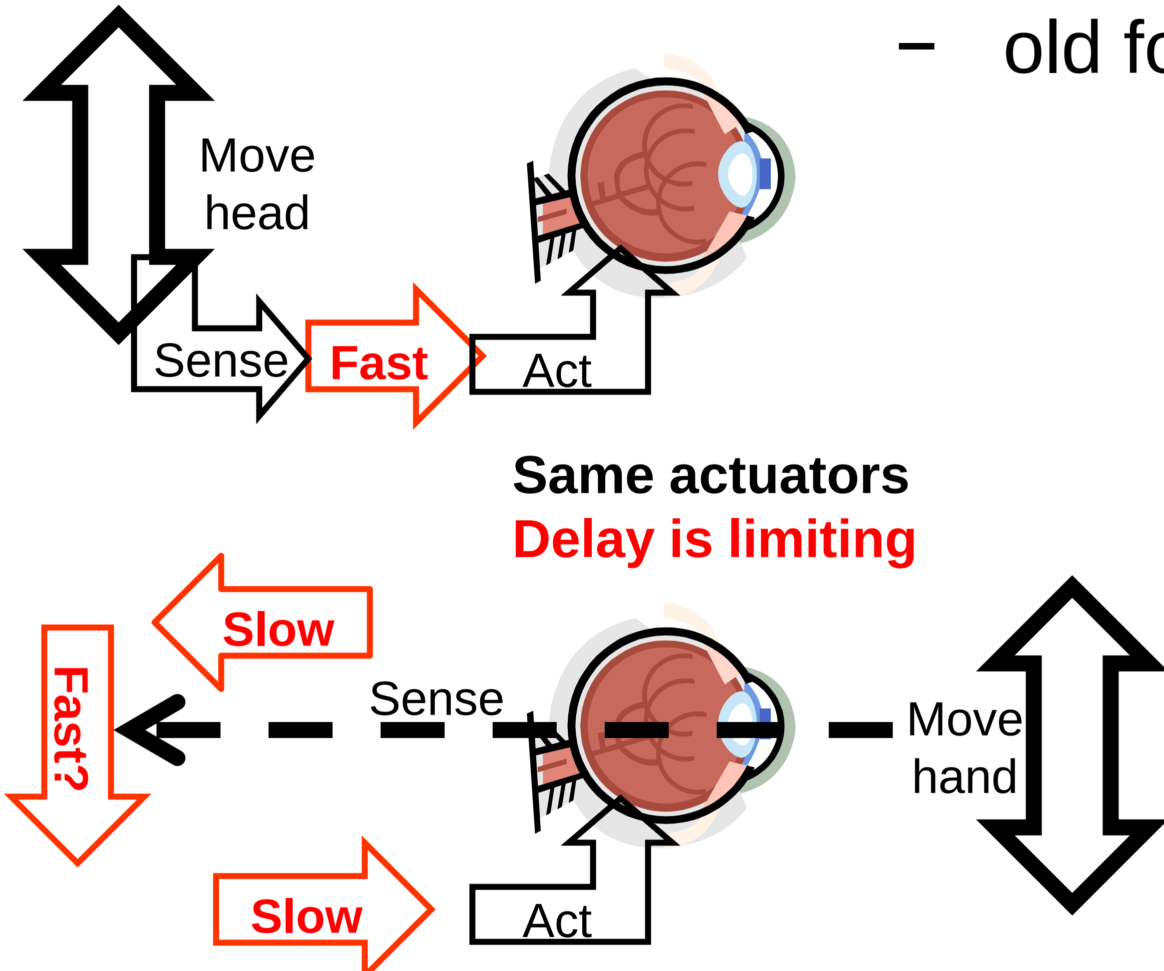
Vestibulo-ocular reflex

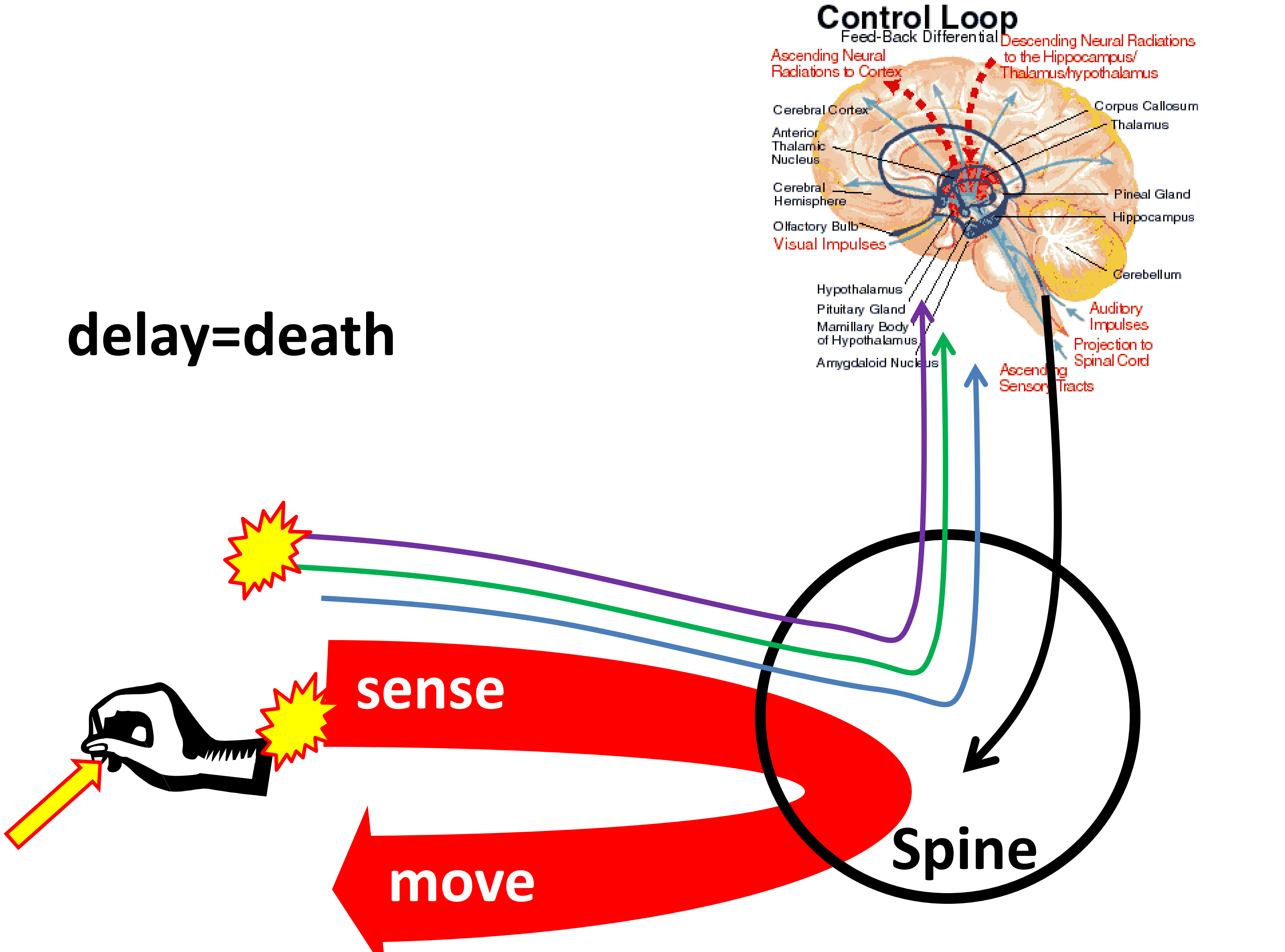



Move
head
Sense
Fast
Act
Same actuators
Delay is limiting
Slow
Fast?
Sense
Move
hand
Slow
Act

Versus standing on one leg

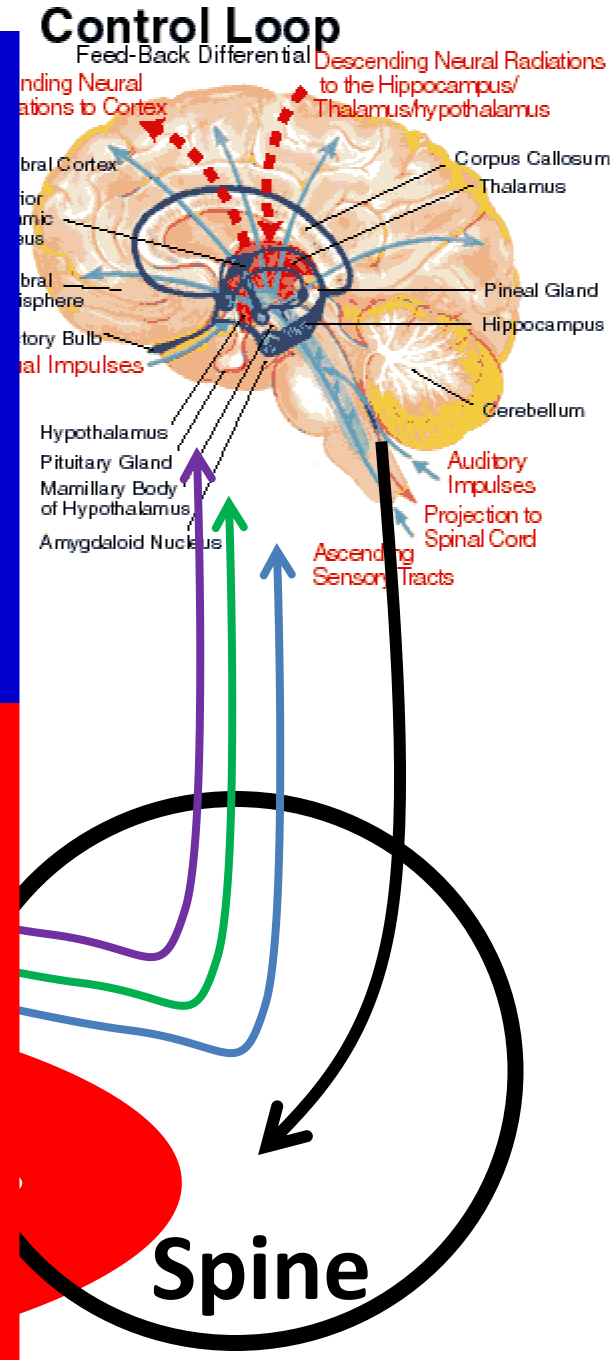
- Eyes open vs closed
- Contrast
  - young surfers
  - old football players



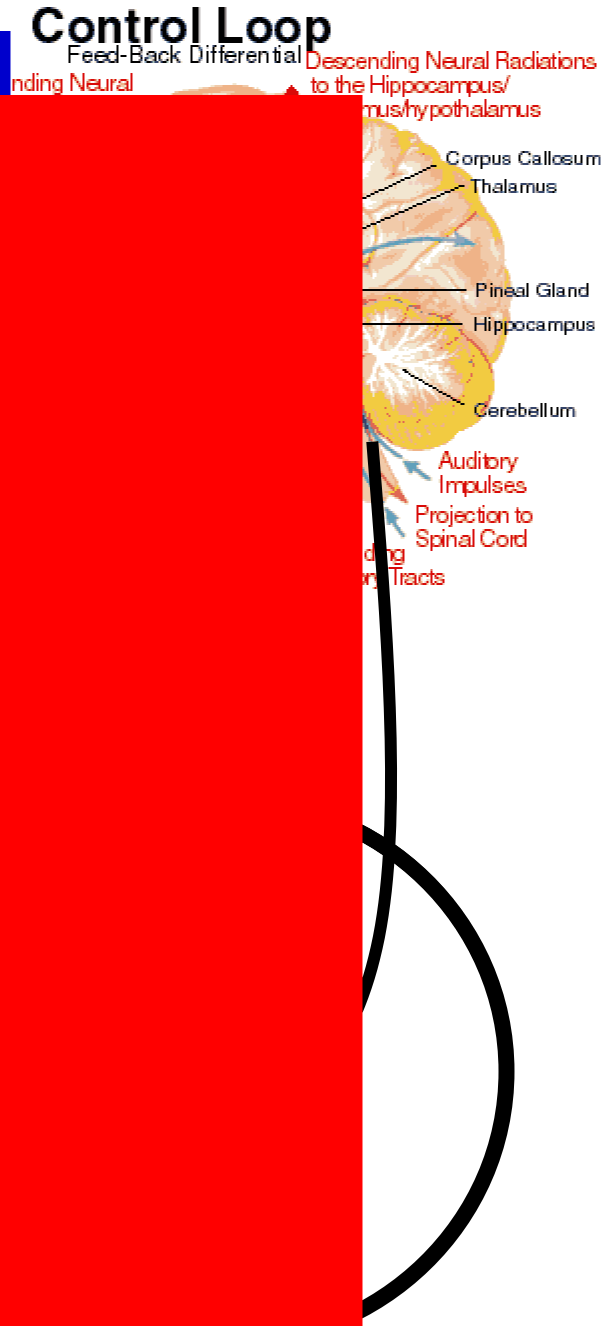

Control Loop
Feed-Back Differential
Ascending Neural Radiations to Cortex
Descending Neural Radiations to the Hippocampus/ Thalamus/hypothalamus
Cerebral Cortex
Corpus Callosum
Thalamus
Anterior Thalamic Nucleus
Cerebral Hemisphere
Pineal Gland
Hippocampus
Olfactory Bulb
Visual Impulses
Cerebellum
Hypothalamus
Pituitary Gland
Mamillary Body of Hypothalamus
Amygdaloid Nucleus
Auditory Impulses
Projection to Spinal Cord
Ascending Sensory Tracts
delay=death
sense
move
Spine

Reflect

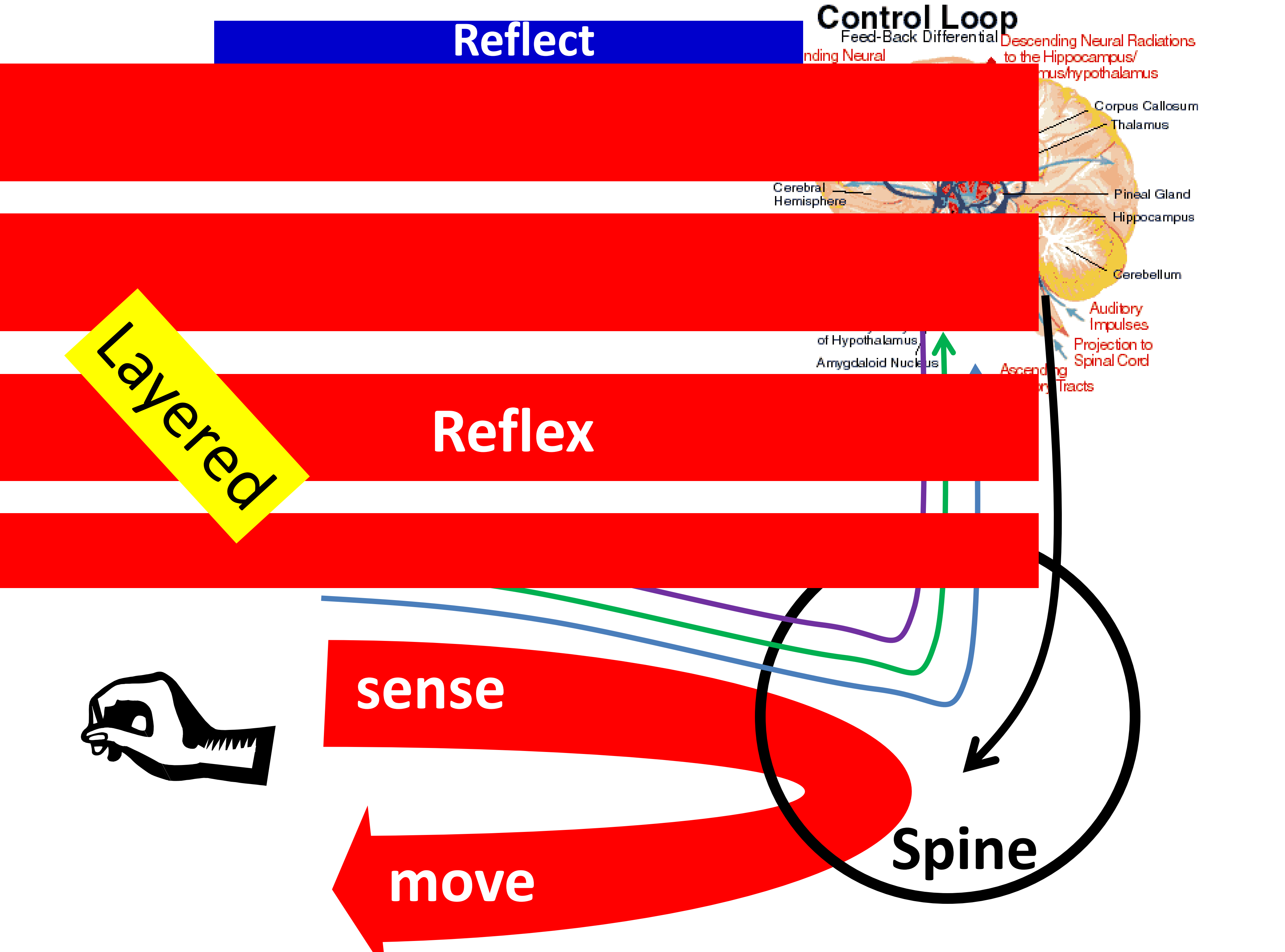
Reflex



Reflect

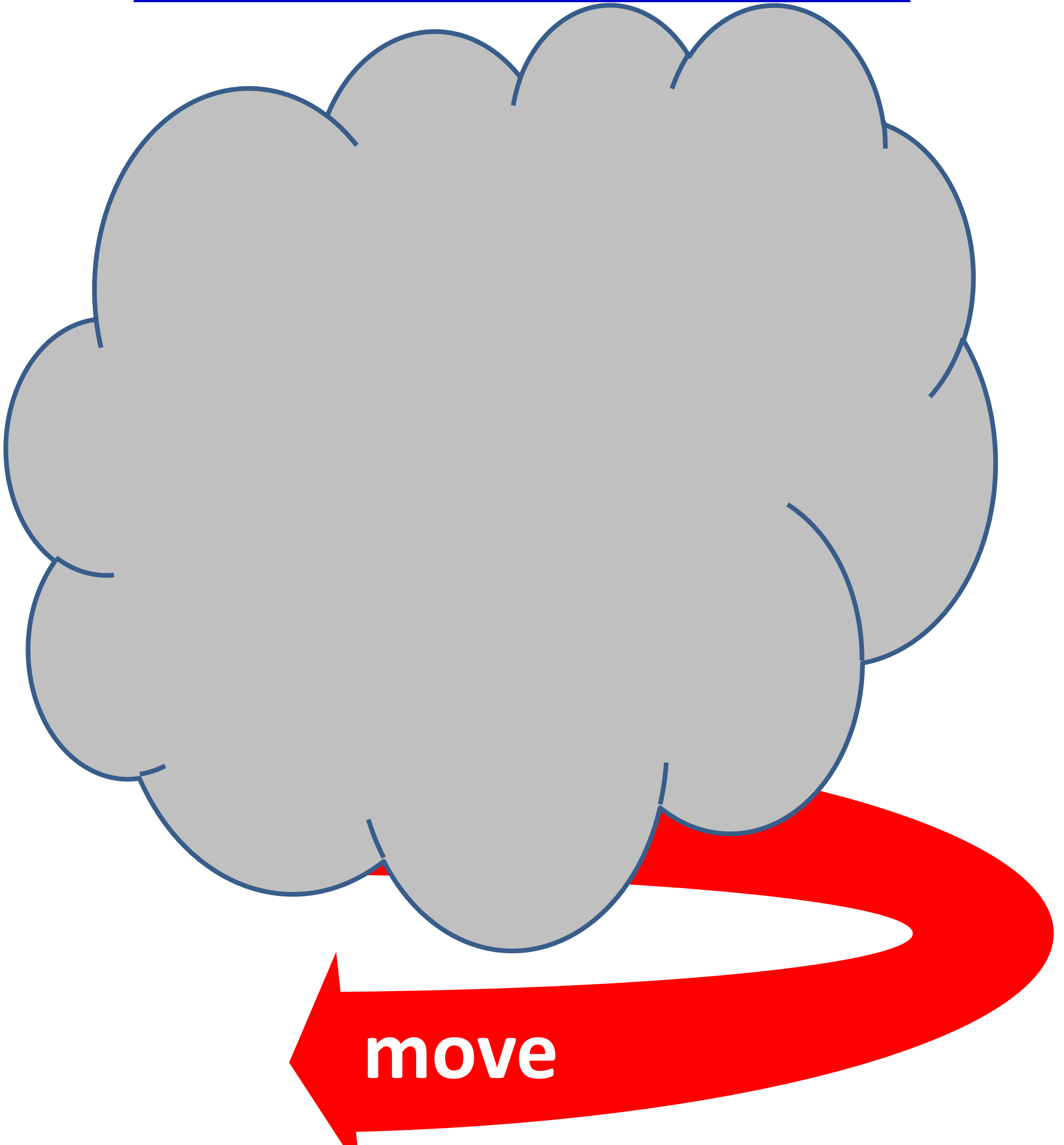


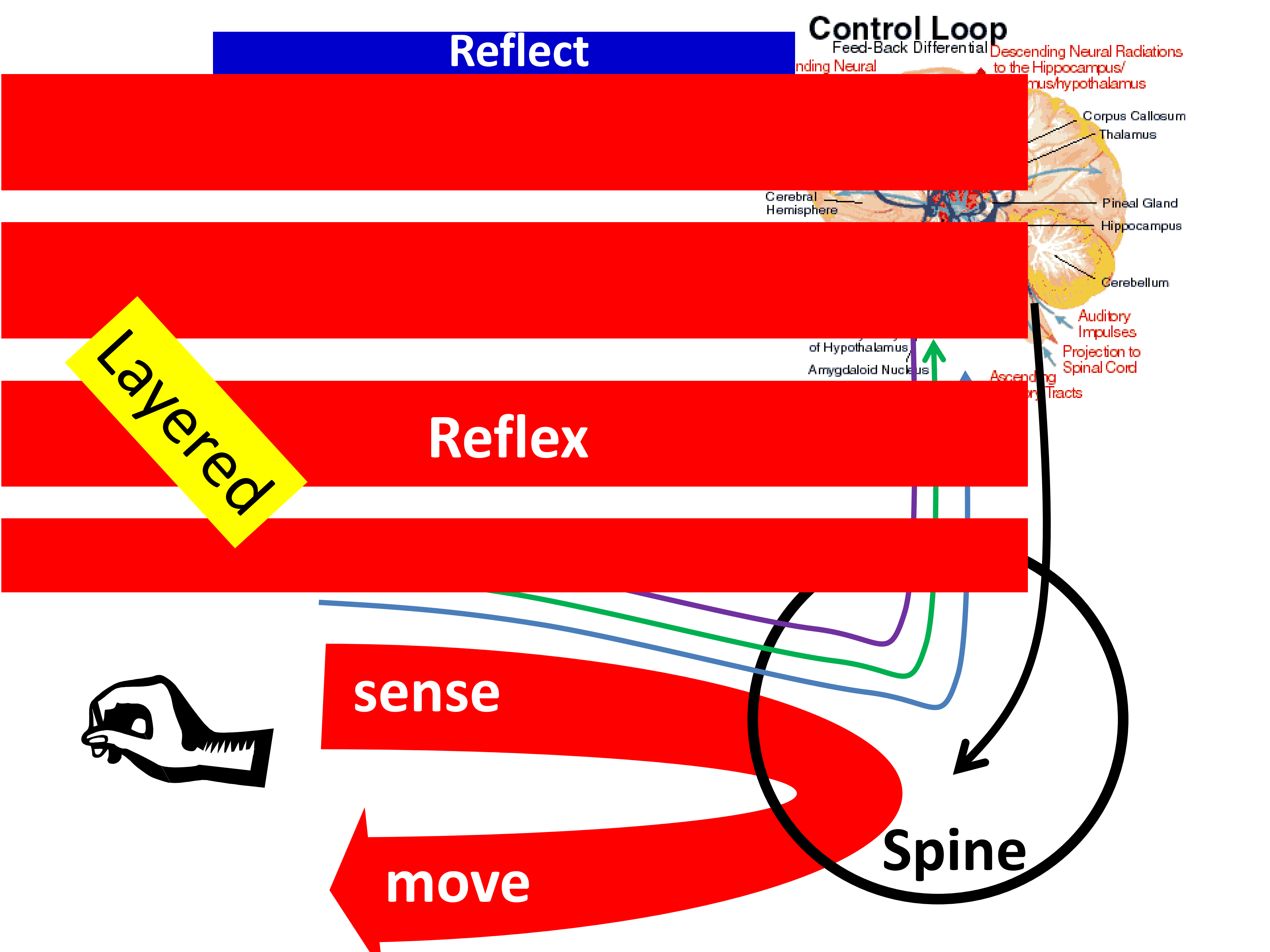
Reflex



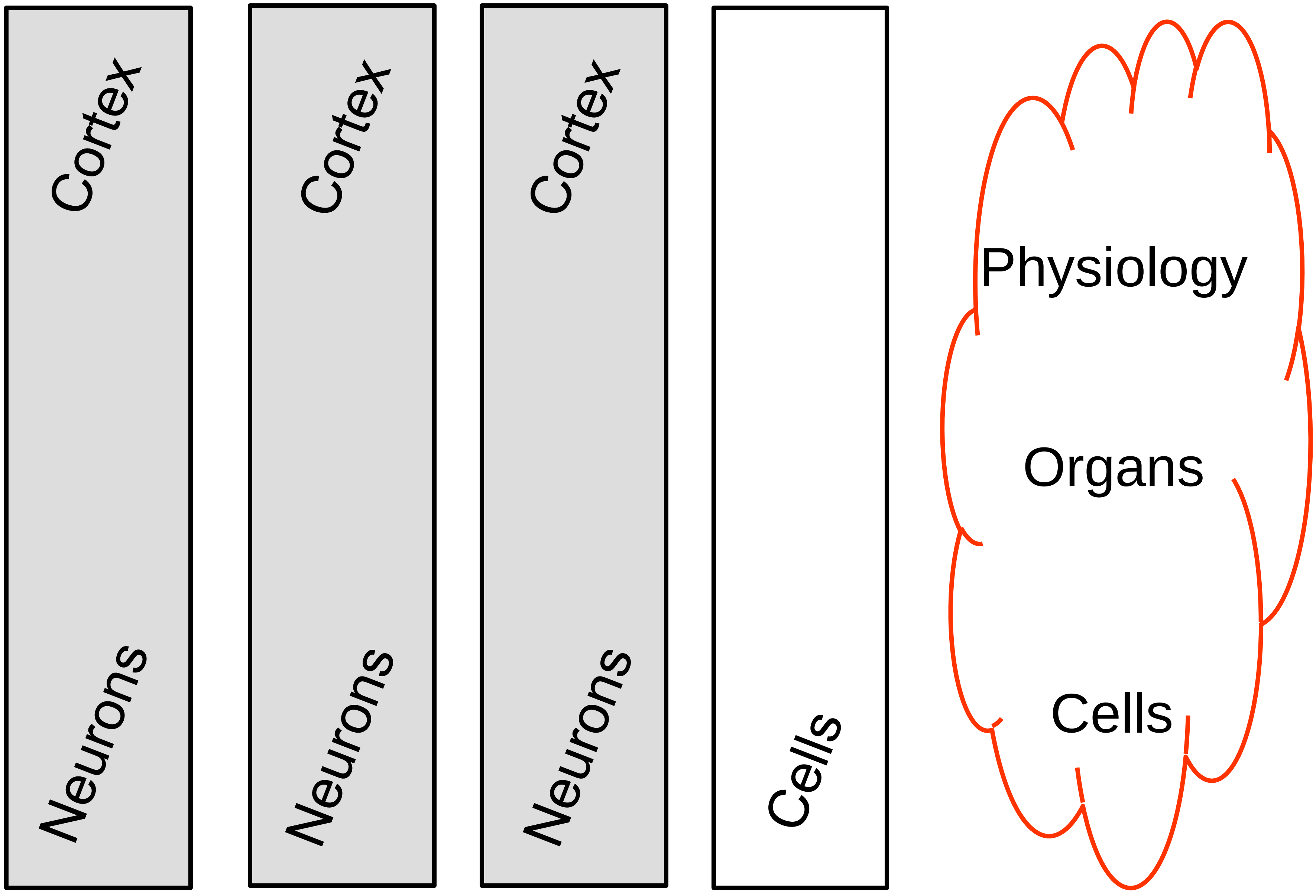
Reflect
Control Loop
Feed-Back Differential
nding Neural
Descending Neural Radiations
to the Hippocampus/
mus/hypothalamus
Corpus Callosum
Thalamus
Cerebral
Hemisphere
Pineal Gland
Hippocampus
Cerebellum
Auditory
Impulses
of Hypothalamus
Projection to
Spinal Cord
Amygdaloid Nucleus
Layered
Reflex
sense
move
Spine

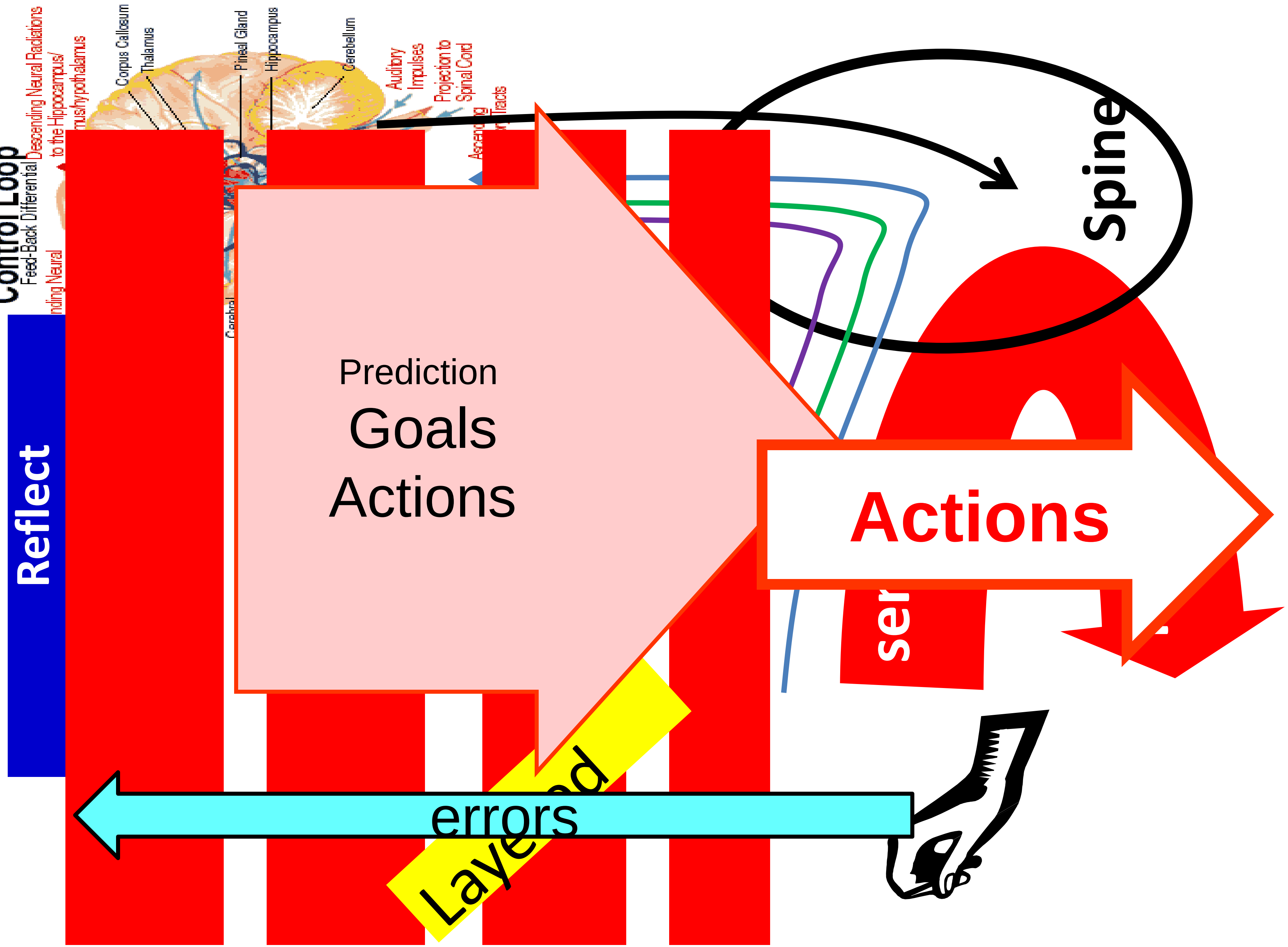
Reflect

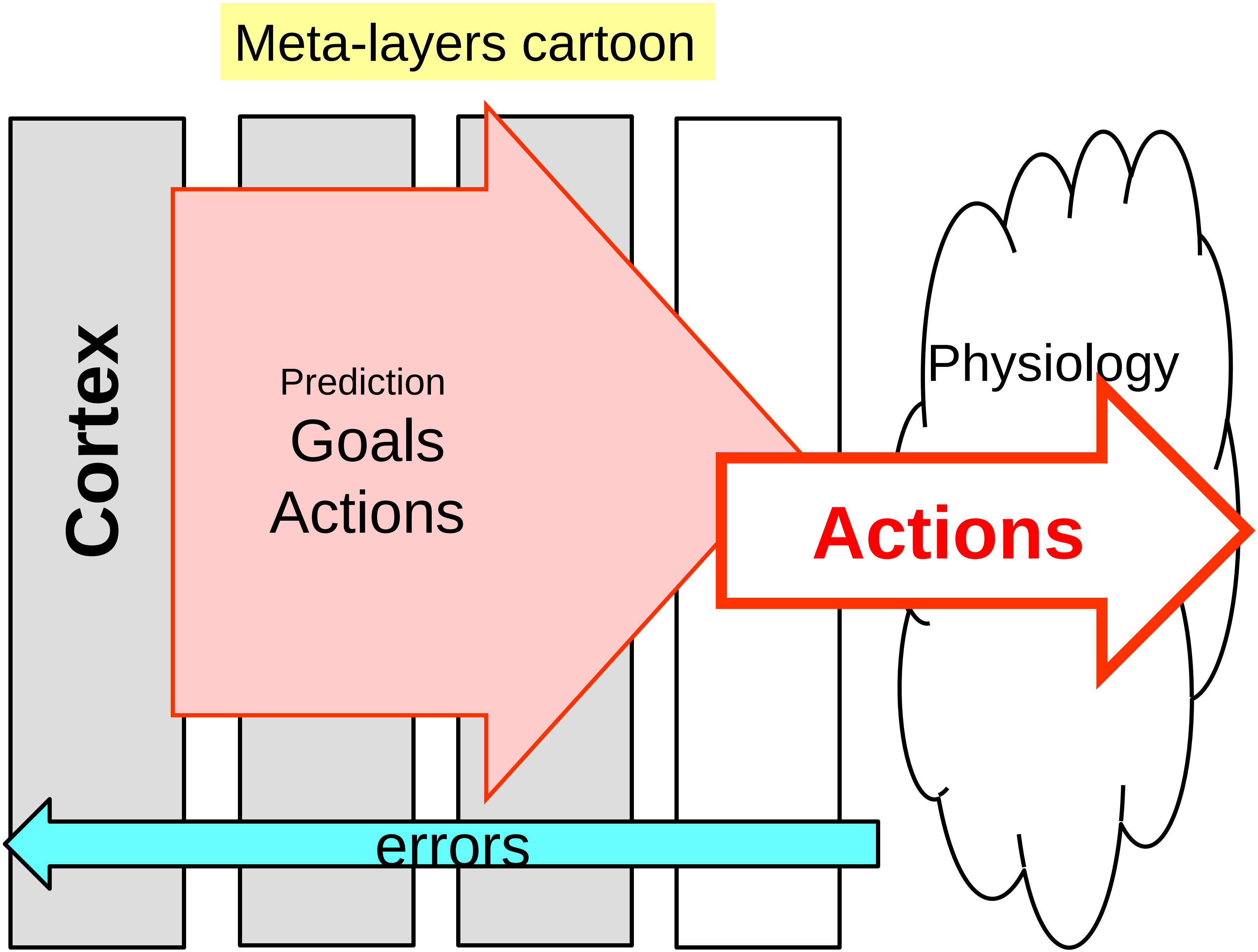



Reflect
Control Loop
Feed-Back Differential
Descending Neural Radiations to the Hippocampus/
Corpus Callosum
Thalamus
Cerebral Hemisphere
Pineal Gland
Hippocampus
Cerebellum
Auditory Impulses
Projection to Spinal Cord
of Hypothalamus
Amygdaloid Nucleus
Layered
Reflex
sense
move
Spine

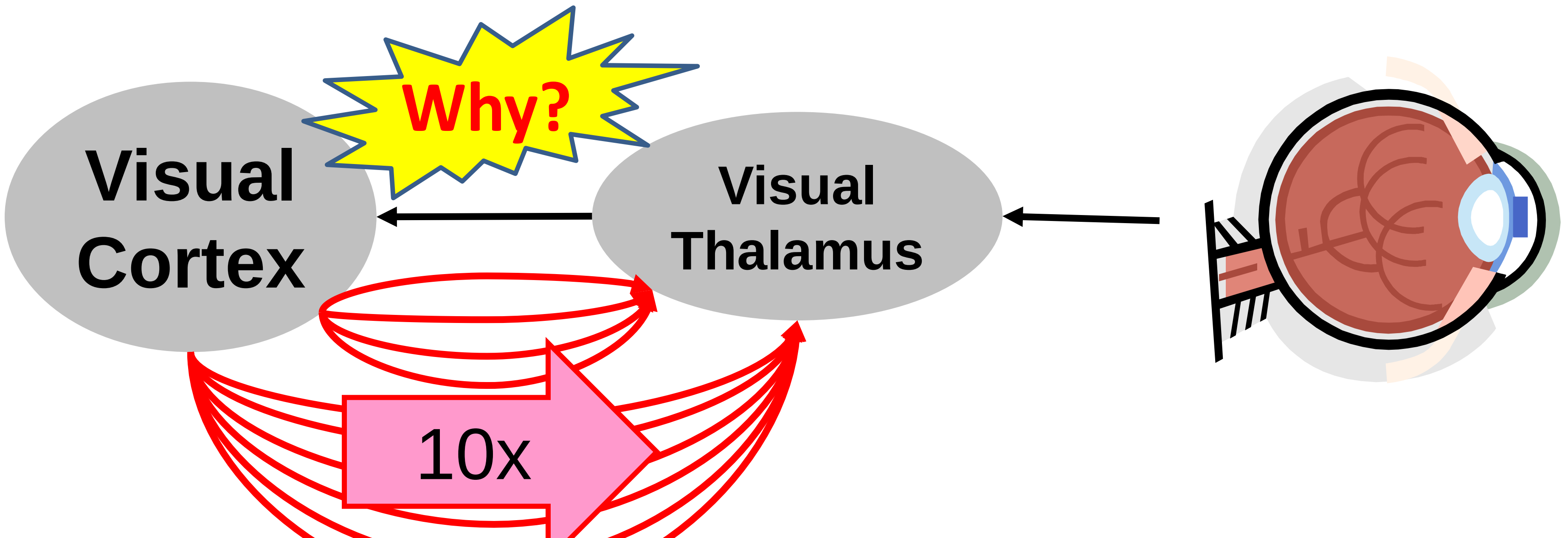
Layered architectures (cartoon)

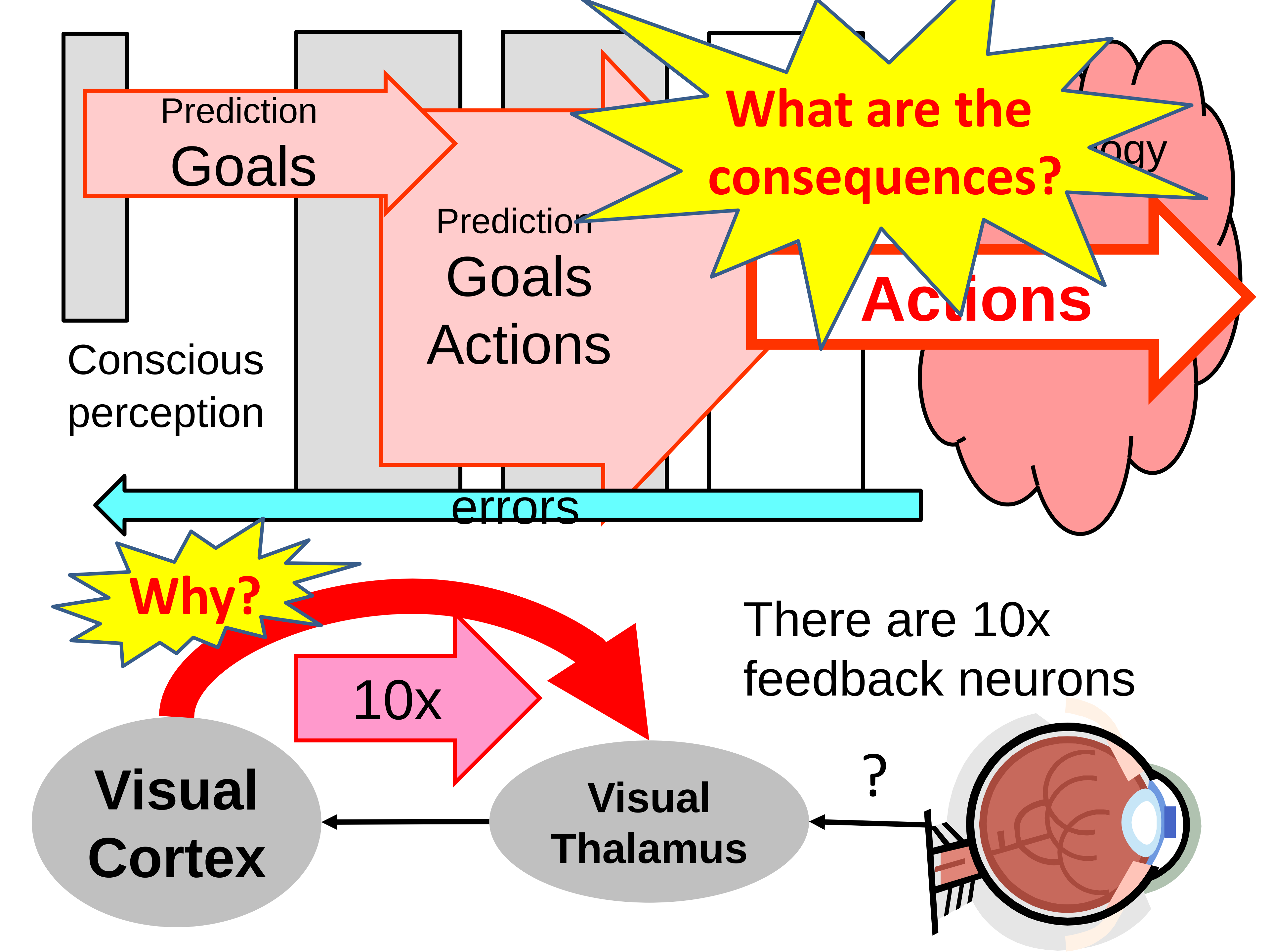



Prediction
Goals
Actions
Actions
errors
Reflect
Spine
Layered
Control Loop
Feed-Back Differential
Descending Neural Radiations to the Hippocampus/
Corpus Callosum
Thalamus
Pineal Gland
Hippocampus
Cerebellum
Auditory Impulses
Projection to Spinal Cord

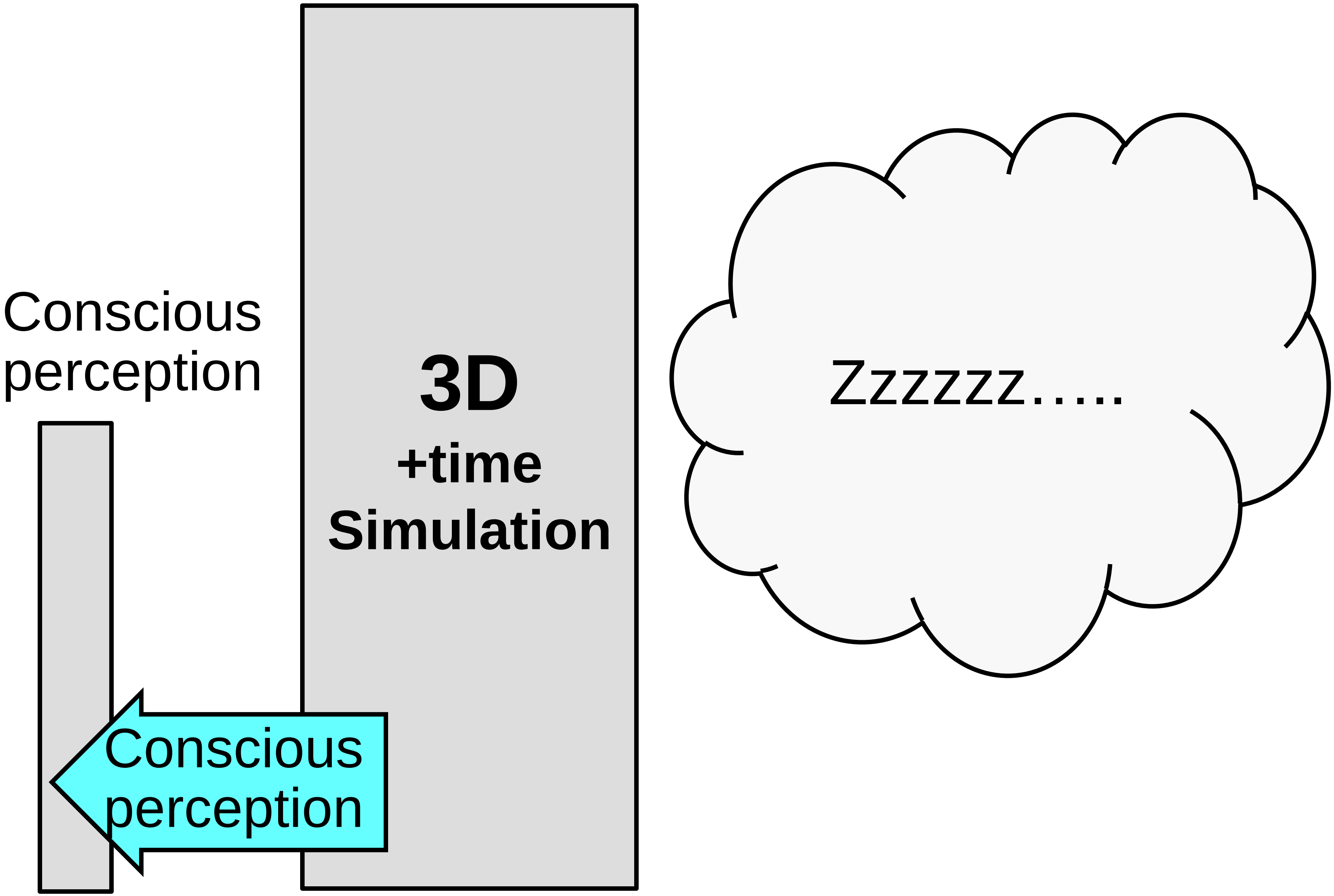


Meta-layers cartoon
Cortex
Prediction
Goals
Actions
Physiology
Actions
errors

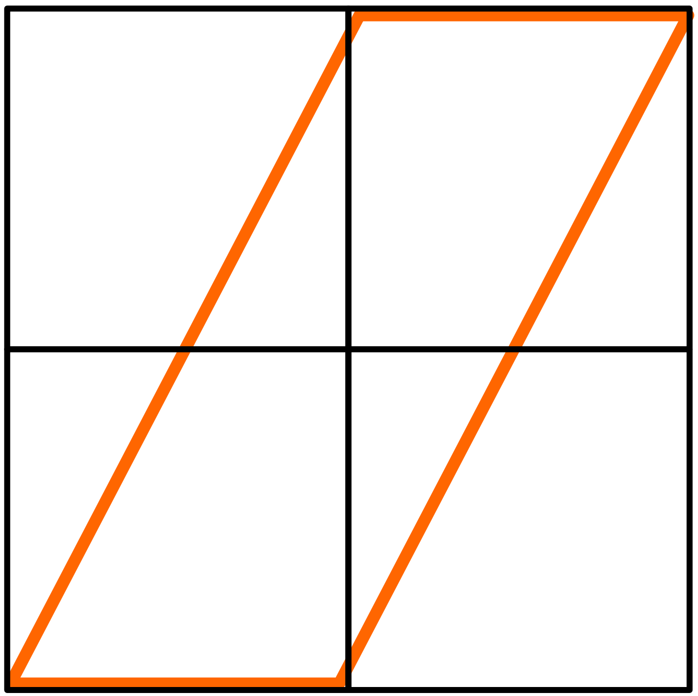

Why?
Visual
Cortex
Visual
Thalamus
10x

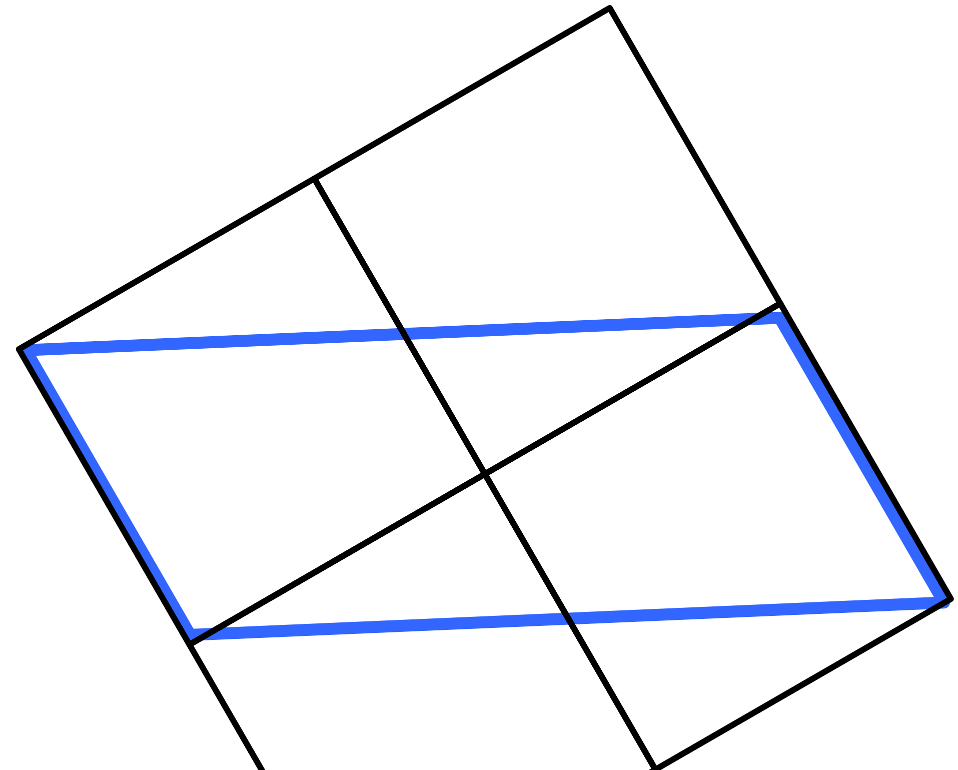

Prediction
Goals
Prediction
Goals
Actions
What are the consequences?
ogy
Actions
Conscious perception
errors
Why?
10x
There are 10x feedback neurons
?
Visual Cortex
Visual Thalamus

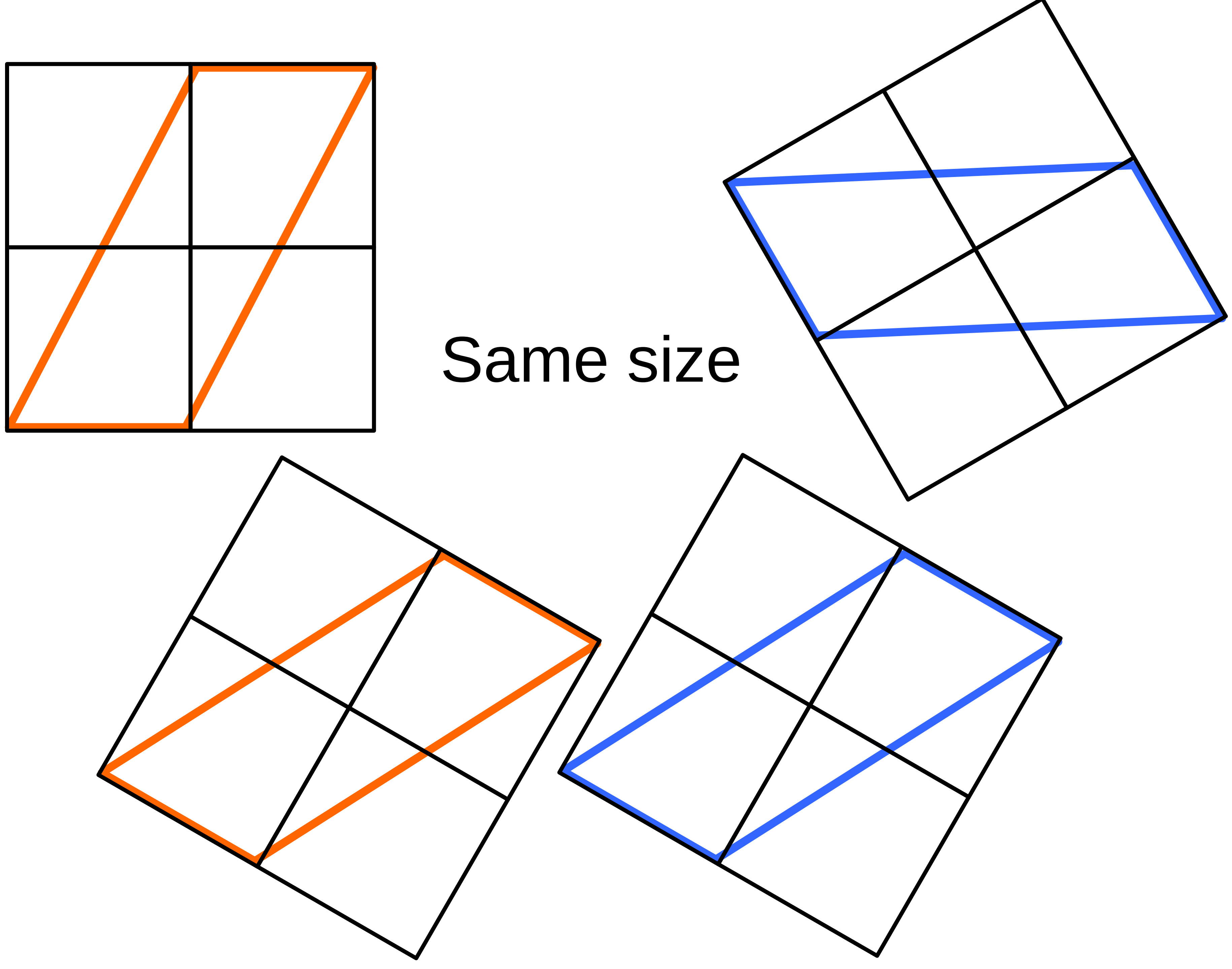
Seeing is ***dreaming***

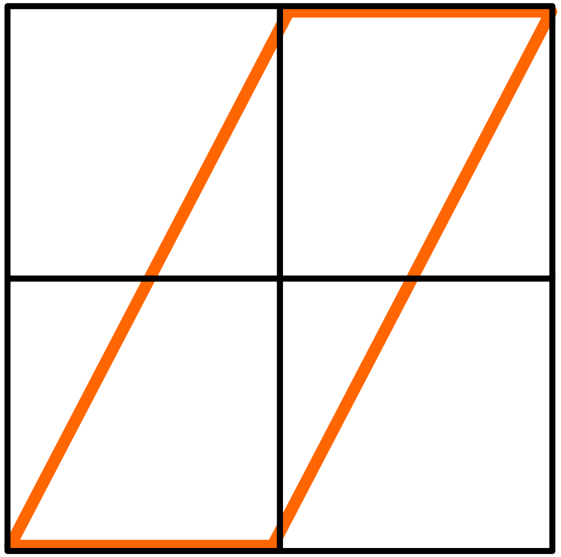


Same size?

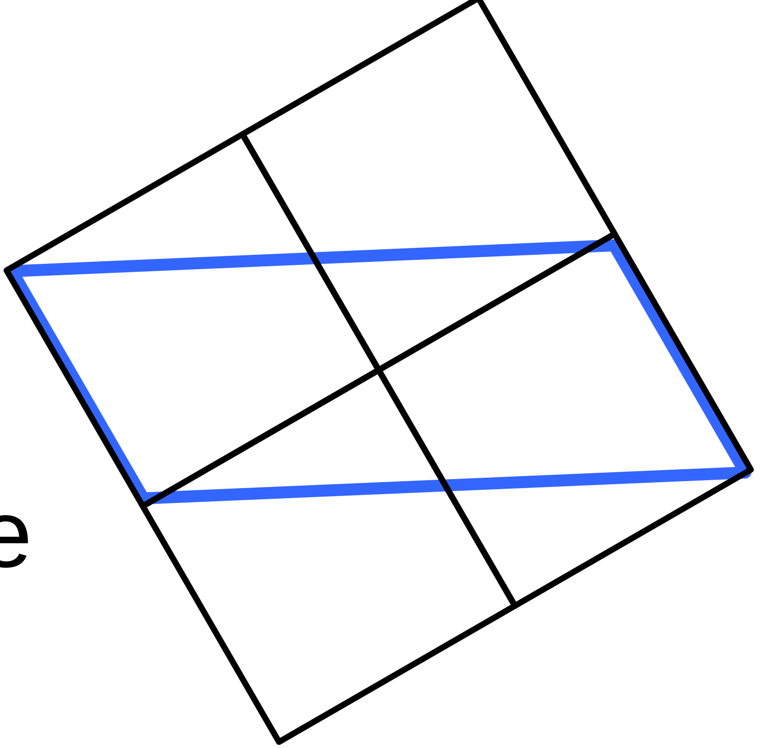


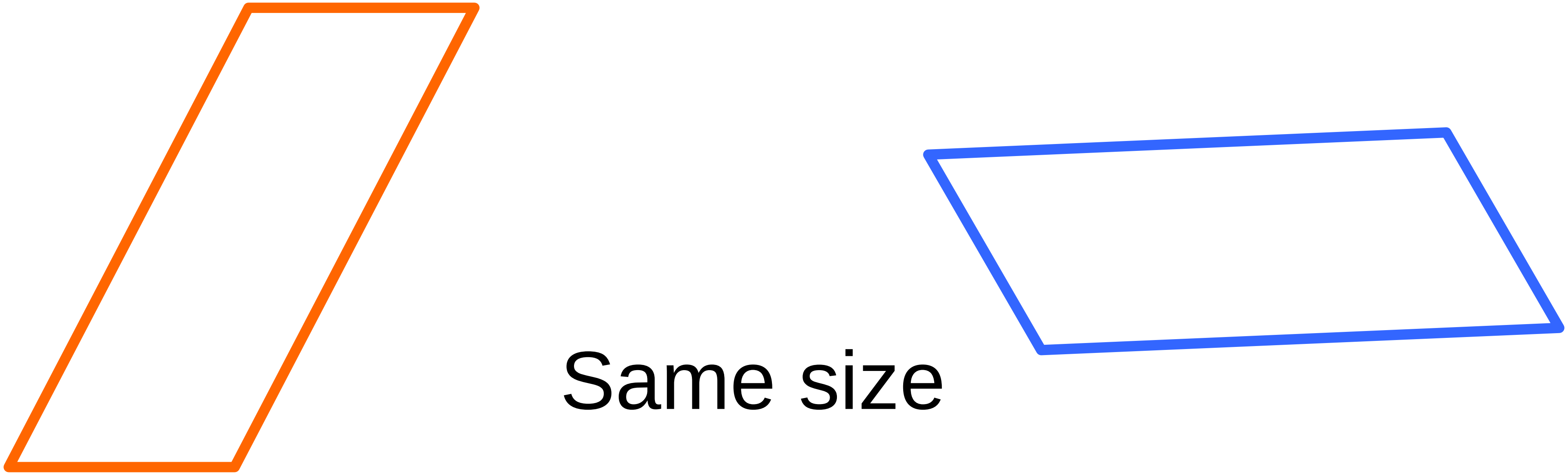



Same size



Same size





Toggle between this slide and the ones before and after

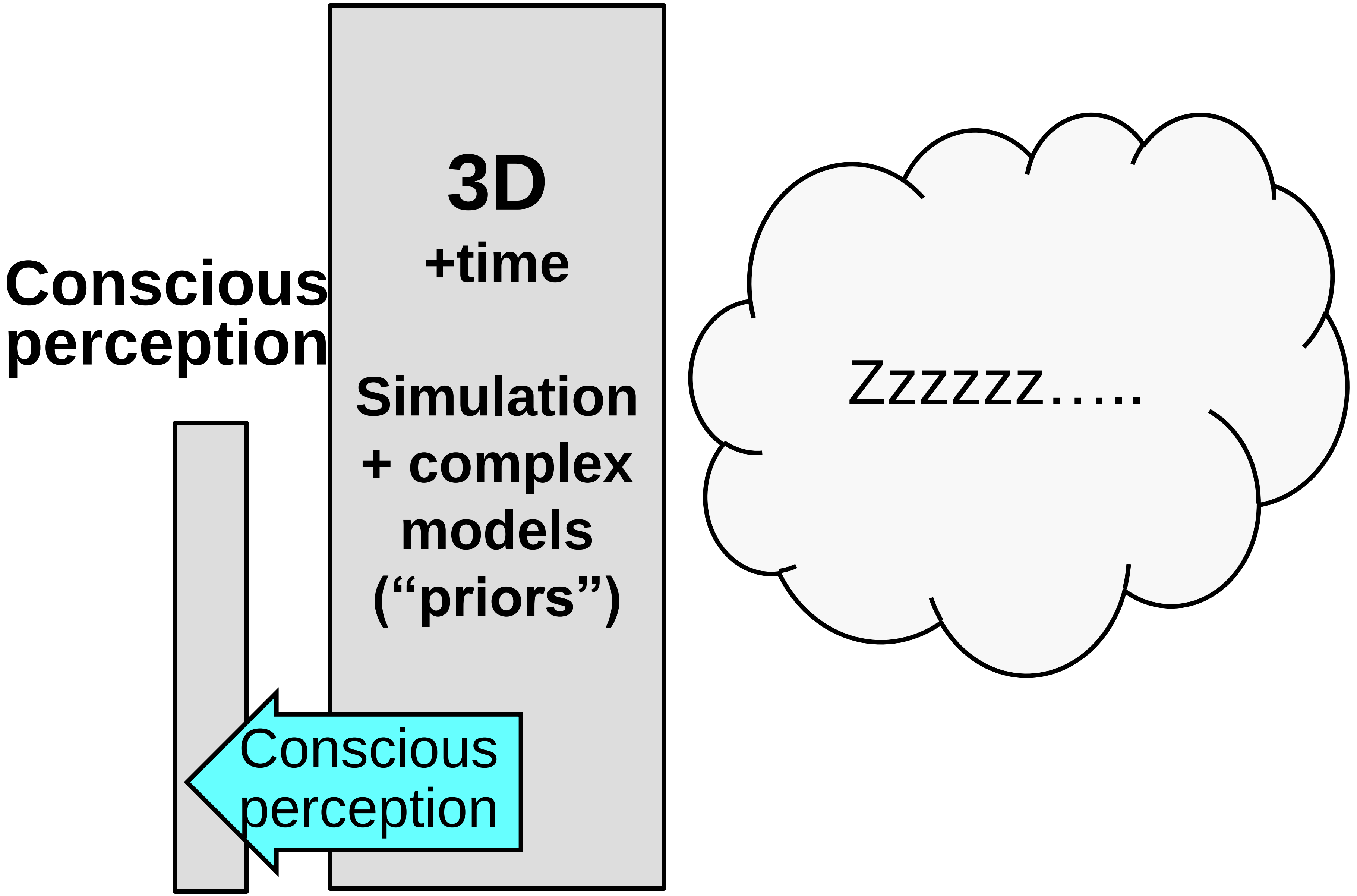
Even when you “know” they are the same, they appear different

Same size?

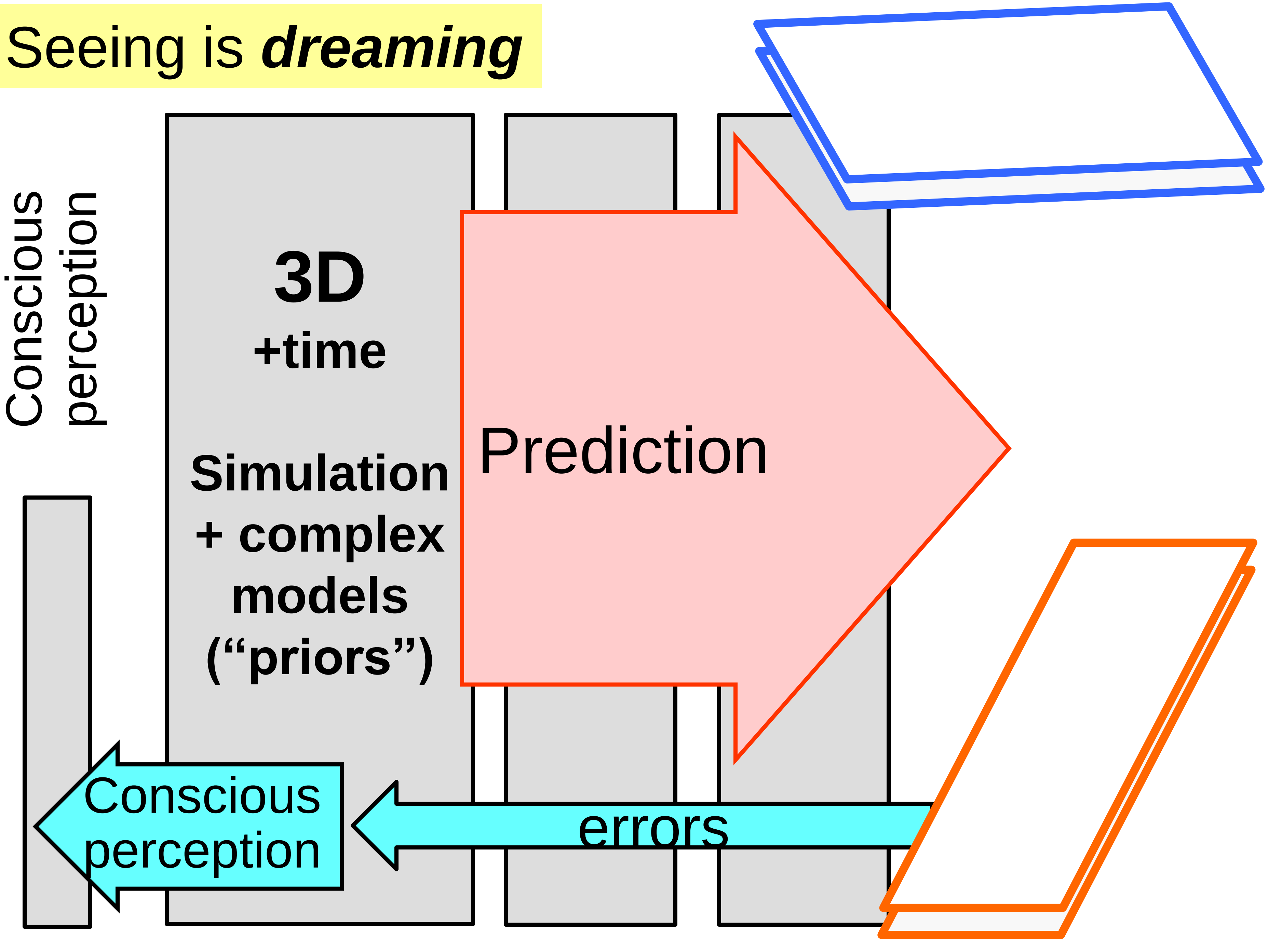
Vision: evolved for complex simulation and control, not 2d static pictures

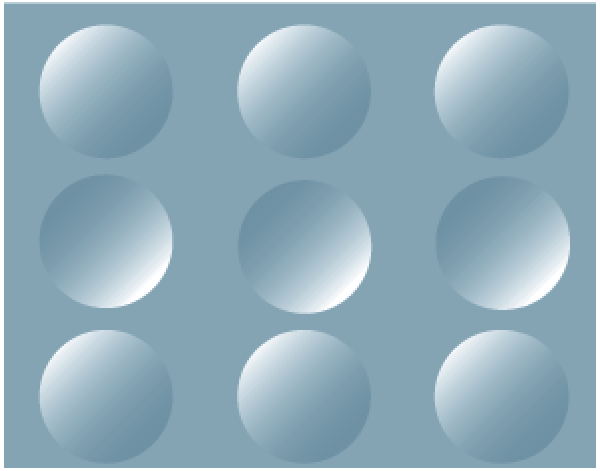
Even when you “know” they are the same, they appear different

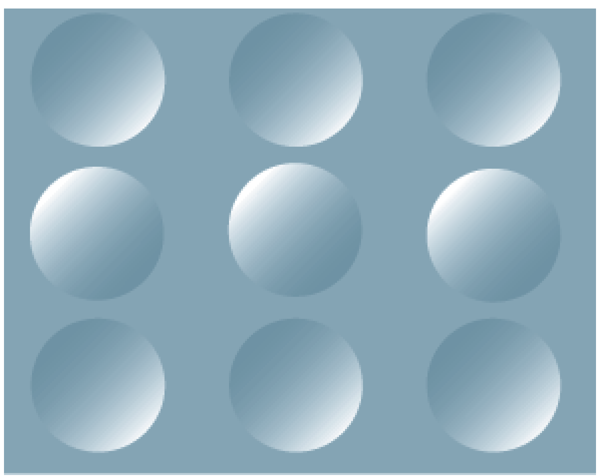
Seeing is ***dreaming***



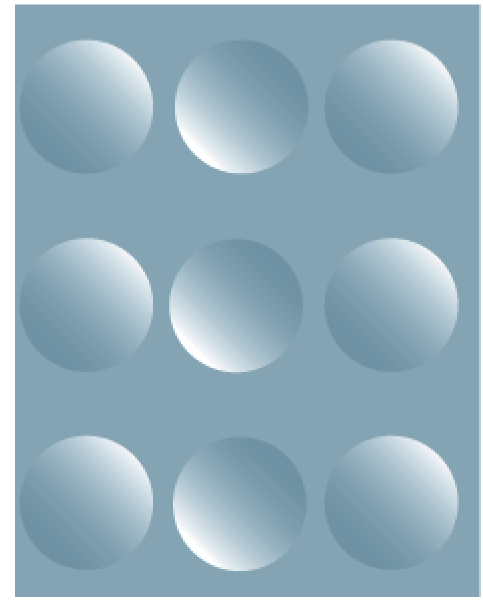
Seeing is ***dreaming***

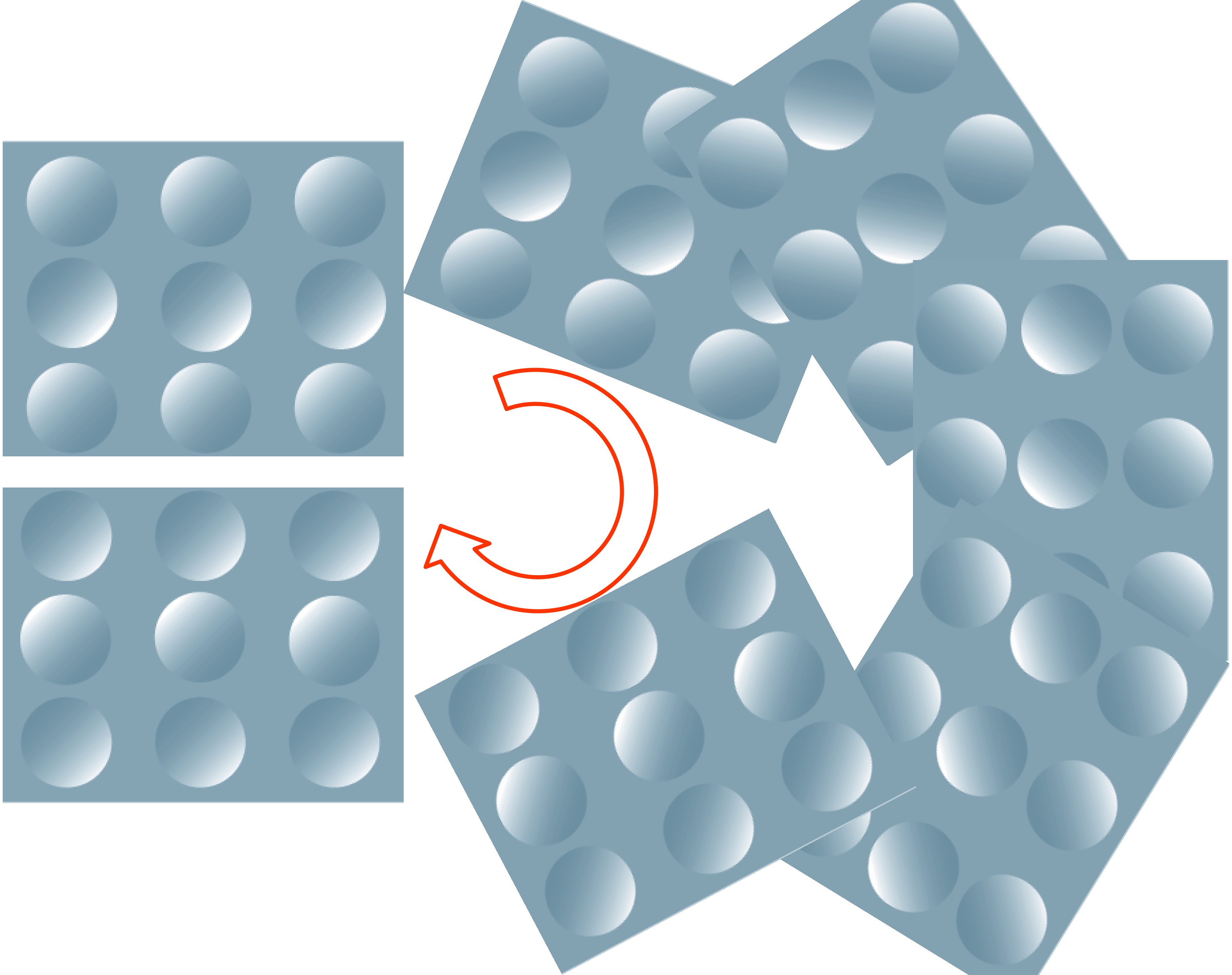






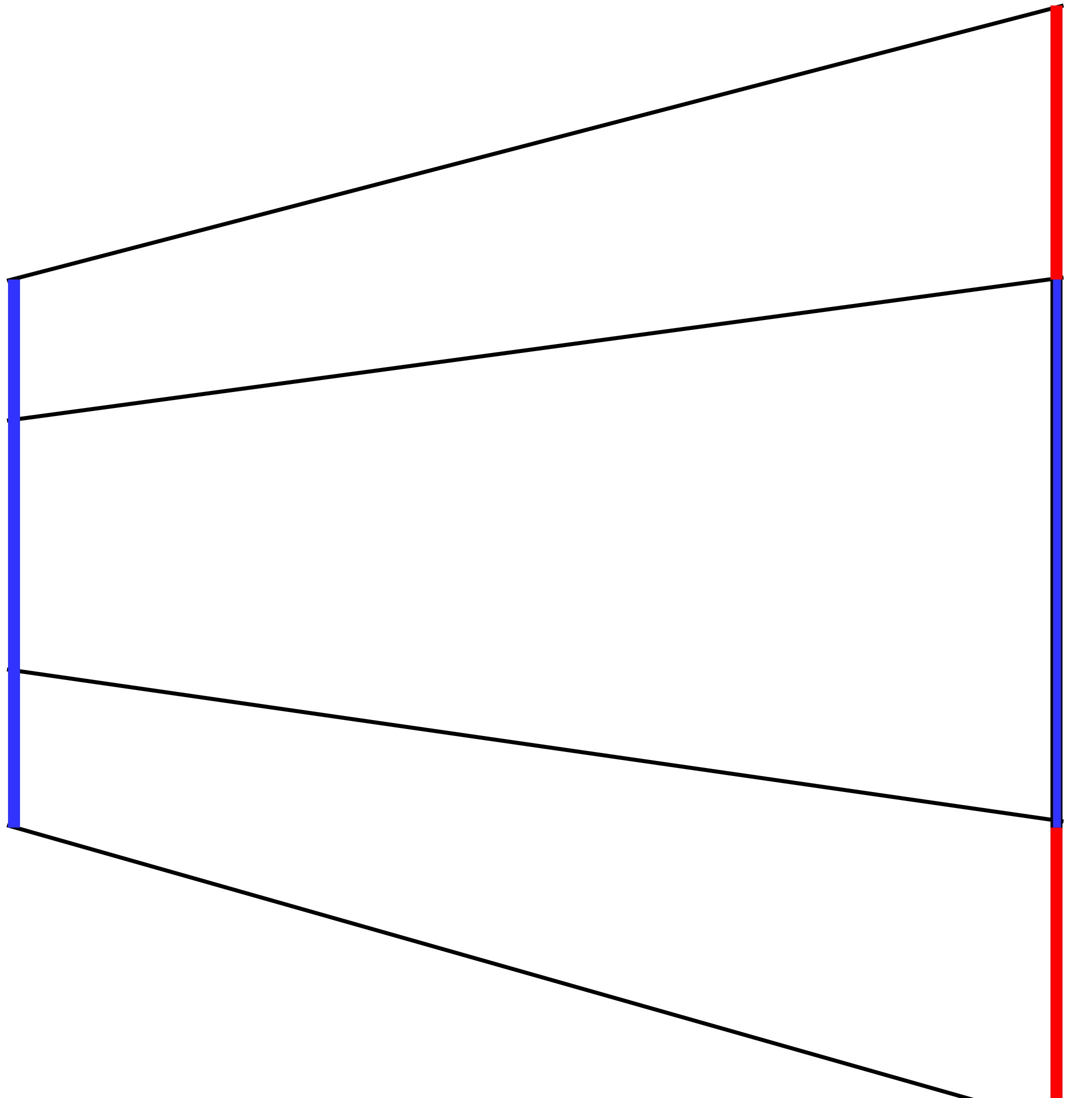
Inferring shape from shading



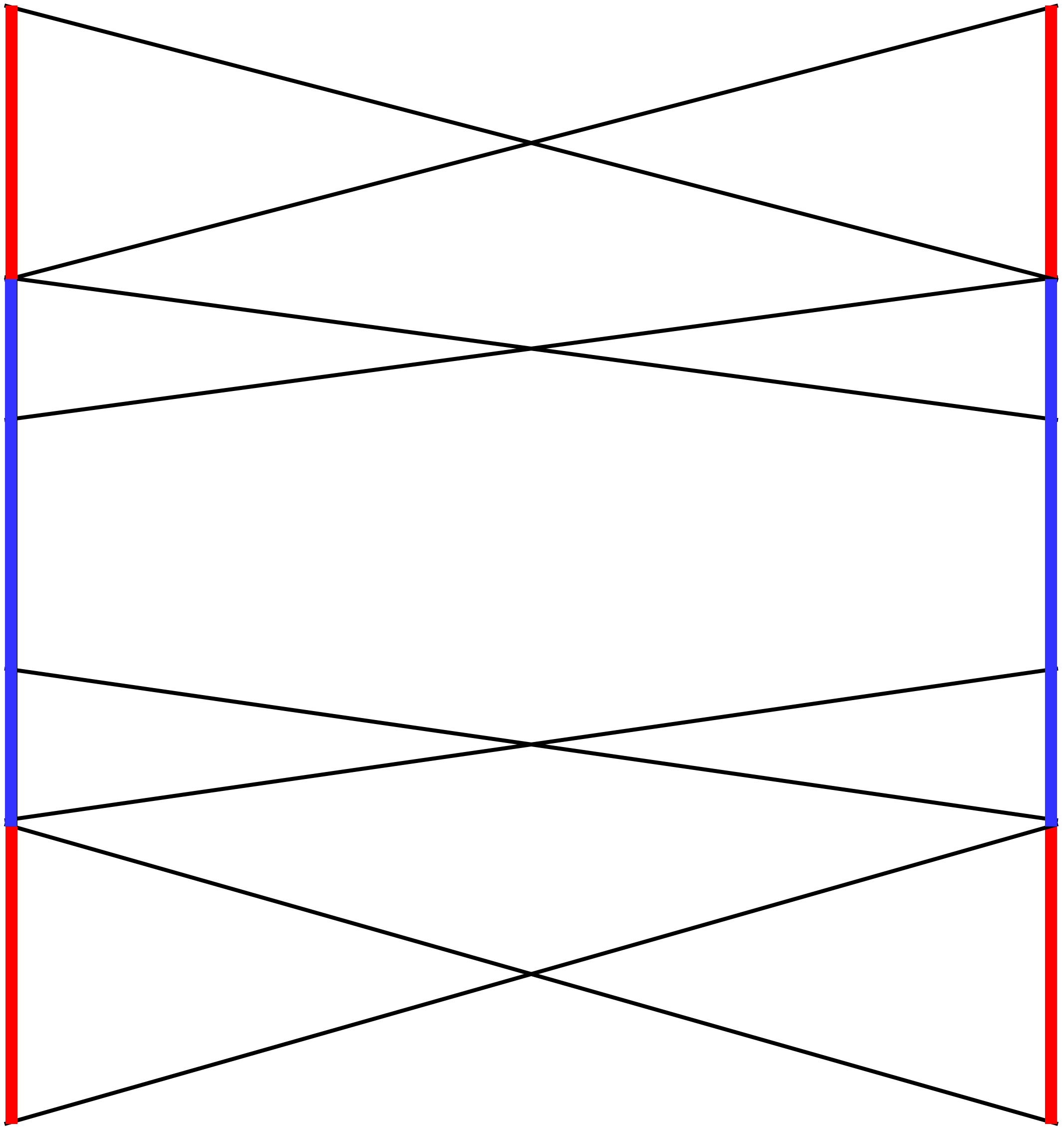


Which blue line is longer?

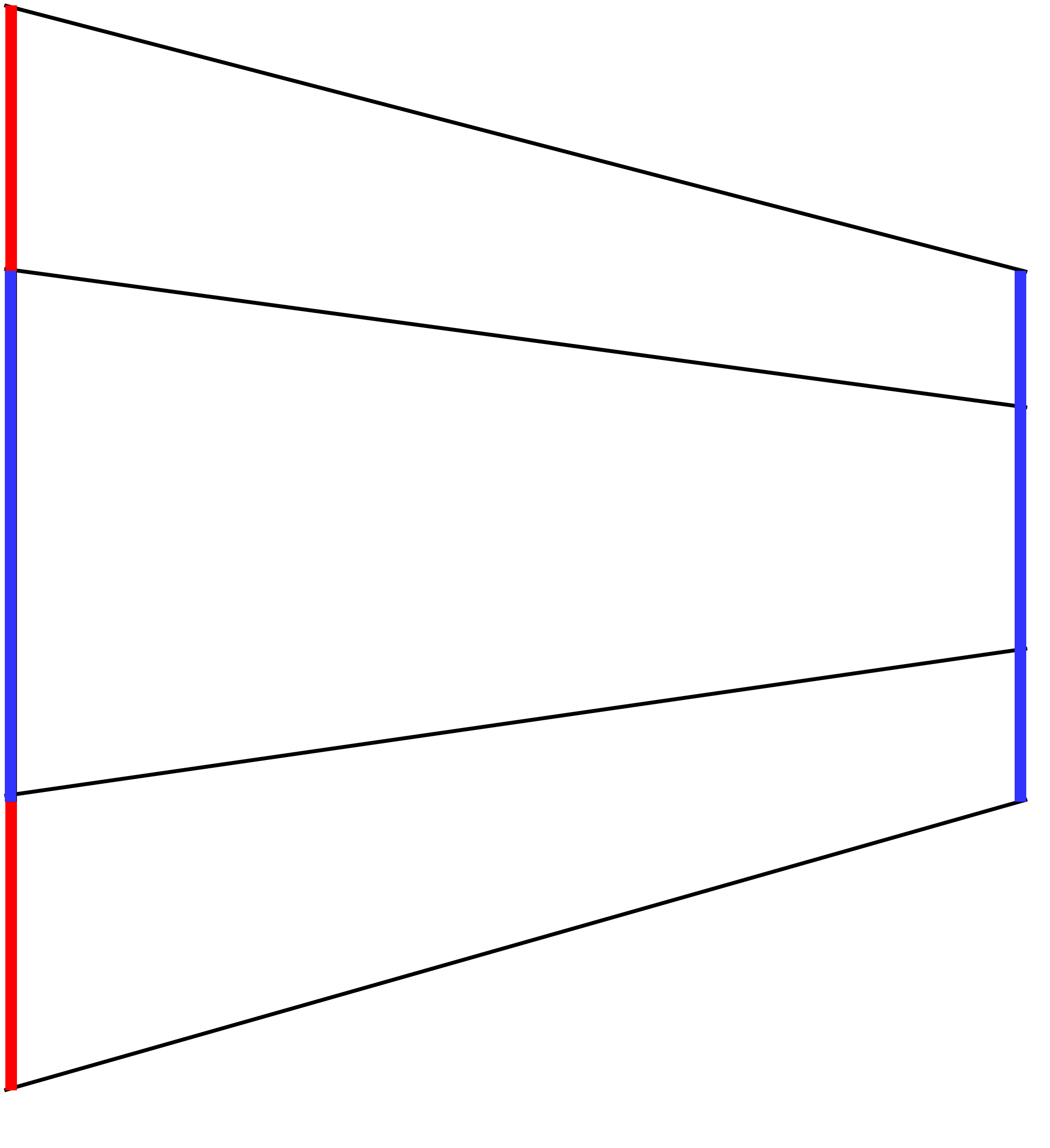
Which blue line is longer?



Which blue line is longer?

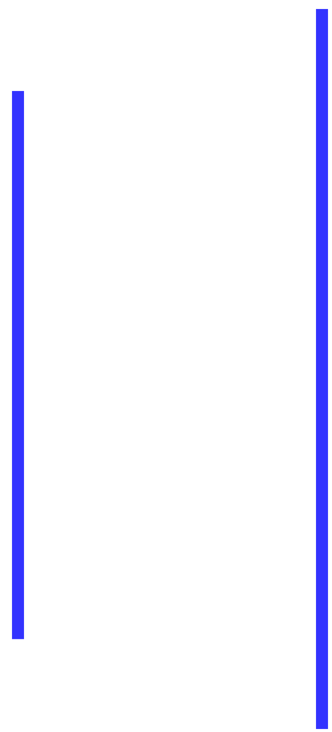


Which blue line is longer?

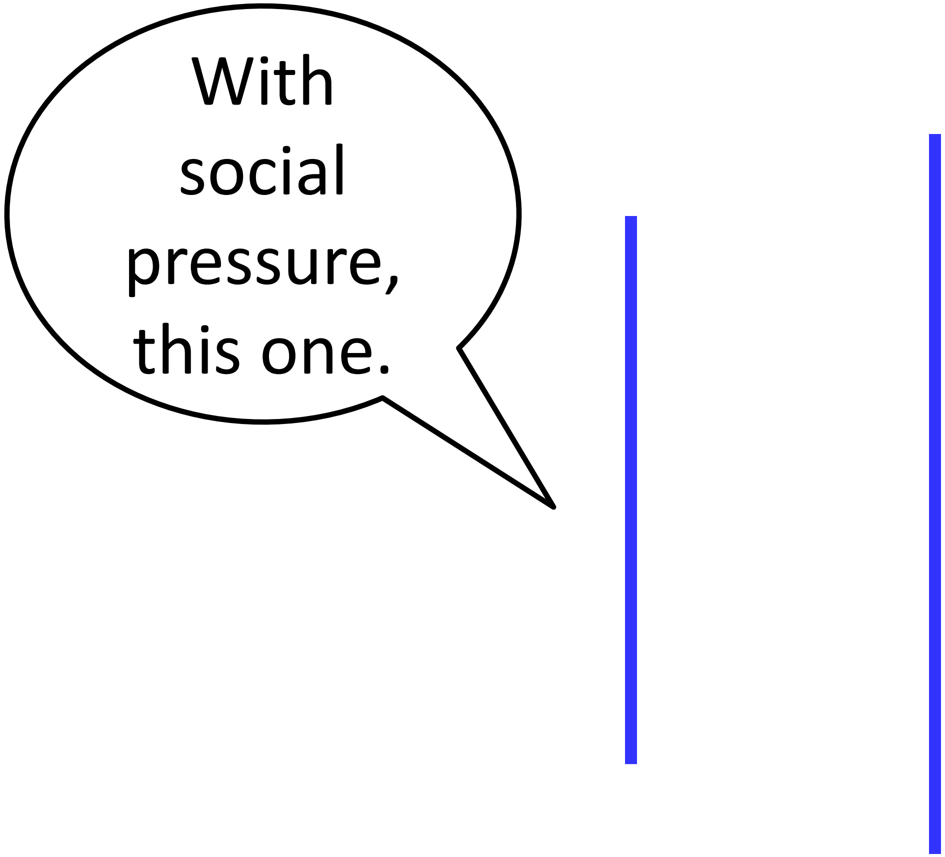


Which blue line is longer?

Which blue line is longer?

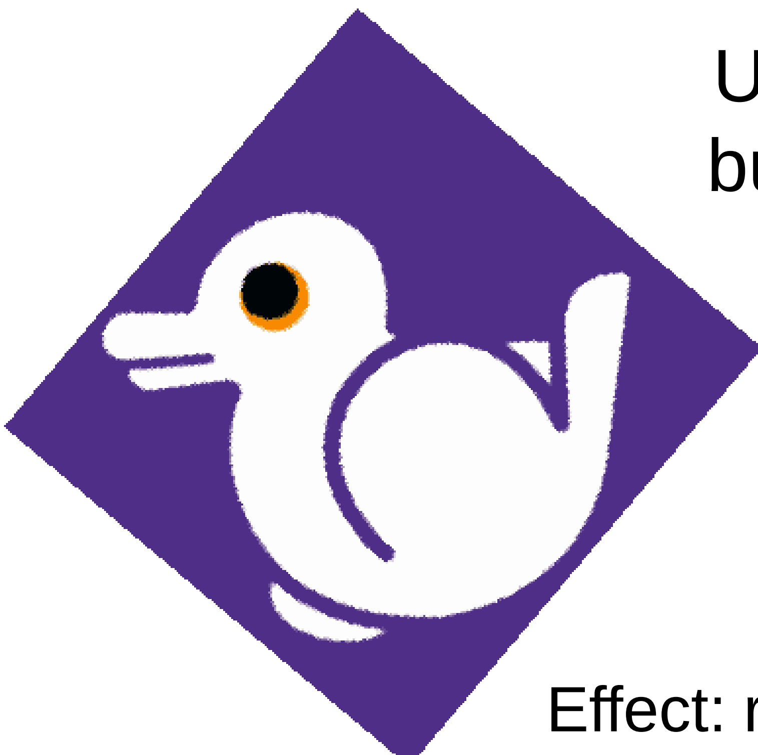


Which blue line is longer?



Standard social psychology experiment.


Unconscious
but high level

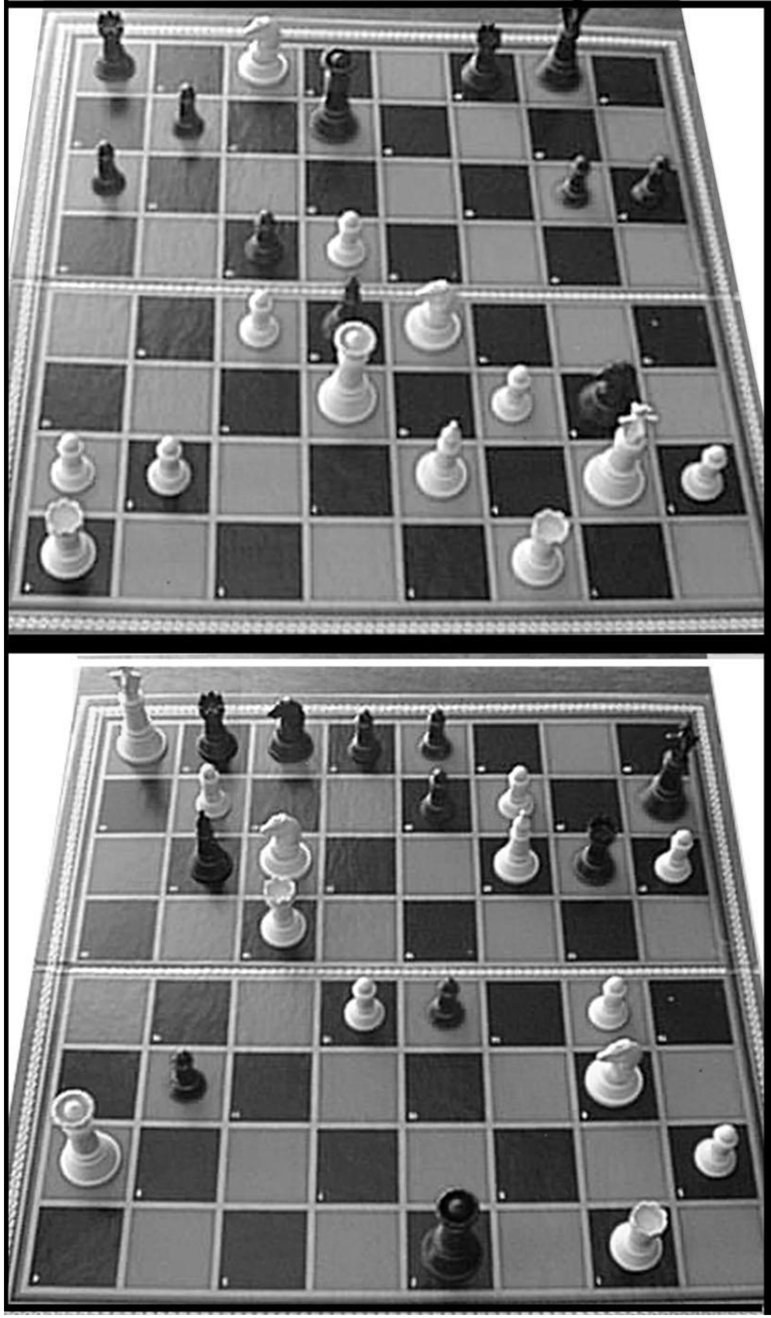


Effect: rival-schemata ambiguity

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

Specialized Face Learning Is Associated with Individual Recognition in Paper Wasps

Science AAAS

Michael J. Sheehan* and Elizabeth A. Tibbetts

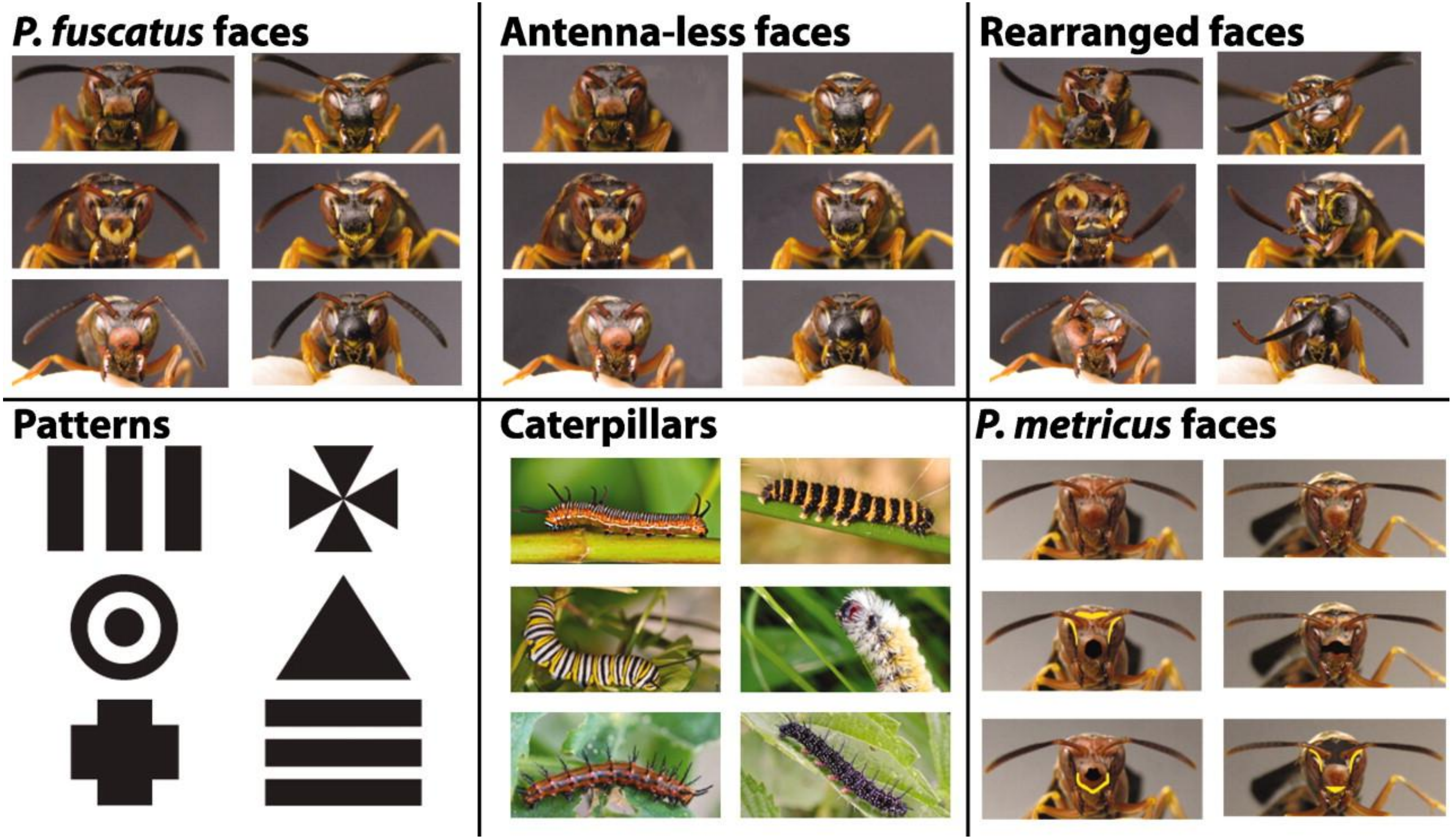
We demonstrate that the evolution of facial recognition in wasps is associated with specialized face-learning abilities. *Polistes fuscatus* can differentiate among normal wasp face images more rapidly and accurately than nonface images or manipulated faces. A close relative lacking facial recognition, *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

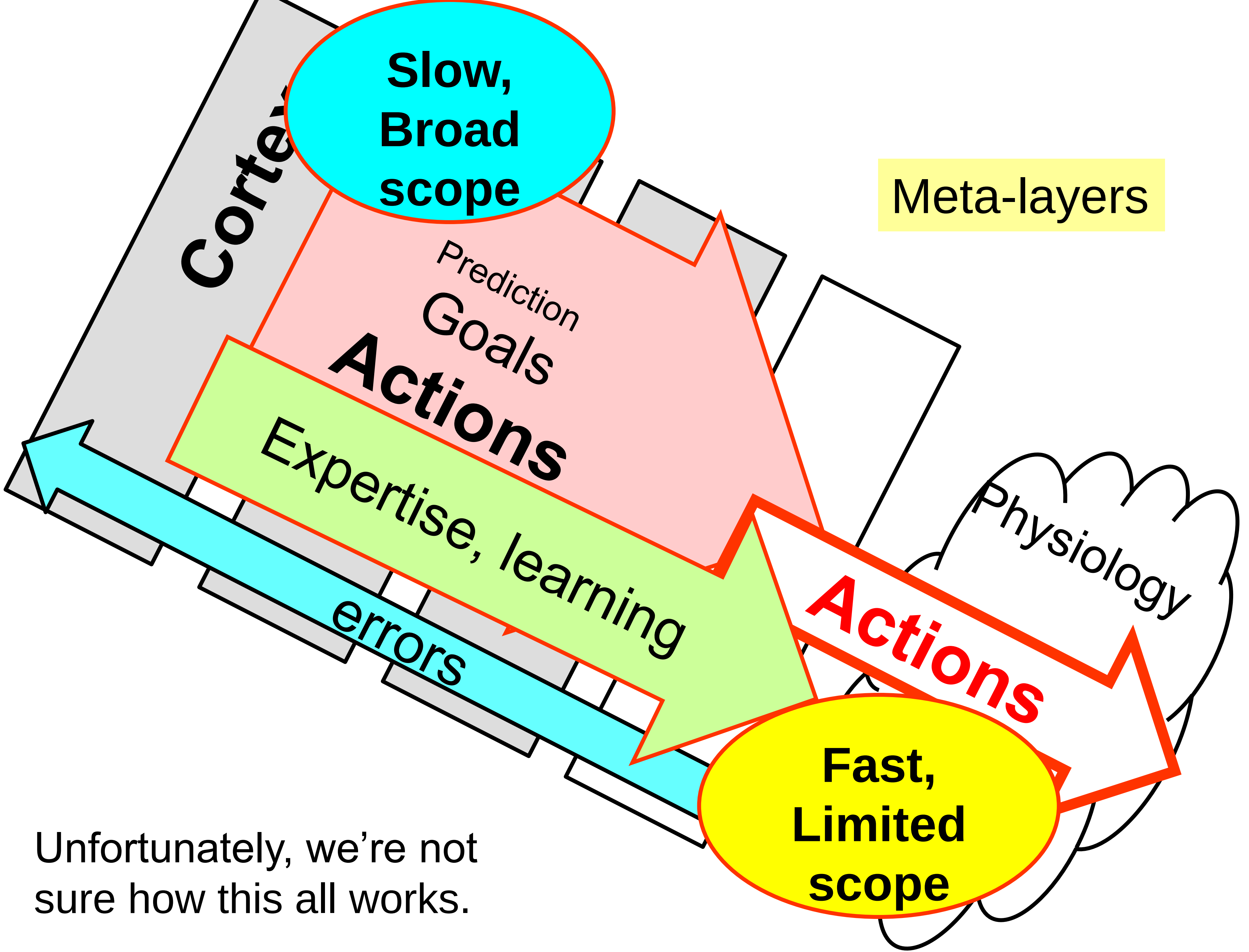
- *Polistes fuscatus* can differentiate among normal wasp face images more rapidly and accurately than nonface images or manipulated faces.
- *Polistes metricus* is a close relative lacking facial recognition and specialized face learning.
- Similar specializations for face learning are found in primates 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.

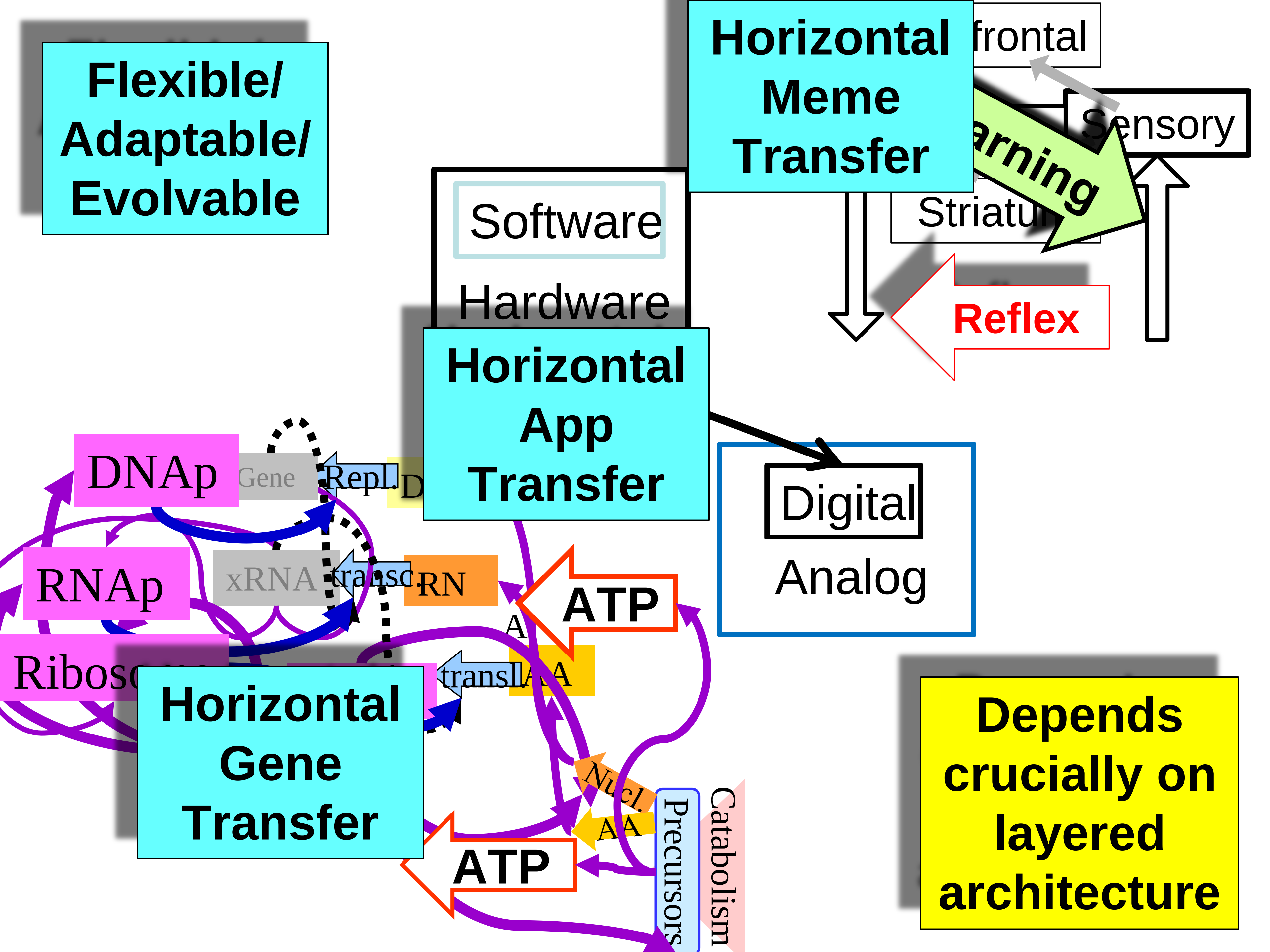


M J Sheehan, E A Tibbetts Science 2011;334:1272-1275

Published by AAAS

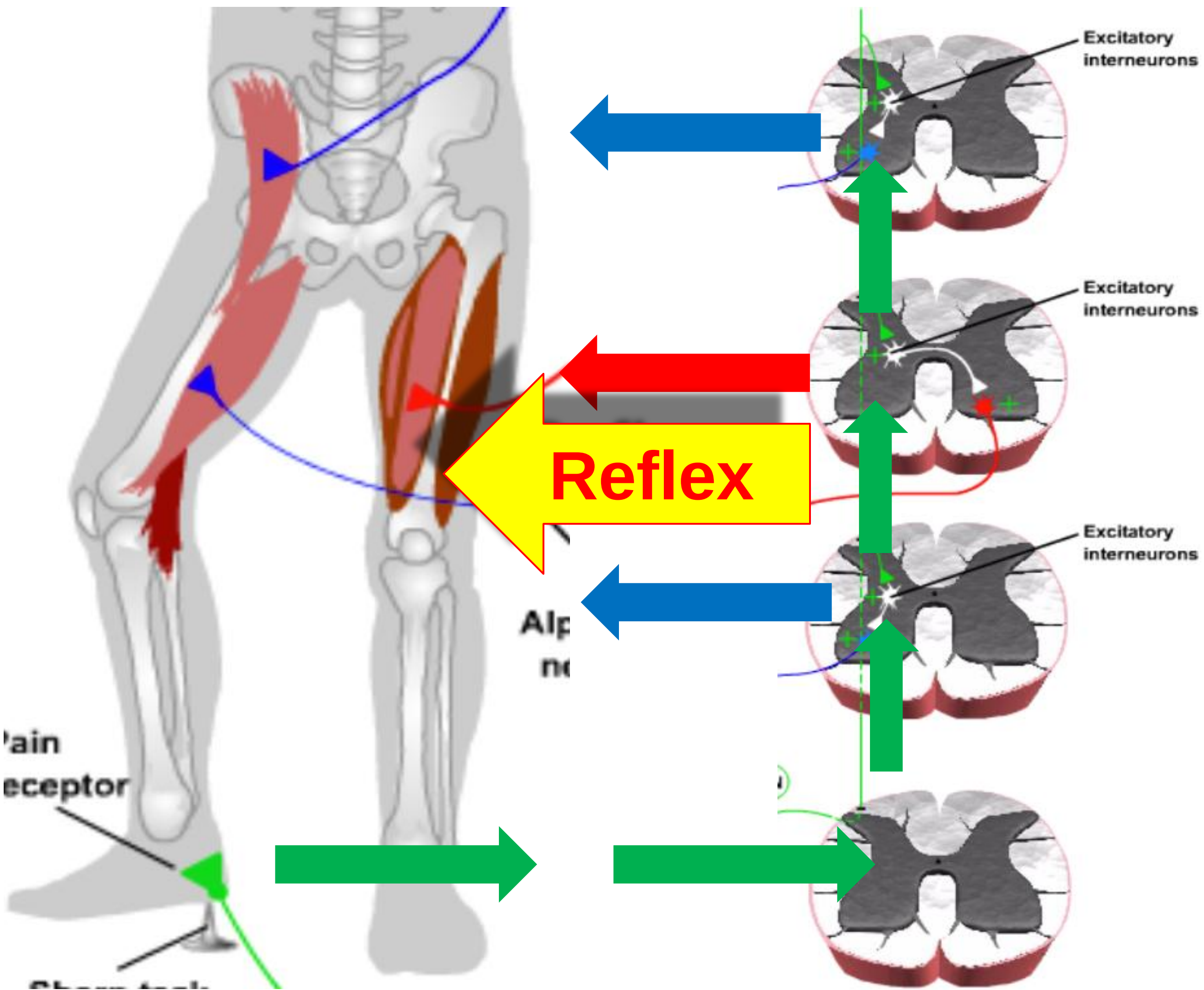


Unfortunately, we're not sure how this all works.



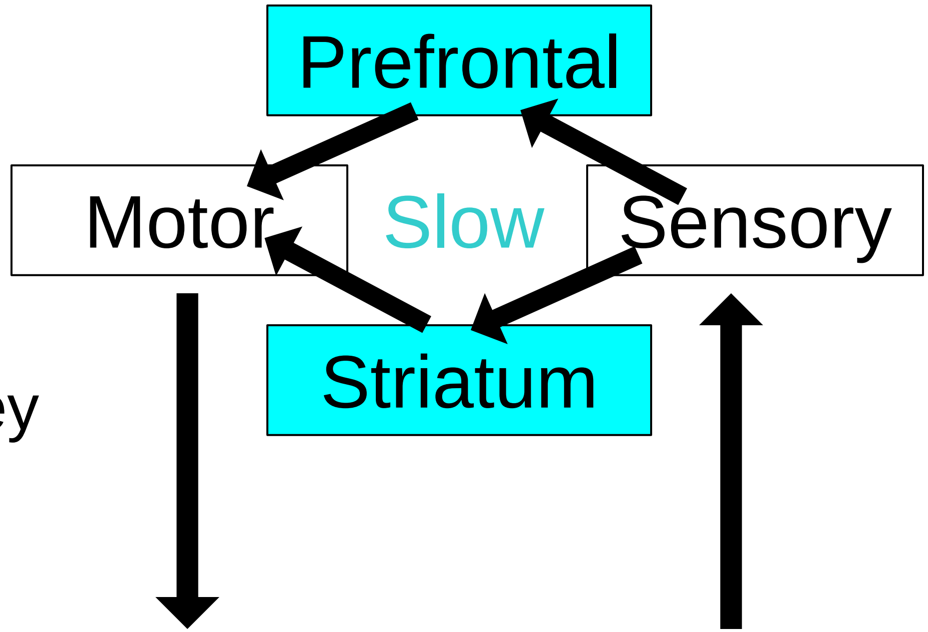
Flexible/
Adaptable/
Evolvable
Horizontal
Meme
Transfer
frontal
Sensory
Learning
Striatum
Reflex
Software
Hardware
Horizontal
App
Transfer
Digital
Analog
DNAp
Gene
Repl.
RNAp
xRNA
transc.
RN
ATP
A
Ribosome
transl.
AA
Horizontal
Gene
Transfer
Nucl.
AA
Precursors
Catabolism
ATP
Depends
crucially on
layered
architecture

Neuro motivation



Fast
Inflexible

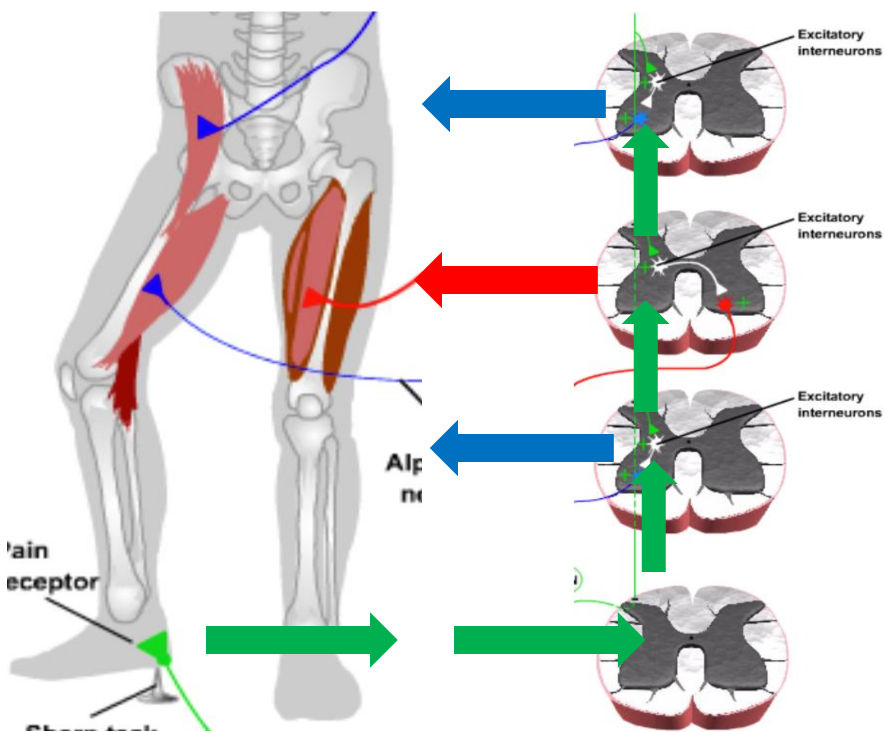
Slow
Flexible



Learning

Ashby & Crossley

- **Acquire**
- Translate/ integrate
- Automate

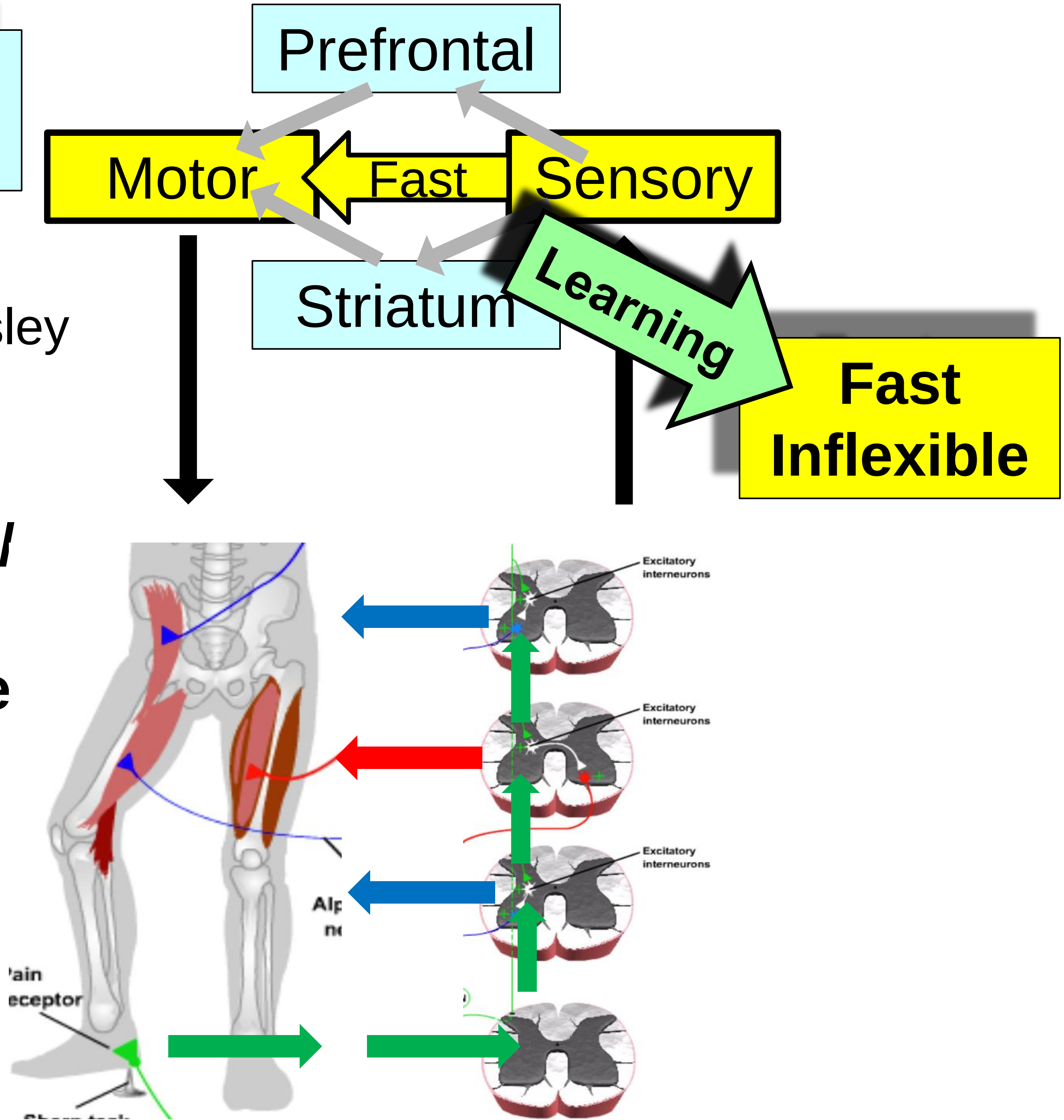


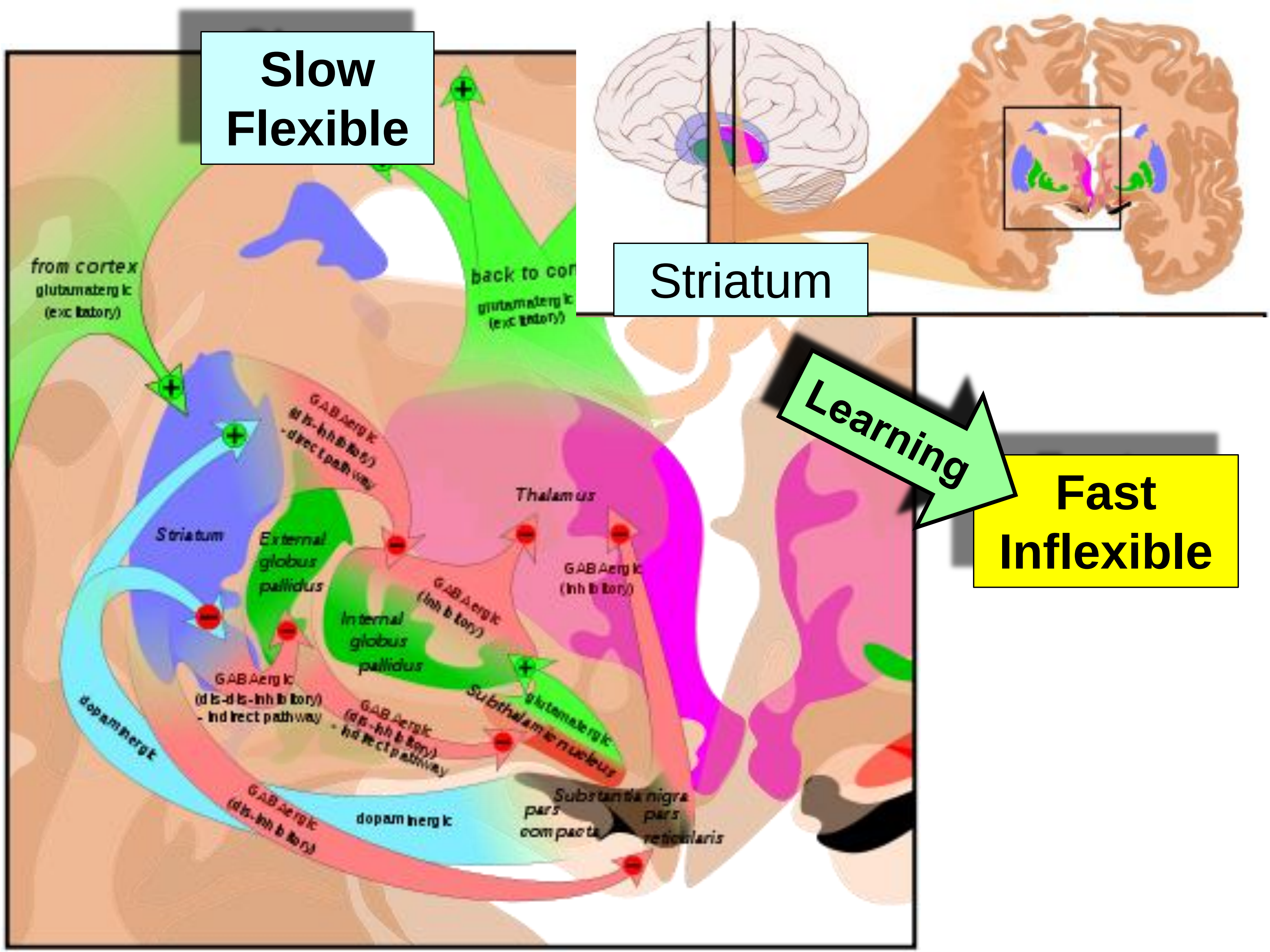
Thanks to
Bassett & Grafton

Slow
Flexible

Ashby & Crossley

- Acquire
- **Translate/ integrate**
- **Automate**

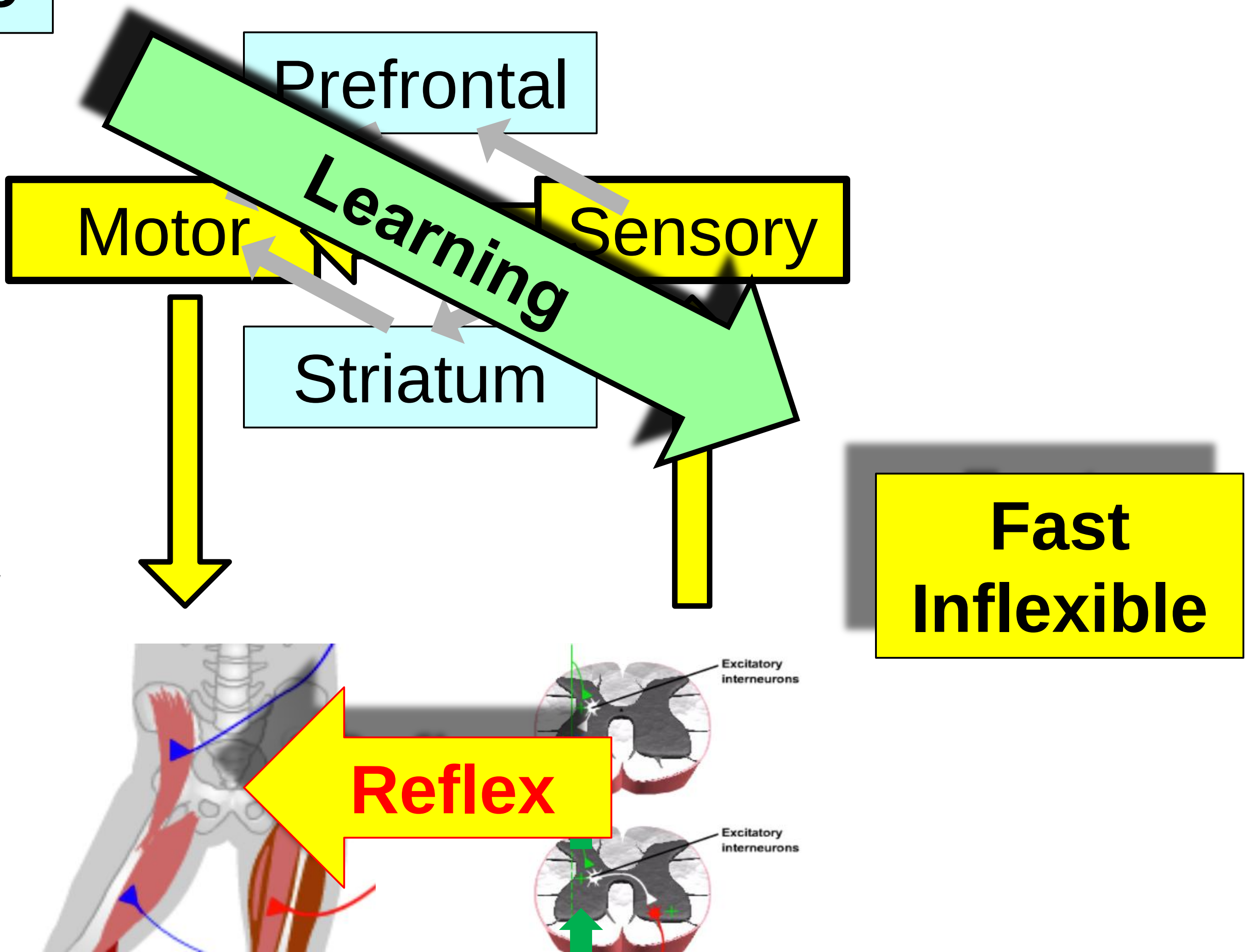




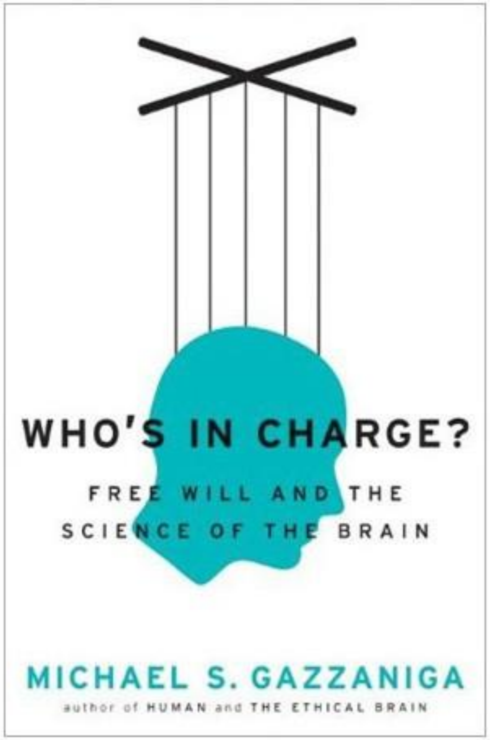
Slow
Flexible
Striatum
Learning
Fast
Inflexible
from cortex
glutamatergic
(excitatory)
back to cor
glutamatergic
(excitatory)
GABAergic
(dis-inhibitory)
- direct pathway
Thalamus
Striatum
External
globus
pallidus
GABAergic
(inhibitory)
GABAergic
(inhibitory)
Internal
globus
pallidus
GABAergic
(dis-dis-inhibitory)
- indirect pathway
GABAergic
(dis-inhibitory)
- indirect pathway
Subthalamic nucleus
glutamatergic
dopaminergic
GABAergic
(dis-inhibitory)
dopaminergic
Substantia nigra
pars
compacta
pars
reticularis

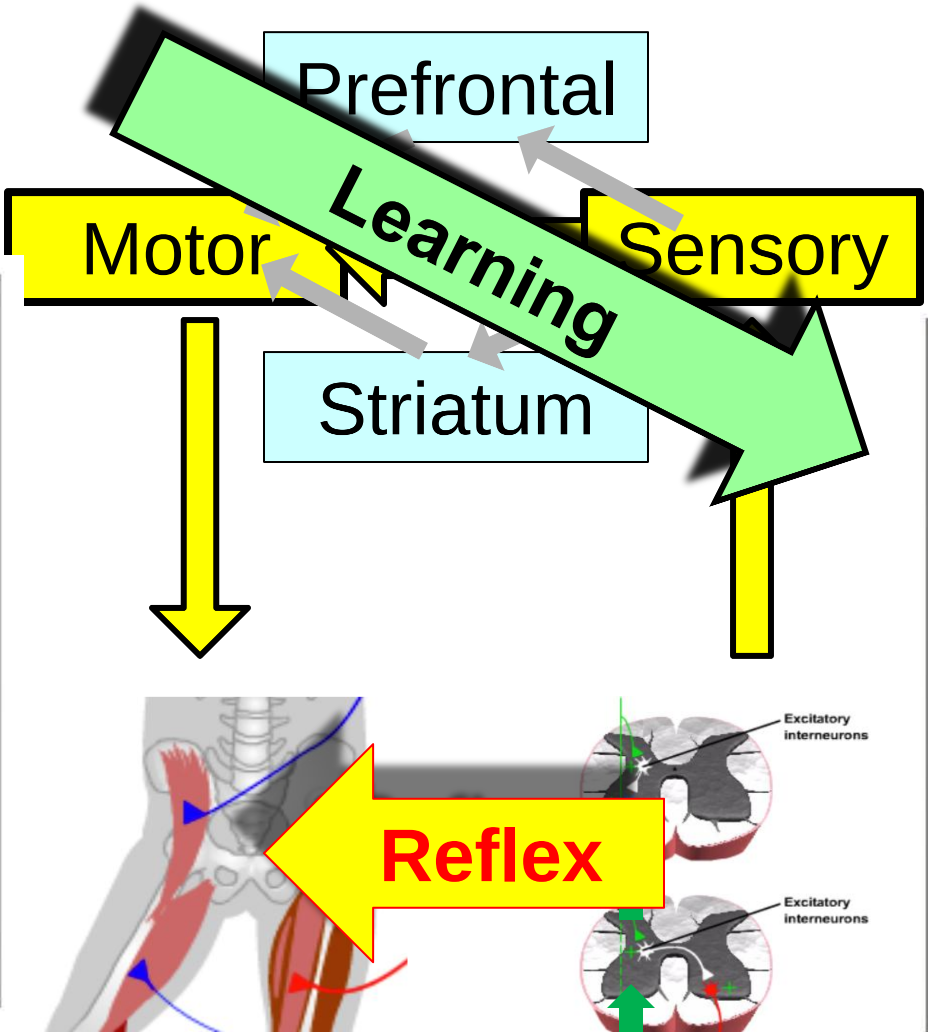
Build on Turing to show what is *necessary* to make this work.

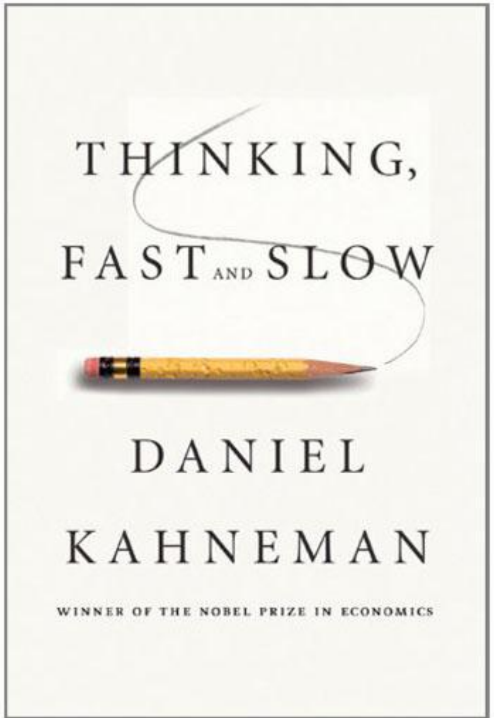
Slow
Flexible

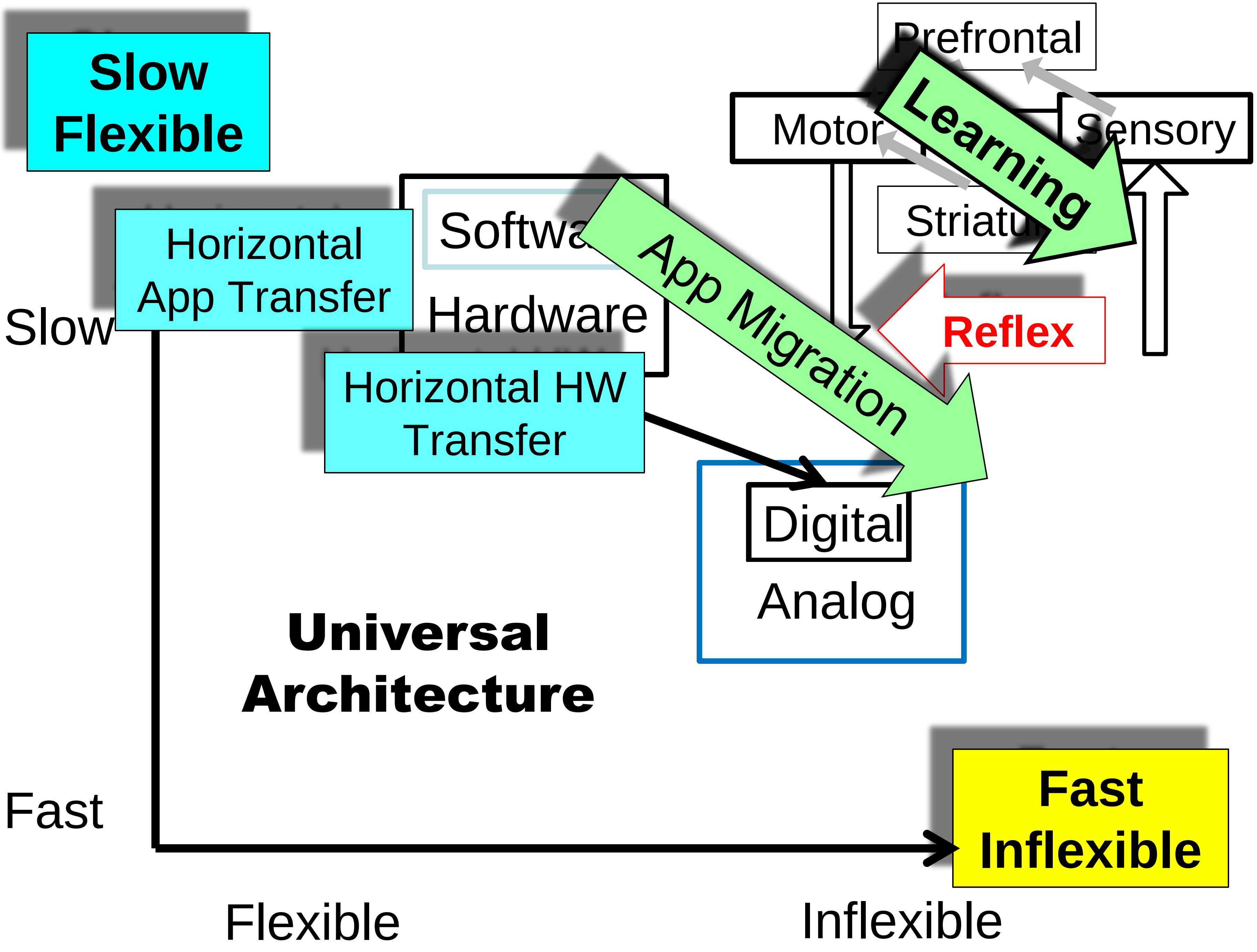


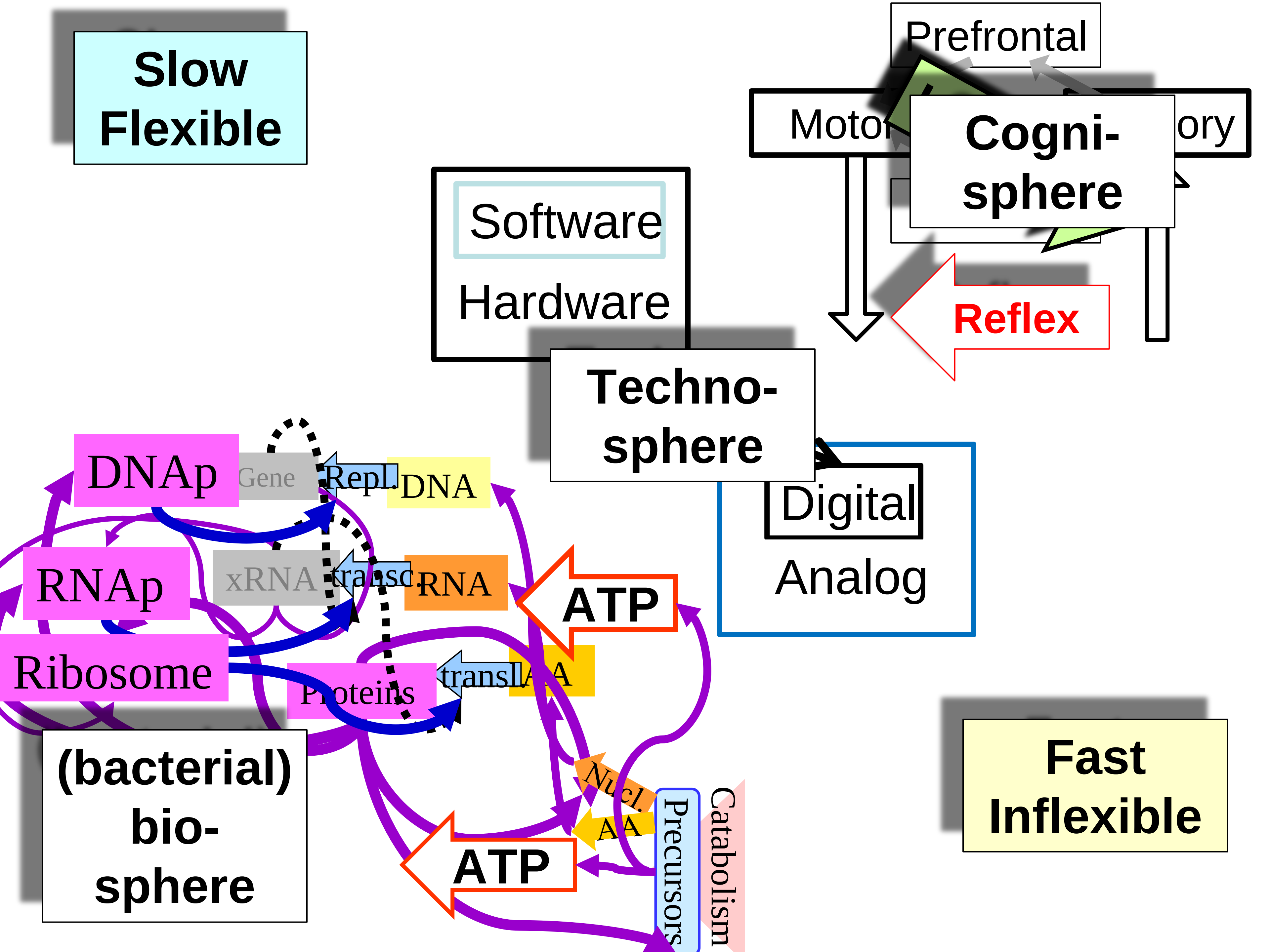
- **Acquire**
- **Translate/ integrate**
- **Automate**


WHO'S IN CHARGE?
FREE WILL AND THE
SCIENCE OF THE BRAIN
MICHAEL S. GAZZANIGA
author of HUMAN and THE ETHICAL BRAIN

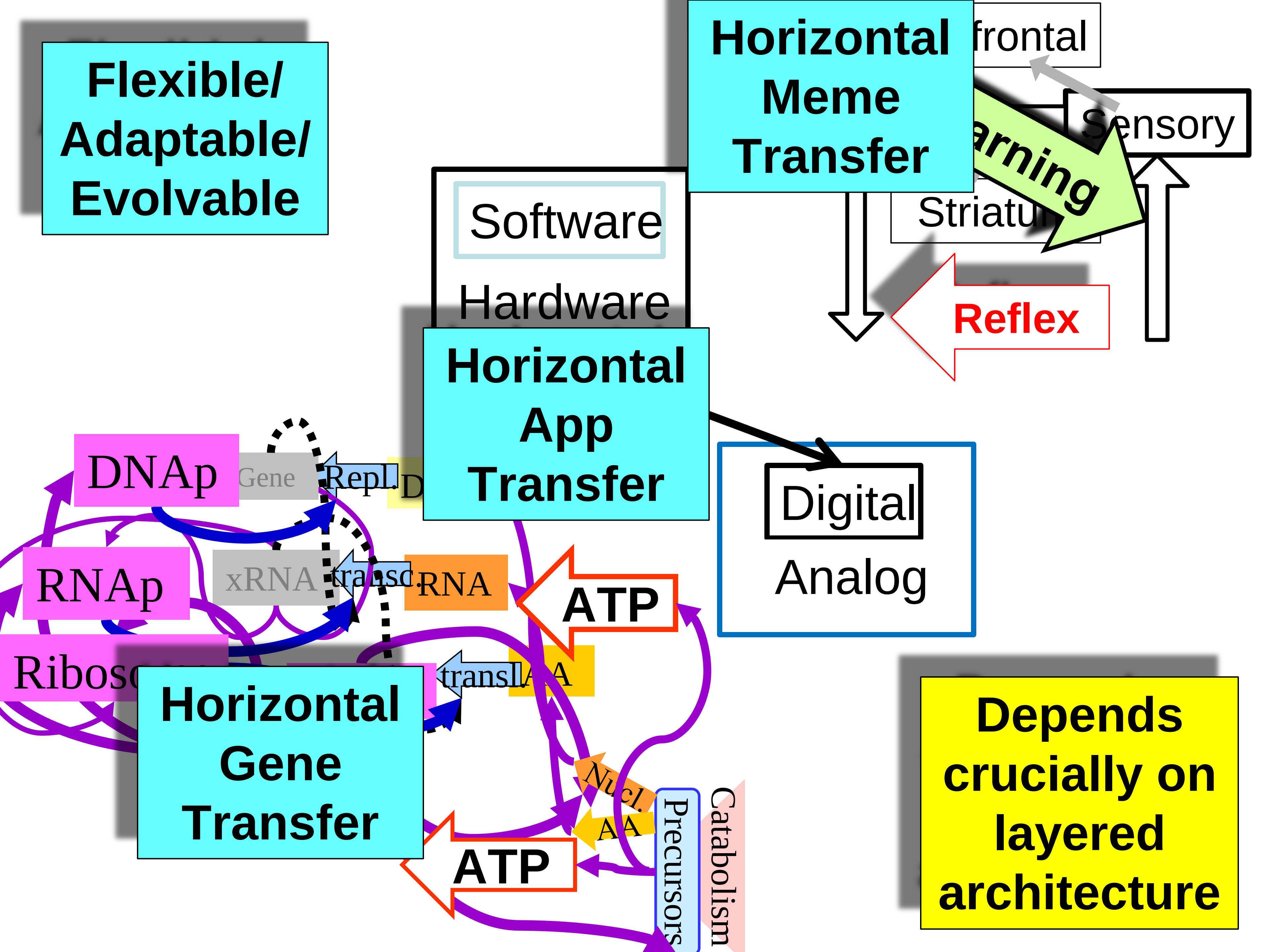

Prefrontal
Motor
Sensory
Learning
Striatum
Excitatory interneurons
Reflex
Excitatory interneurons


THINKING,
FAST AND SLOW
DANIEL
KAHNEMAN
WINNER OF THE NOBEL PRIZE IN ECONOMICS

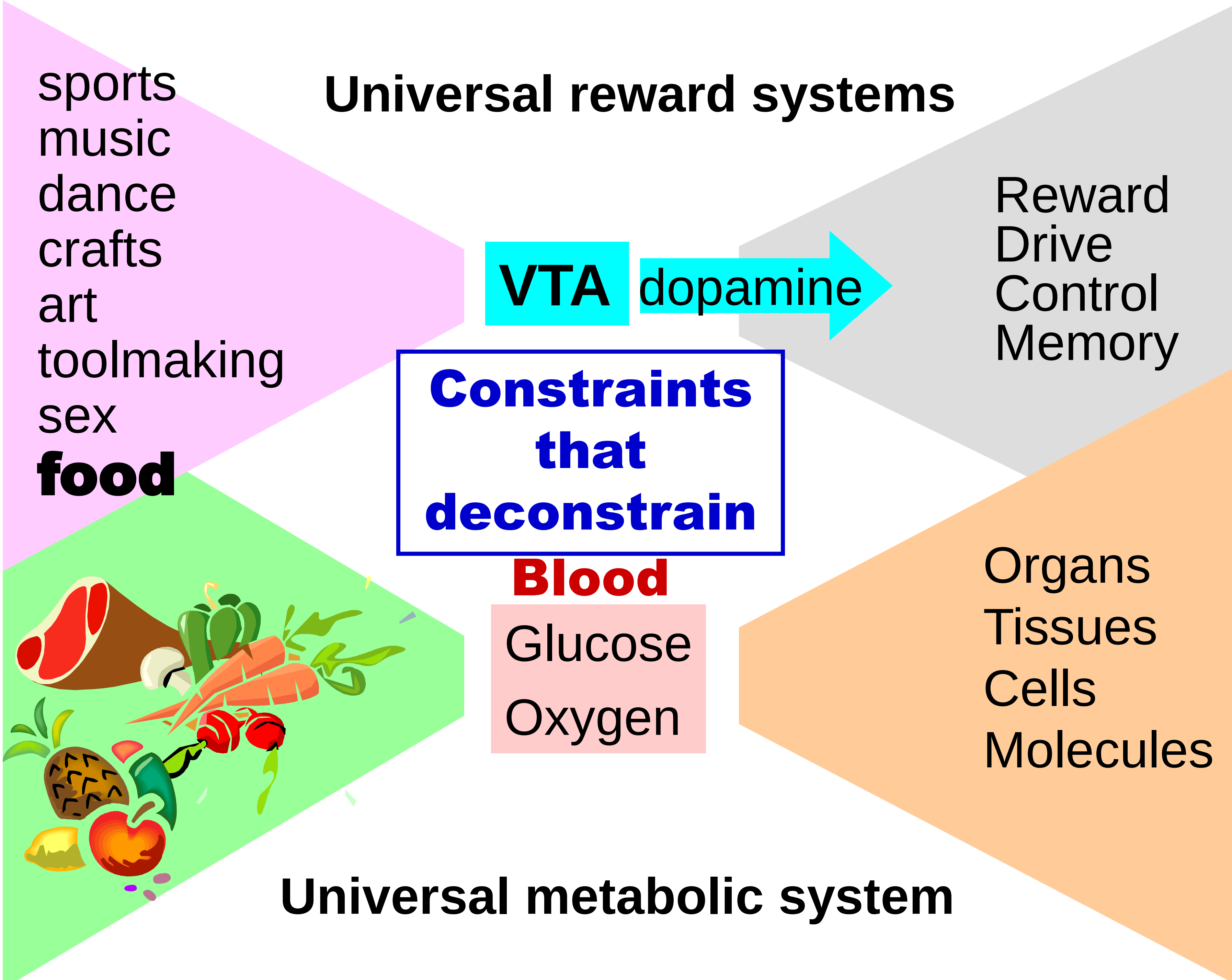

Slow
Flexible
Prefrontal
Motor
Sensory
Learning
Striatu
Softwa
Hardware
Horizontal
App Transfer
App Migration
Reflex
Slow
Horizontal HW
Transfer
Digital
Analog
Universal
Architecture
Fast
Inflexible
Fast
Flexible
Inflexible



Slow
Flexible
Prefrontal
Motor
ory
Cogni-
sphere
Software
Hardware
Reflex
Techno-
sphere
Digital
Analog
DNAp
Gene
Repl.
DNA
RNAp
xRNA
transc.
RNA
ATP
Ribosome
Proteins
transl.
AA
Nucl.
AA
Precursors
Catabolism
ATP
(bacterial)
bio-
sphere
Fast
Inflexible



Flexible/
Adaptable/
Evolvable
Horizontal
Meme
Transfer
frontal
Sensory
arning
Striatu
Software
Hardware
Reflex
Horizontal
App
Transfer
Digital
Analog
DNAp
Gene
Repl.
RNAp
xRNA
transc.
RNA
ATP
Ribos
transl.
AA
Horizontal
Gene
Transfer
Nucl.
AA
ATP
Precursors
Catabolism
Depends
crucially on
layered
architecture


Universal reward systems
sports
music
dance
crafts
art
toolmaking
sex
food
VTA
dopamine
Reward
Drive
Control
Memory
Constraints that deconstrain
Blood
Glucose
Oxygen
Organs
Tissues
Cells
Molecules
Universal metabolic system

Modularity 2.0

Constraints

dopamine

Blood

Glucose

Oxygen

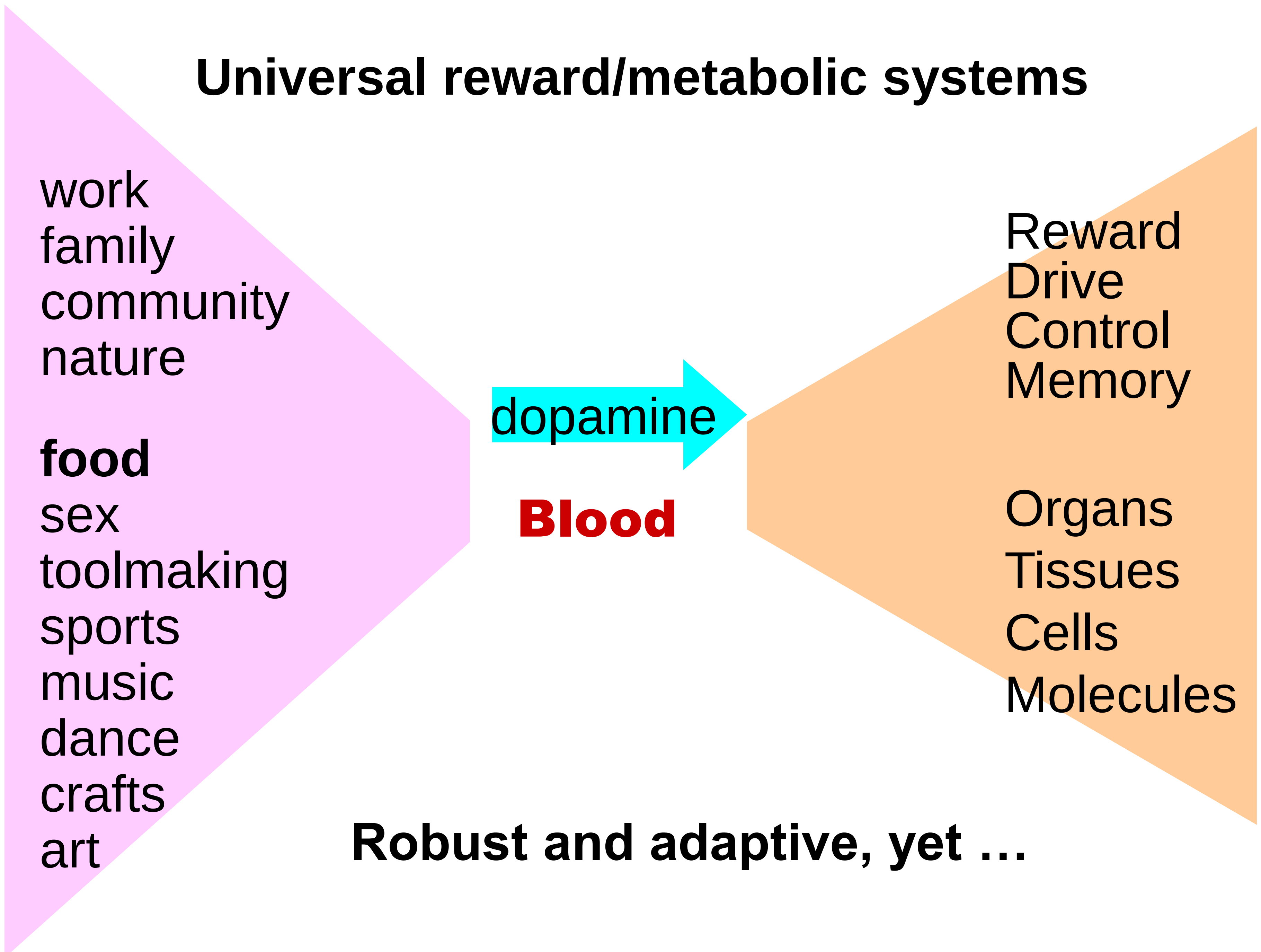
Modularity 2.0

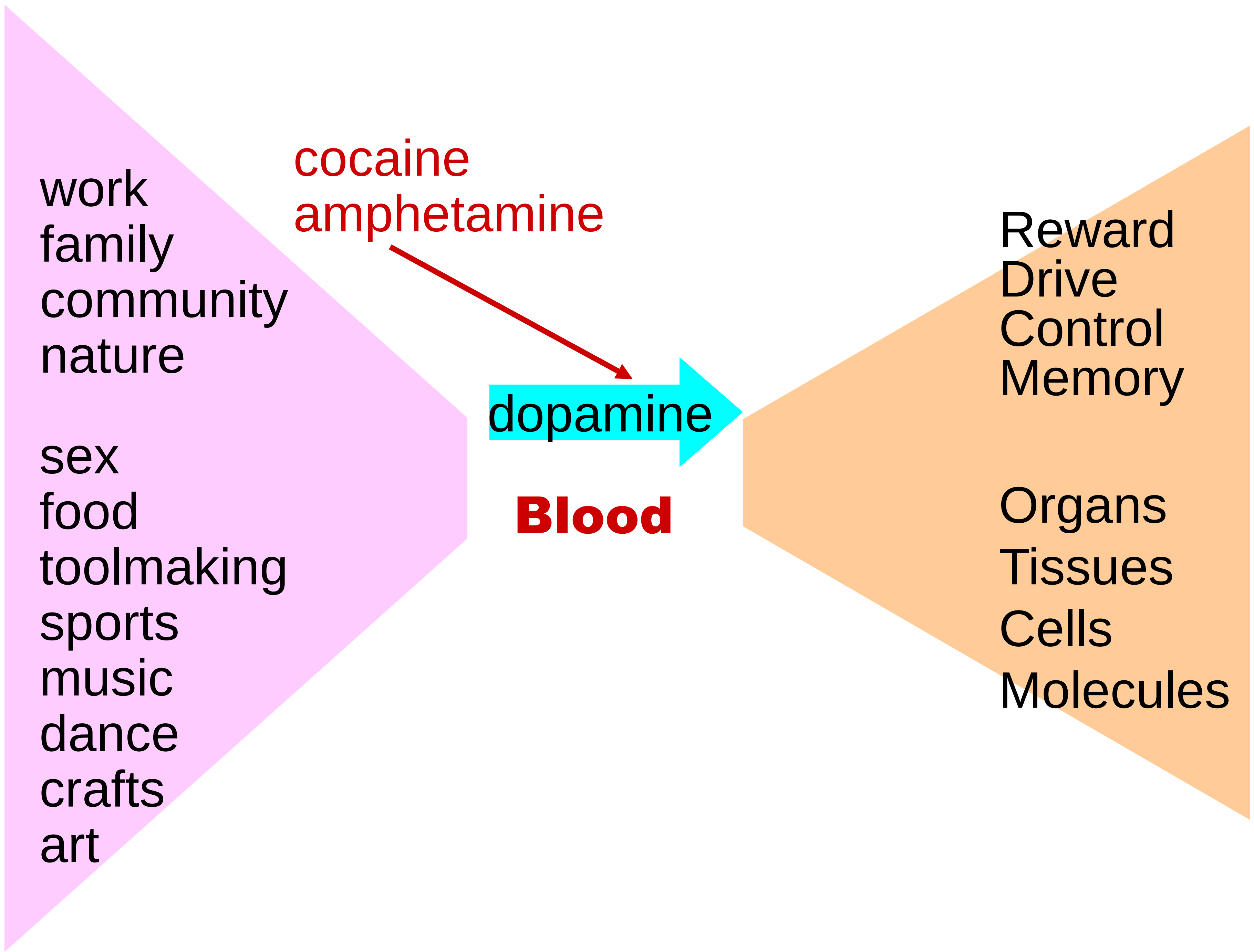
sports
music
dance
crafts
art
toolmaking
sex
food

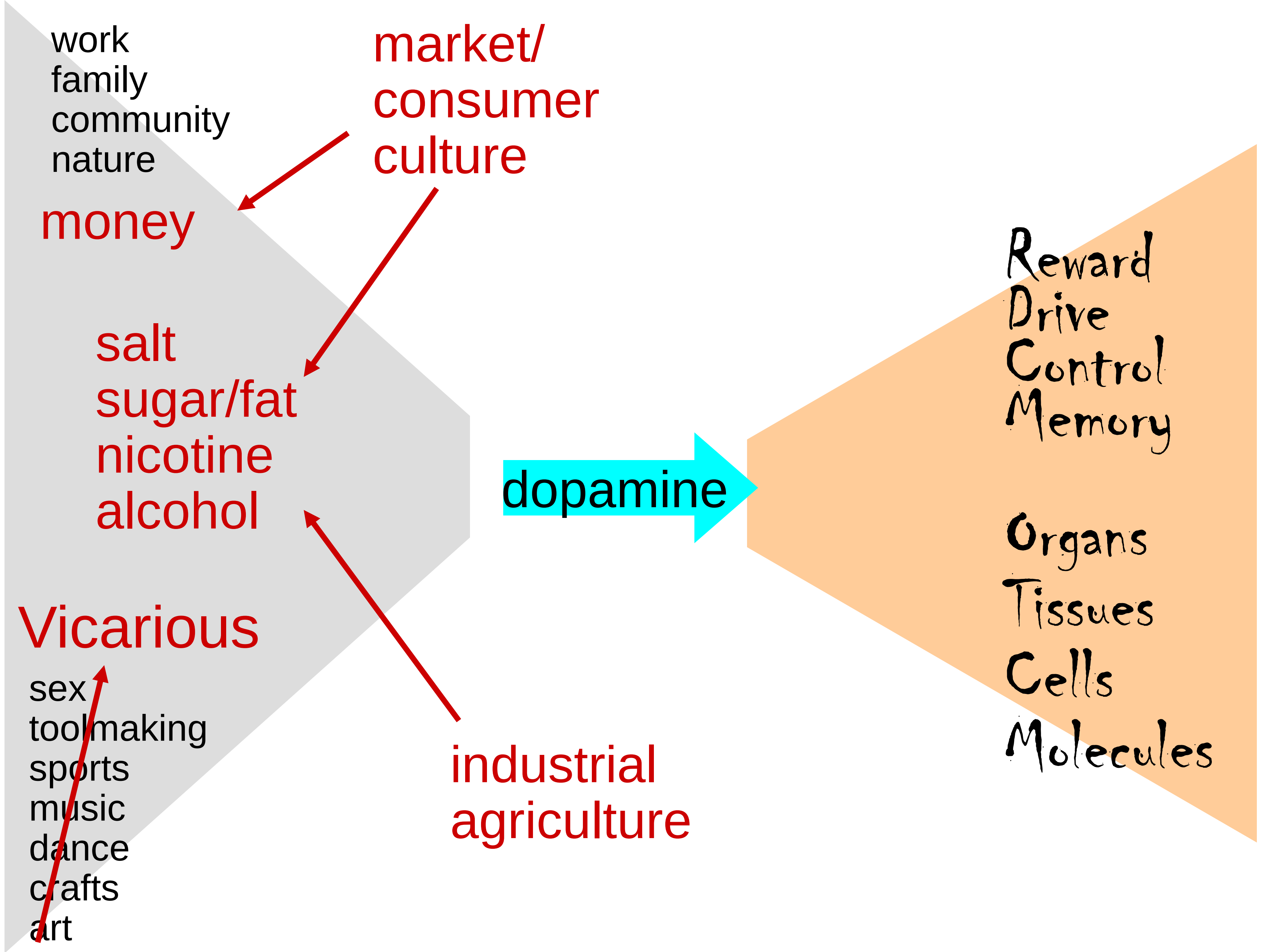
that deconstrain

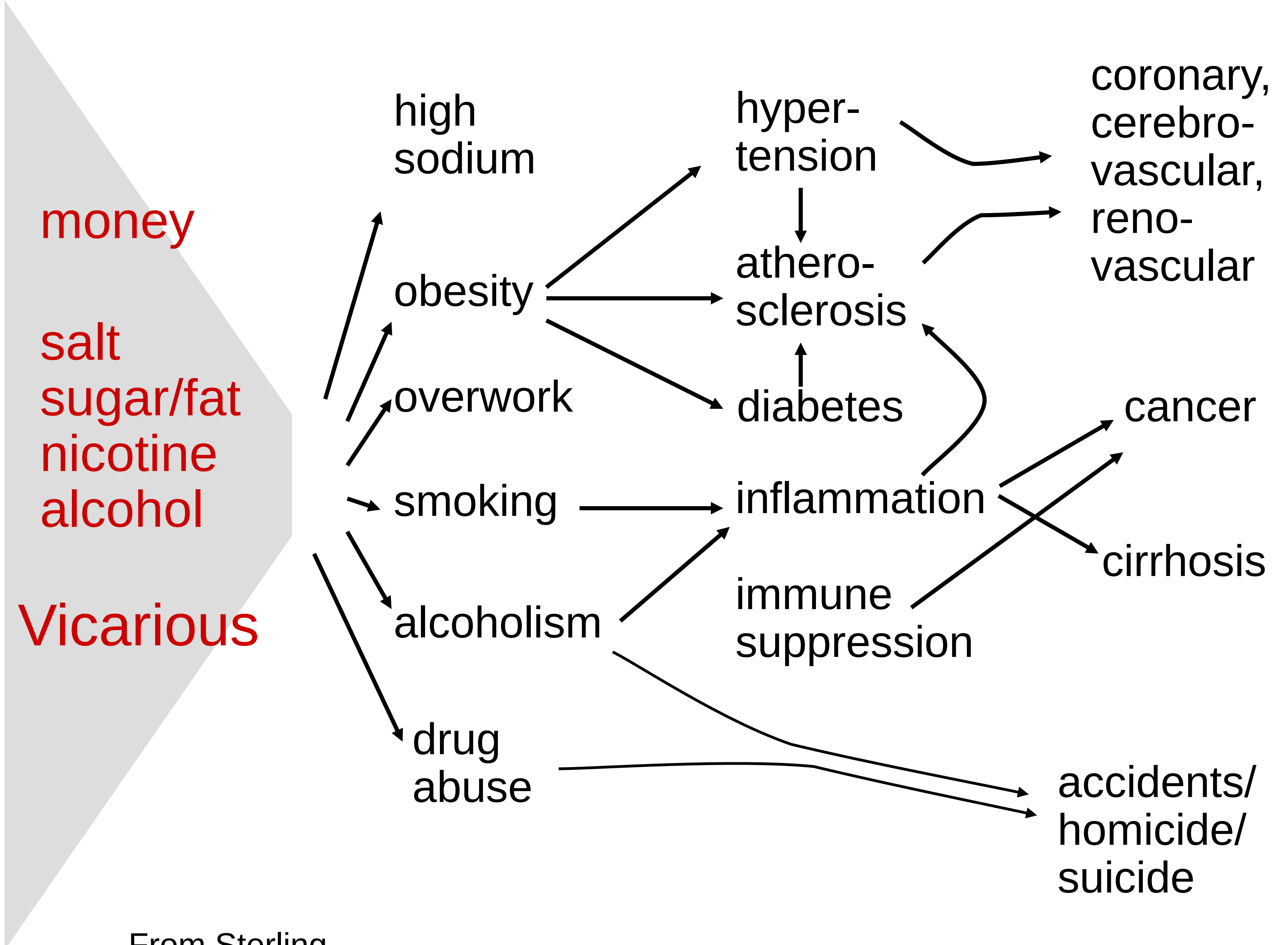
Reward
Drive
Control
Memory

Organs
Tissues
Cells
Molecules

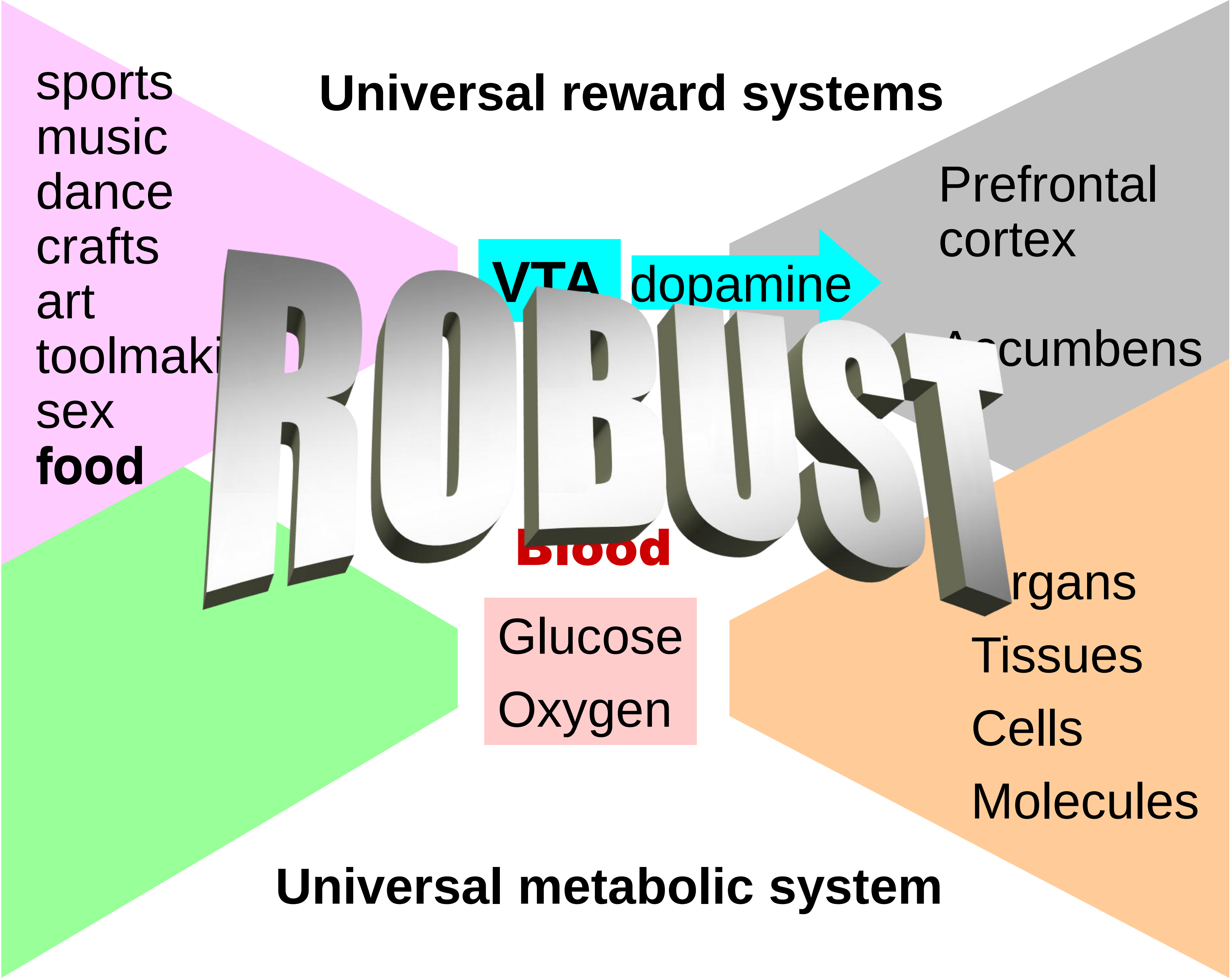

Universal reward/metabolic systems
work
family
community
nature
food
sex
toolmaking
sports
music
dance
crafts
art
dopamine
Blood
Reward
Drive
Control
Memory
Organs
Tissues
Cells
Molecules
Robust and adaptive, yet …


work
family
community
nature
sex
food
toolmaking
sports
music
dance
crafts
art
cocaine
amphetamine
dopamine
Blood
Reward
Drive
Control
Memory
Organs
Tissues
Cells
Molecules

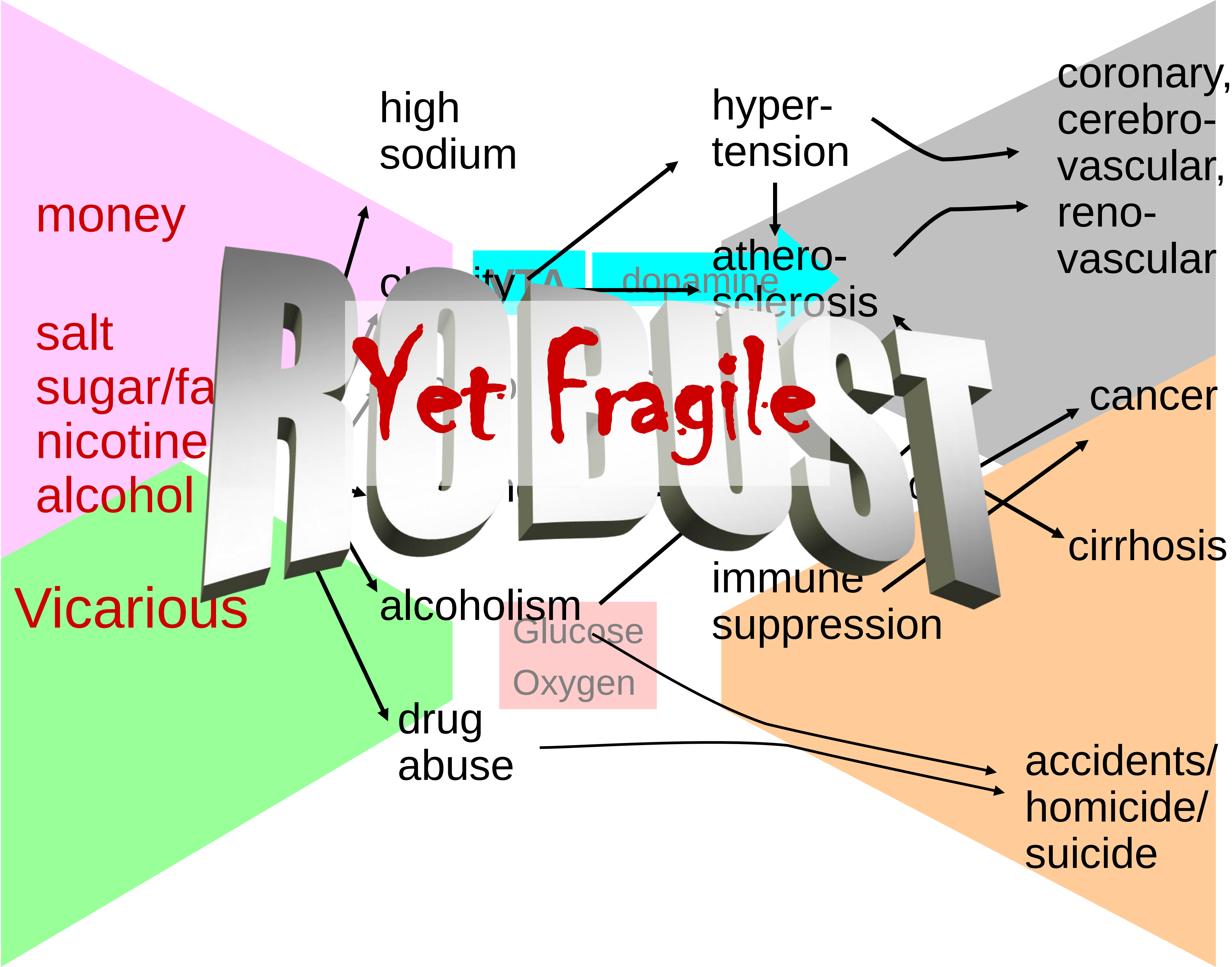

work
family
community
nature
market/
consumer
culture
money
salt
sugar/fat
nicotine
alcohol
dopamine
Reward
Drive
Control
Memory
Organs
Tissues
Cells
Molecules
Vicarious
sex
toolmaking
sports
music
dance
crafts
art
industrial
agriculture



From Sterling

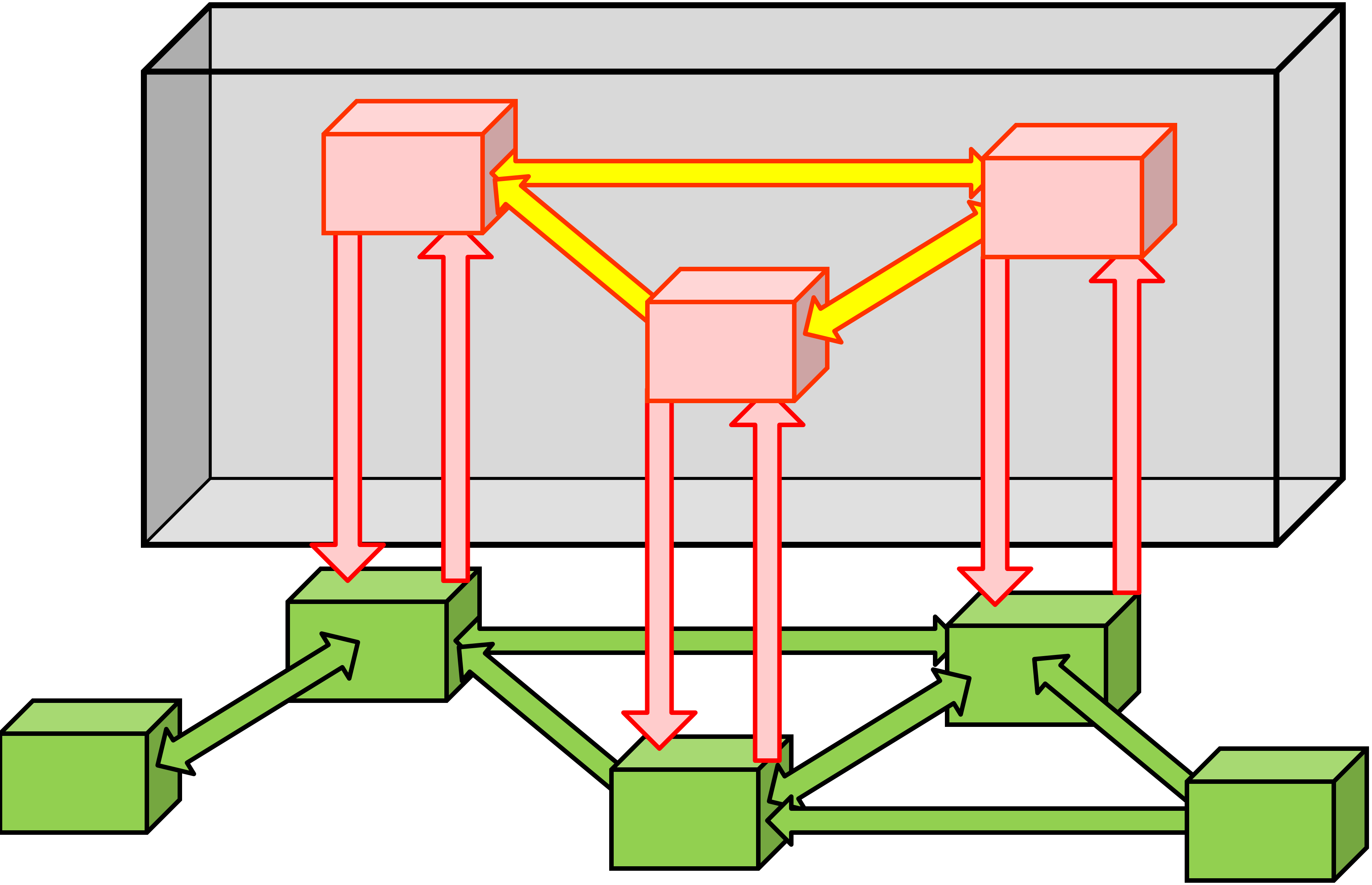


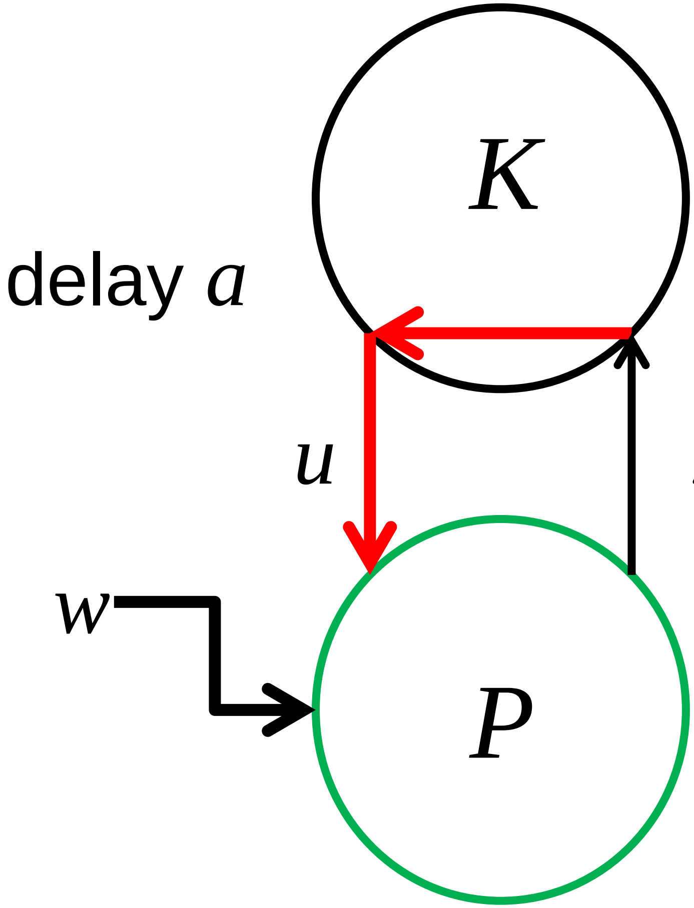
Universal reward systems
sports
music
dance
crafts
art
toolmaki
sex
food
VTA
dopamine
Prefrontal
cortex
ccumbens
ROBUST
Blood
Glucose
Oxygen
rgans
Tissues
Cells
Molecules
Universal metabolic system



high
sodium
hyper-
tension
coronary,
cerebro-
vascular,
reno-
vascular
money
athero-
sclerosis
VTA
dopamine
salt
sugar/fa
nicotine
alcohol
ROBUST
Yet Fragile
cancer
cirrhosis
Vicarious
immune
suppression
alcoholism
Glucose
Oxygen
drug
abuse
accidents/
homicide/
suicide

What about: CNS and Cyber-physical: decentralized control with internal delays?





No delay or
no uncertainty

$$u_{t-a} = -\left(p x_t + w_t \right)$$

$$\Rightarrow \|x\| \approx 0 \quad \|u\| \approx \|w\|$$

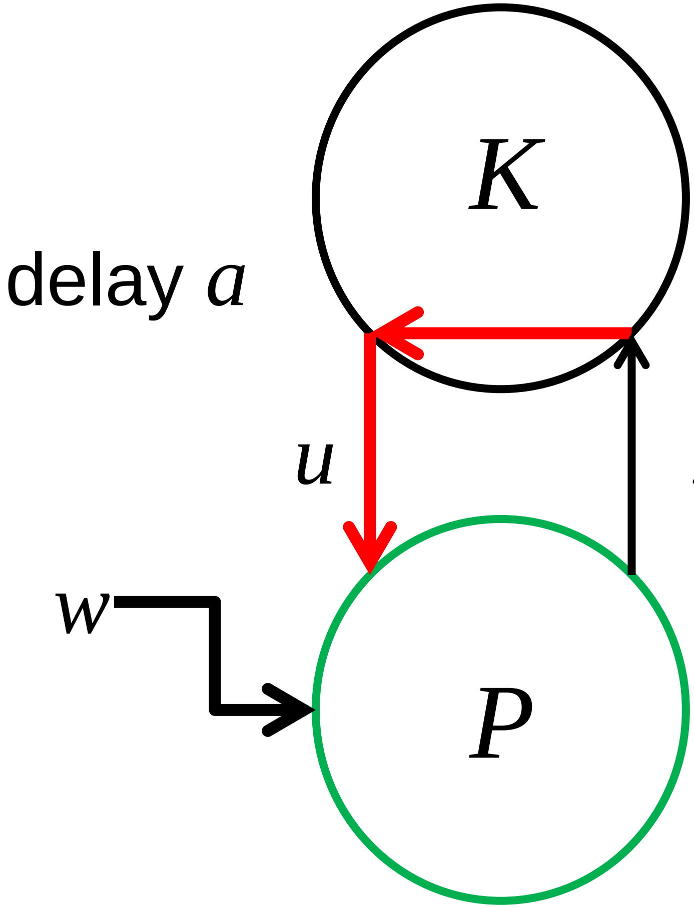
With delay ***and***
uncertainty

$$x_{t+1} = p x_t + w_t + u_{t-a}$$

$$p > 1$$

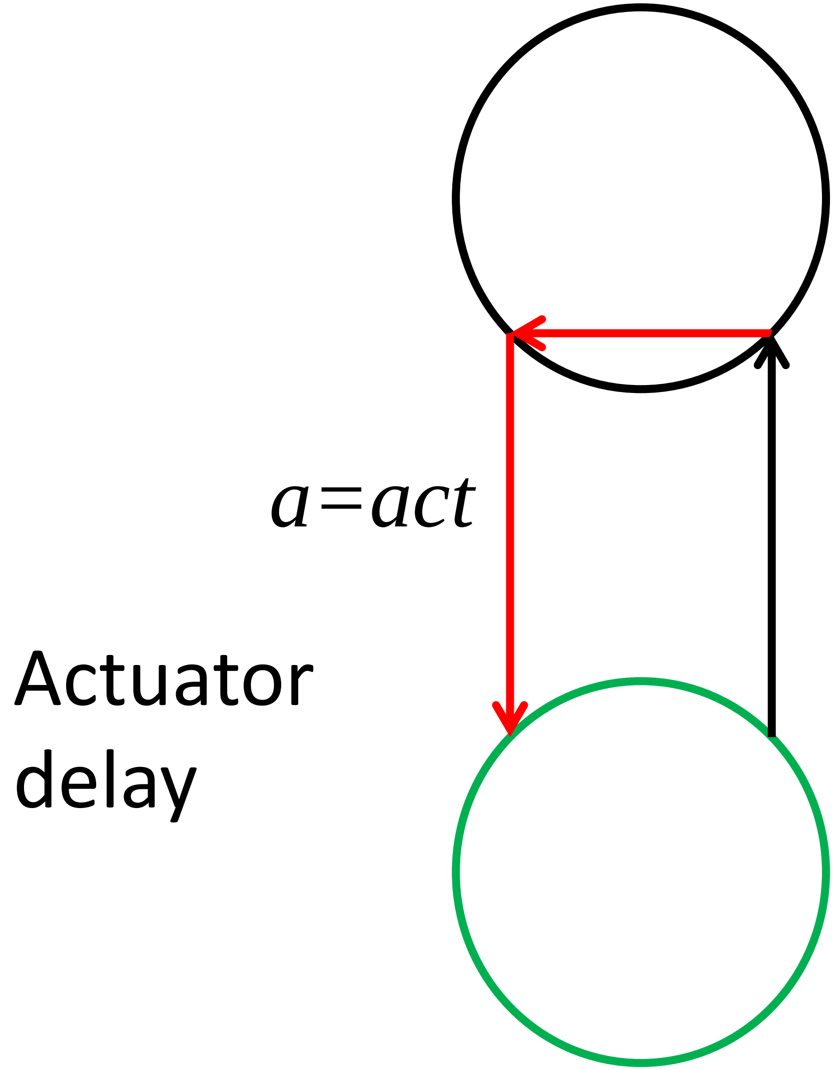
$$\Rightarrow \|x\| \approx \|u\| \approx p^a \|w\|$$

Focus on delays

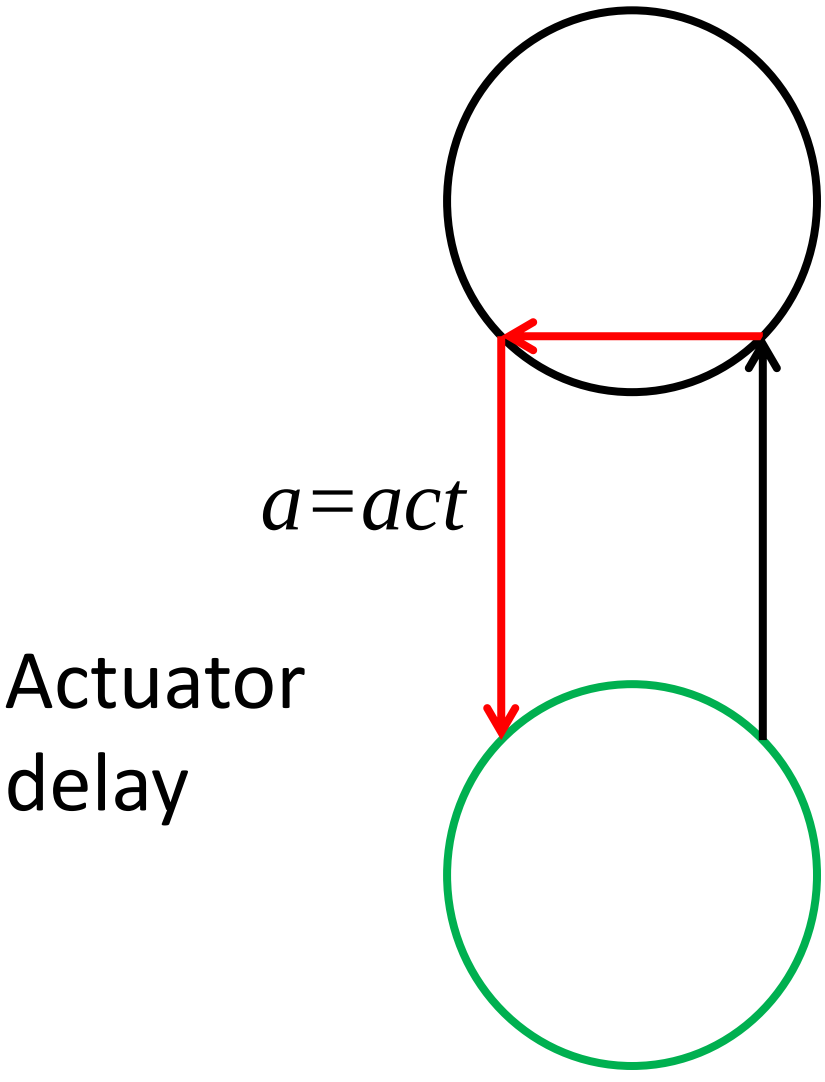


$$x_{t+1} = px_t + w_t + u_{t-a}$$

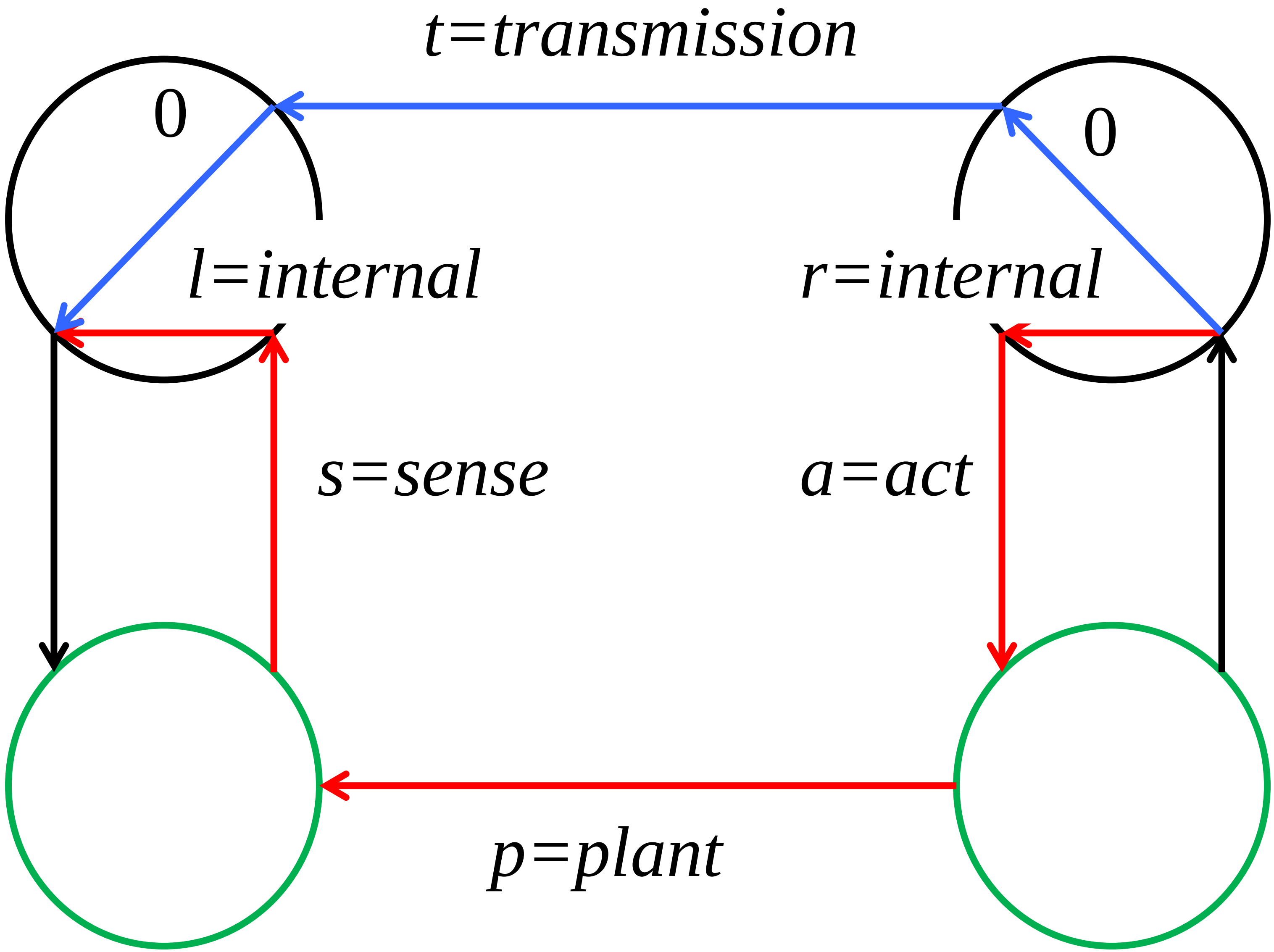
$$p > 1$$

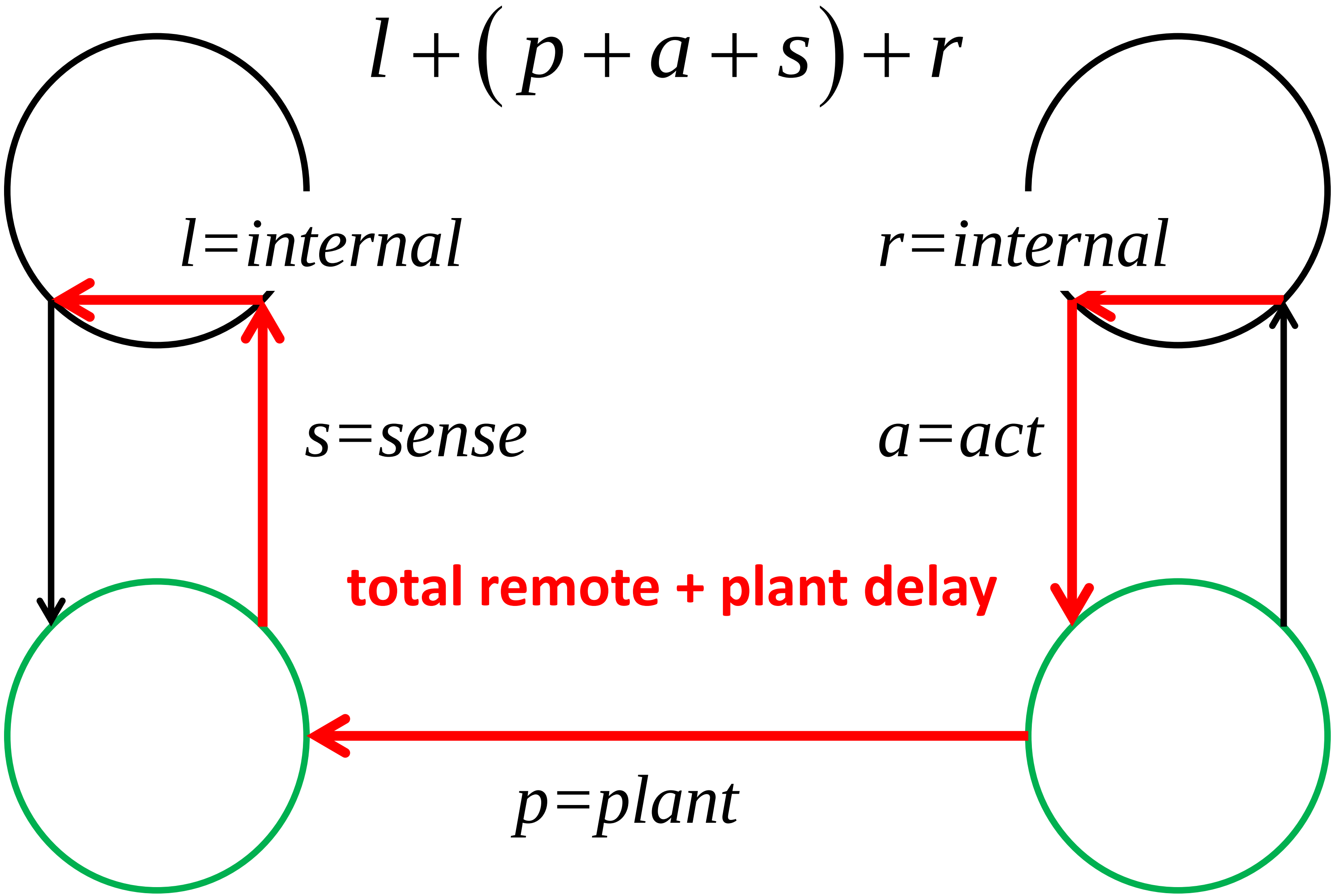


Focus on delays

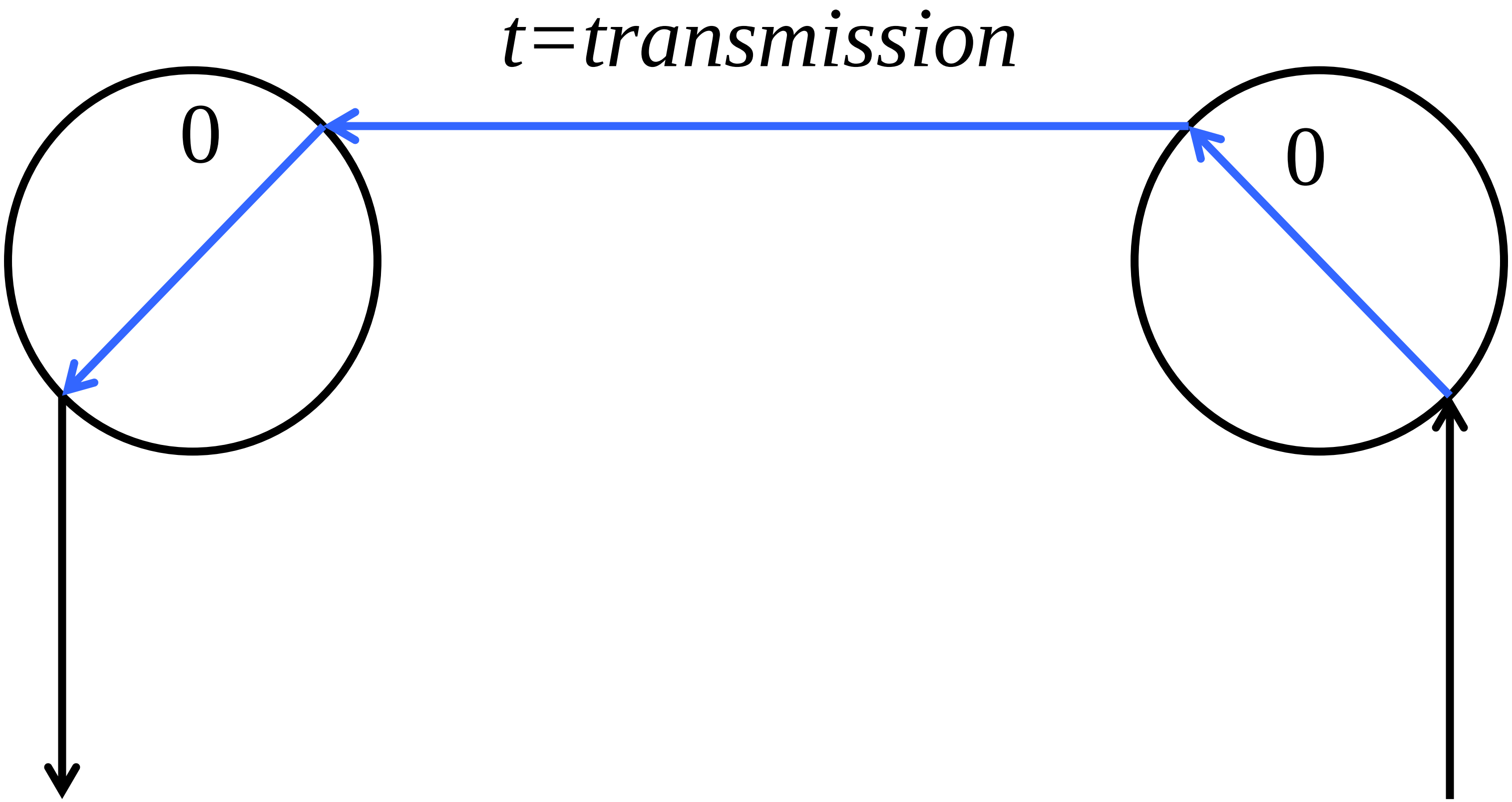


Decentralized control



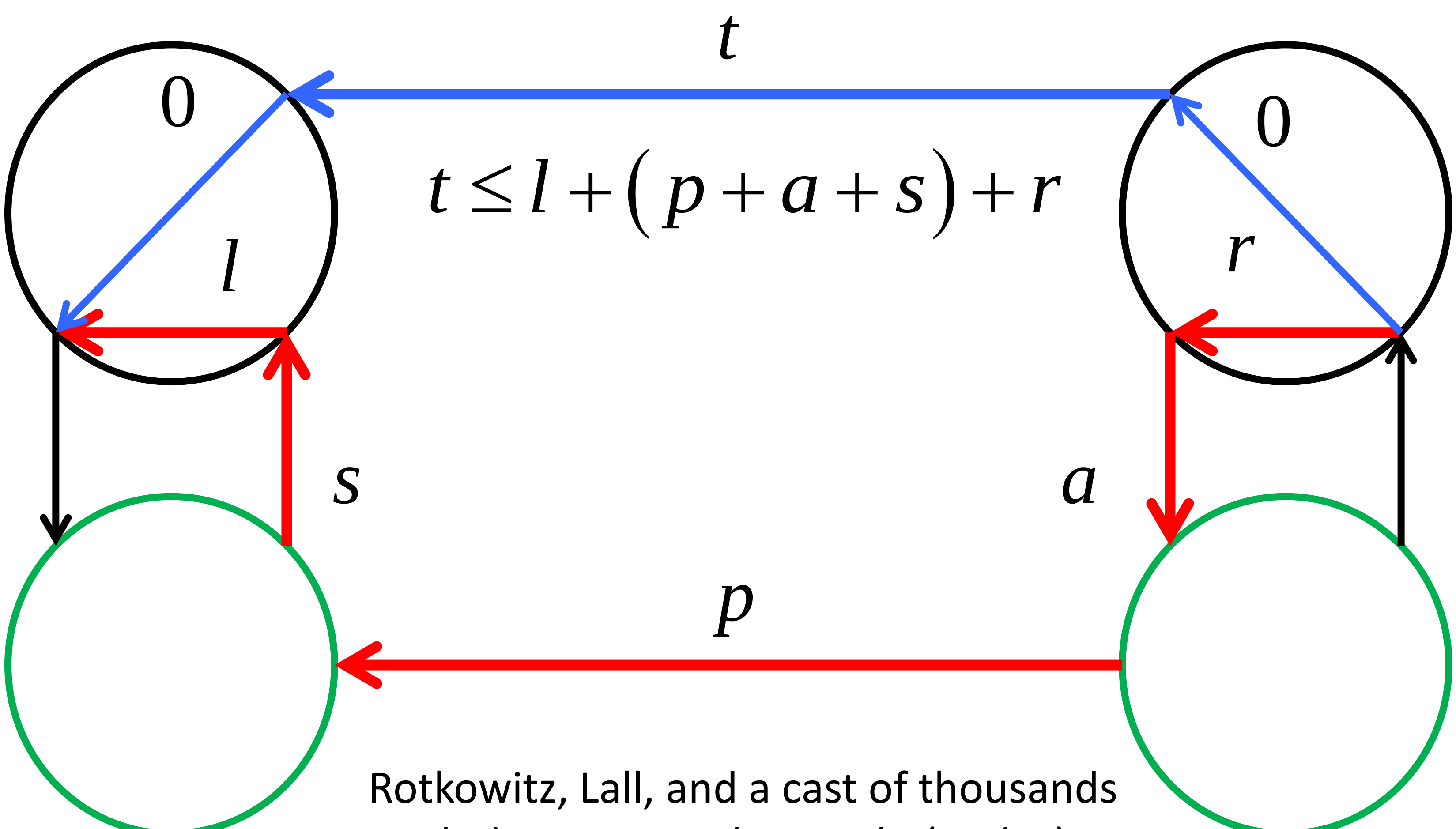

$l+(p+a+s)+r$
l=internal
r=internal
s=sense
a=act
total remote + plant delay
p=plant

Communications delay



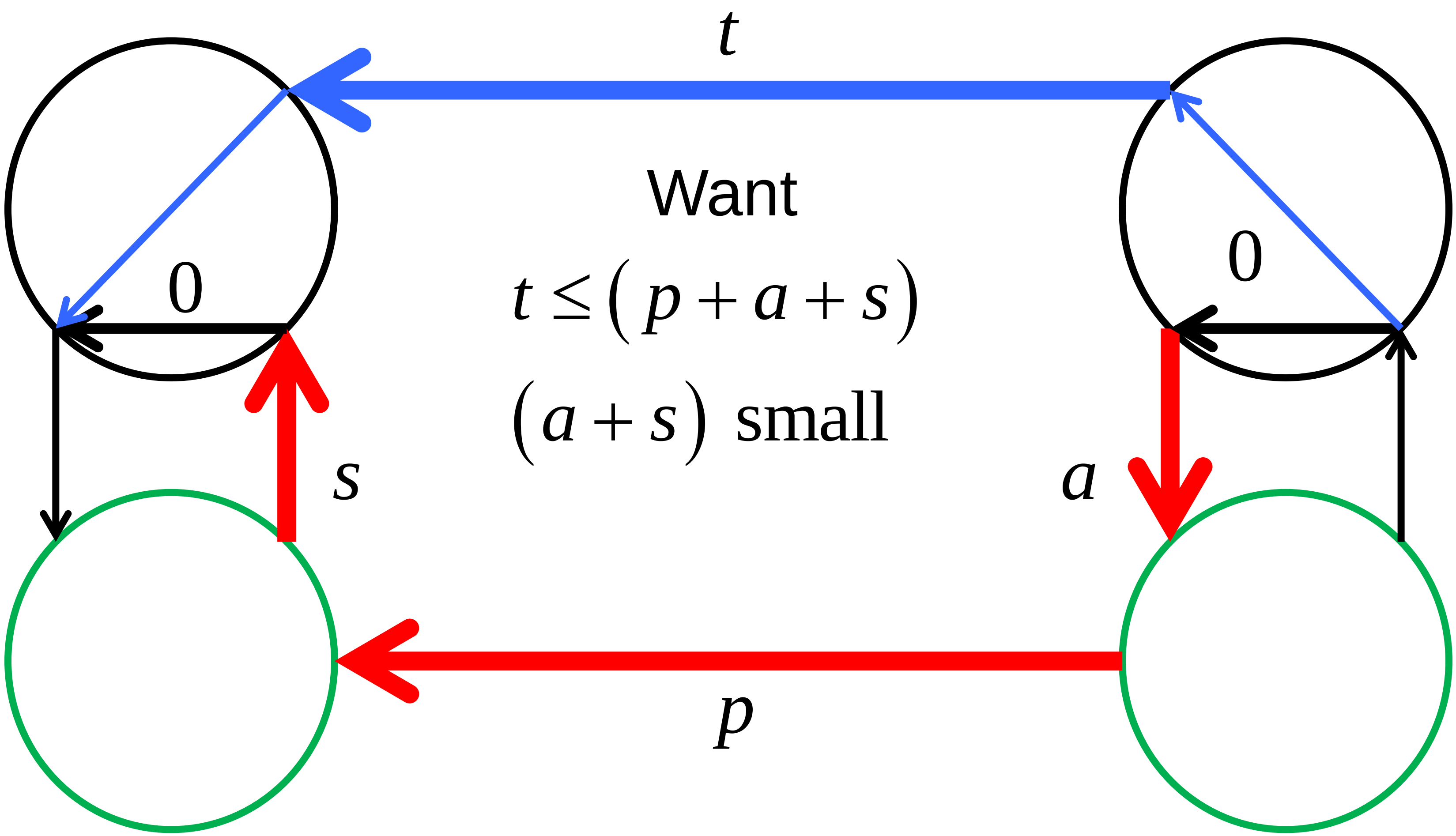
$$t \le l + (p + a + s) + r$$

Then decentralized control design can be made ***convex***



Rotkowitz, Lall, and a cast of thousands
including Lamperski, Parrilo (Friday)…

A primary driver of human brain evolution?

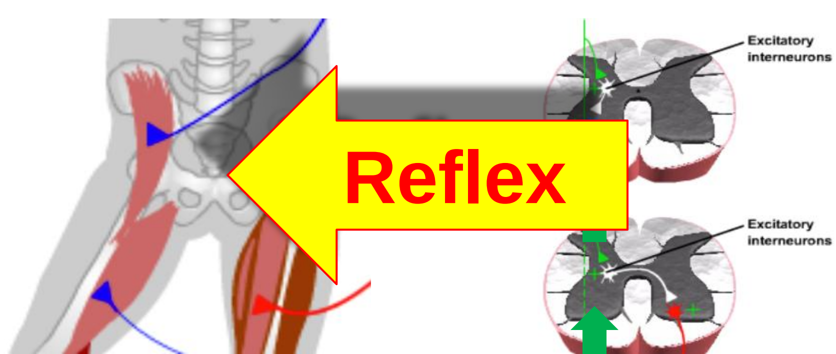


Wolpert, Grafton, etc

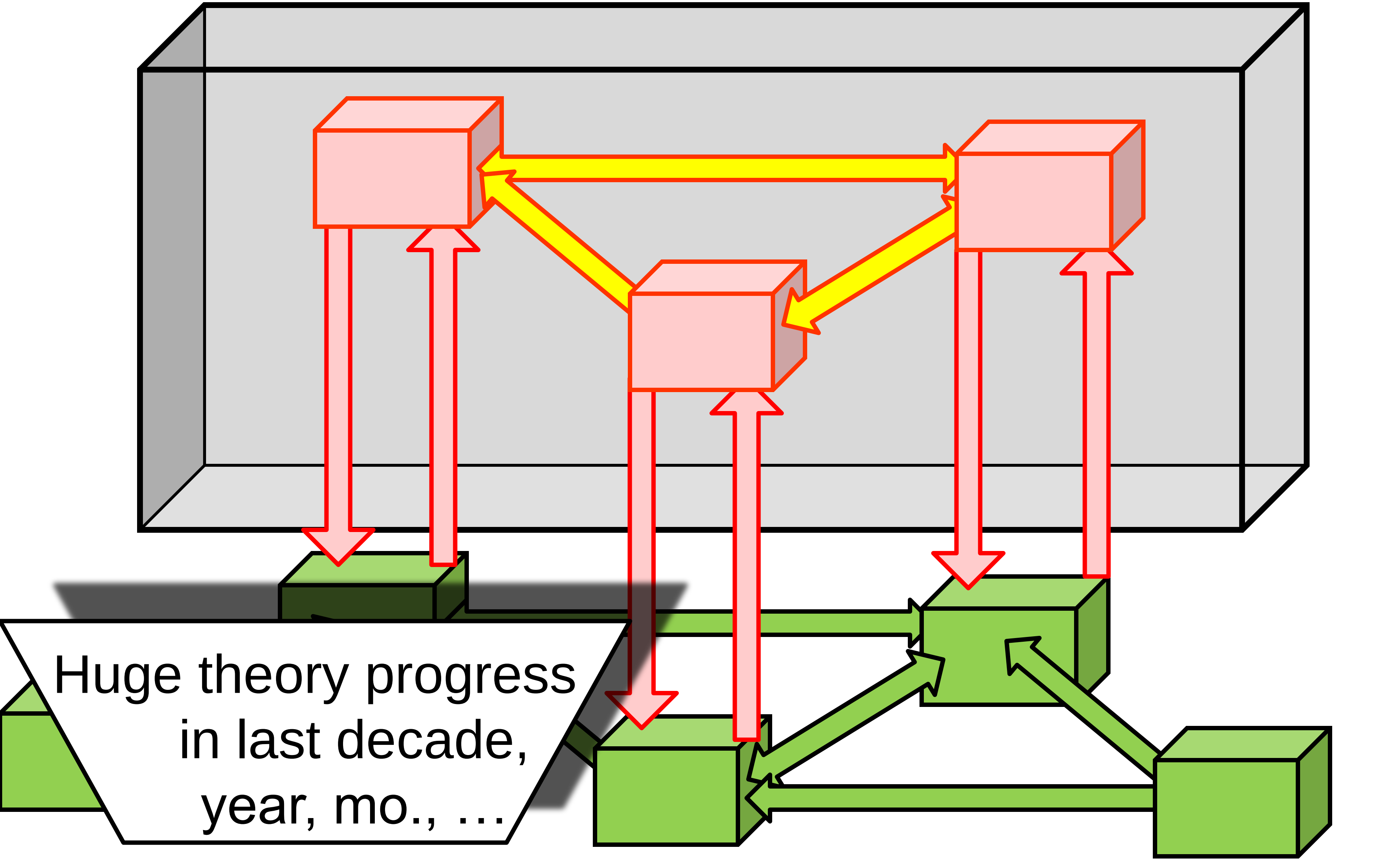
robust

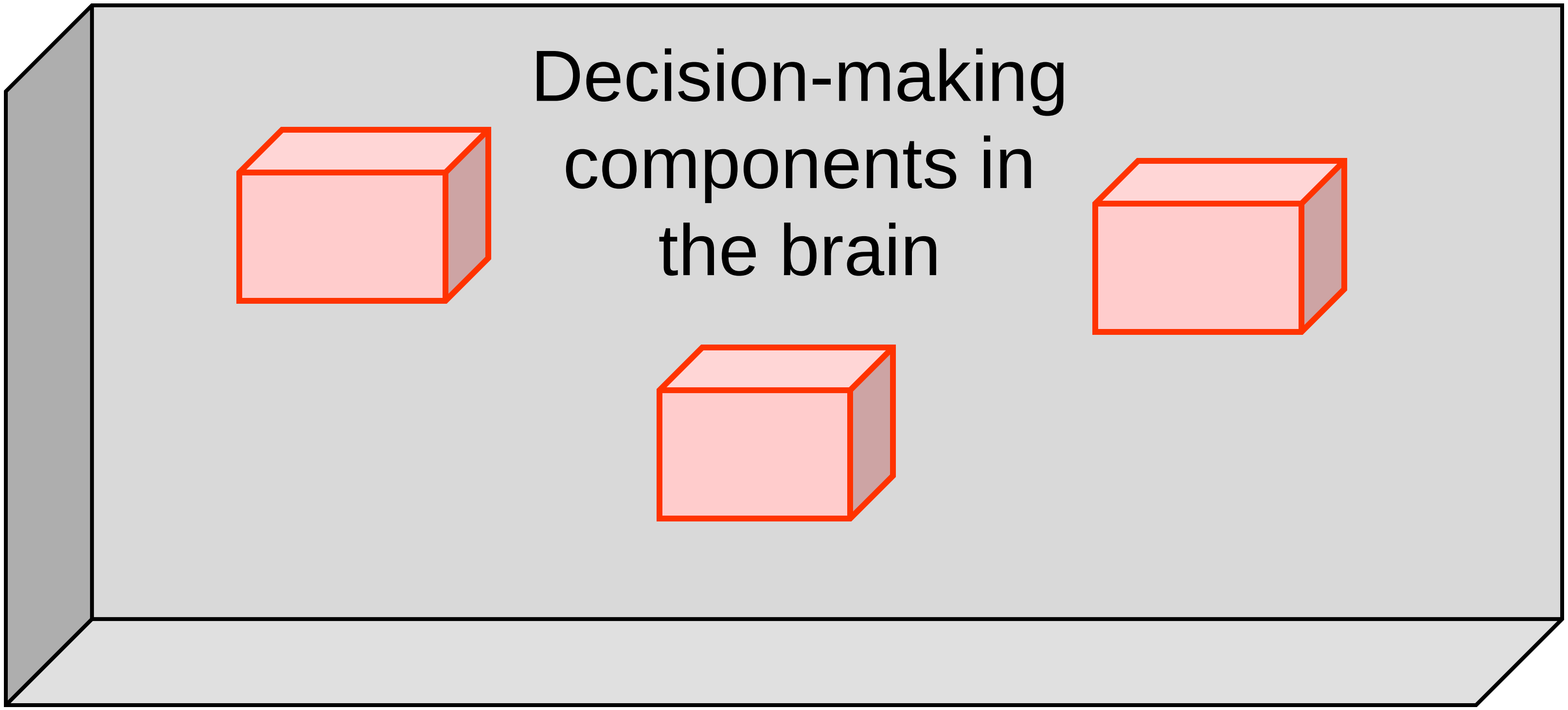
Brain as ~~optimal~~ controller

- Acquire
- Translate/ integrate
- **Automate**

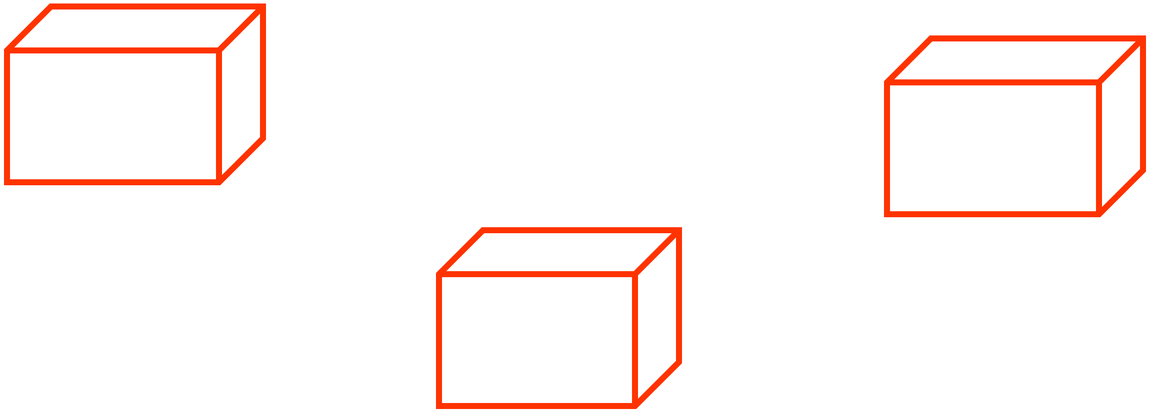


Going beyond black box: control is decentralized with internal delays.

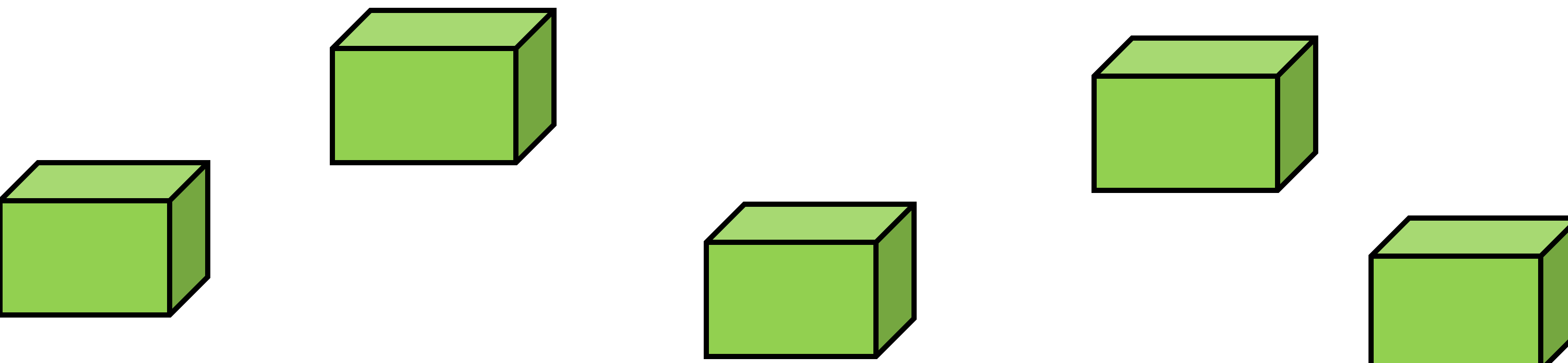




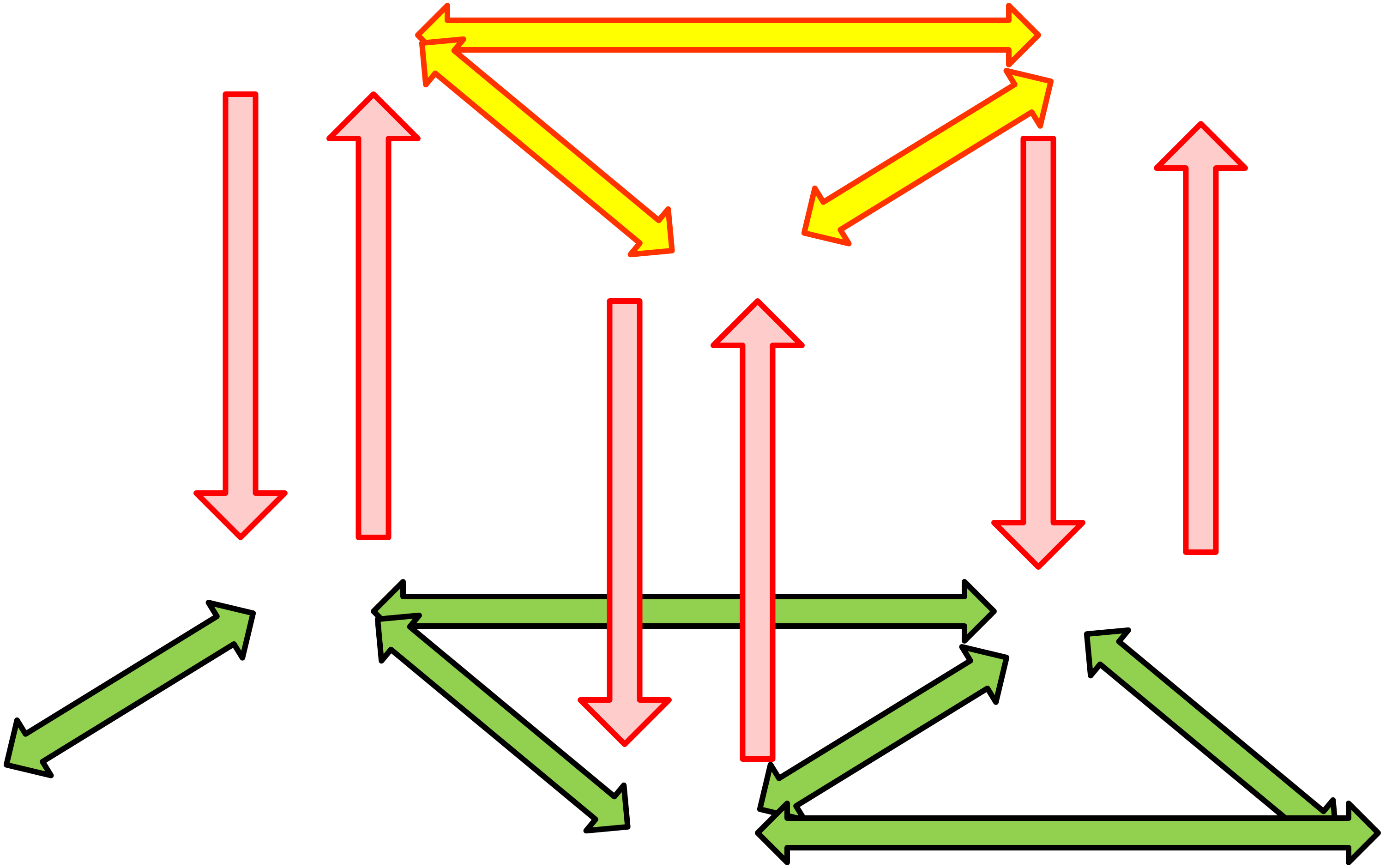
Decentralized, but initially assume
computation is fast and memory is abundant.



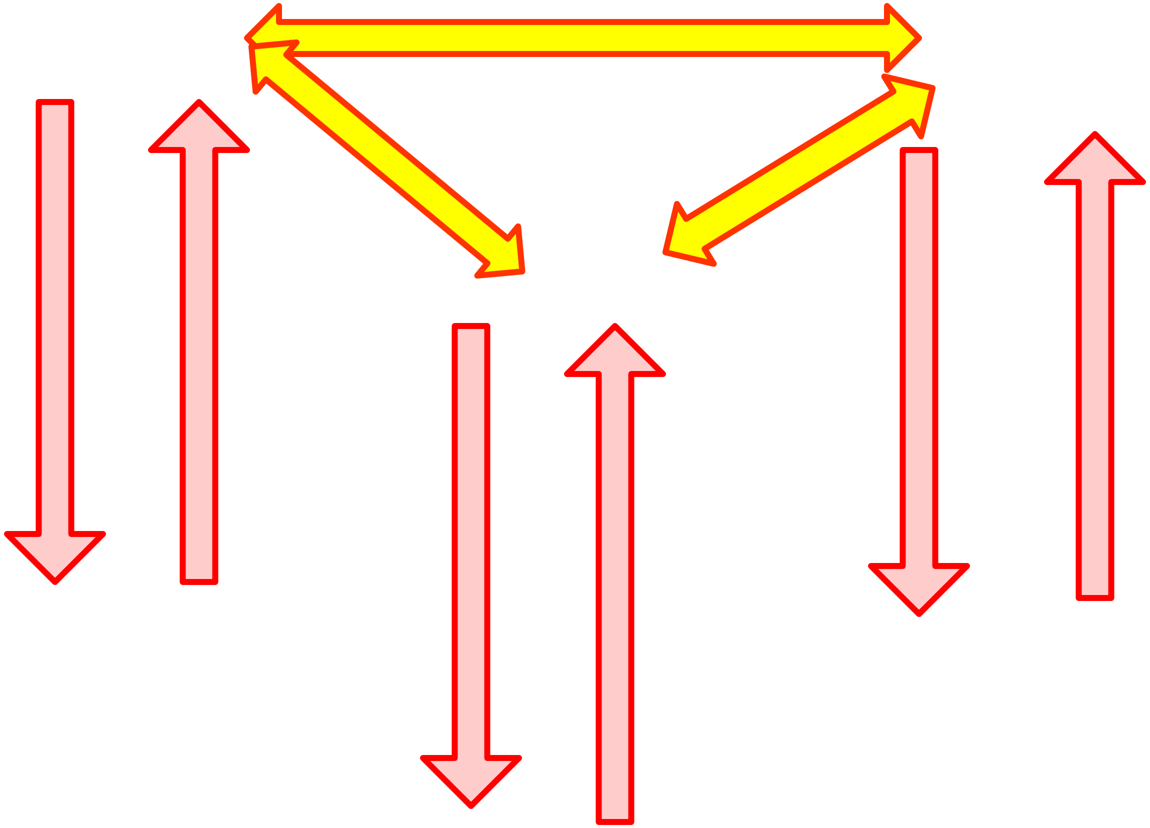
Plant is also distributed with its own component dynamics



Internal delays between brain components, and their sensor and actuators, and also externally between plant components



Internal delays involve both computation and communication latencies



Compute

Communicate

Turing

This progress is important.

Shannon

Delay is *most* important

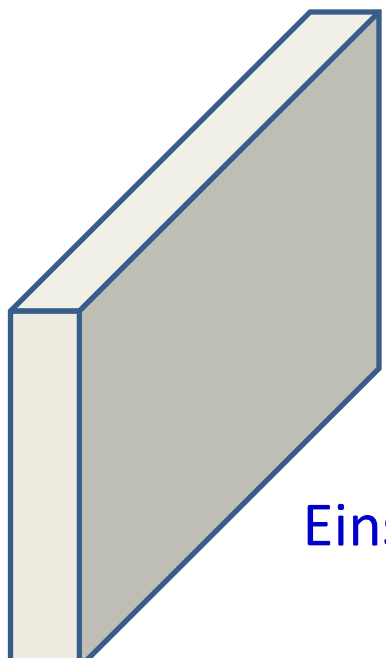
New progress! →

Delay is ~~*least*~~ important

Carnot

Boltzmann

Bode



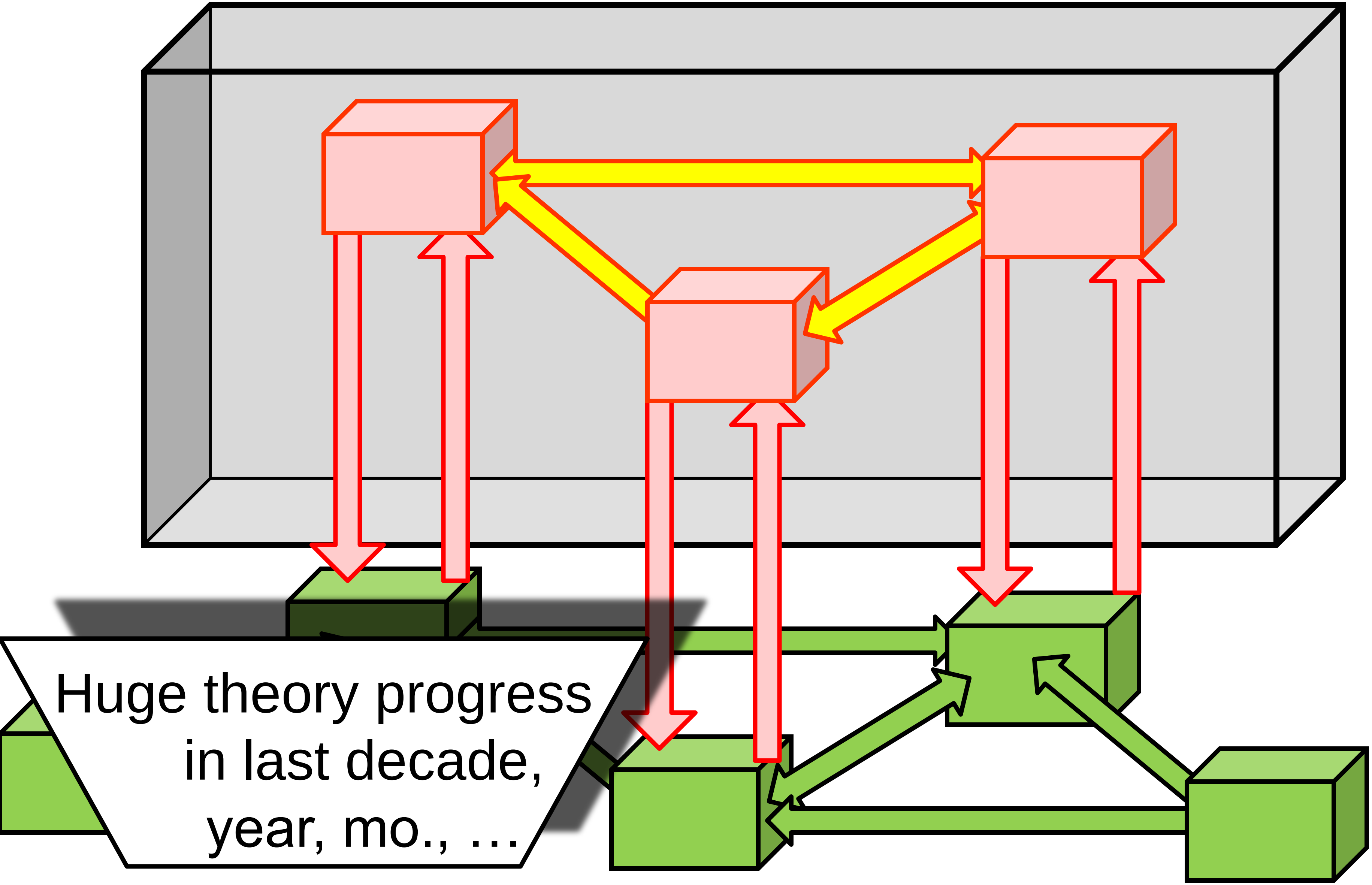
Heisenberg

Einstein

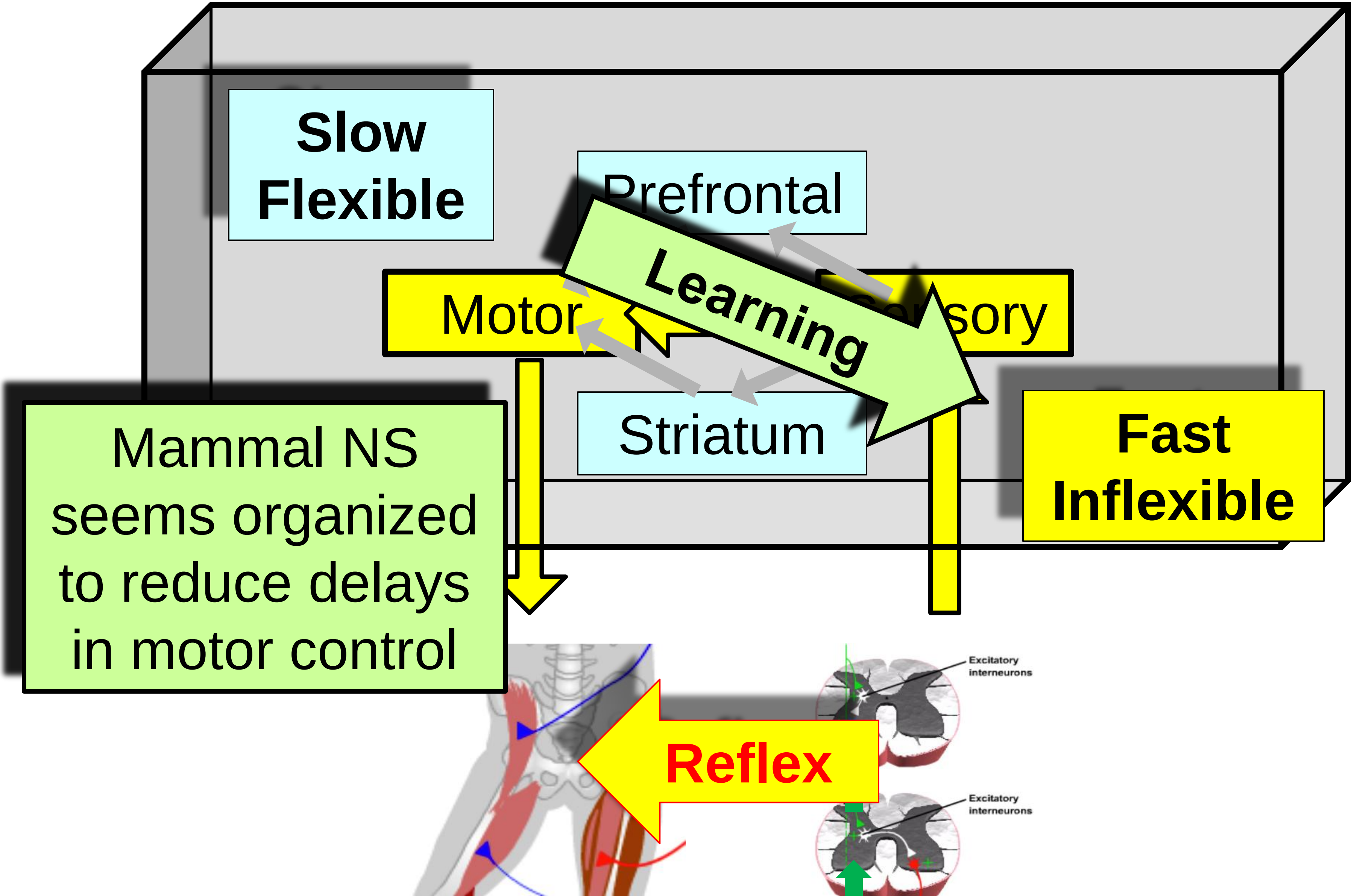
Control, OR

Physics

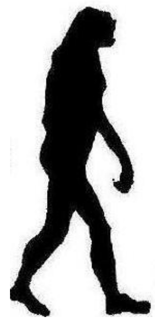
Going beyond black box: control is decentralized with internal delays.



Going beyond black box: control is decentralized with internal delays.



weak
fragile
slow



Human evolution

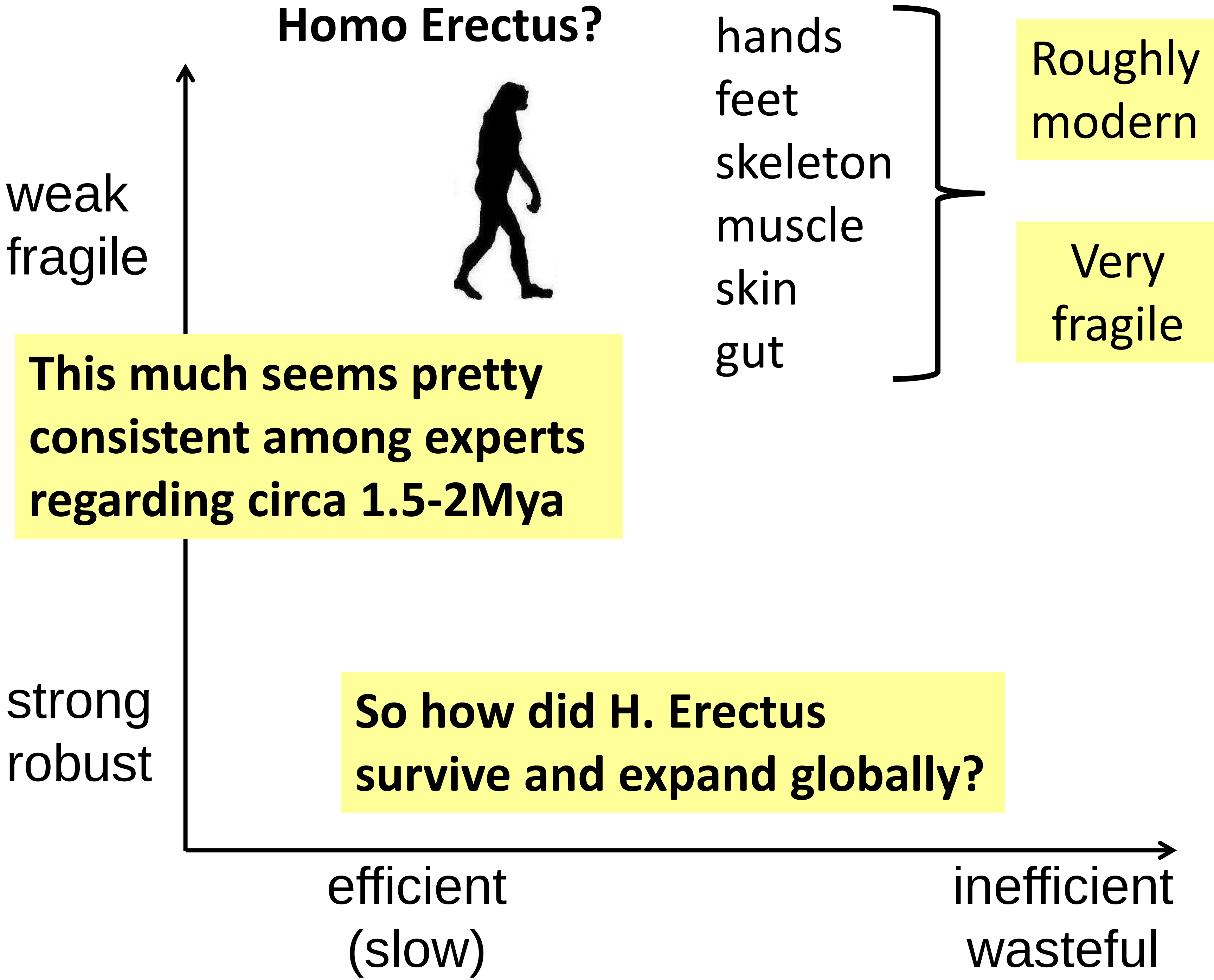
hands
feet
skeleton
muscle
skin
gut
long helpless childhood

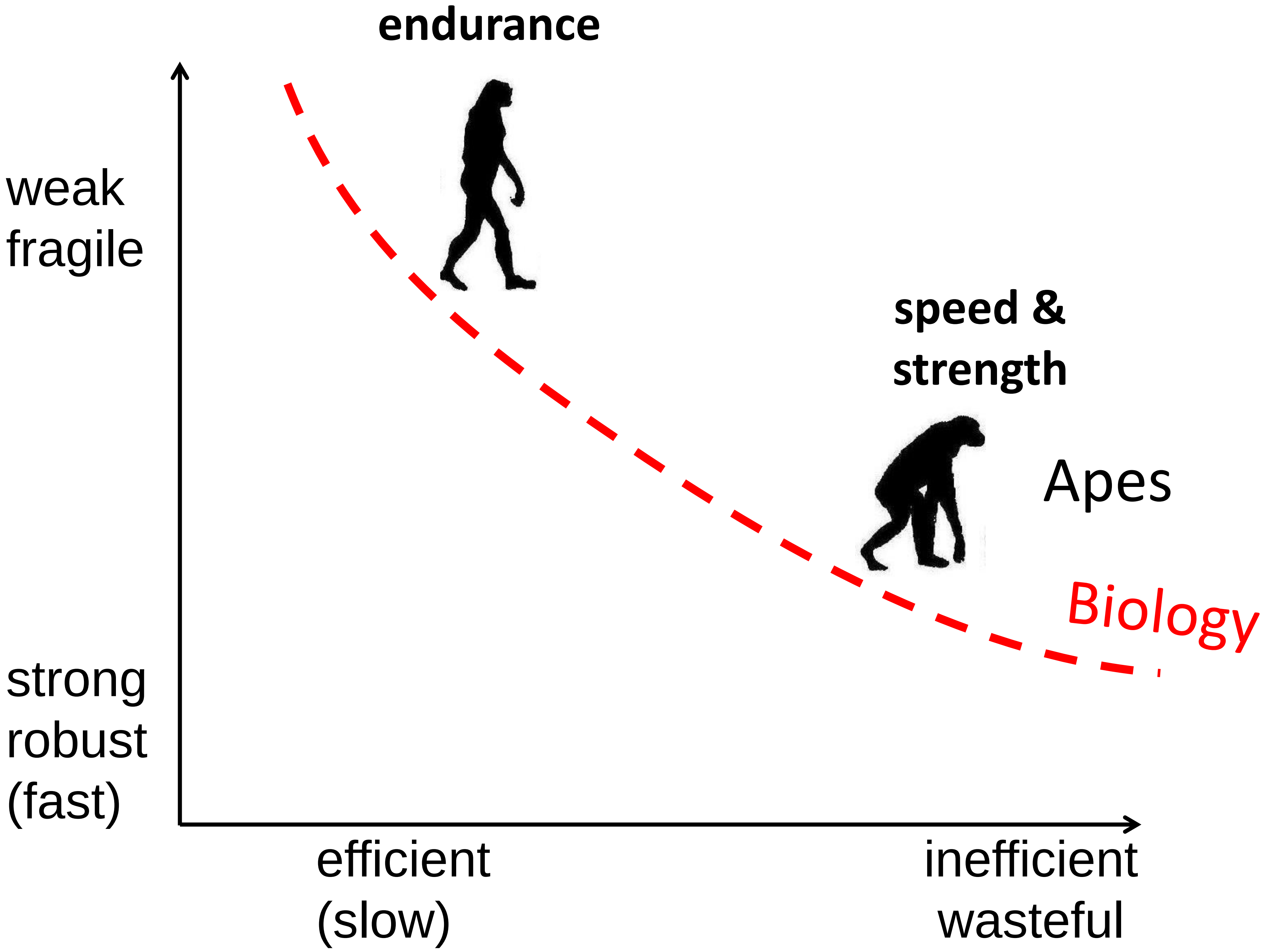
All very different.

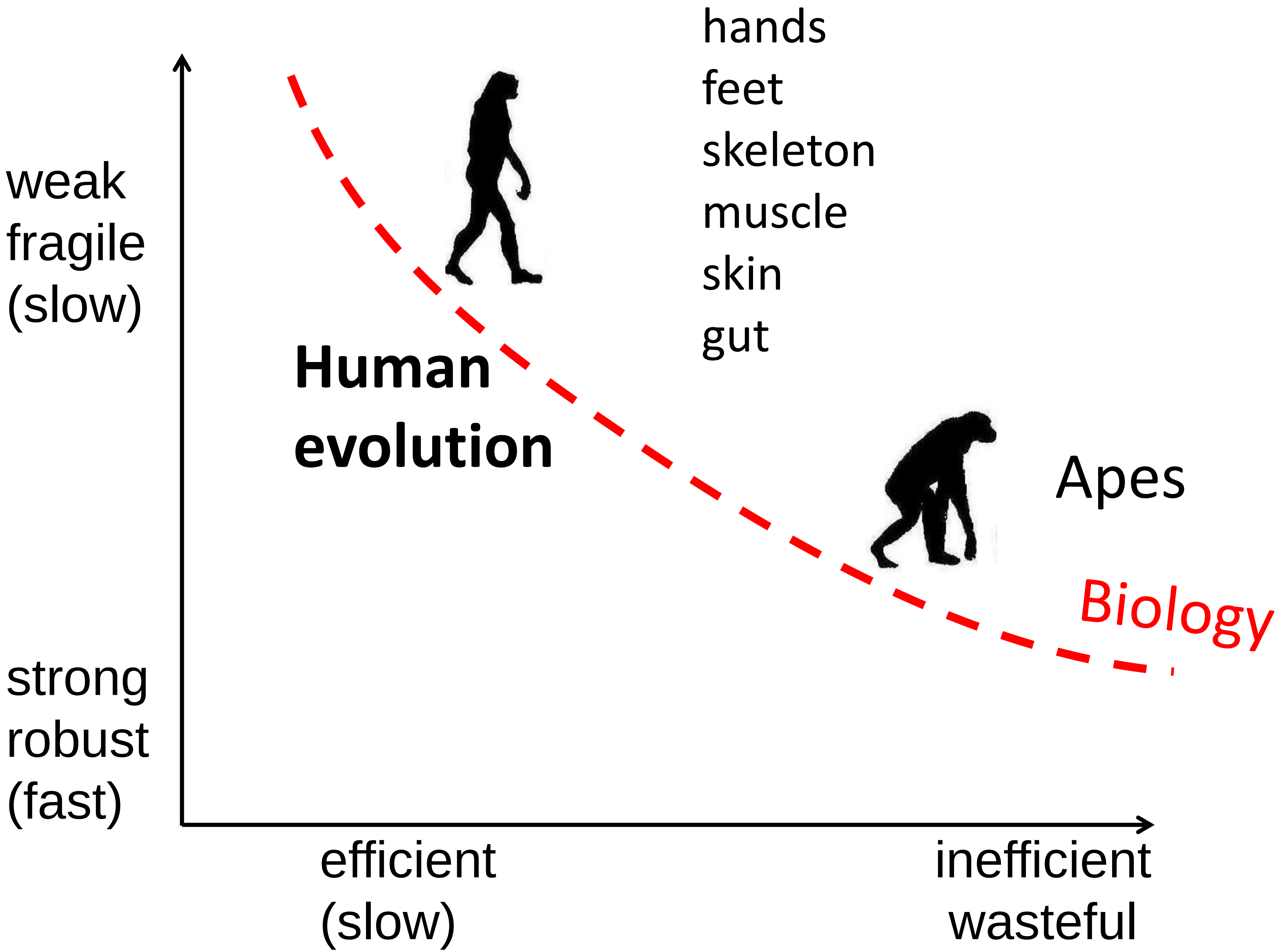
Apes

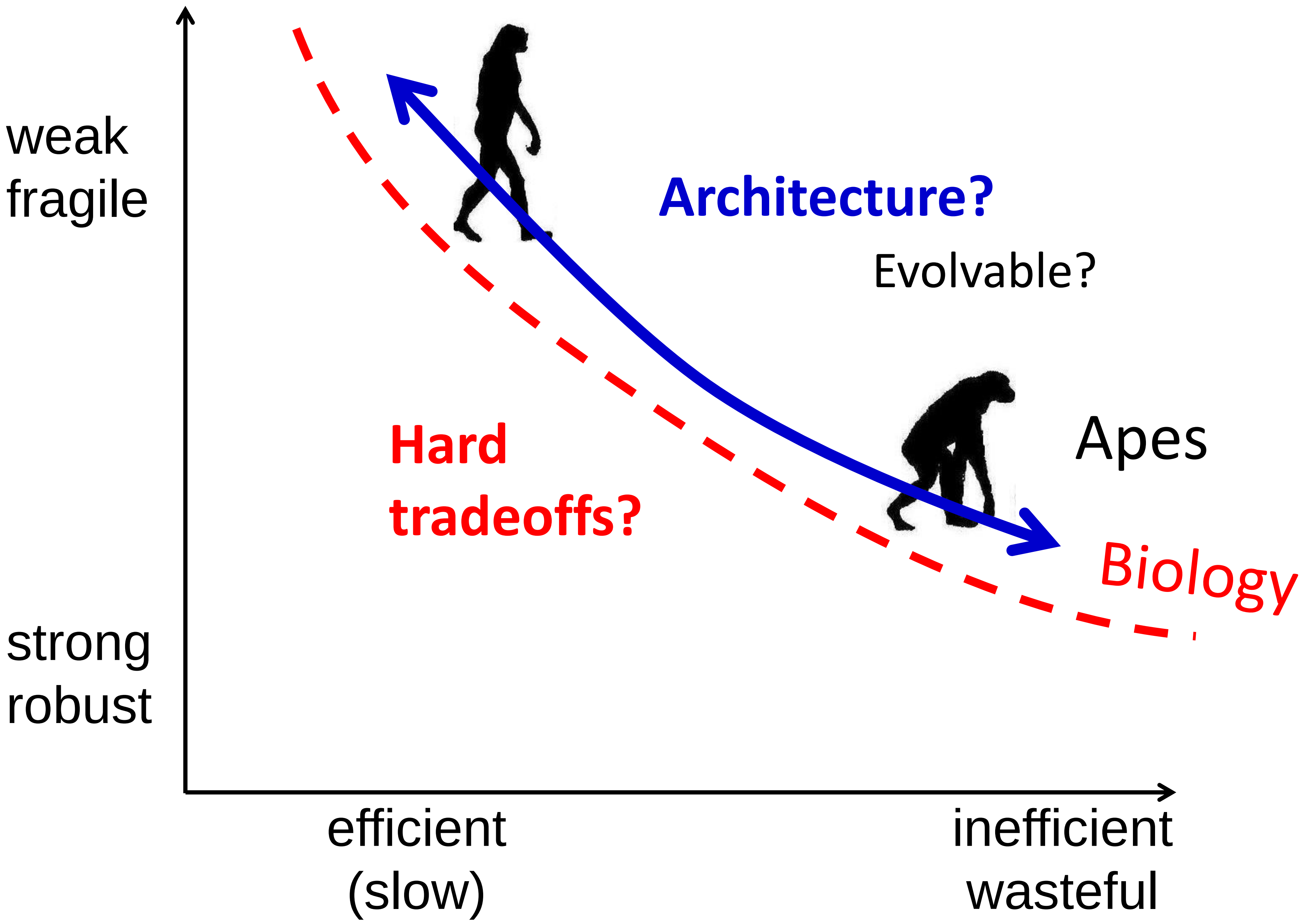
strong
robust
fast

How is this progress?

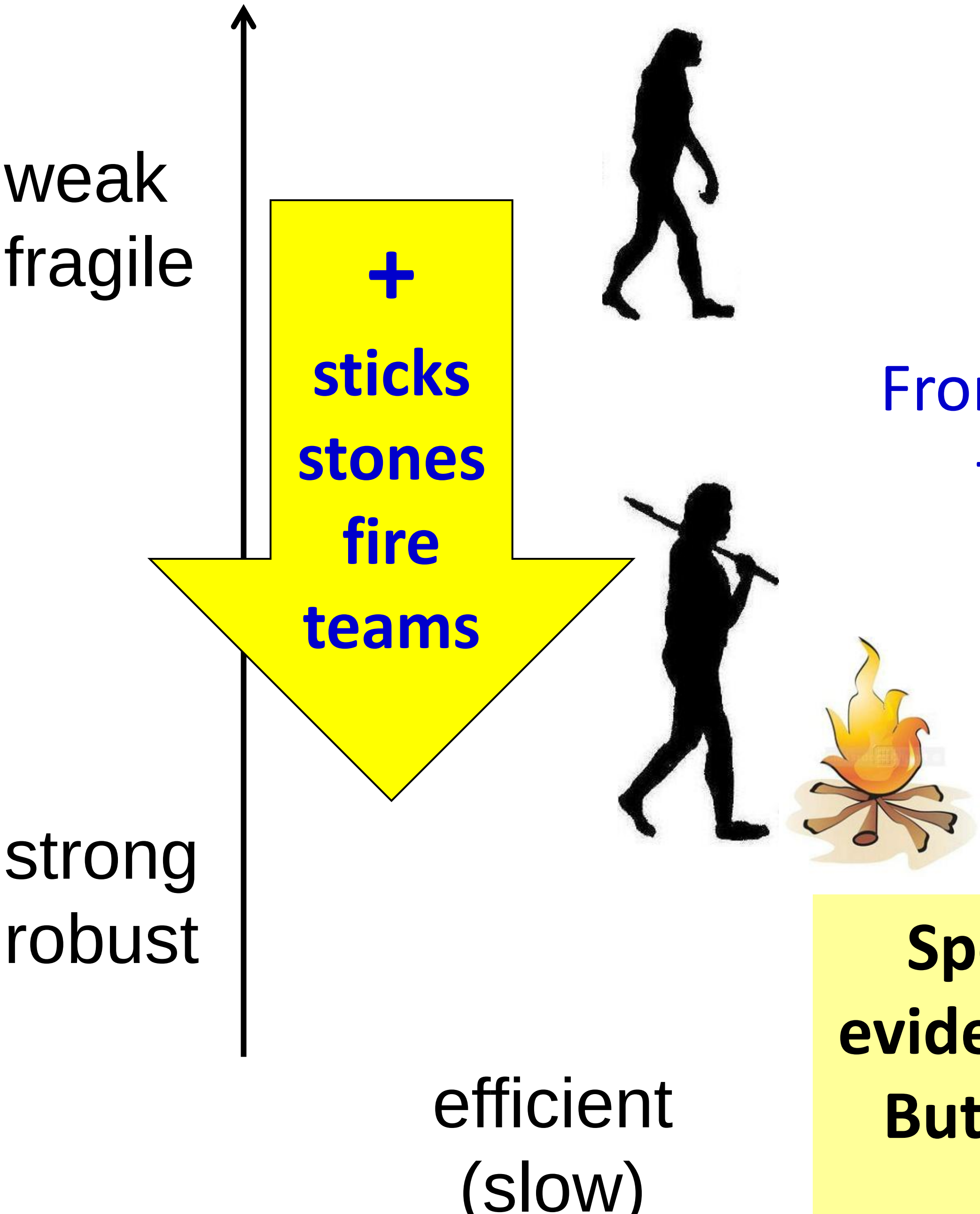

Homo Erectus?
hands
feet
skeleton
muscle
skin
gut
Roughly modern
Very fragile
weak
fragile
This much seems pretty consistent among experts regarding circa 1.5-2Mya
strong
robust
So how did H. Erectus survive and expand globally?
efficient
(slow)
inefficient
wasteful


endurance
weak
fragile
speed &
strength
Apes
Biology
strong
robust
(fast)
efficient
(slow)
inefficient
wasteful


hands
feet
skeleton
muscle
skin
gut
weak
fragile
(slow)
Human
evolution
Apes
Biology
strong
robust
(fast)
efficient
(slow)
inefficient
wasteful


weak
fragile
strong
robust
Architecture?
Evolvable?
Hard
tradeoffs?
Apes
Biology
efficient
(slow)
inefficient
wasteful

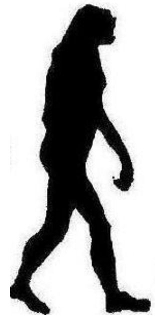
endurance



From weak prey
to invincible
predator?

Speculation? There is only evidence for crude stone tools. But sticks, fire, teams might not leave a record?

weak
fragile



Speculation? With only evidence for crude stone tools. But sticks and fire might not leave a record?

+
sticks
stones
fire
teams

From weak prey to invincible predator

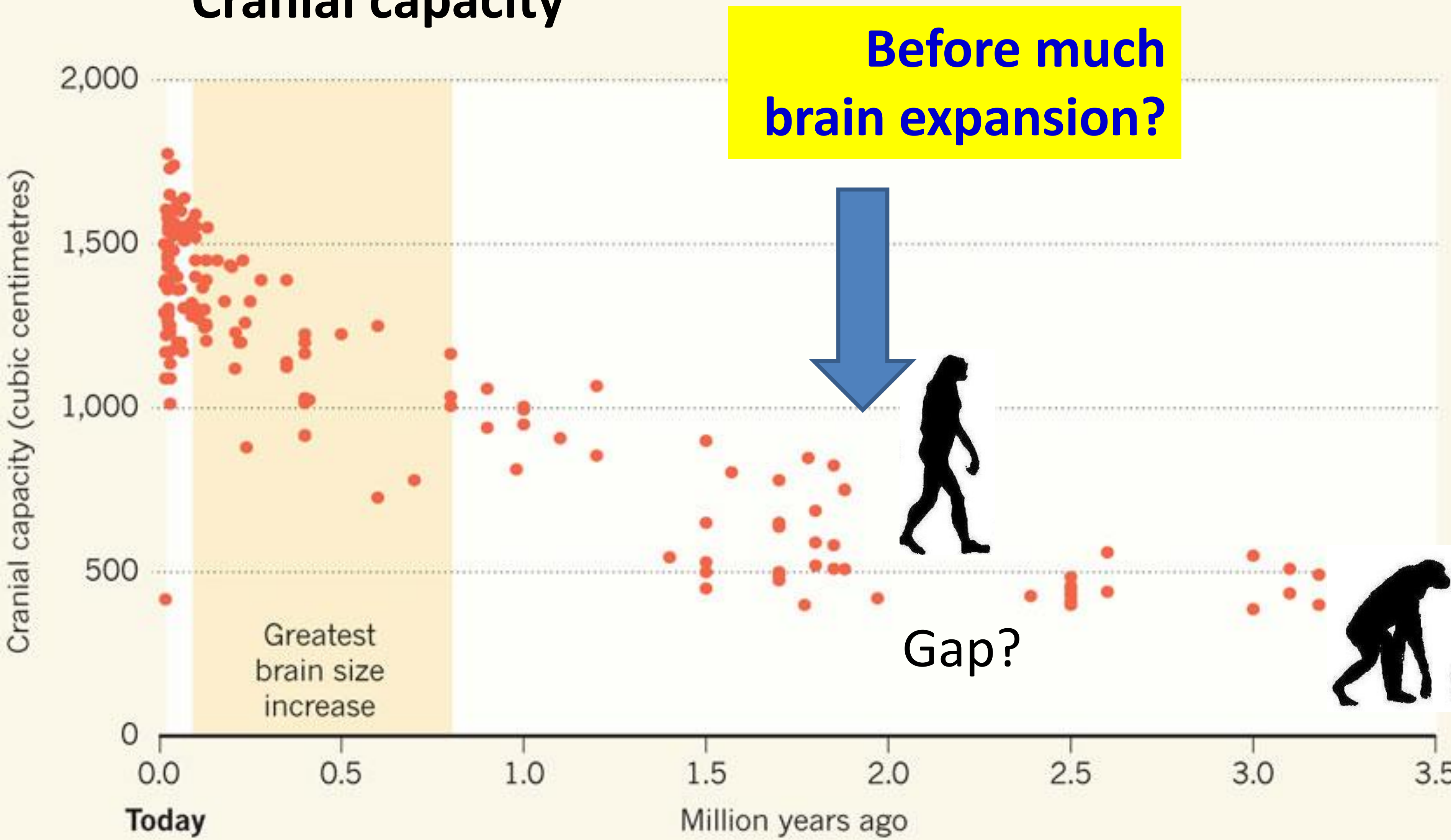
Before much brain expansion?

strong
robust

Plausible but speculation?

efficient
(slow)

Cranial capacity

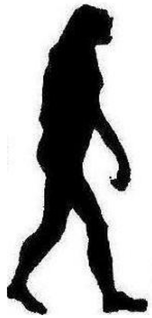


Today

2Mya

weak
fragile

strong
robust



hands
feet
skeleton
muscle
skin
gut

+
sticks
stones
fire

From weak prey
to invincible
predator

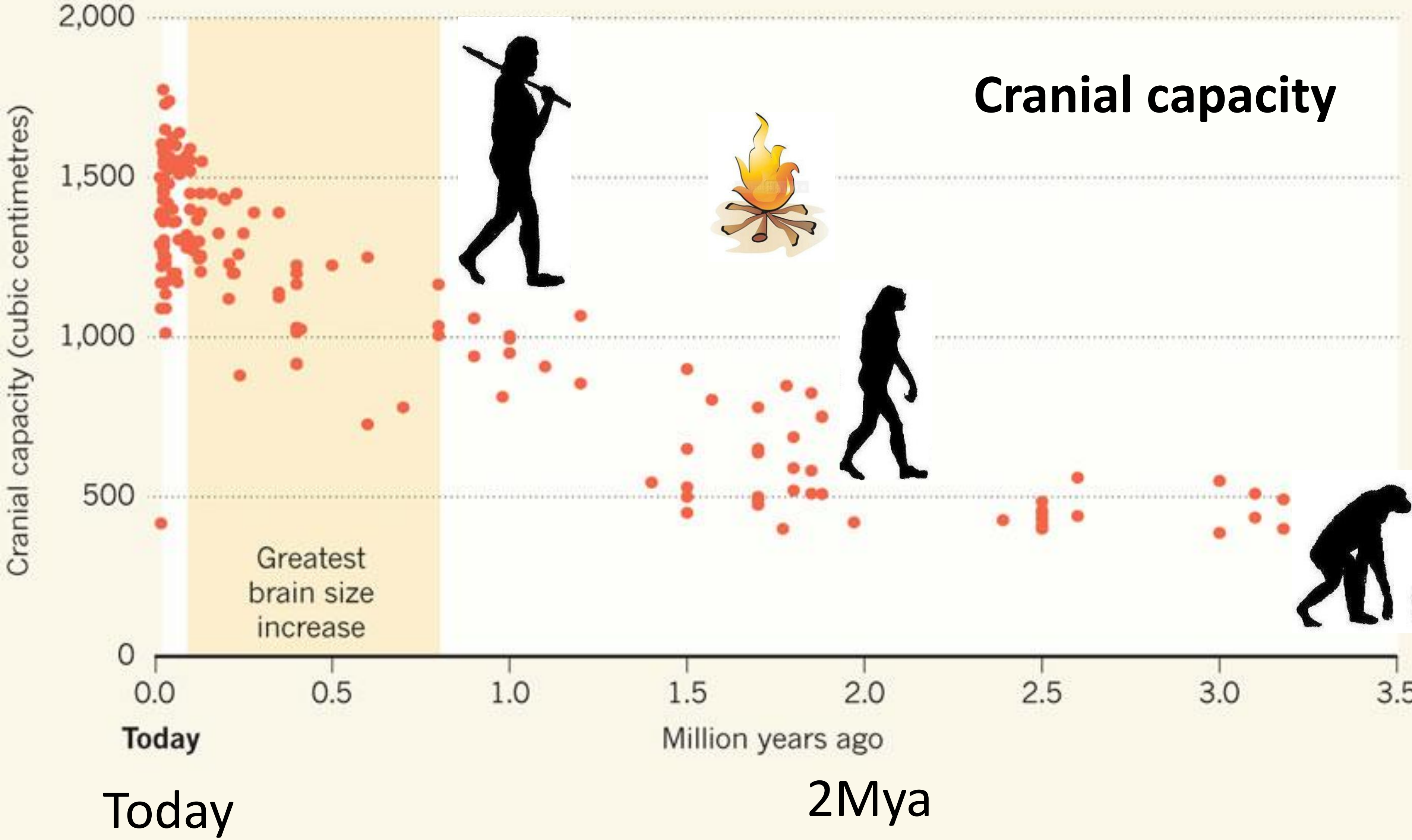
Before much
brain expansion?

efficient
(slow)

Key point:
Our physiology,
technology,
and brains
have co-
evolved

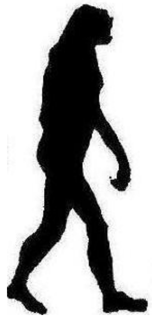
Probably true
no matter what

Huge
implications.



Cranial capacity
2,000
1,500
1,000
500
0
Cranial capacity (cubic centimetres)
Greatest
brain size
increase
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Today
Million years ago
Today
2Mya

weak
fragile



hands
feet
skeleton
muscle
skin
gut

Key point needing more discussion:
The evolutionary challenge of big brains is ***homeostasis***, not basal metabolic load.

From weak prey
to invincible
predator

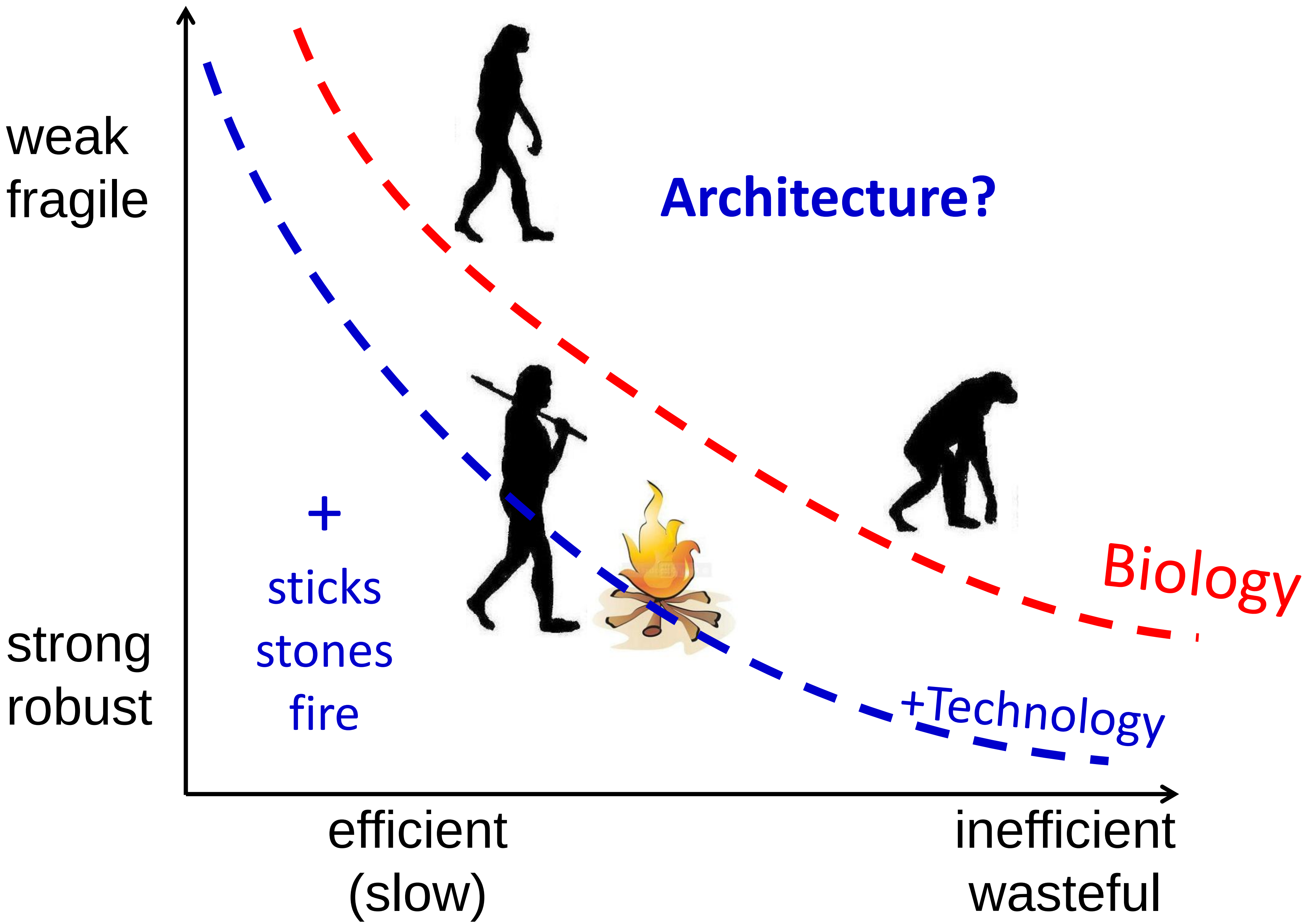
\+
sticks
stones
fire

strong
robust

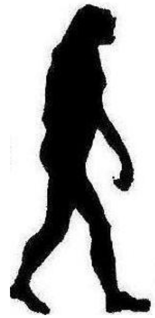
Before much
brain expansion?

efficient
(slow)

Huge
implications.


weak
fragile
strong
robust
efficient
(slow)
inefficient
wasteful
Architecture?
Biology
+
sticks
stones
fire
+Technology

weak
fragile



hands
feet
skeleton
muscle
skin
gut

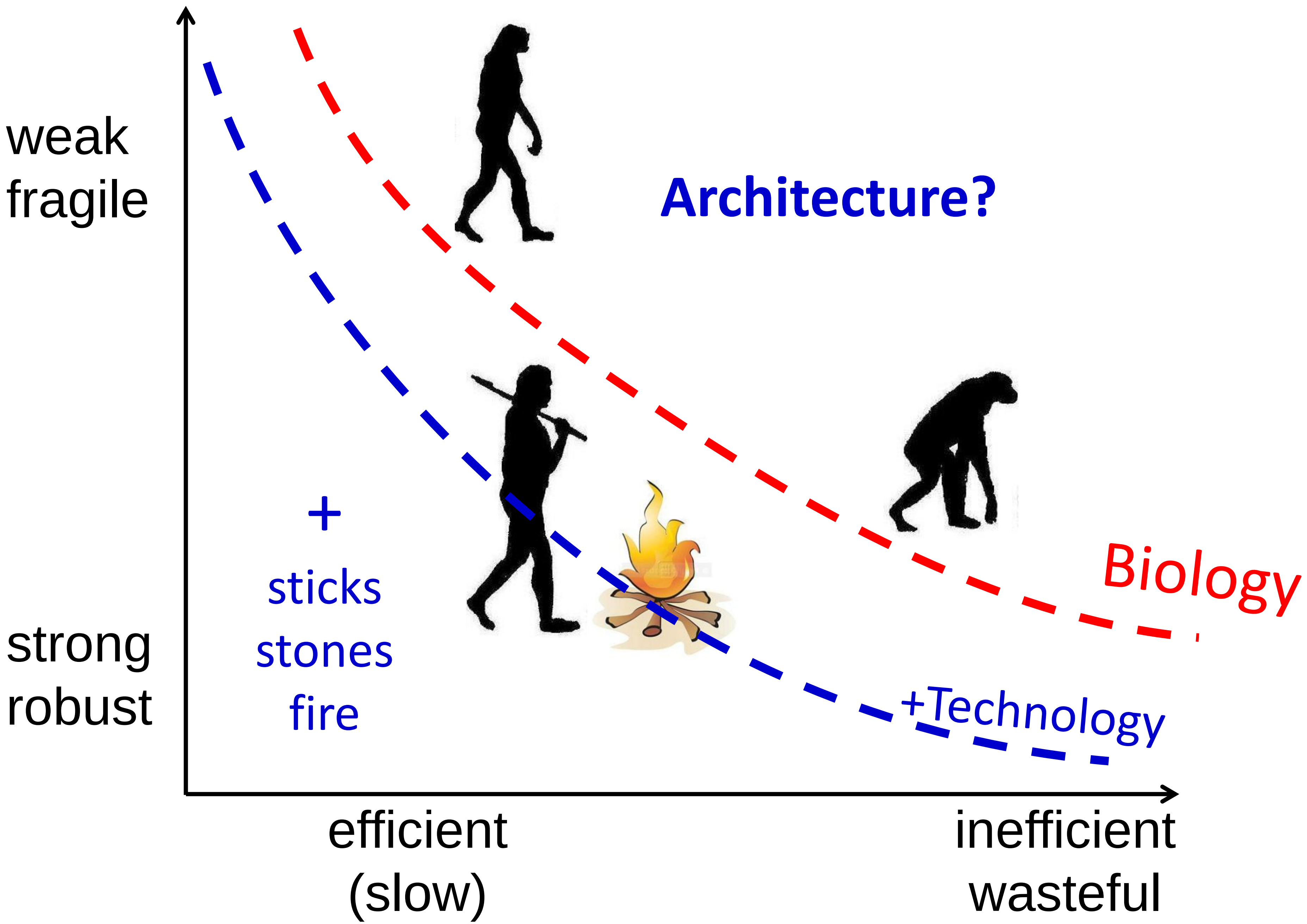
+
sticks
stones
fire

From weak prey
to invincible
predator

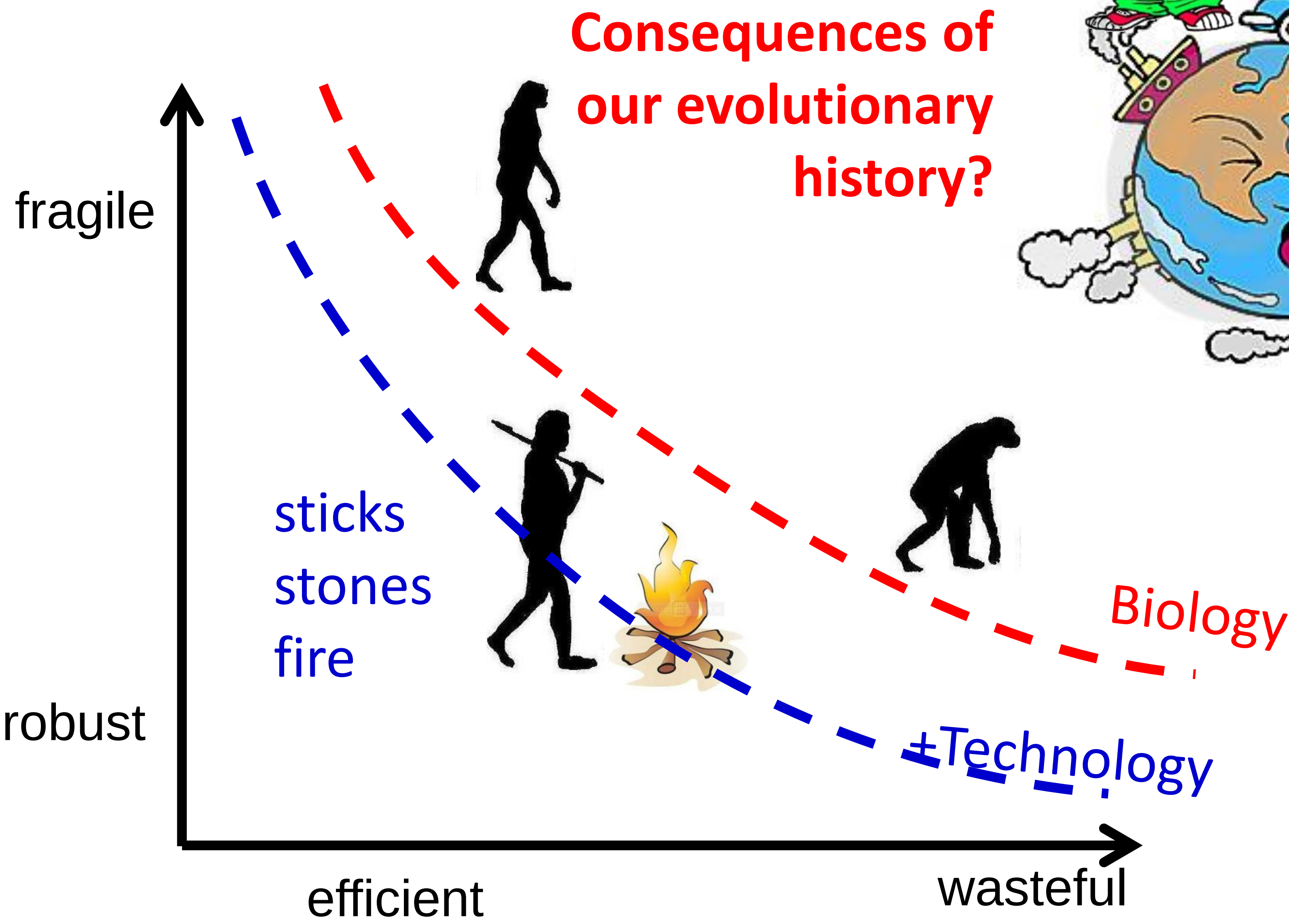
strong
robust

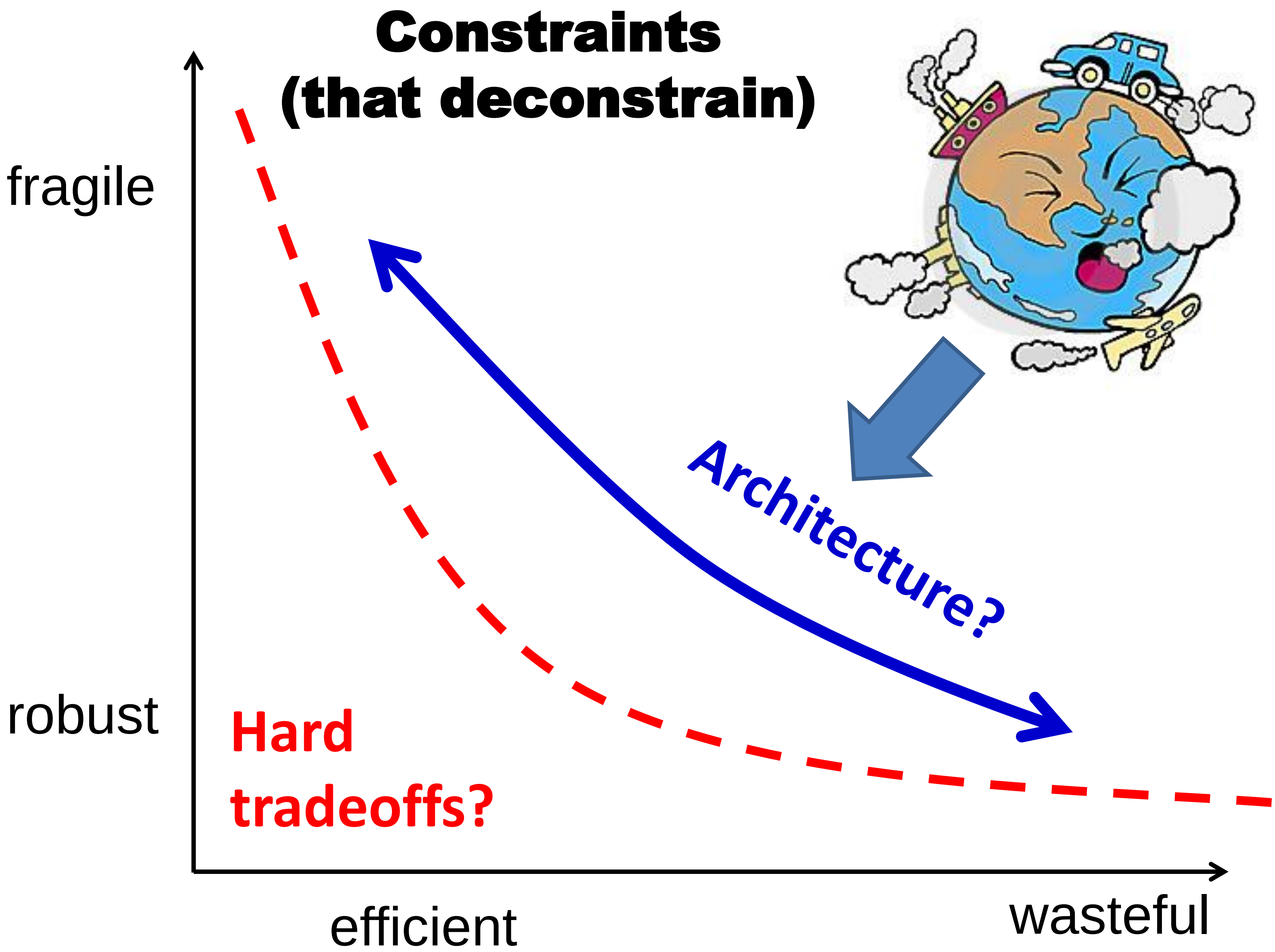
efficient
(slow)

Before much
brain expansion?


weak
fragile
strong
robust
Architecture?
+
sticks
stones
fire
Biology
+Technology
efficient
(slow)
inefficient
wasteful

Human complexity?




Constraints
(that deconstrain)
fragile
robust
Architecture?
Hard
tradeoffs?
efficient
wasteful