Universal laws and architectures

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

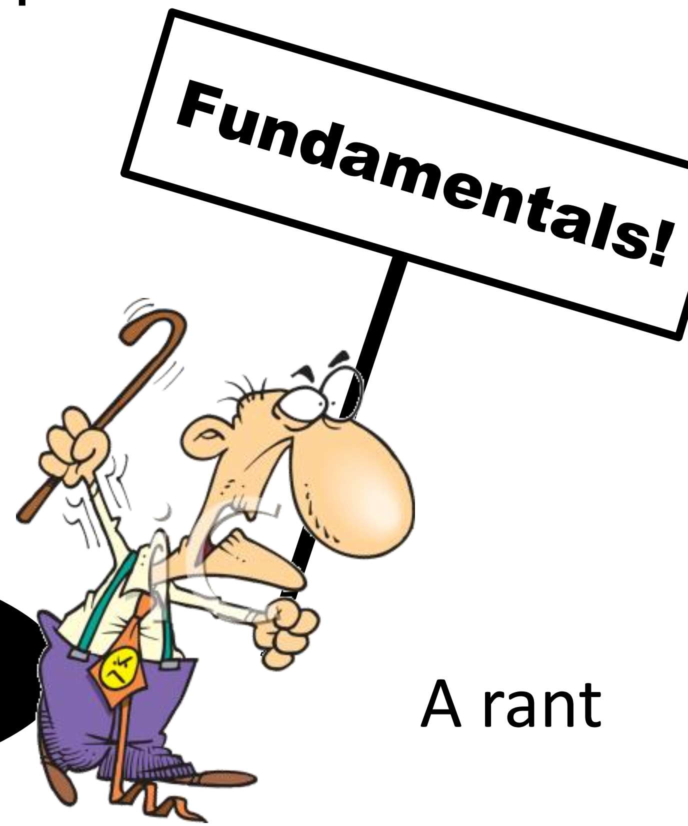
Turing on layering

The 'skin of an onion' analogy is also helpful. In considering the functions of the mind or the brain we find certain operations which we can explain in purely mechanical terms. This we say does not correspond to the real mind: it is a sort of skin which we must strip off if we are to find the real mind. But then in what remains we find a further skin to be stripped off, and so on. Proceeding in this way do we ever come to the 'real' mind, or do we eventually come to the skin which has nothing in it? In the latter case the whole mind is mechanical.

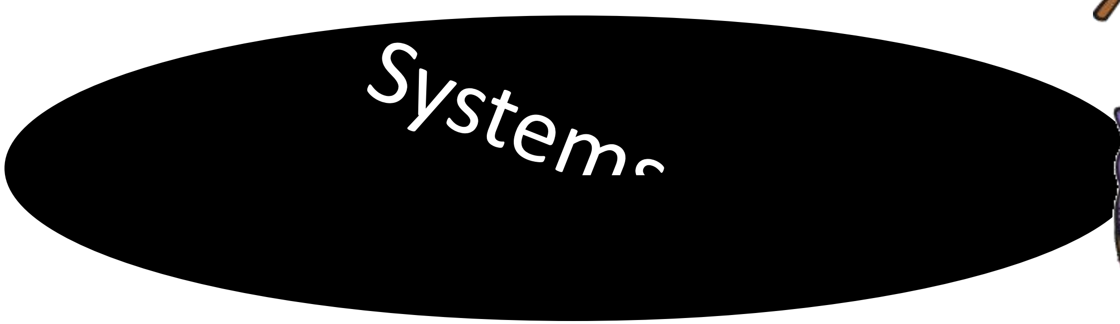
1950, Computing Machinery and Intelligence, *Mind*

“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 for motivation



*try to get you
to read them?



A rant

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.**

Very 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.

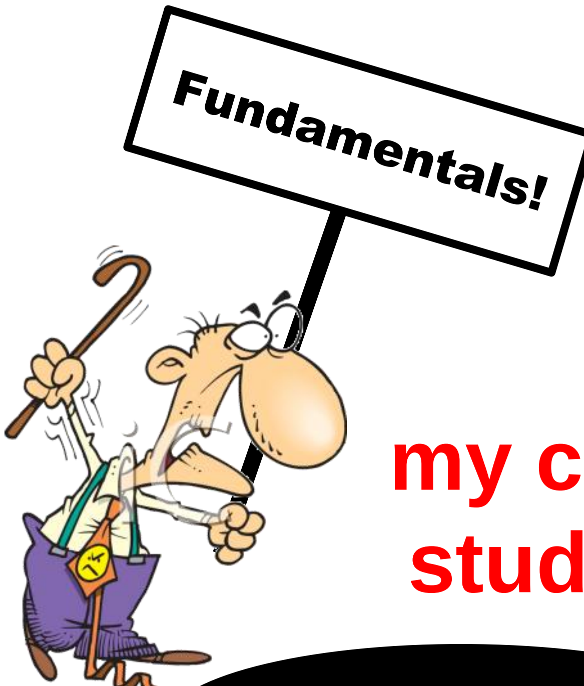
evolved for sensorimotor control and retain much of that evolved architecture, then the apparent distinctions between perceptual, cognitive, and motor processes may be another form of illusion (9), reinforcing the claim that robust control and adaptive feedback (7, 11) rather than more conventional serial 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

my case studies

- Lots from cell biology
  - glycolytic oscillations for hard limits
  - bacterial layering for architecture
- Networking and “clean slate” architectures
  - wireless end systems
  - info or content centric application layer
  - integrate routing, control, scheduling, coding, caching
  - control of cyber-physical
  - PC, OS, VLSI, antennas, etc (IT components)
- Neuroscience
  - brains
  - neuroendocrine control
- Medical and exercise physiology

- **Cell biology**
- **Networking &"clean slate" architectures**
- **Neuroscience**
- **Medical physiology**
- Smartgrid, cyber-phys
- Wildfire ecology
- Earthquakes
- Lots of aerospace
- Physics:
  - turbulence,
  - stat mech (QM?)
- "Toy":
  - Lego,
  - clothing,
  - buildings, …
- **Synesthesia**

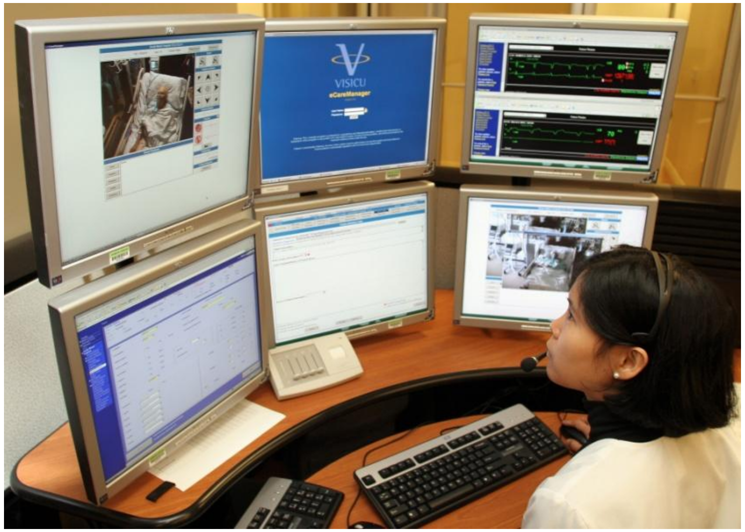


my case studies

Existing design frameworks

- Sophisticated components
- Poor integration
- Limited theoretical framework

Fix?



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

Leo Tolstoy,
Anna Karenina,
Chapter 1, first line

- What could this mean? Given incredible ***diversity*** of people and environments?
- It has to be a statement about organization, and specifically ***architecture***.
- Happy = empathy + cooperation + simple rules?

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

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
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failure transparent
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precision
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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

Simplified, minimal requirements

accessible
accountable
accurate
adaptable
administrable
affordable
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credible
process capable
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Requirements on systems and architectures

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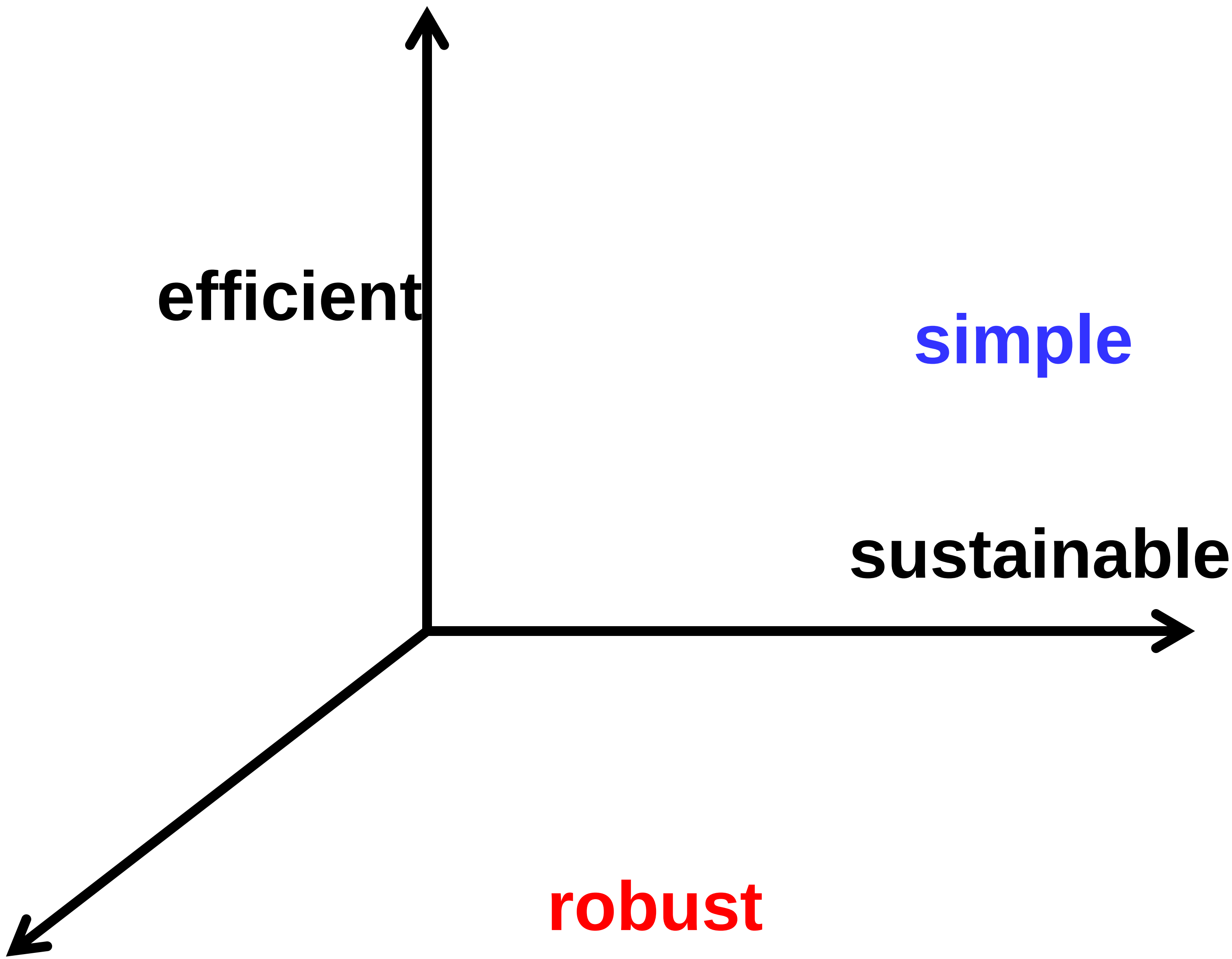
simple

sustainable

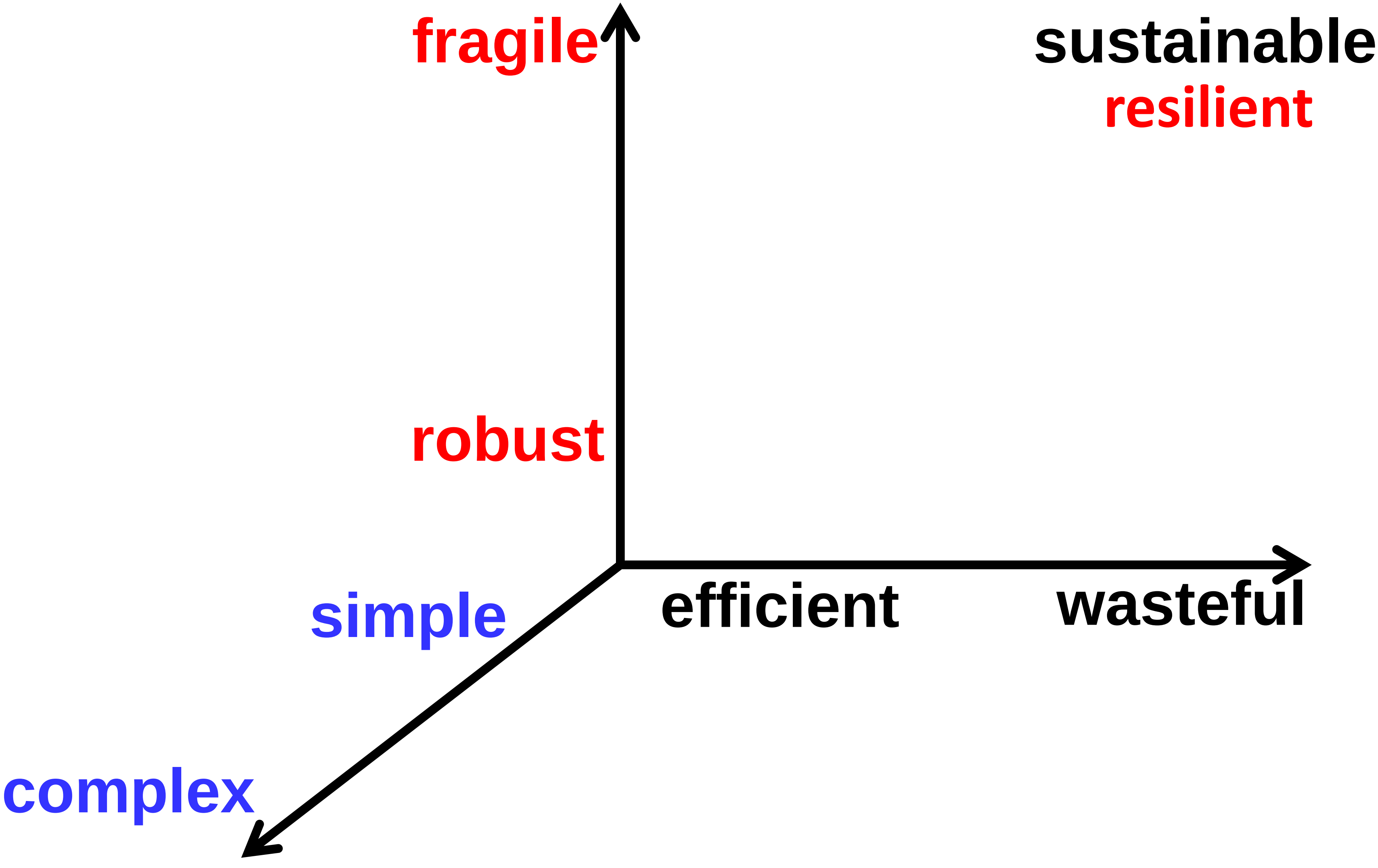
resilient

robust

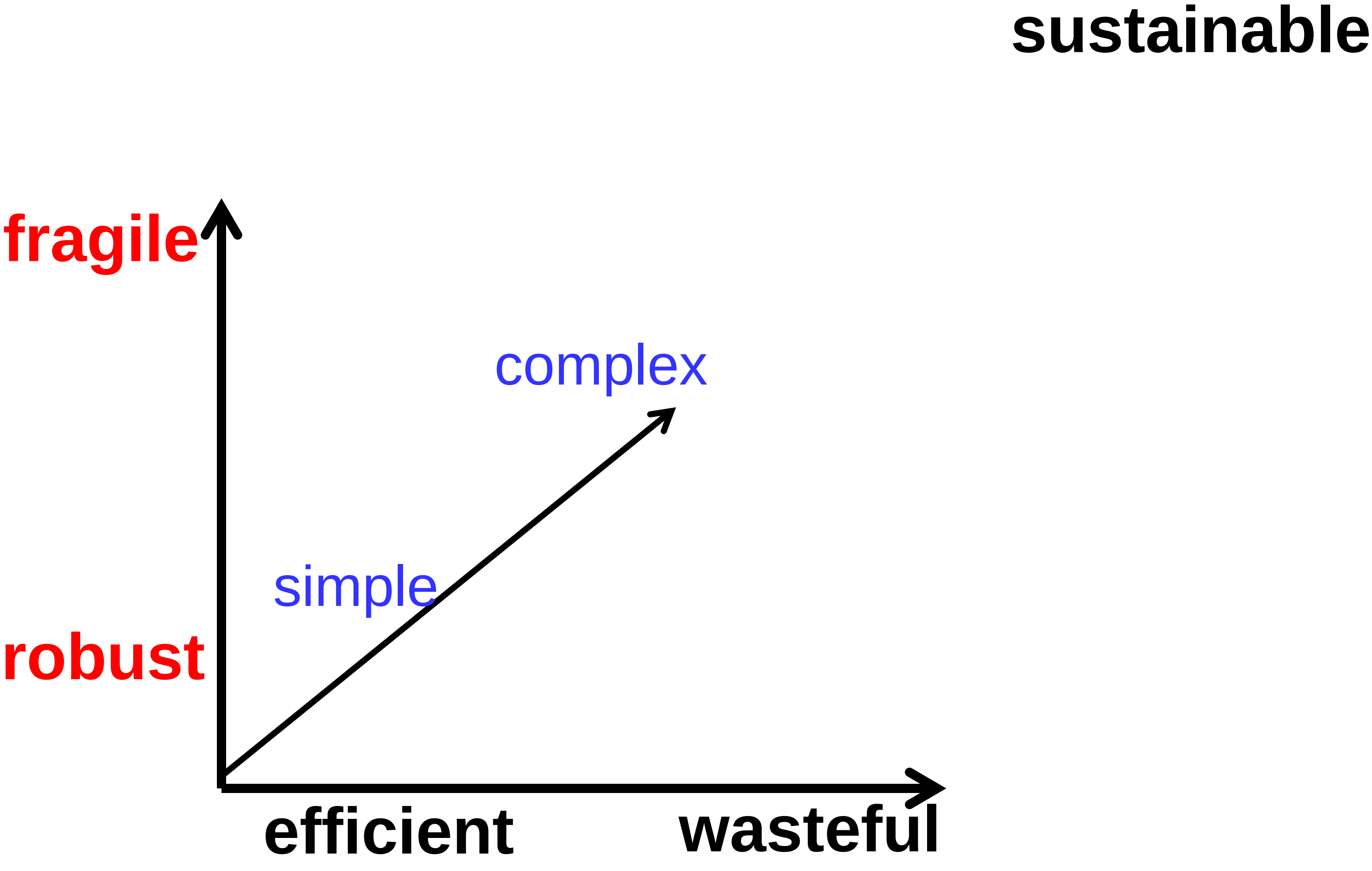
Requirements on systems and architectures



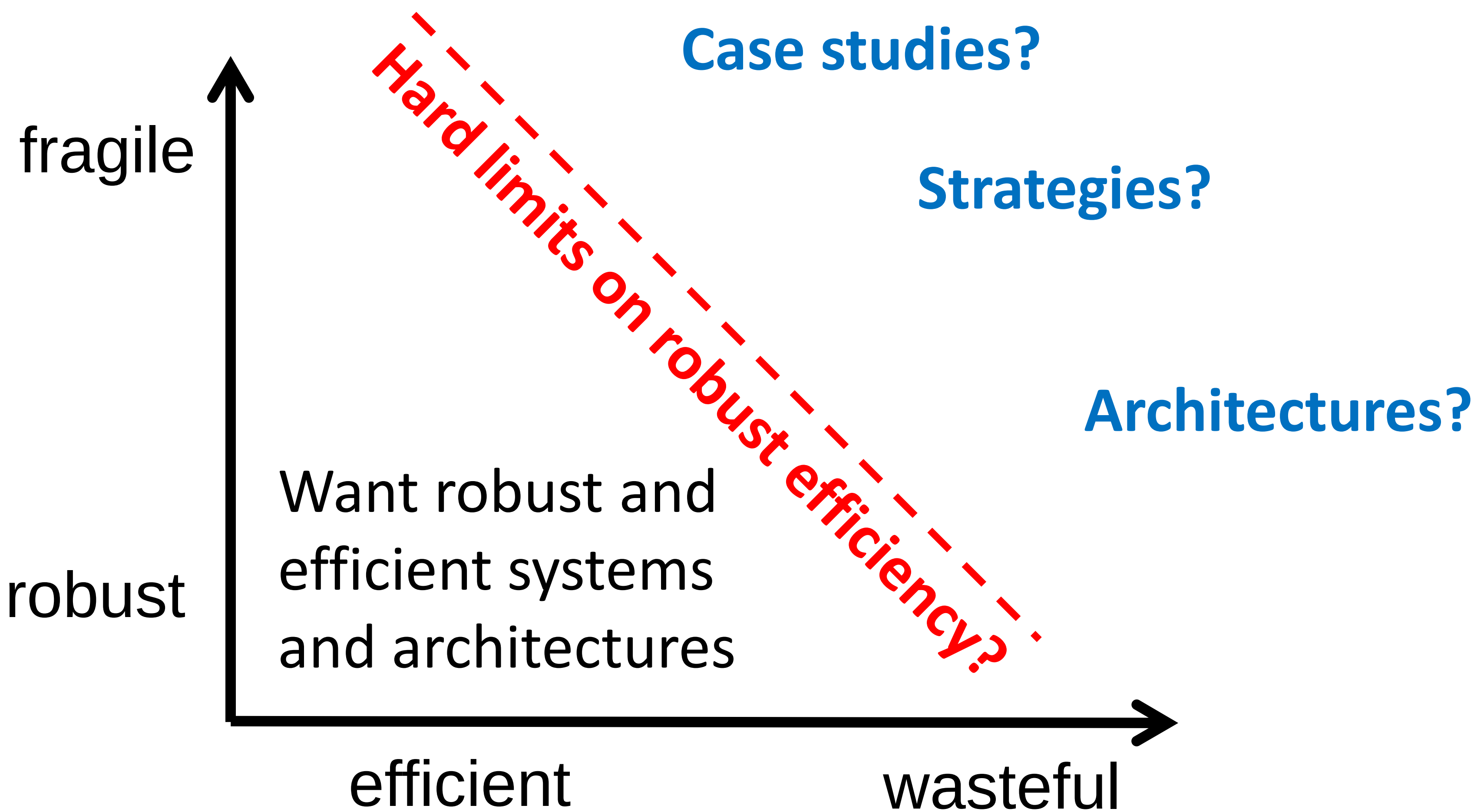
Requirements on systems and architectures



Requirements on systems and architectures



Want to understand the space of systems/architectures



Resilient architectures are all alike; every brittle system is brittle in its own way.

Apologies to Tolstoy

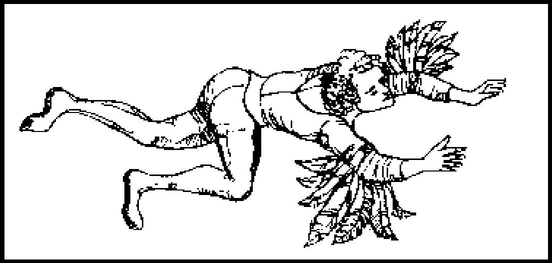
- Resilience includes robustness, efficiency, sustainability, scalability, etc etc
- Effective architectures provide flexible tradeoffs across all these dimensions
- Subject to “laws” which are hard constraints on what is achievable
- Defer resolving terminology, focus on…
- **Theorems and concrete case studies**

Resilient architectures are all alike; every brittle system is brittle in its own way.

Good architecture =

“constrains that deconstrain”

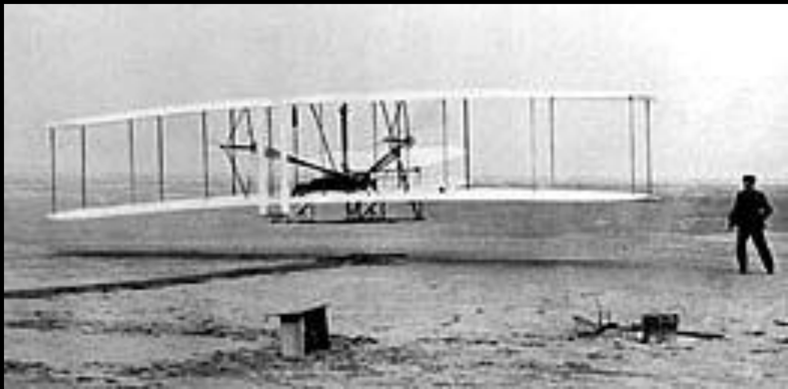
(Gerhart and Kirschner)



The dangers of naïve biomemetics

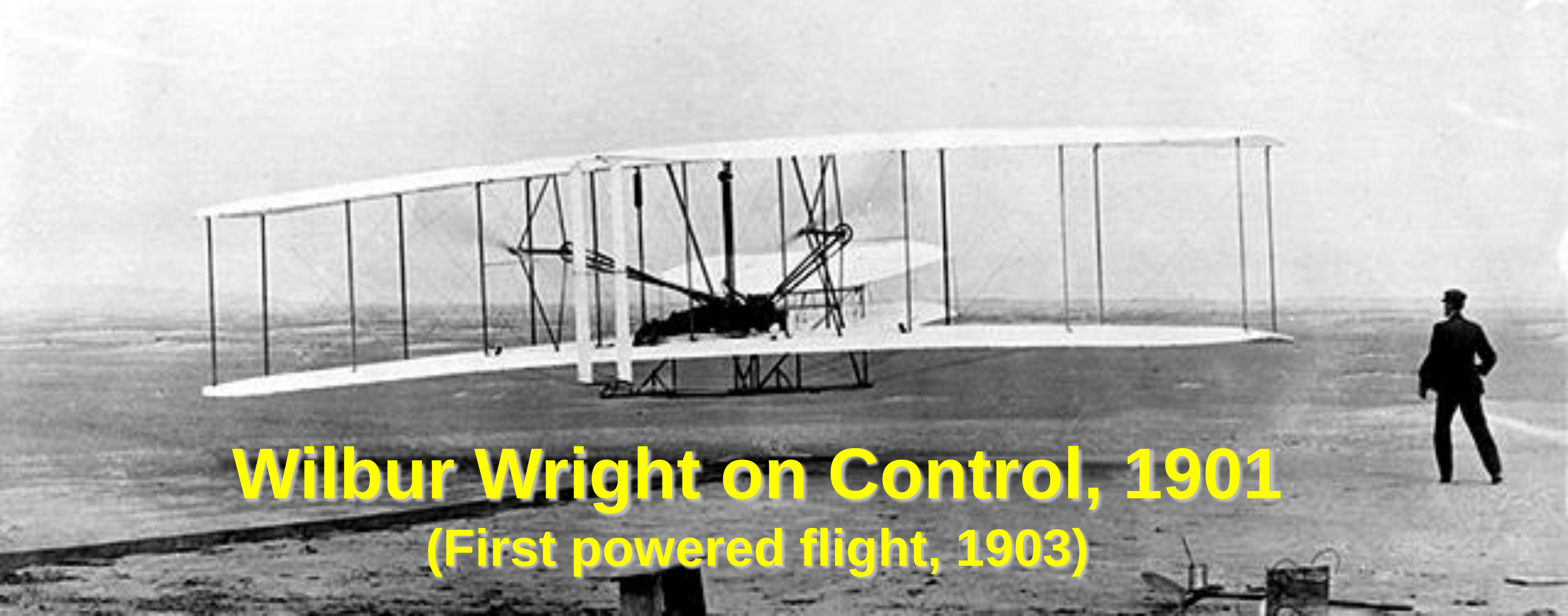
Feathers
and
flapping?

Or lift, drag, propulsion,
and ***control***?



Getting it (W)right, 1901

- "We know how to construct airplanes..." (lift and drag)
- "… also know how to build engines." (propulsion)
- "When... balance and steer[ing]... has been worked out, the age of flying will have arrived, for all other difficulties are of minor importance." (control)



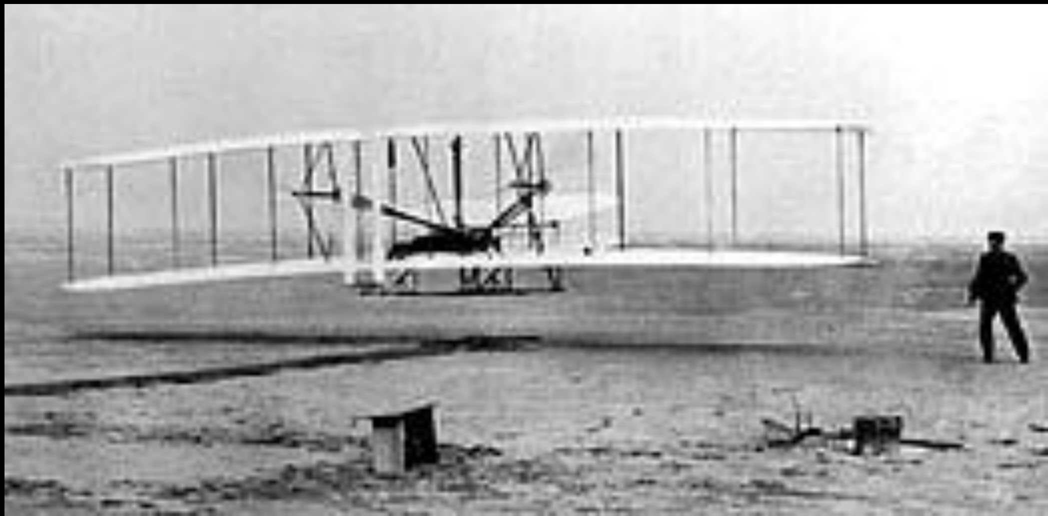
Wilbur Wright on Control, 1901

(First powered flight, 1903)

Universals?

Feathers and flapping?

Lift, drag, propulsion, and ***control***?

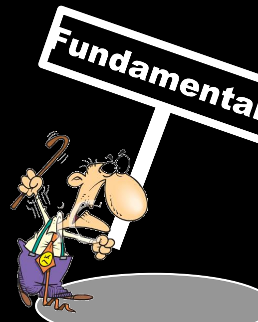


Universals?

- Complexity $\leftarrow$ control, robust/fragile tradeoffs
- Fragility $\leftarrow$ Hijacking, side effects, unintended…
- Of mechanisms evolved for robustness
- Math: robust/fragile constraints (“conservation laws”)

Both

Accident or necessity?



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.

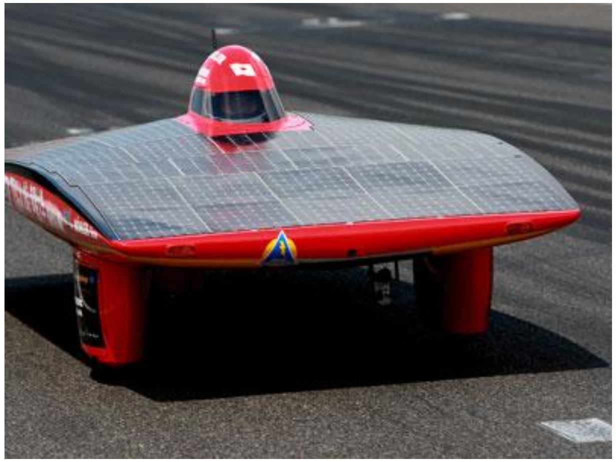
Highly optimized tolerance (HOT) is a conceptual framewo for examining organization and structure in complex systen (18). Theoretically, HOT builds on models and mathemati from physics and engineering, and identifies robustness tradeof as a principle underlying mechanism for complexity and pow law statistics. 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 der 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

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



Current Technology?

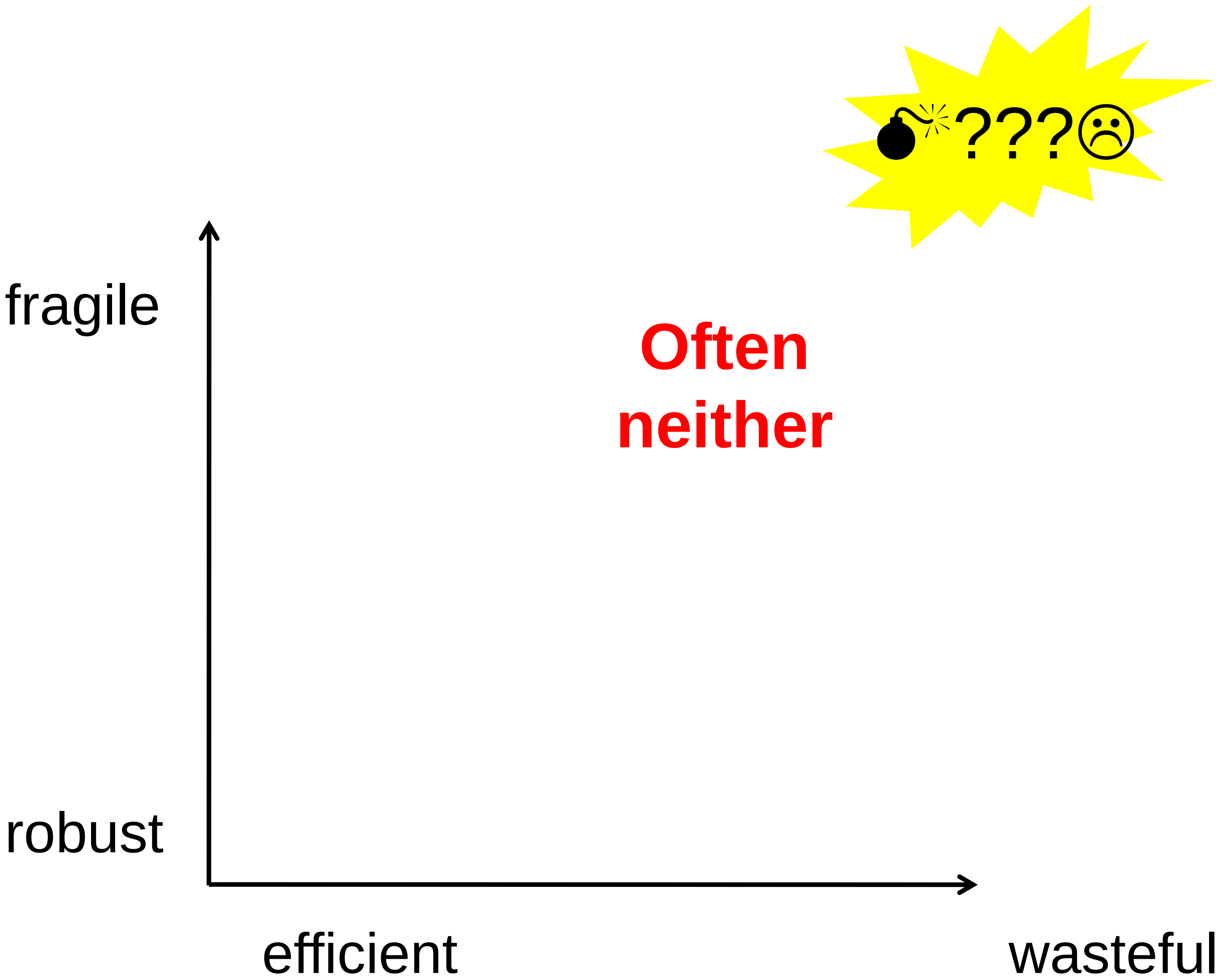
fragile

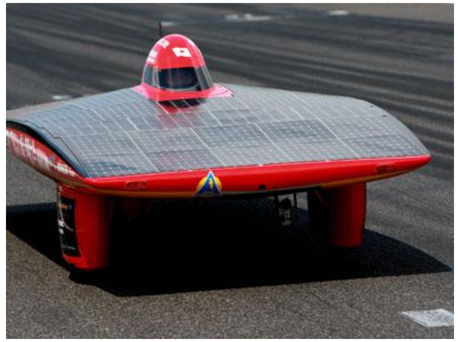
At best we get one

robust

efficient

wasteful


💣???☹
fragile
Often neither
robust
efficient
wasteful



💣???☹

Bad architectures?

fragile

?

gap?

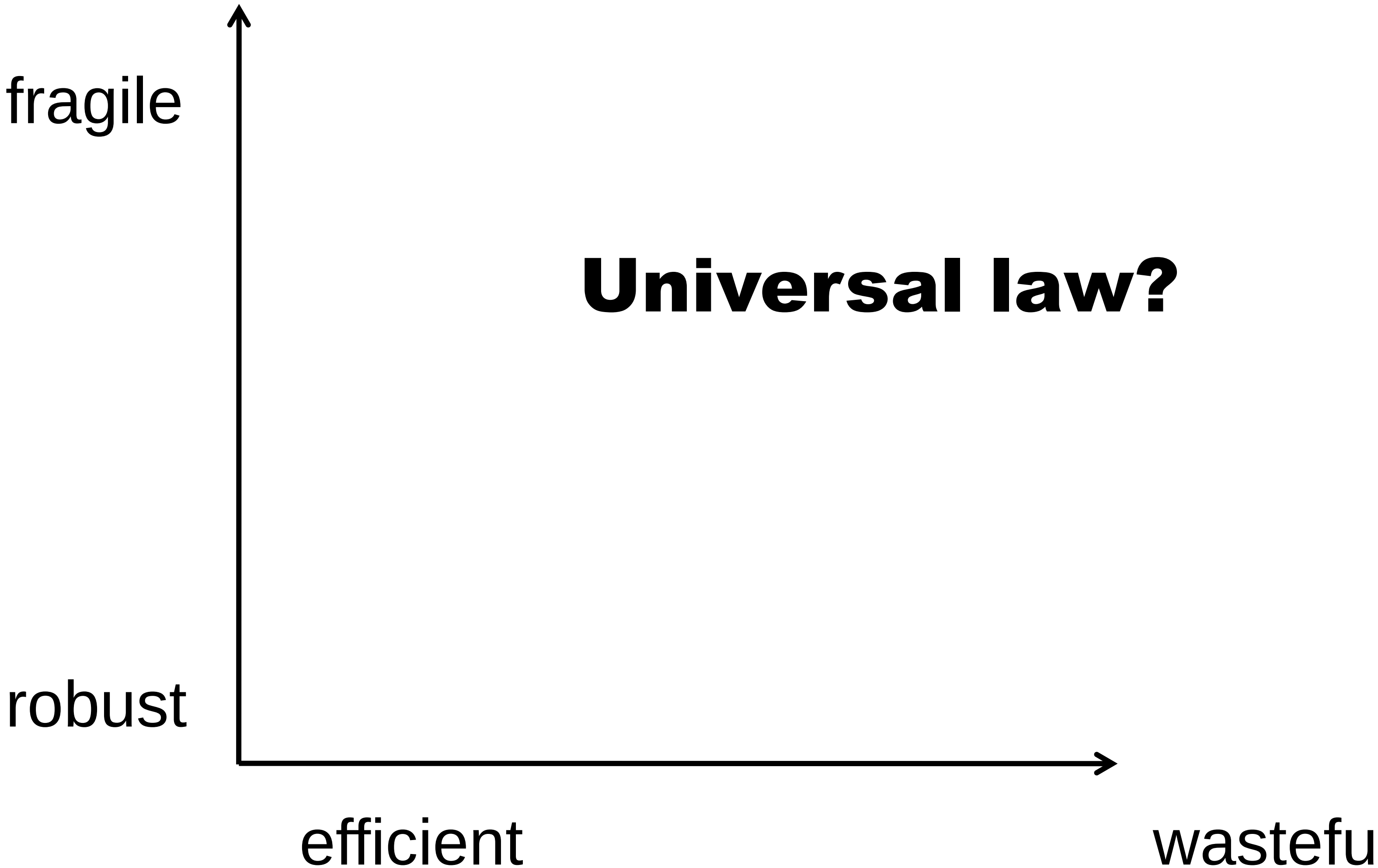
Bad theory?

?

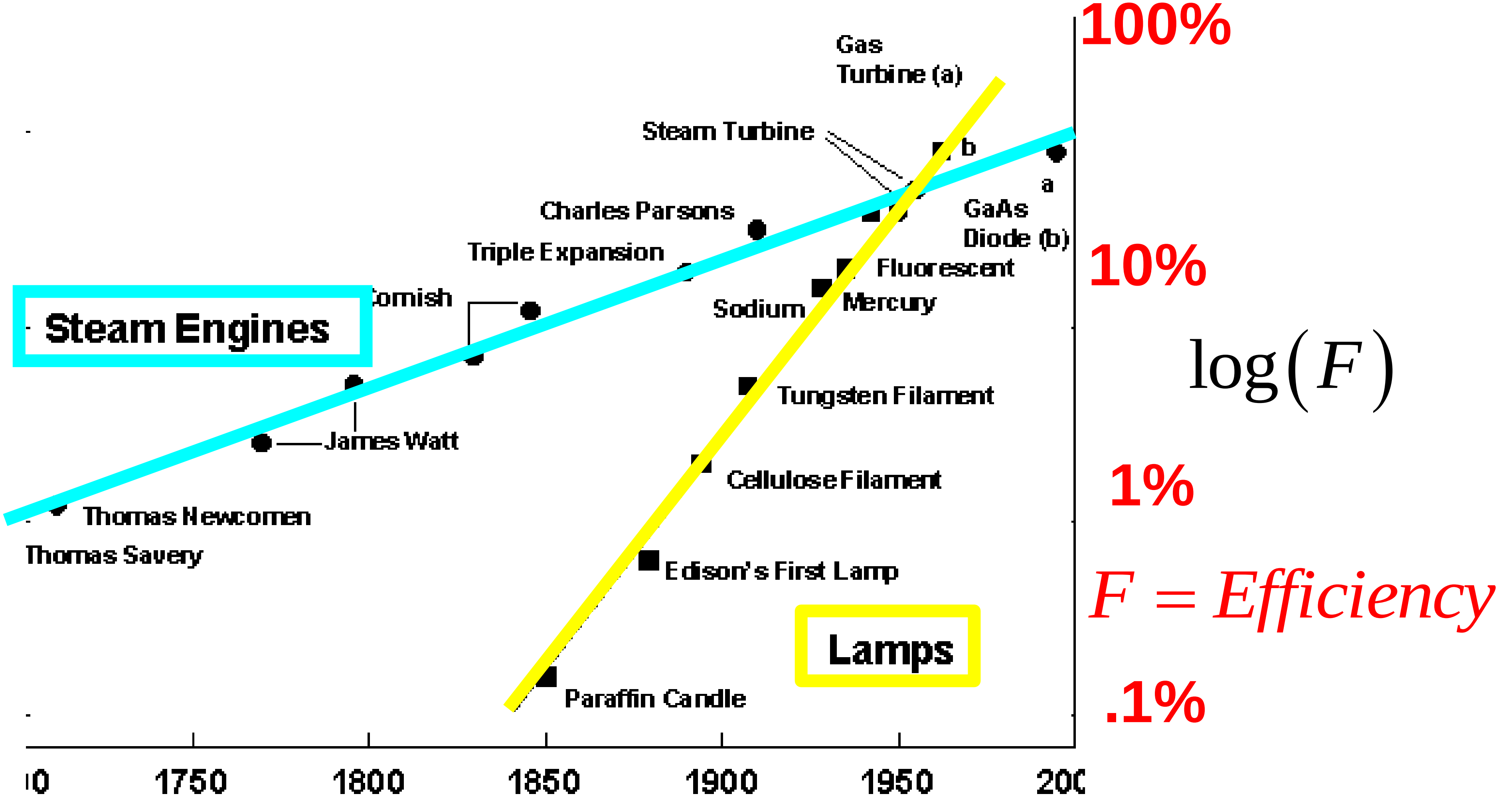
robust

efficient

wasteful

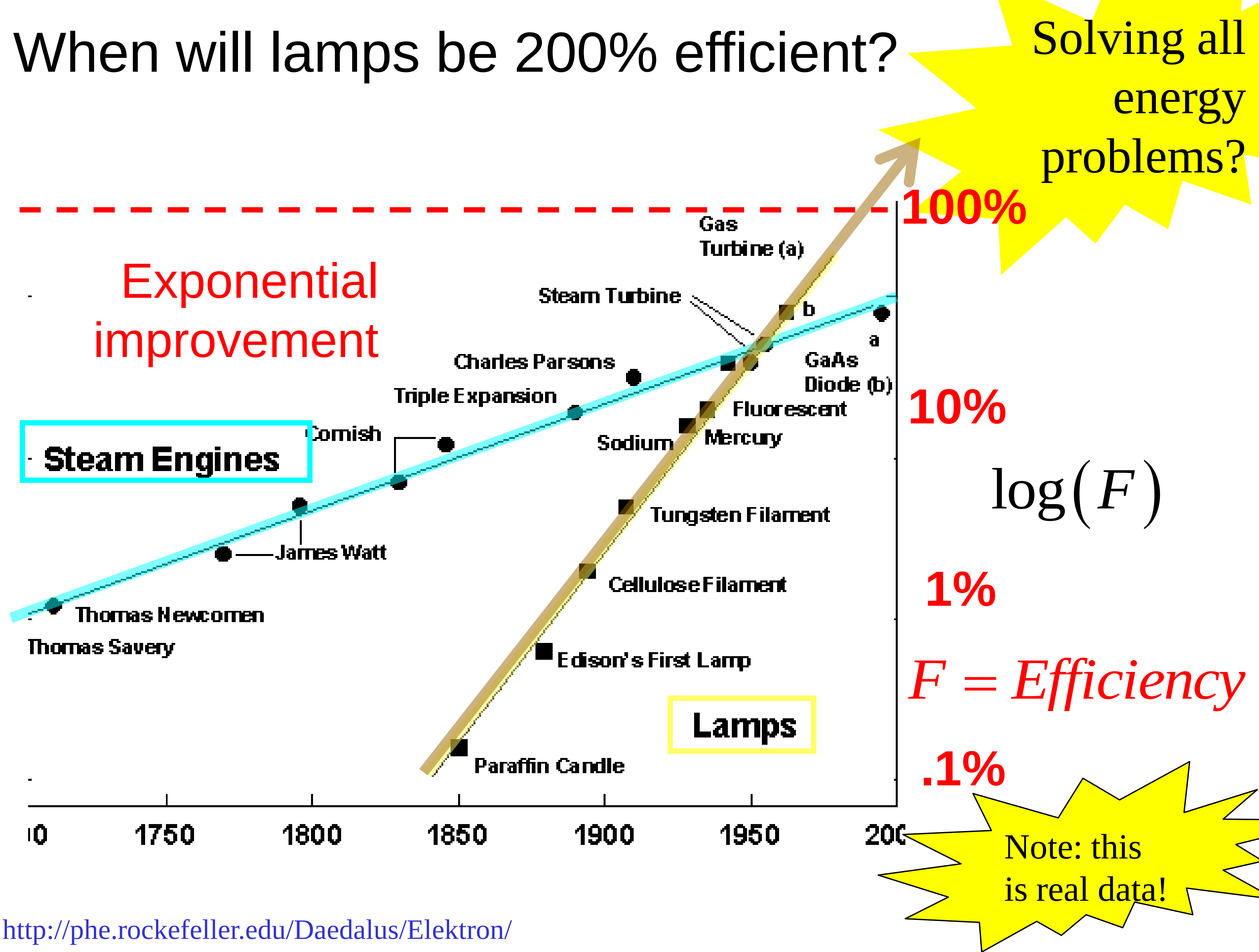

fragile
Universal law?
robust
efficient
wasteful

Exponential improvement in efficiency *F*



http://phe.rockefeller.edu/Daedalus/Elektron/

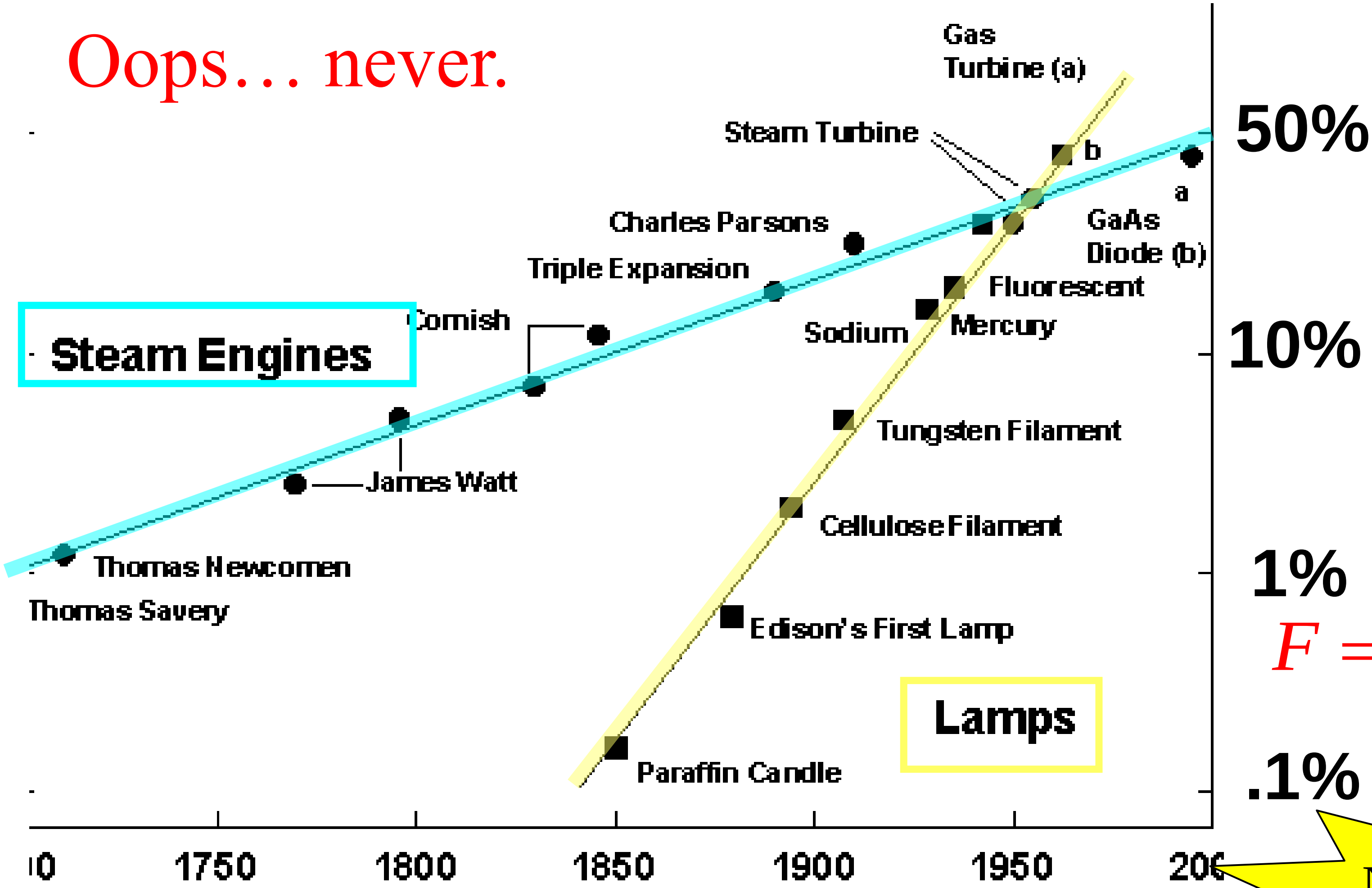
When will lamps be 200% efficient?



http://phe.rockefeller.edu/Daedalus/Elektron/

When will lamps be 200% efficient?

Oops… never.



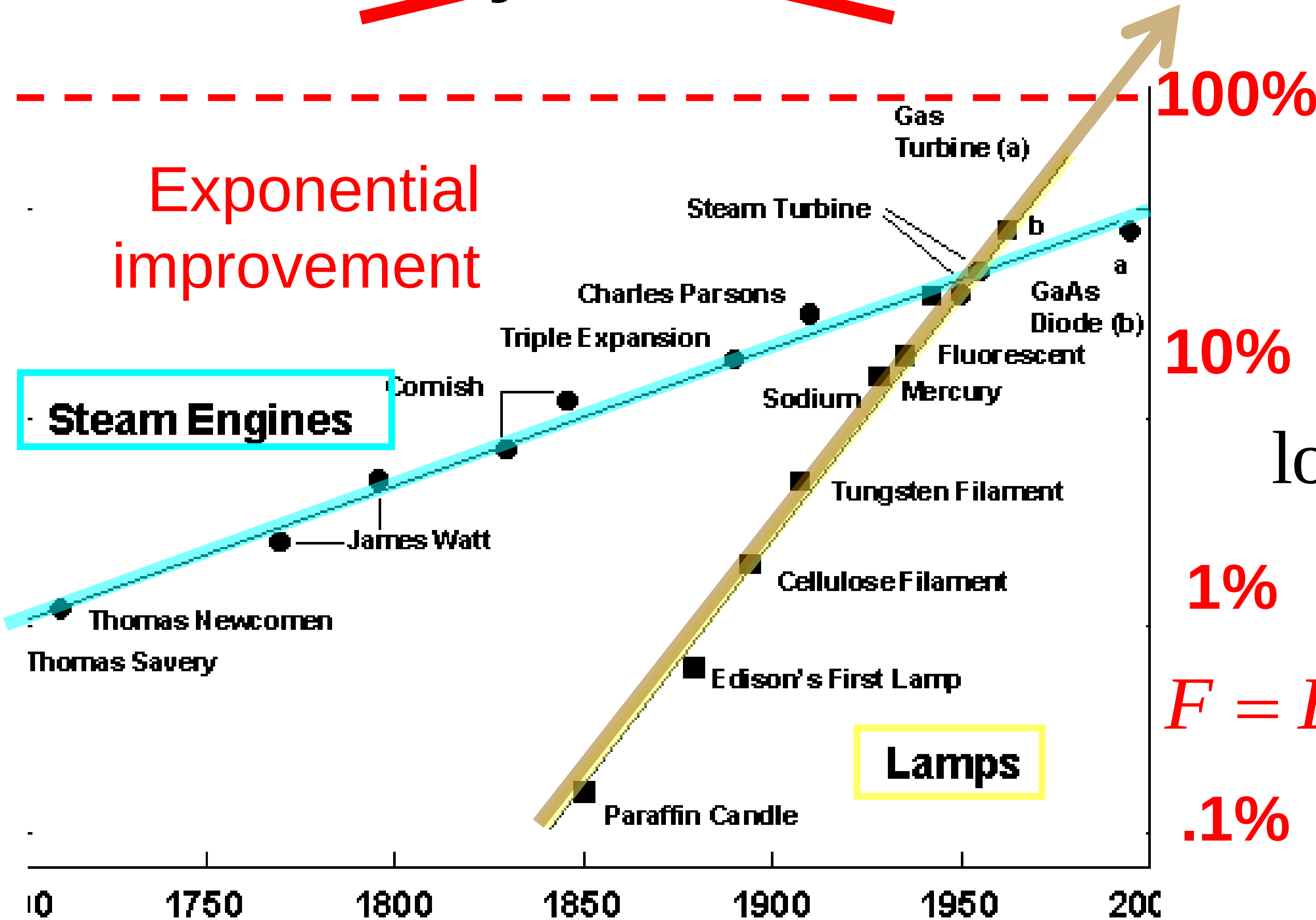
$$\frac{F}{1-F}$$

$F = Efficiency$

Note: need to plot it right.

http://phe.rockefeller.edu/Daedal

~~Doyle's law?~~

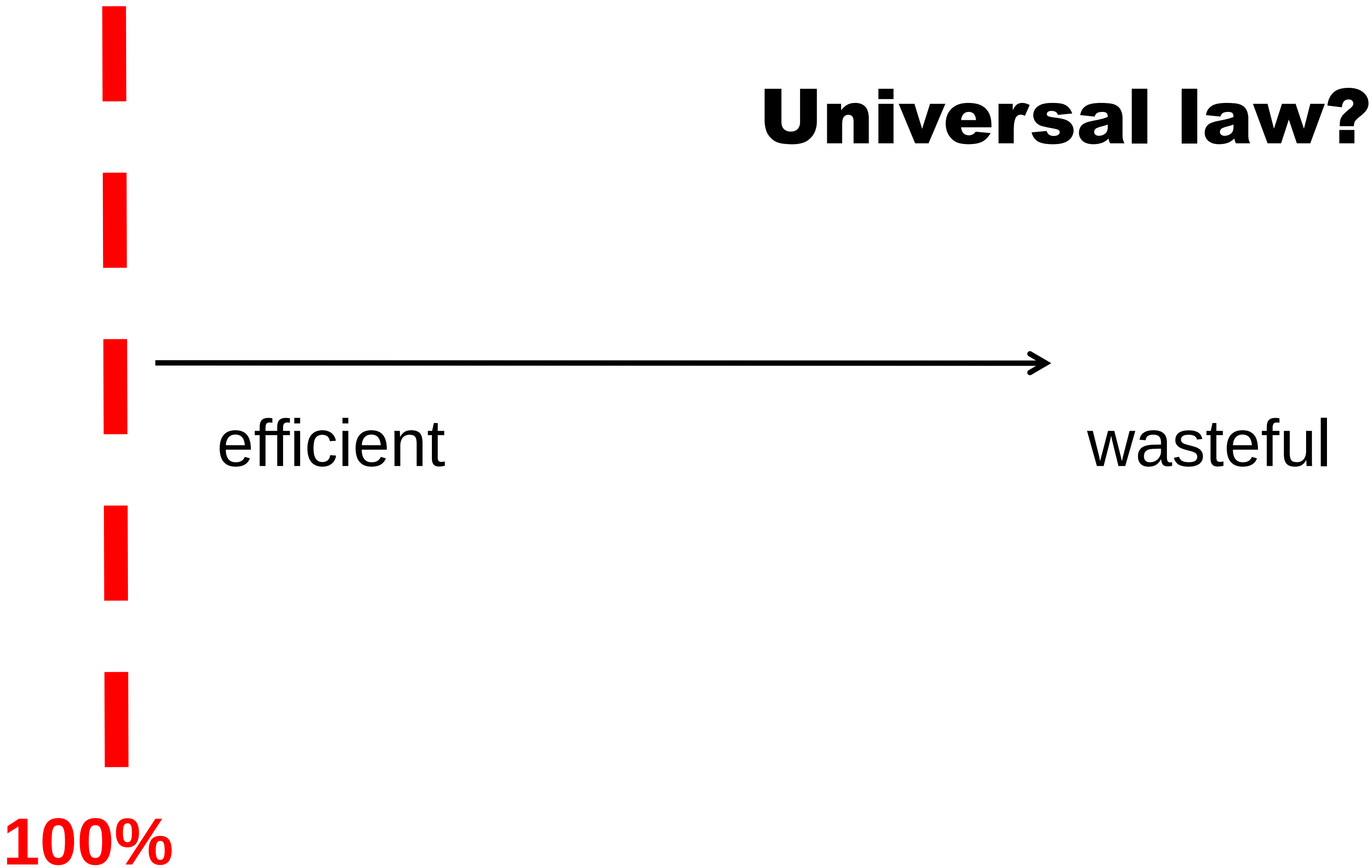


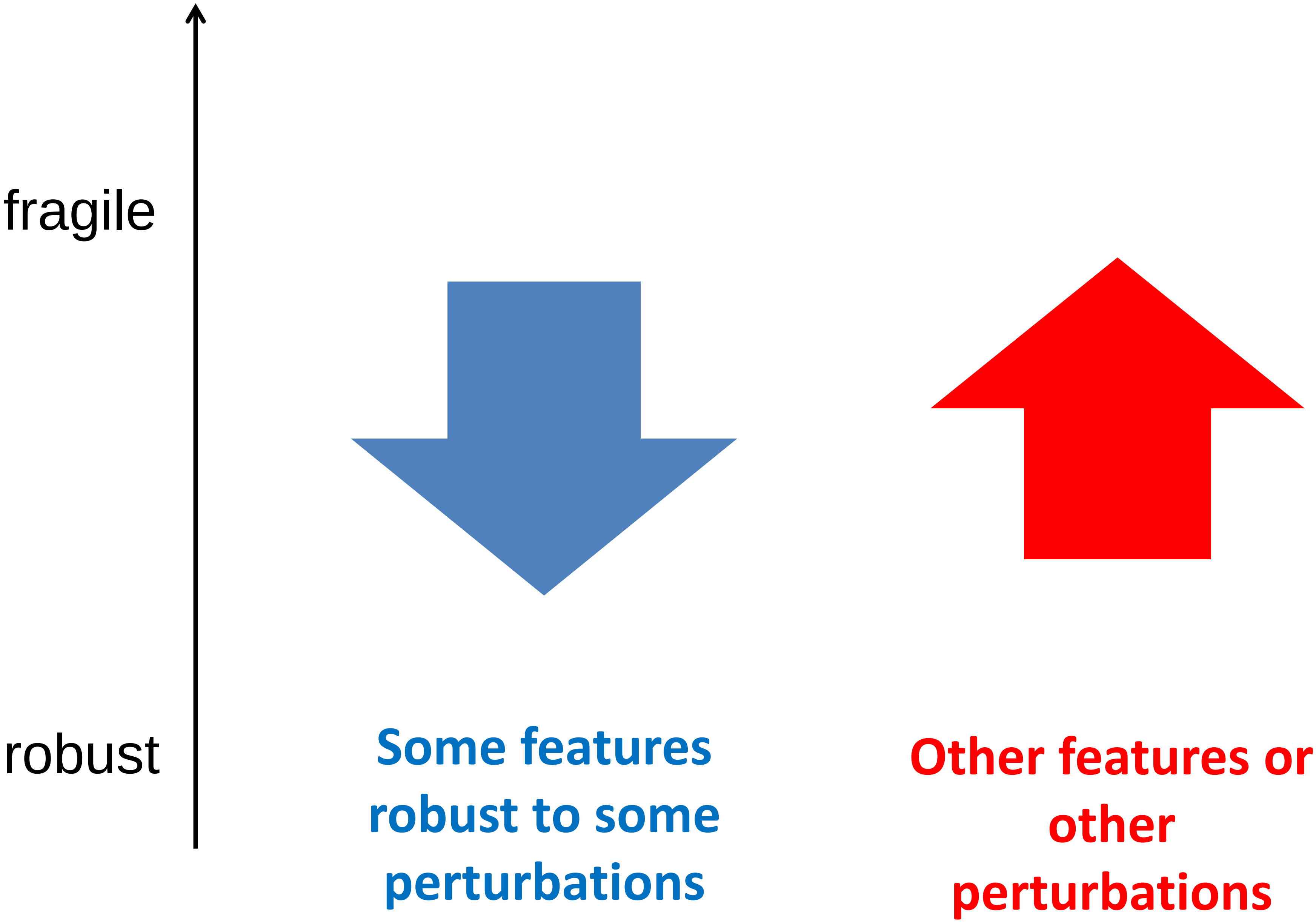
$\log(F)$

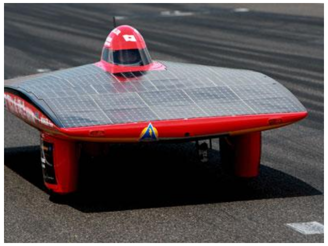
$F = Efficiency$

http://phe.rockefeller.edu/Daedalus/Elektron/

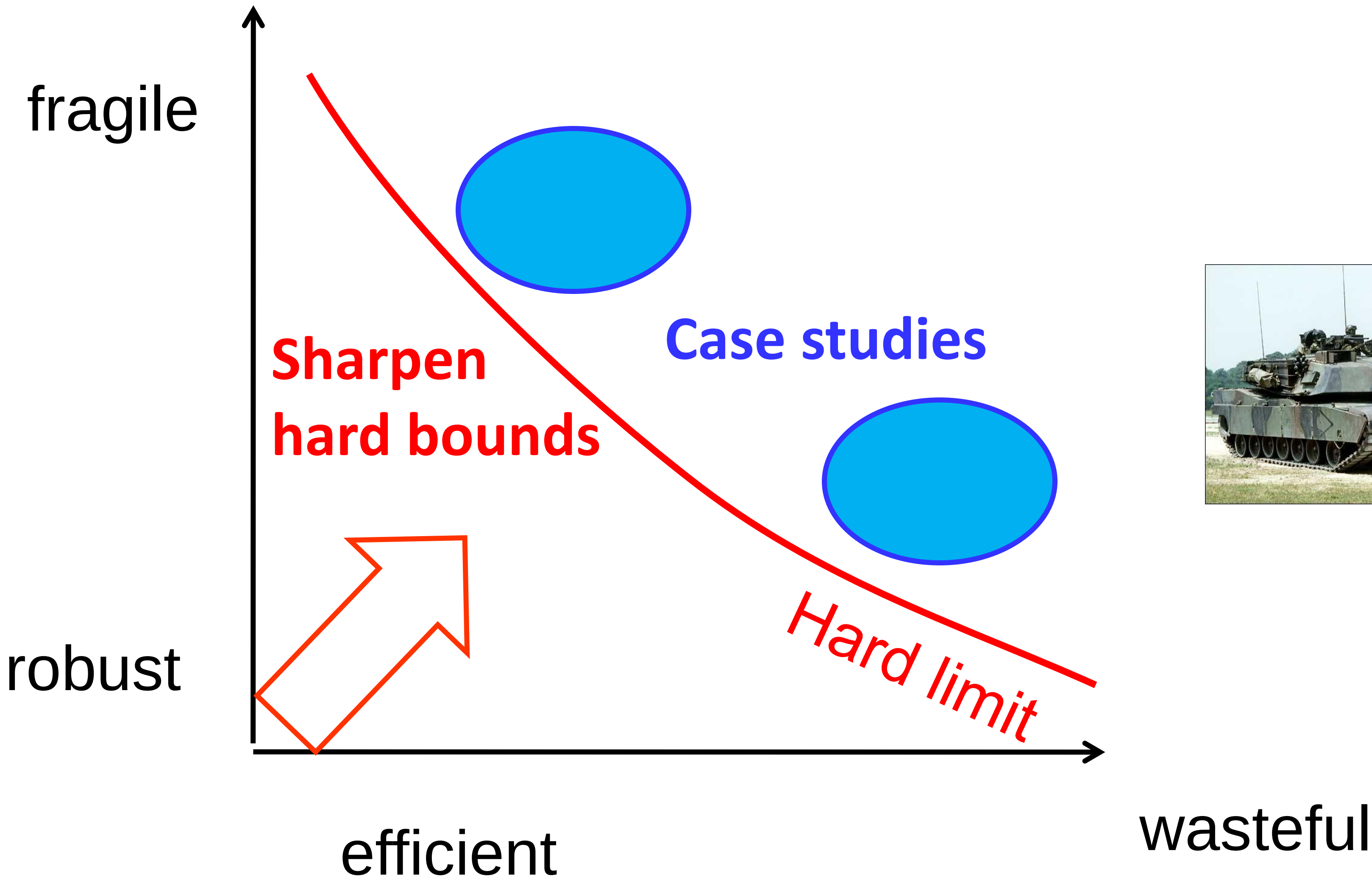
Universal law


Universal law?
efficient
wasteful
100%


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



laws and architectures?



Control, OR

Kalman

Comms

Pontryagin

Bode

Shannon

Nash

Theory?

Deep, but fragmented, incoherent, incomplete

Von Neumann

Carnot

Turing

Boltzmann

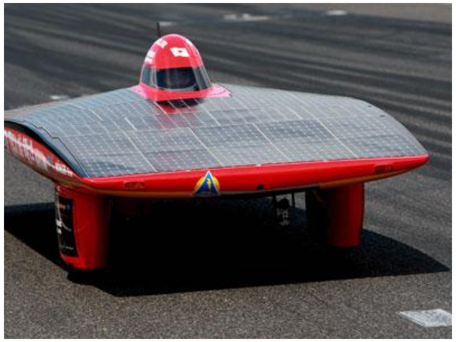
Godel

Heisenberg

Compute

Einstein

Physics



💣???☹

Bad architectures?

fragile

?

gap?

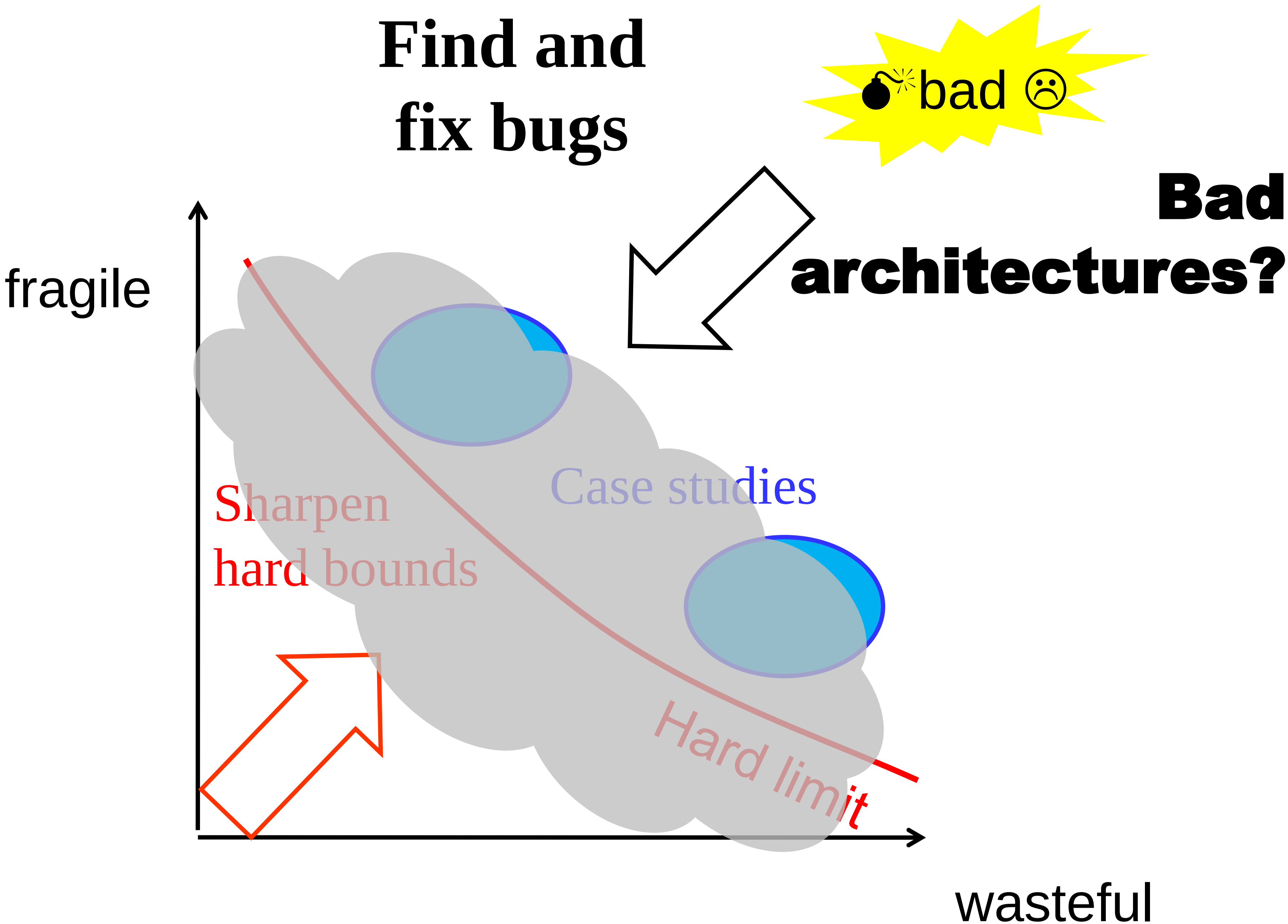
Bad theory?

?

robust

efficient

wasteful


Find and
fix bugs
💣bad ☹
Bad
architectures?
fragile
Case studies
Sharpen
hard bounds
Hard limit
wasteful

Compute

Turing (1912-1954)

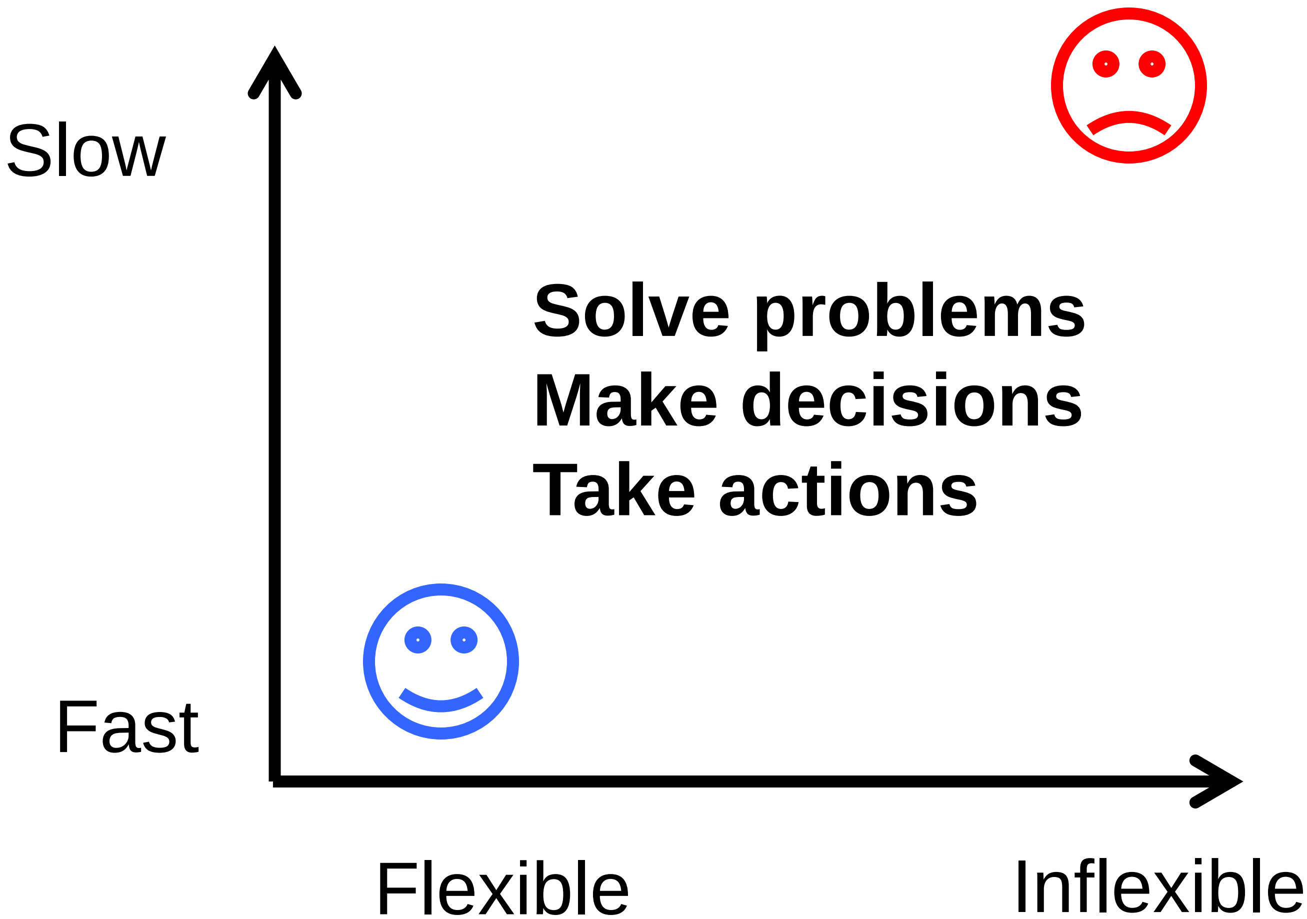
- Turing 100th birthday in 2012
- Turing
  - machine (math, CS)
  - test (AI, neuroscience)
  - pattern (biology)
- Arguably greatest*
  - all time math/engineering combination
  - WW2 hero
  - “invented” software

*Also world-class runner.

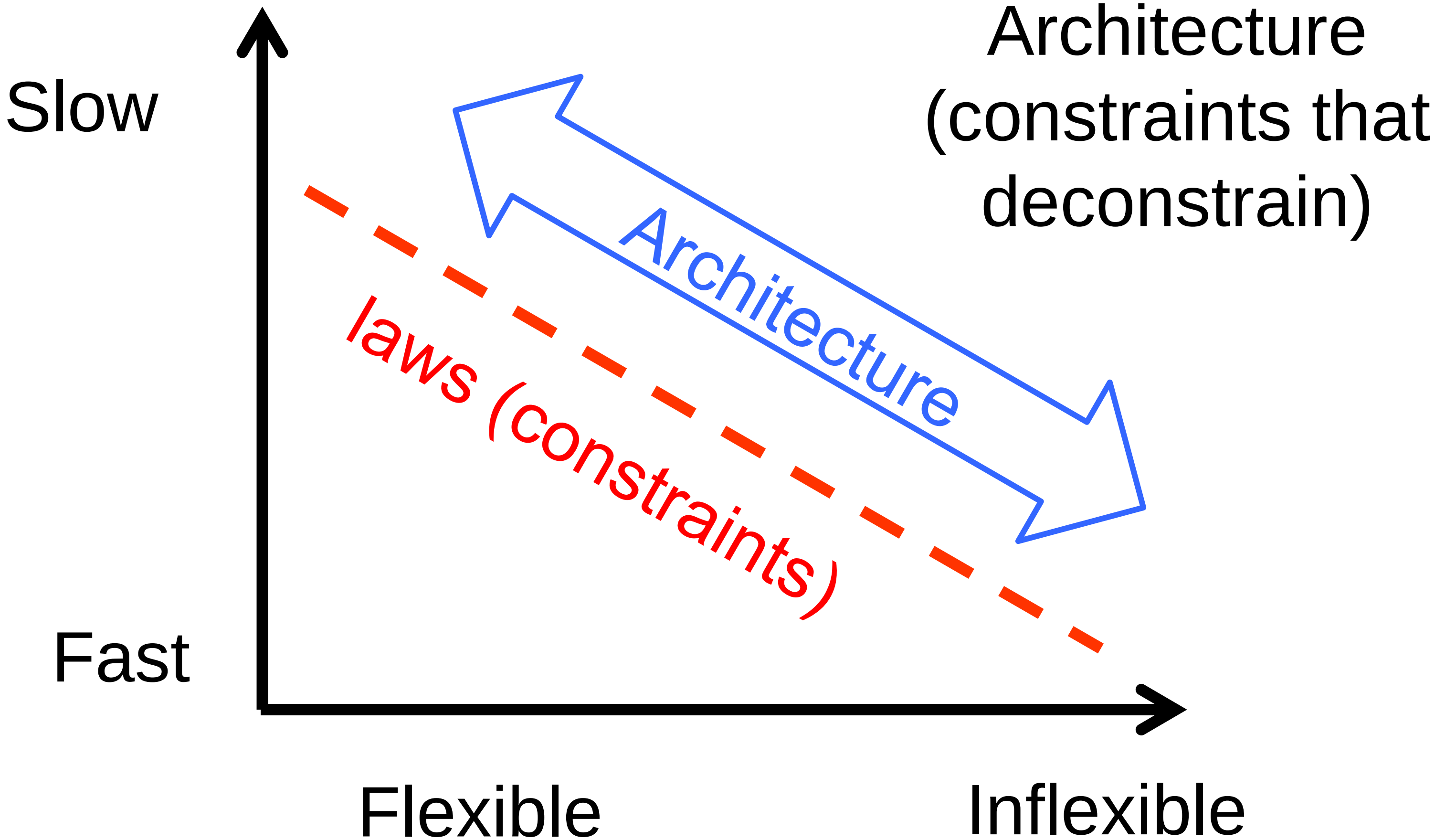
Key papers/results

- 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

Fast and flexible



Laws and architectures



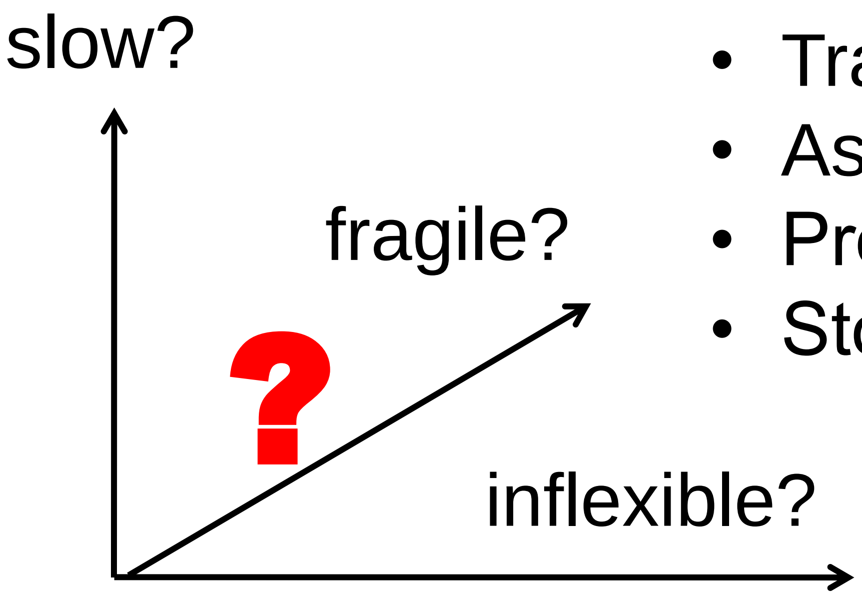
Compute

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

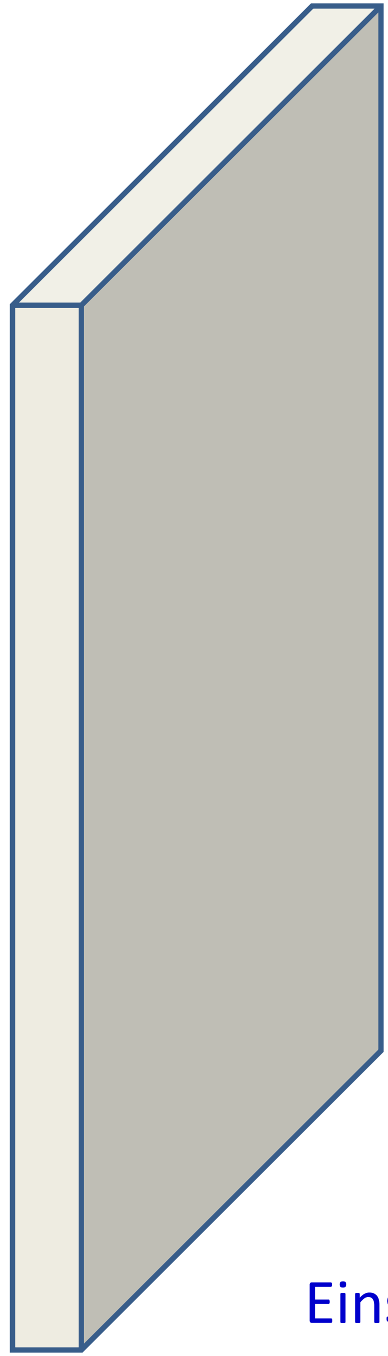
Compute

Turing

Delay is *most* important

Bode

Control, OR



Communicate

Shannon

Delay is *least* important

Carnot

Boltzmann

Heisenberg

Einstein

Physics

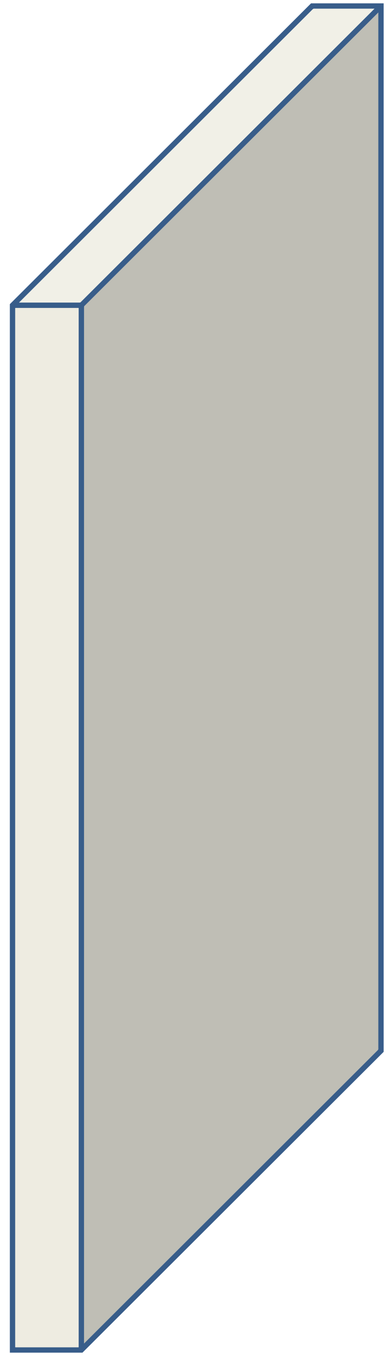
Compute

Turing

Delay is *most* important

Bode

Control, OR



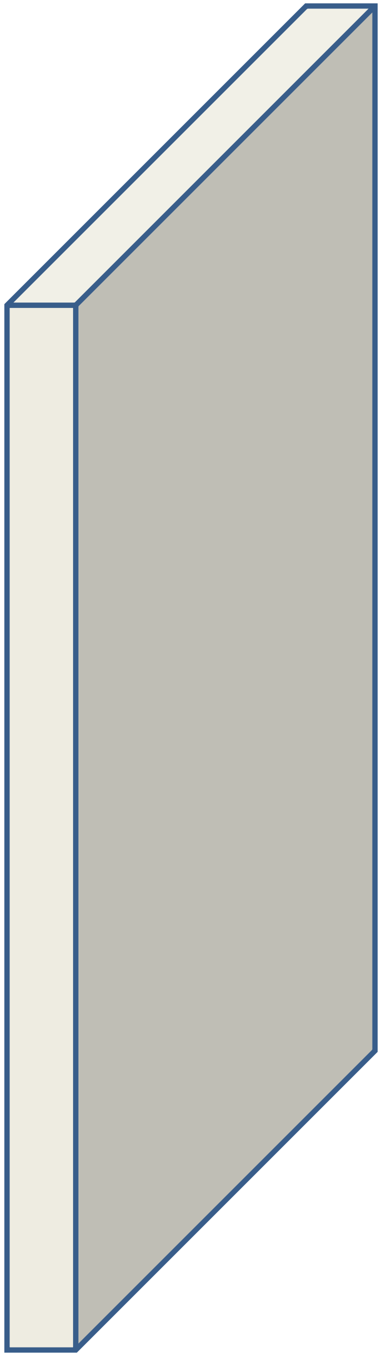
Compute

Turing

Delay is *most* important

Bode

Control, OR



Turing as "new" starting point?

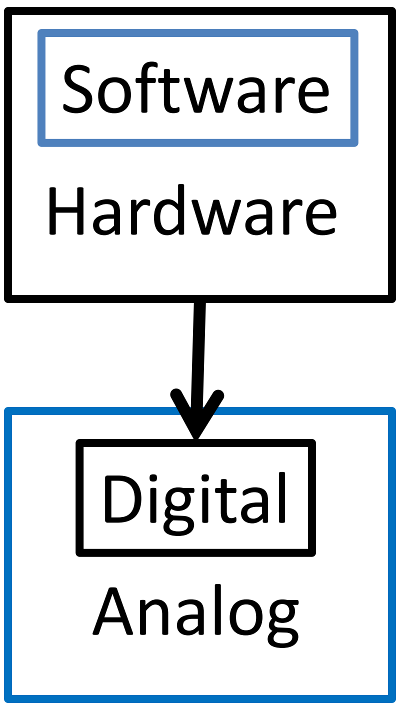
Compute

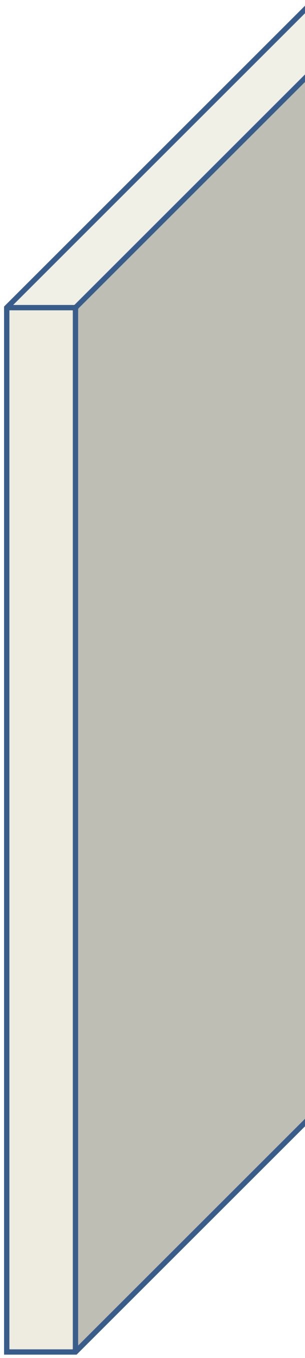
Turing

Delay is *most* important

Bode

Control, OR

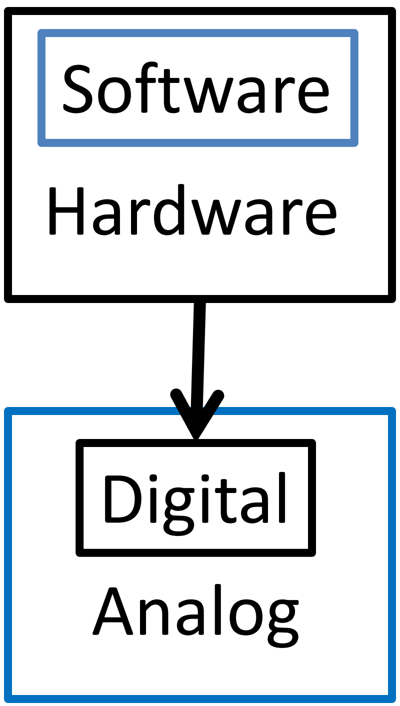




Turing as "new" starting point?

Essentials:

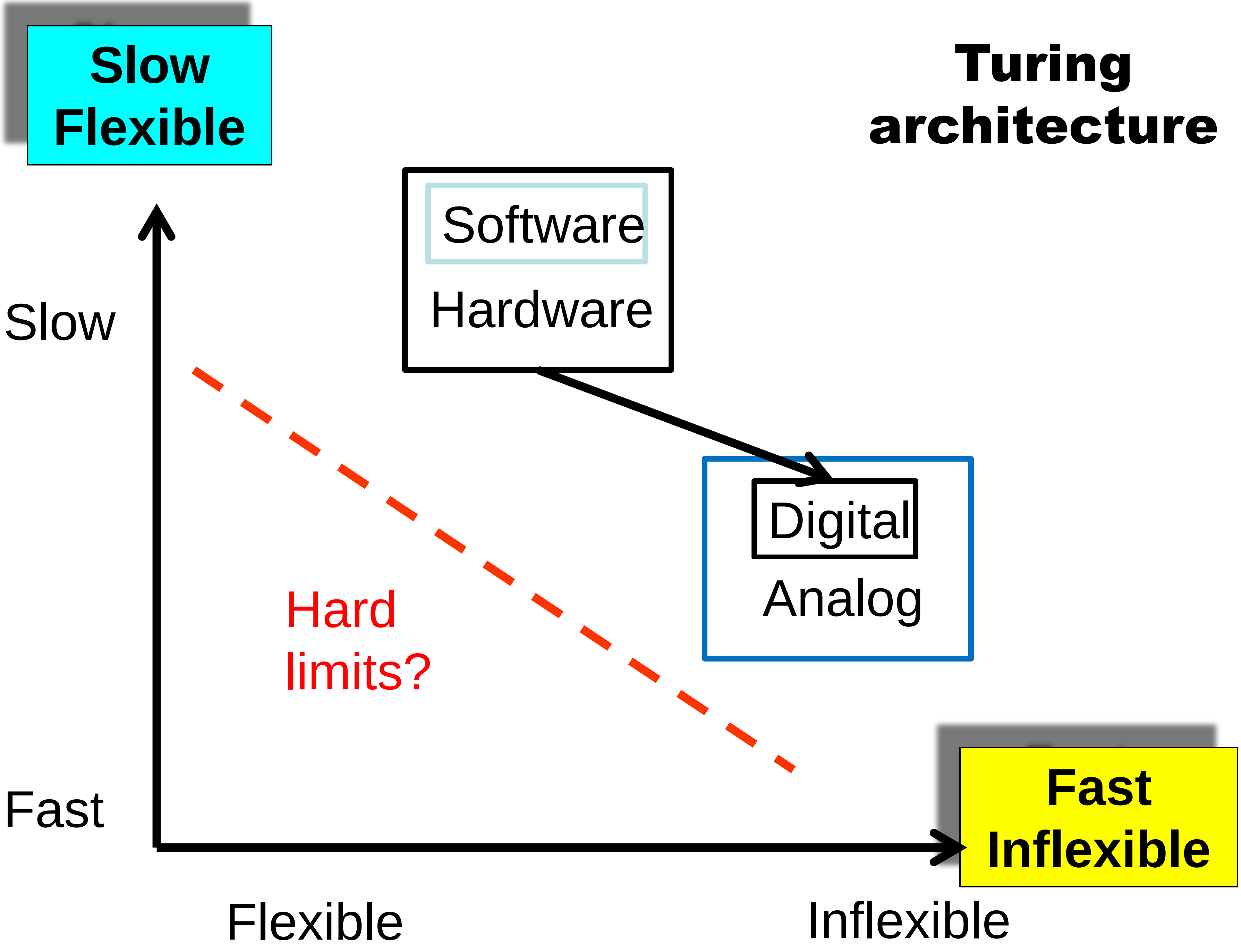
0. **Model**
1. **Universal laws**
2. **Universal architecture**
3. **Practical implementation**



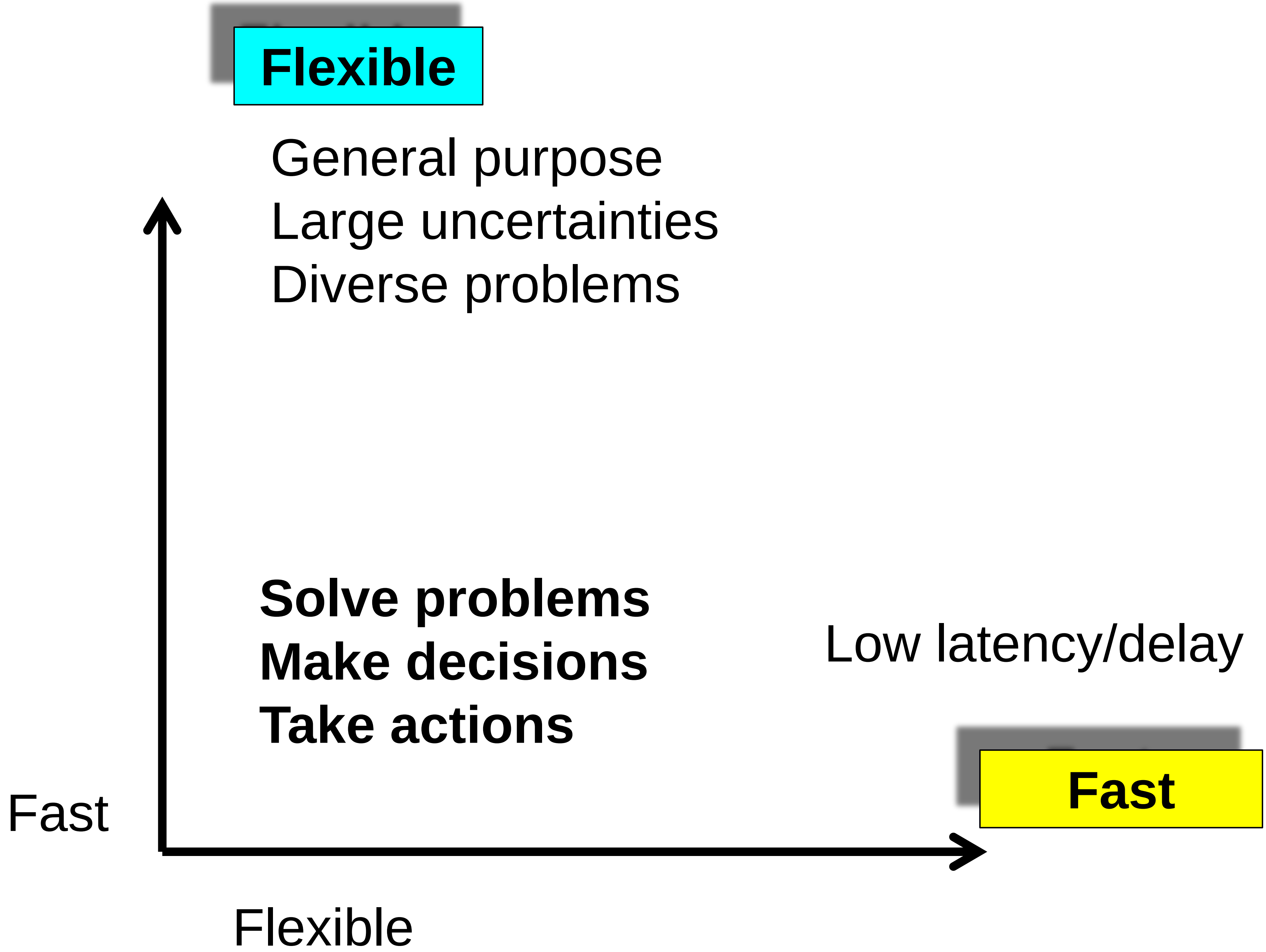
Turing's 3 step research:

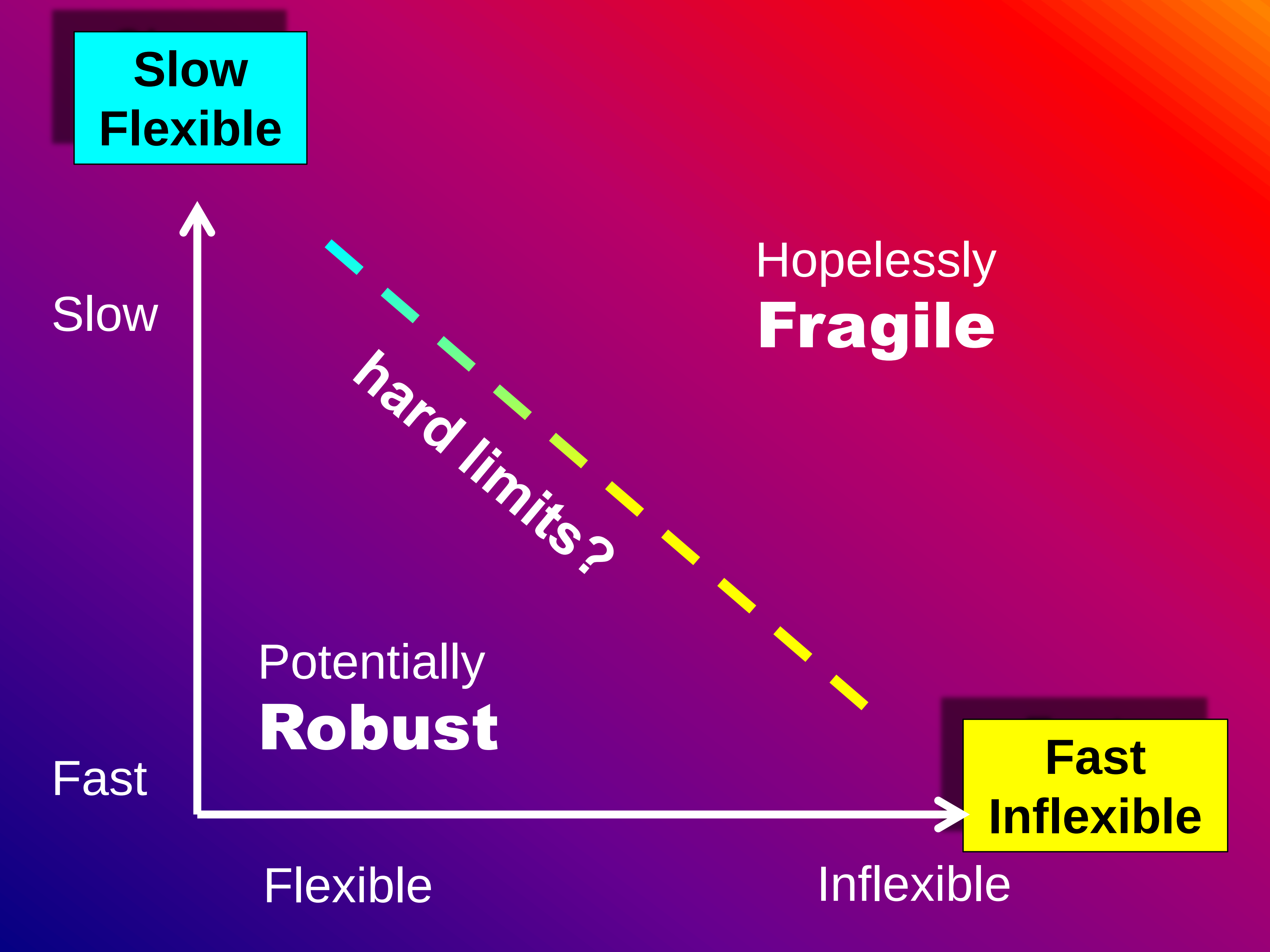
0. Virtual (TM) machines
1. hard limits, (un)decidability using standard model (TM)
2. Universal architecture achieving hard limits (UTM)
3. Practical implementation in digital electronics (biology?)

Who/what

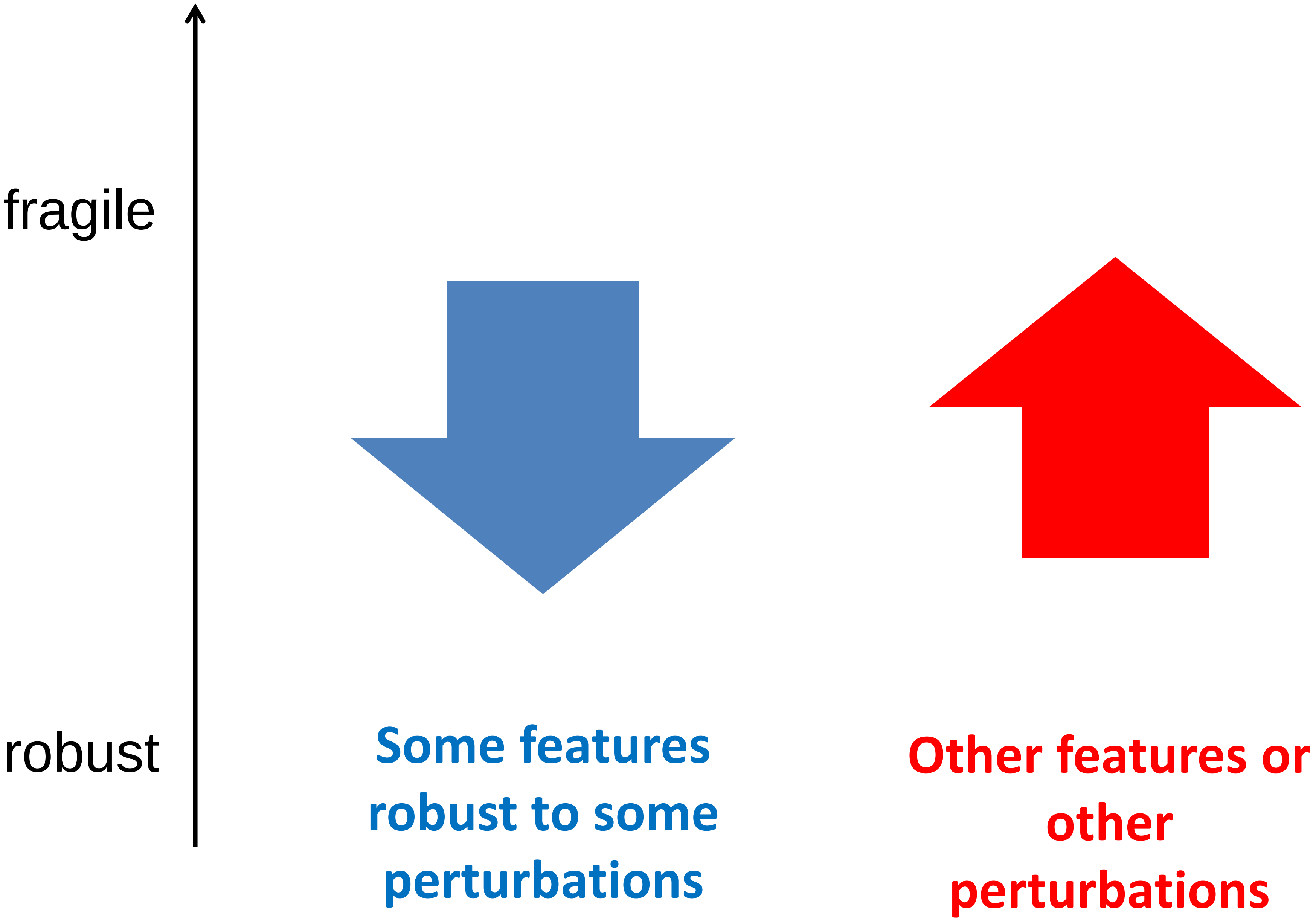


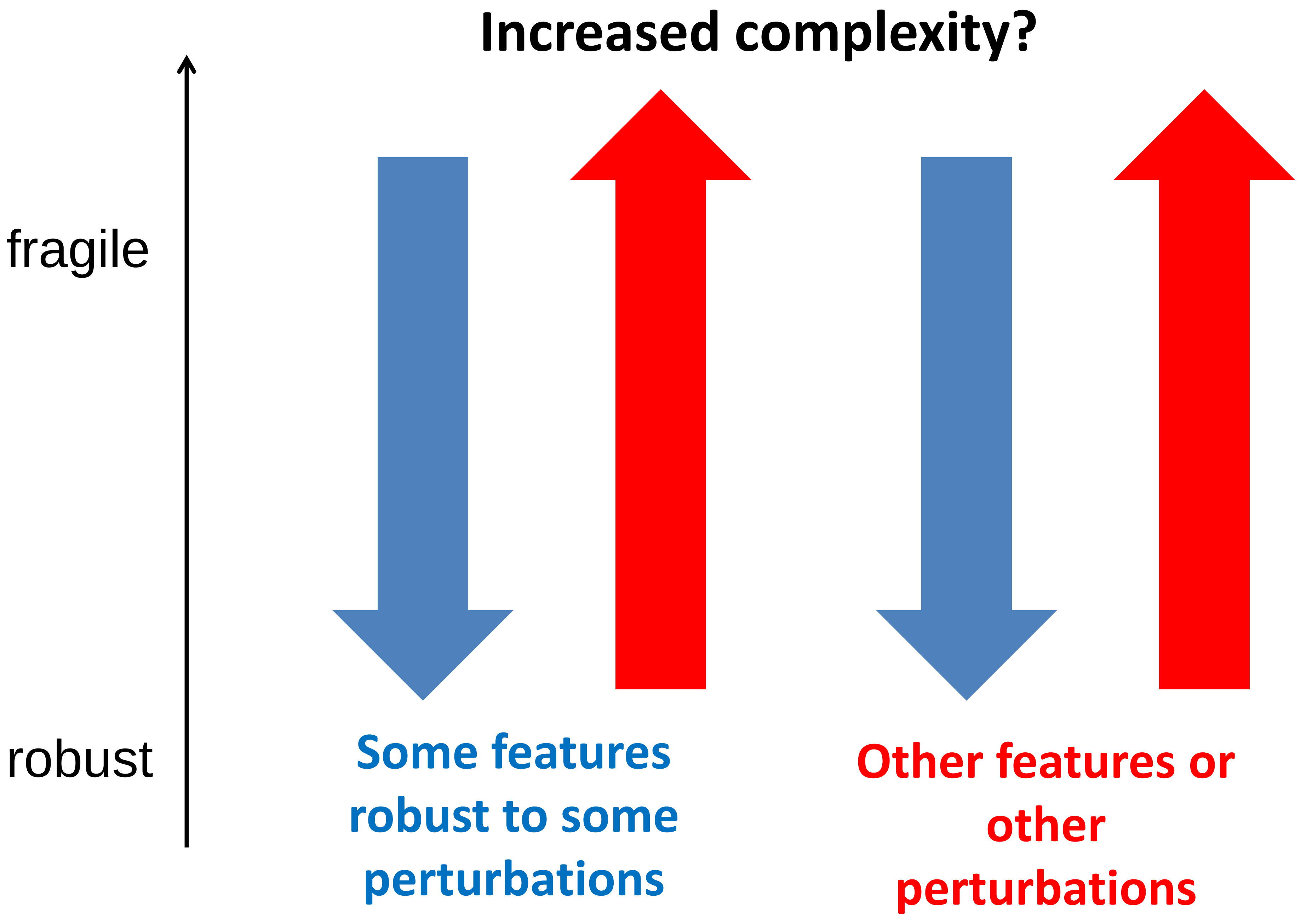
Slow
Flexible
Turing
architecture
Software
Hardware
Slow
Digital
Analog
Hard
limits?
Fast
Fast
Inflexible
Flexible
Inflexible


Flexible
General purpose
Large uncertainties
Diverse problems
Solve problems
Make decisions
Take actions
Low latency/delay
Fast
Fast
Flexible



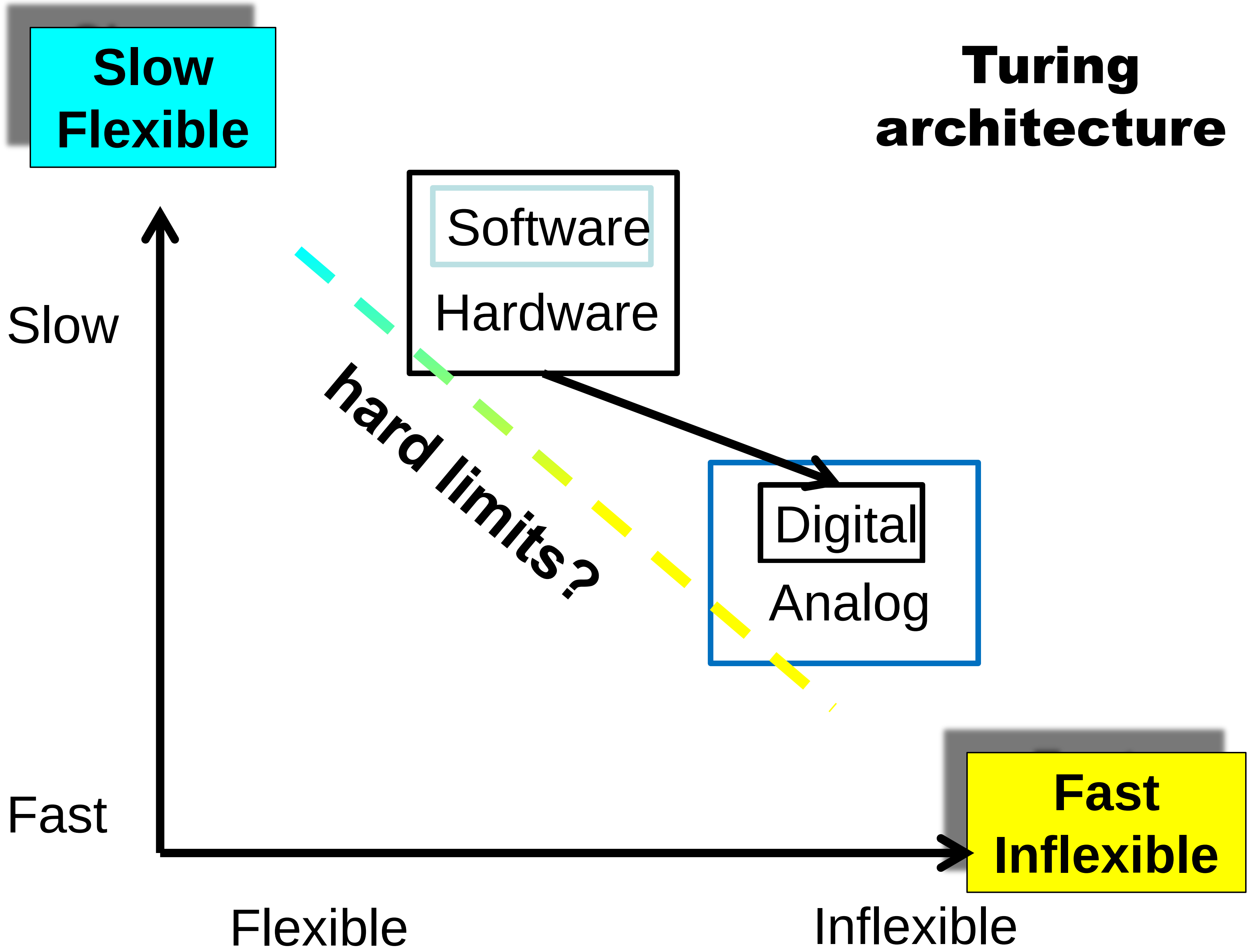
Slow
Flexible
Hopelessly
Fragile
Slow
hard limits?
Potentially
Robust
Fast
Fast
Inflexible
Flexible
Inflexible

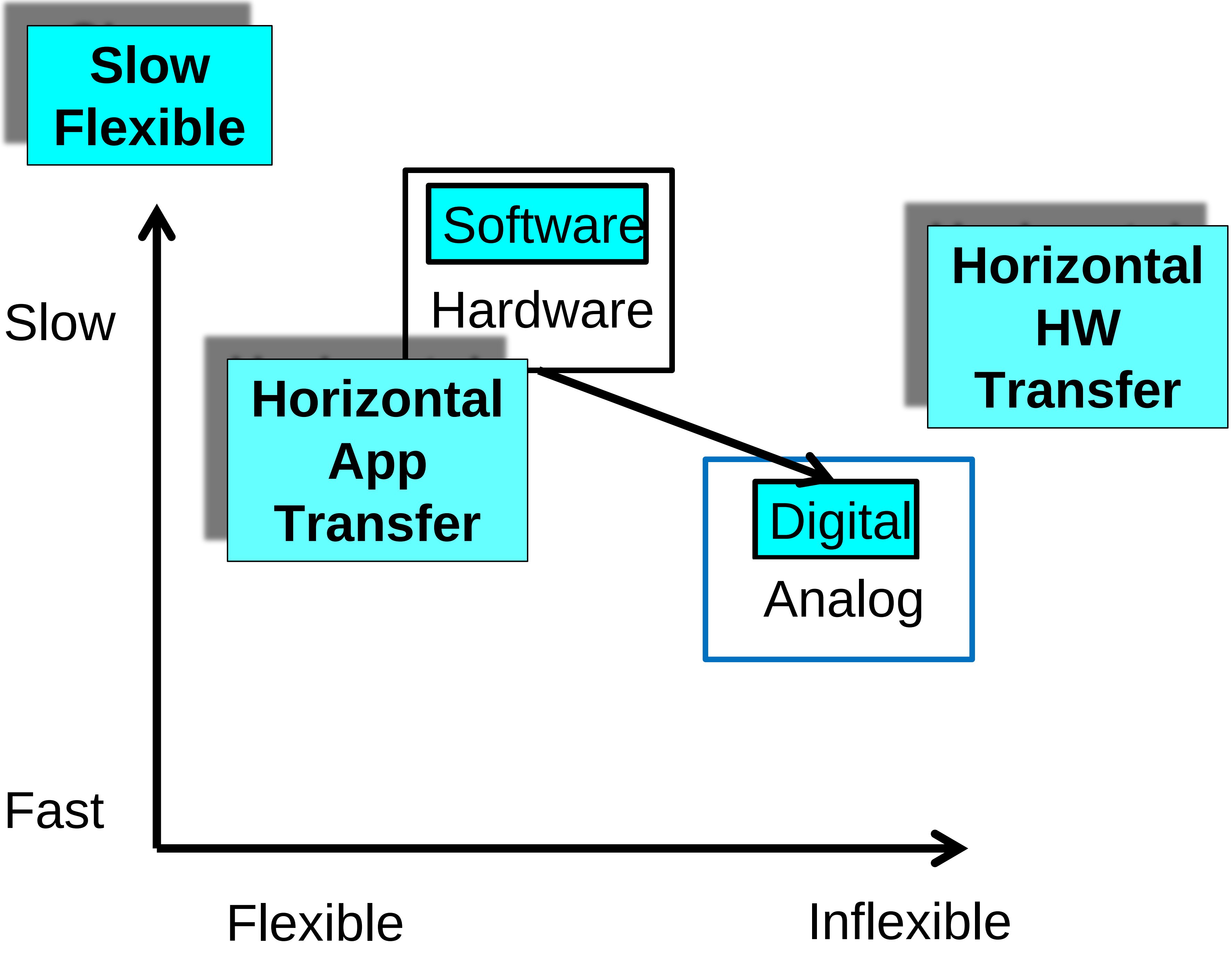

fragile
robust
Some features robust to some perturbations
Other features or other perturbations


Increased complexity?
fragile
robust
Some features robust to some perturbations
Other features or other perturbations

Robust		Fragile
Modular	*and*	Distributed
Simple	~~***xor***~~	Complex
Plastic		Frozen
Evolvable		Frozen

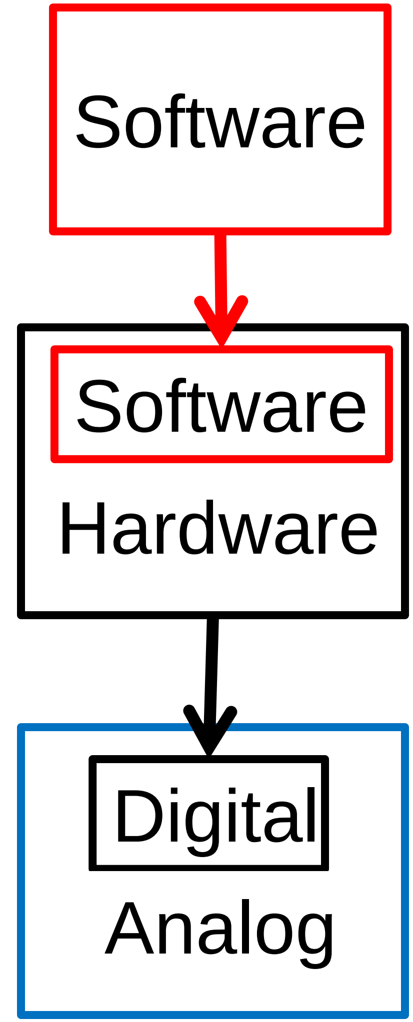
tradeoffs


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


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

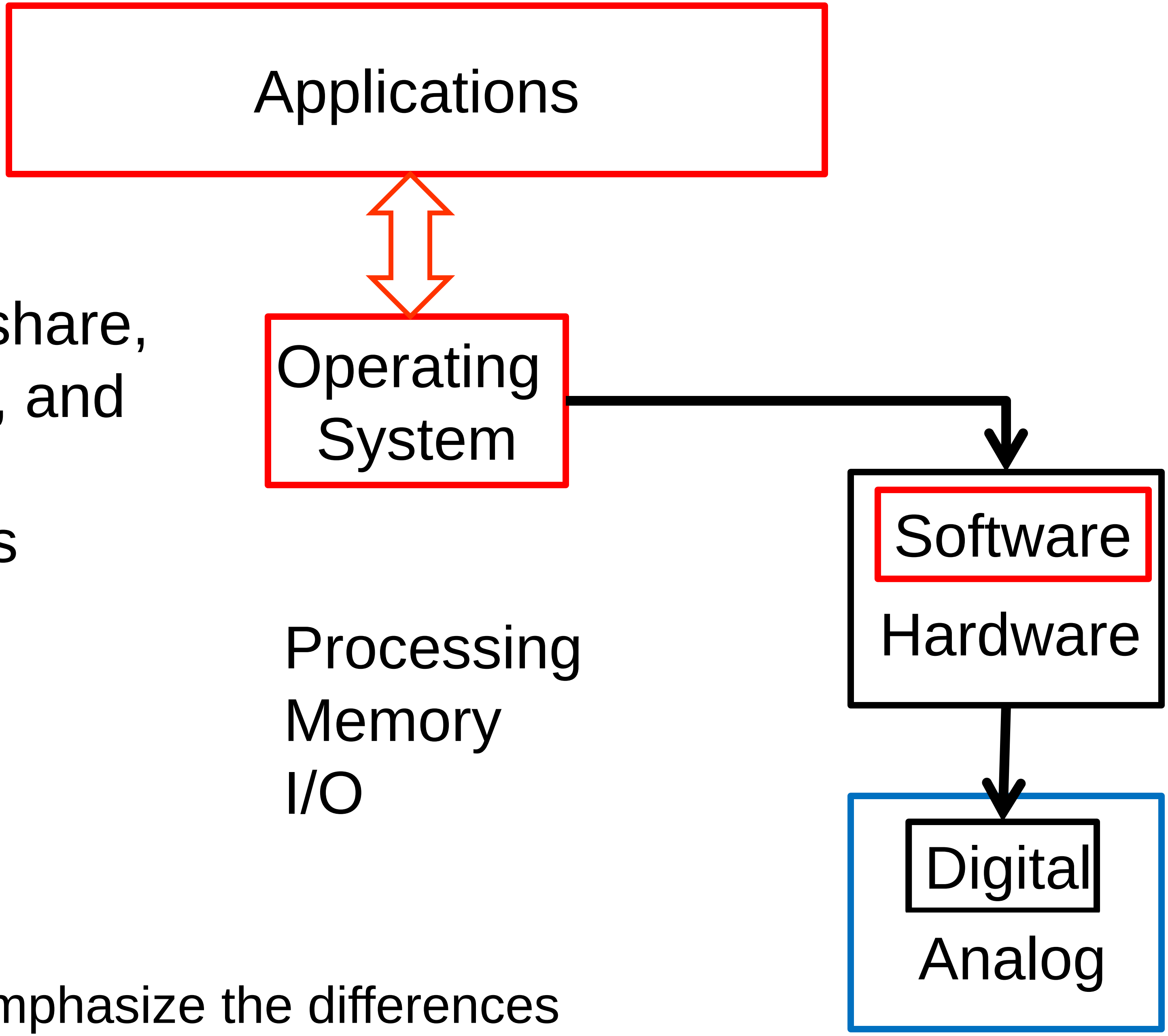
Slow execution
Flexible reprogramming

Faster execution
Less flexible

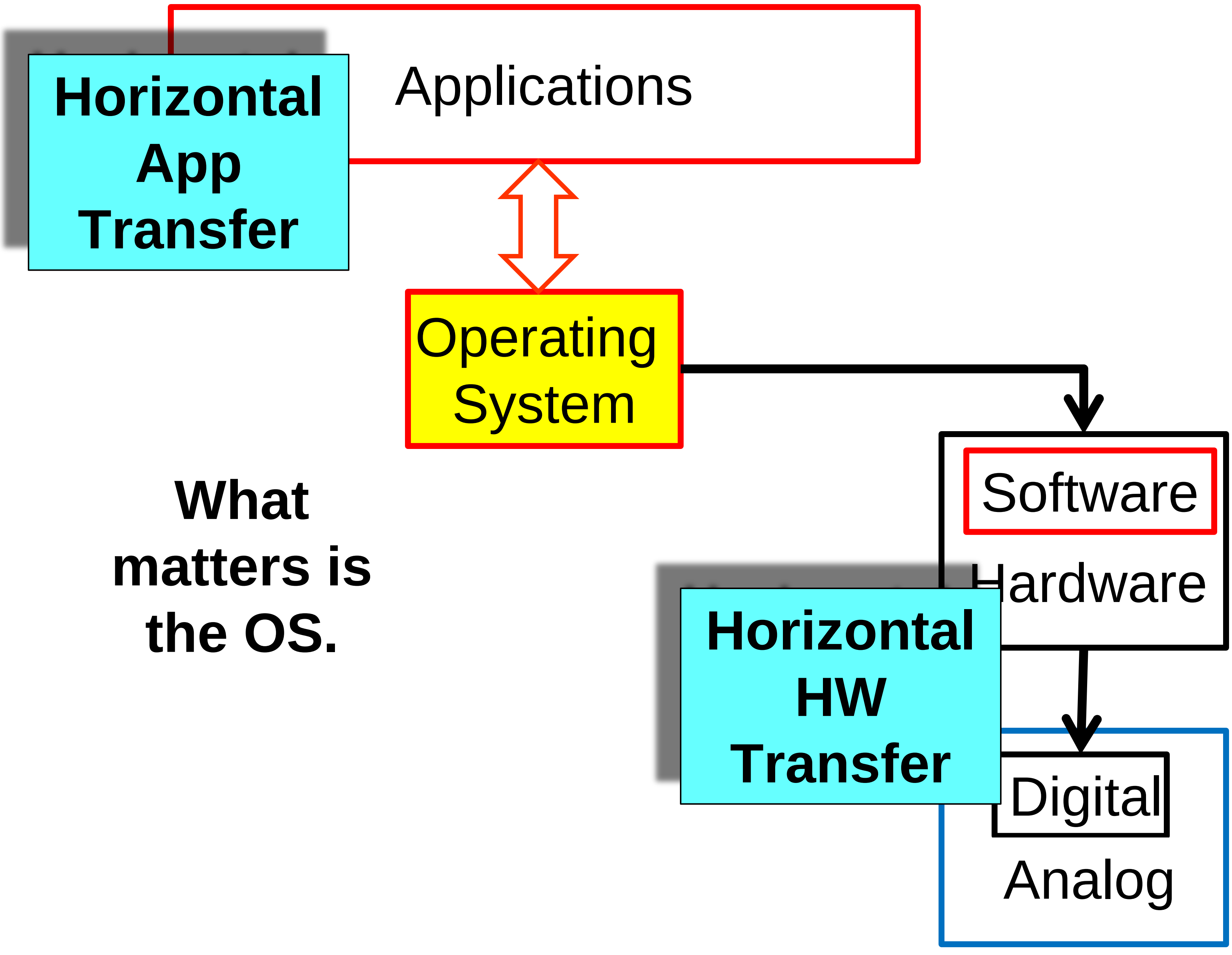


Modern technology gives lots of intermediate alternatives.

Control, share, virtualize, and manage resources

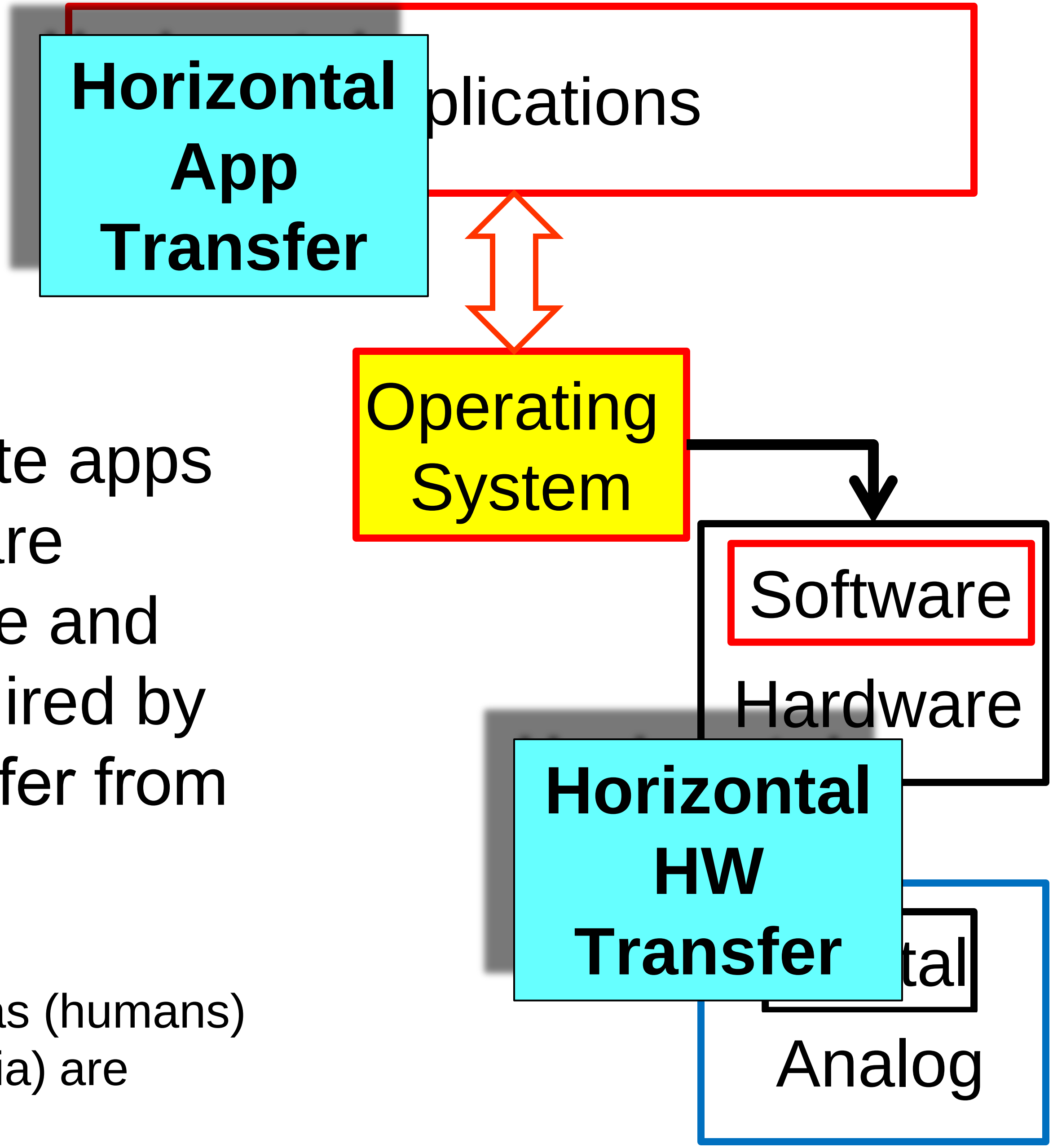


Want to emphasize the differences between these two types of layering.


Applications
Horizontal App Transfer
Operating System
What matters is the OS.
Software
Hardware
Horizontal HW Transfer
Digital
Analog

- Some people write apps and build hardware
- But most software and hardware is acquired by “horizontal” transfer from others

- Similarly, most new ideas (humans) and new genes (bacteria) are acquired horizontally



Compute

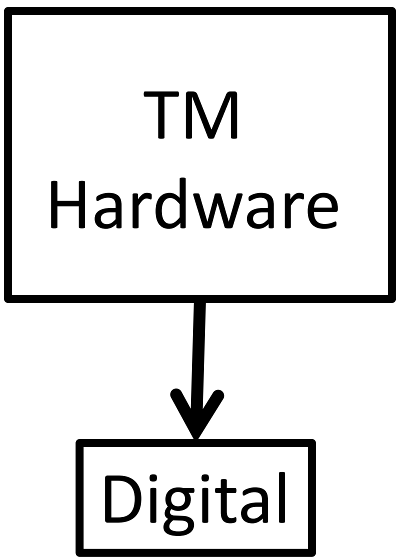
Turing

Why

Necessity

Essentials:

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



Turing's 3 step research:

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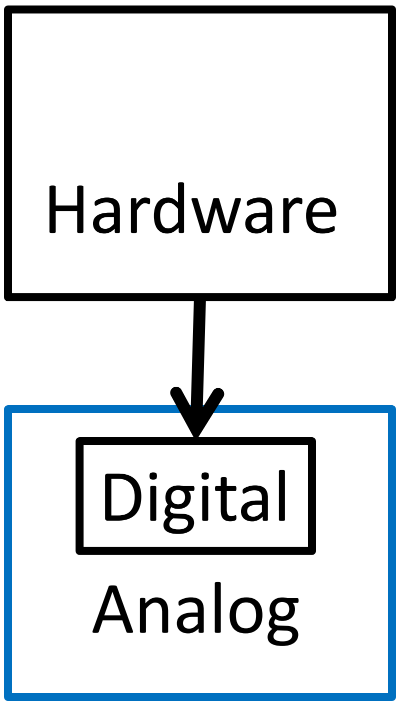
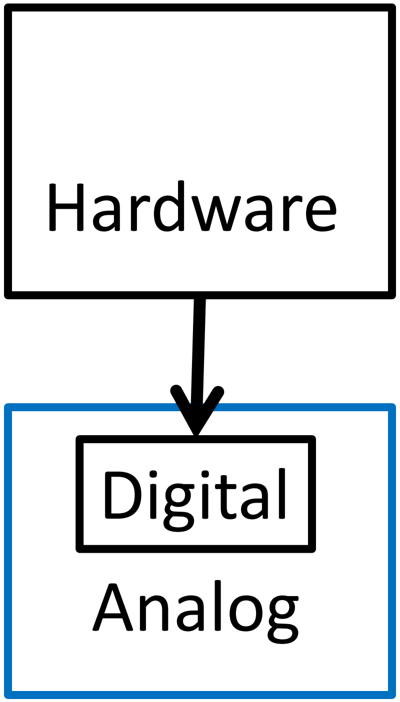


- …being digital should be of greater interest than that of being electronic. That it is electronic is certainly important because these machines owe their high speed to this… But this is virtually all that there is to be said on that subject.
- That the machine is digital however has more subtle significance.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

1947 Lecture to LMS

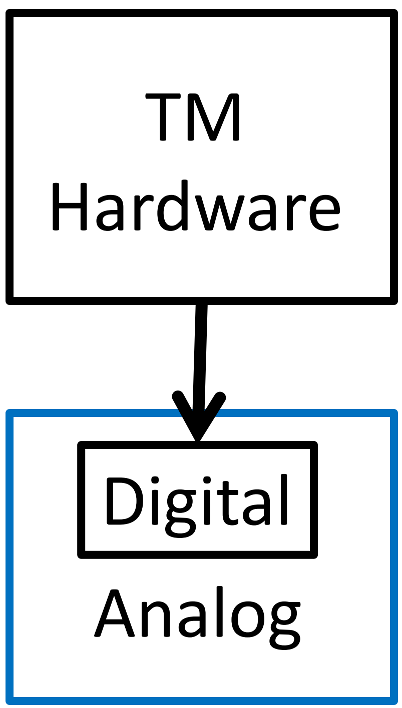


- … digital … of greater interest than that of being electronic …
- …any desired degree of accuracy…
- This accuracy is not obtained by more careful machining of parts, control of temperature variations, and such means, but by a slight increase in the amount of equipment in the machine.

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

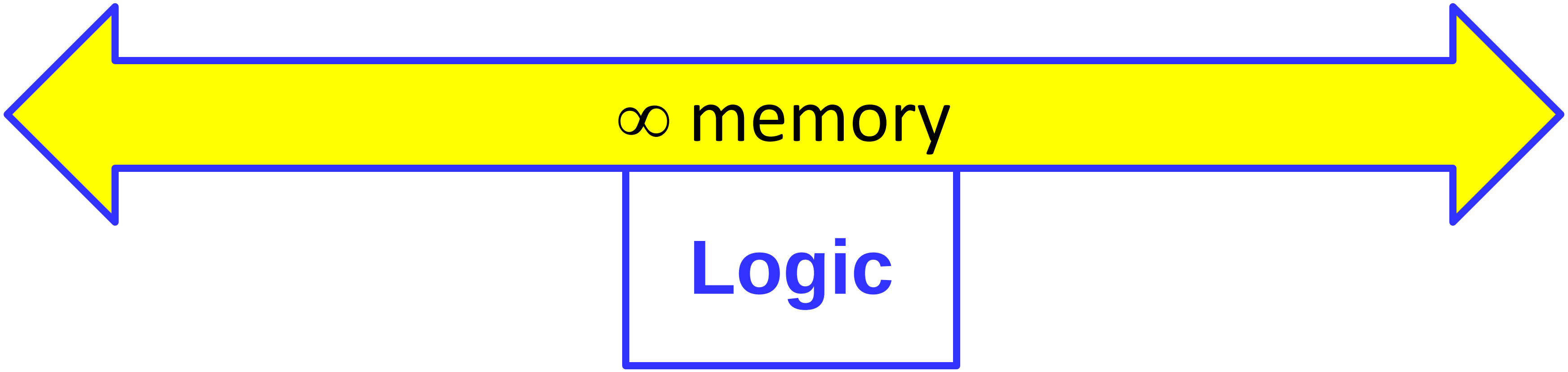
- … quite small errors in the initial conditions can have an overwhelming effect at a later time. The displacement of a single electron by a billionth of a centimetre at one moment might make the difference between a man being killed by an avalanche a year later, or escaping.

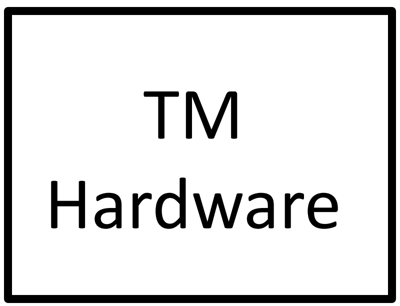
1950, Computing Machinery and Intelligence, *Mind*

• … quite 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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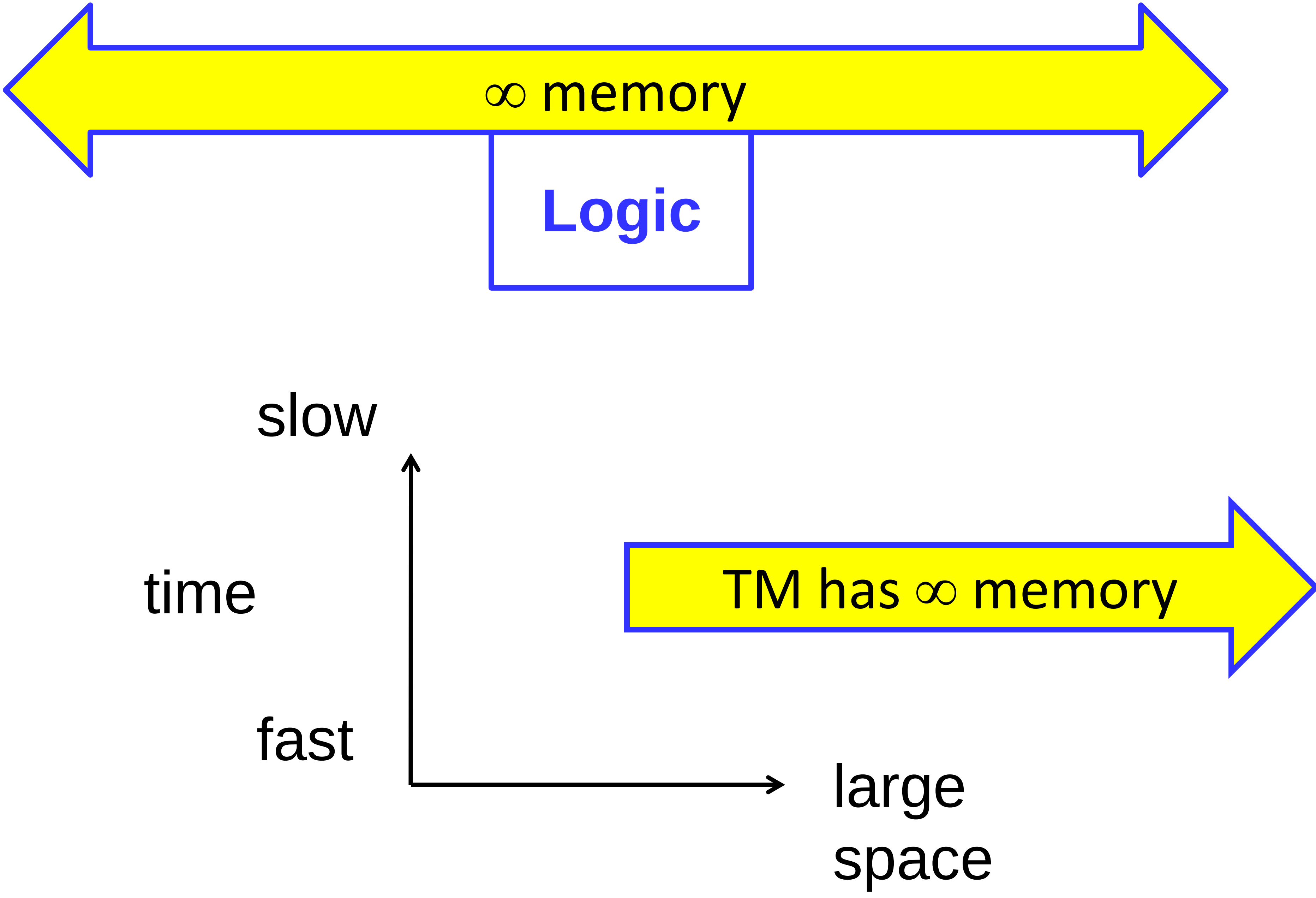
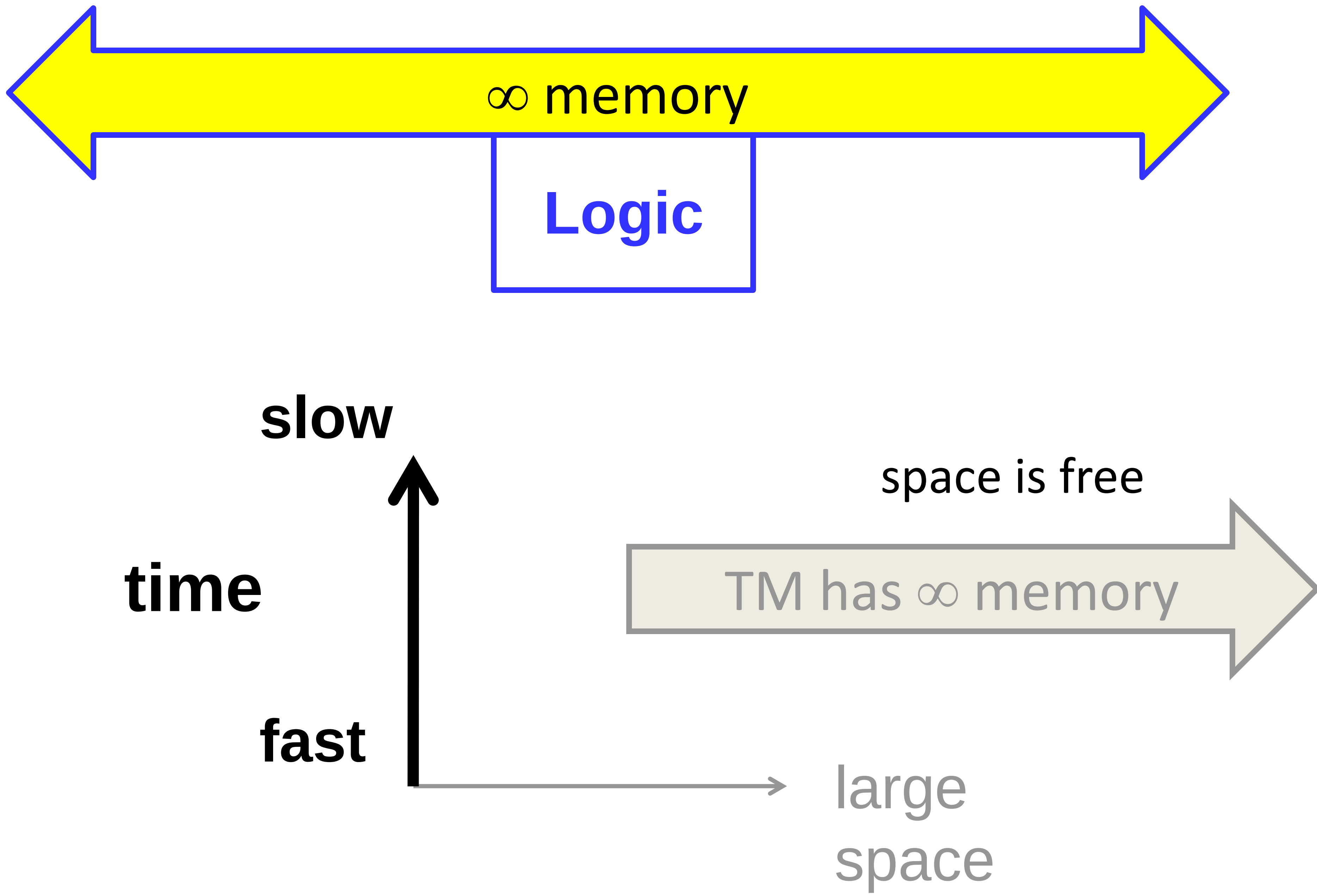
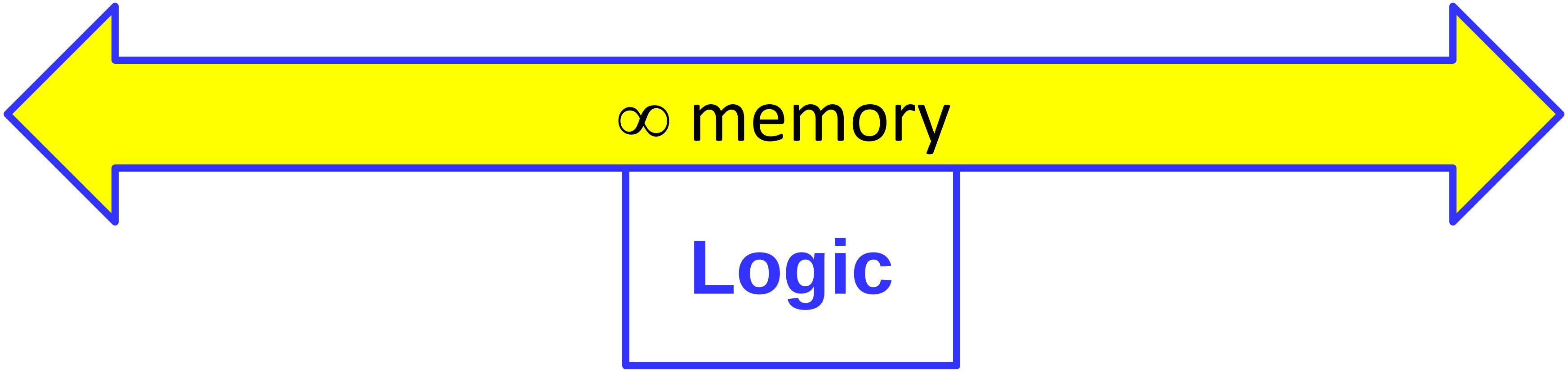


∞ memory
Logic
slow
time
fast
TM has ∞ memory
large
space



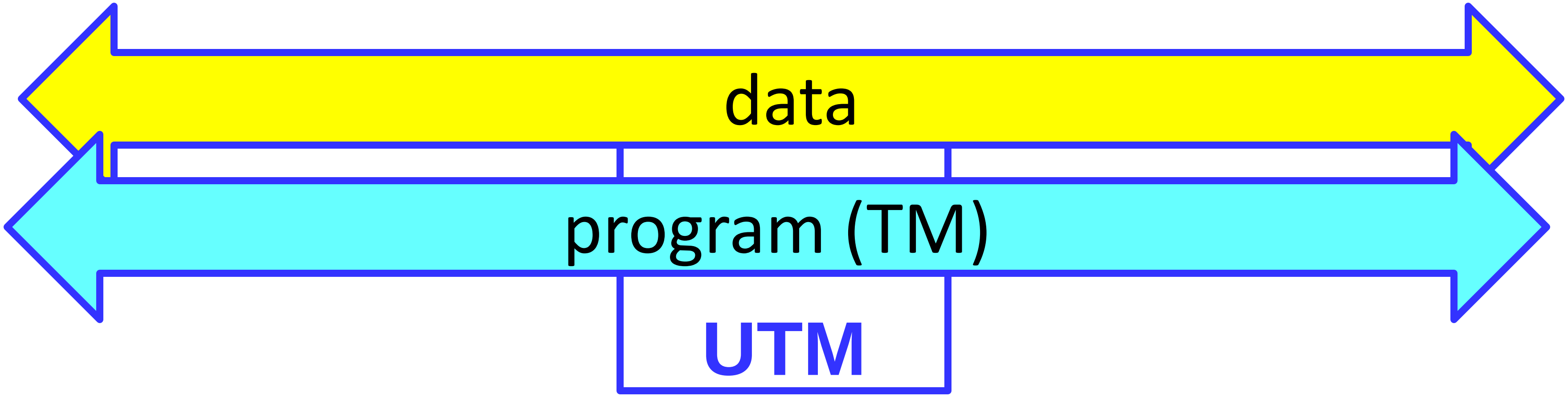
∞ memory
Logic
slow
time
fast
space is free
TM has ∞ memory
large
space



time?

Decidable problem = ∃ algorithm that solves it

Most naively posed problems are undecidable.



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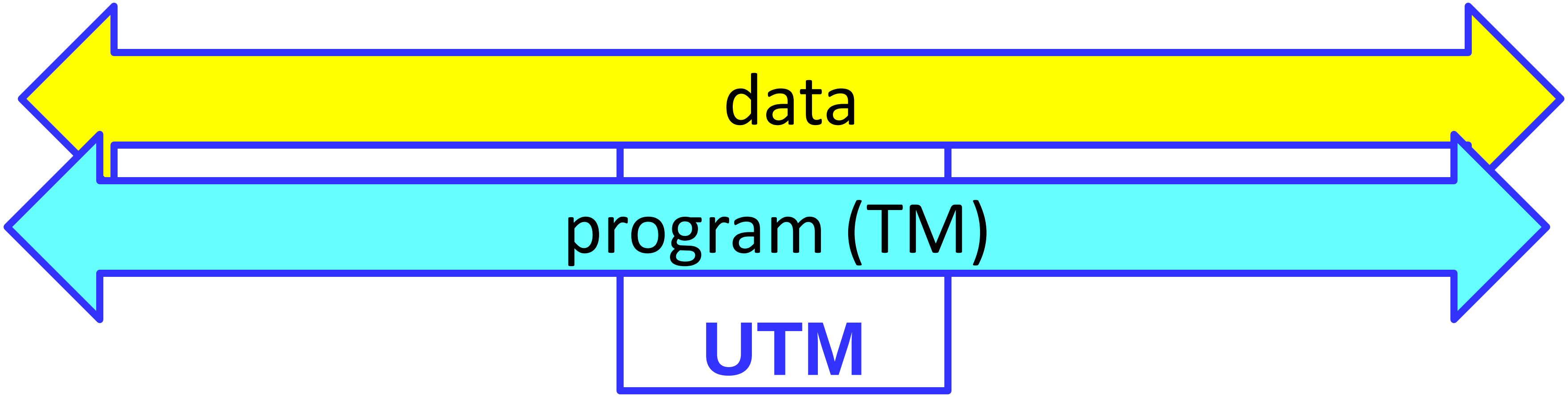
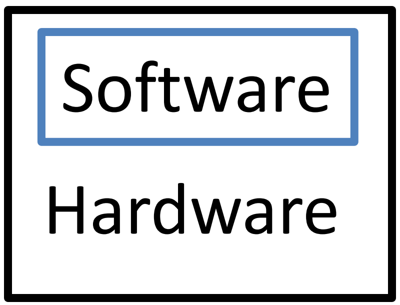
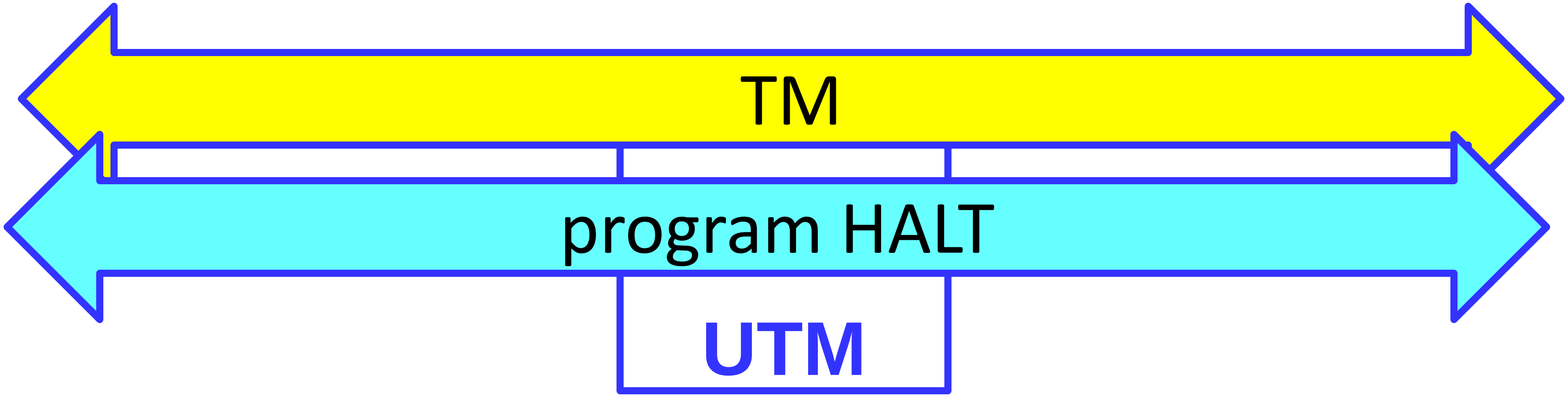




2. Universal architecture achieving hard limits (UTM)

- 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.

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

Thm: No such H exists.

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

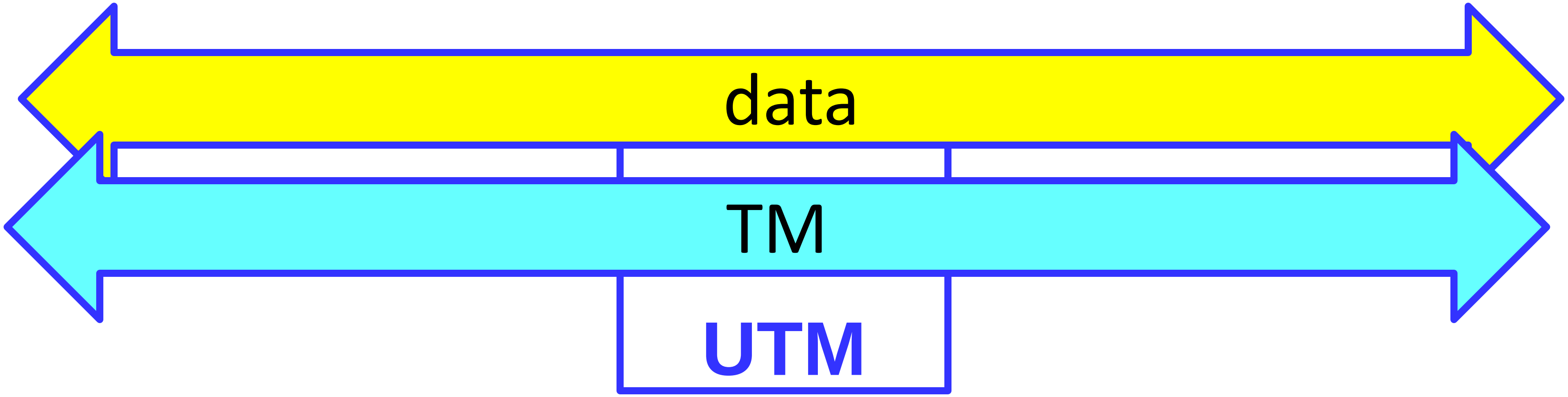
$$H'(TM, input) \triangleq \begin{cases} 1 \text{ if } H(TM, input) = 0 \\ \text{loop forever otherwise} \end{cases}$$

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

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

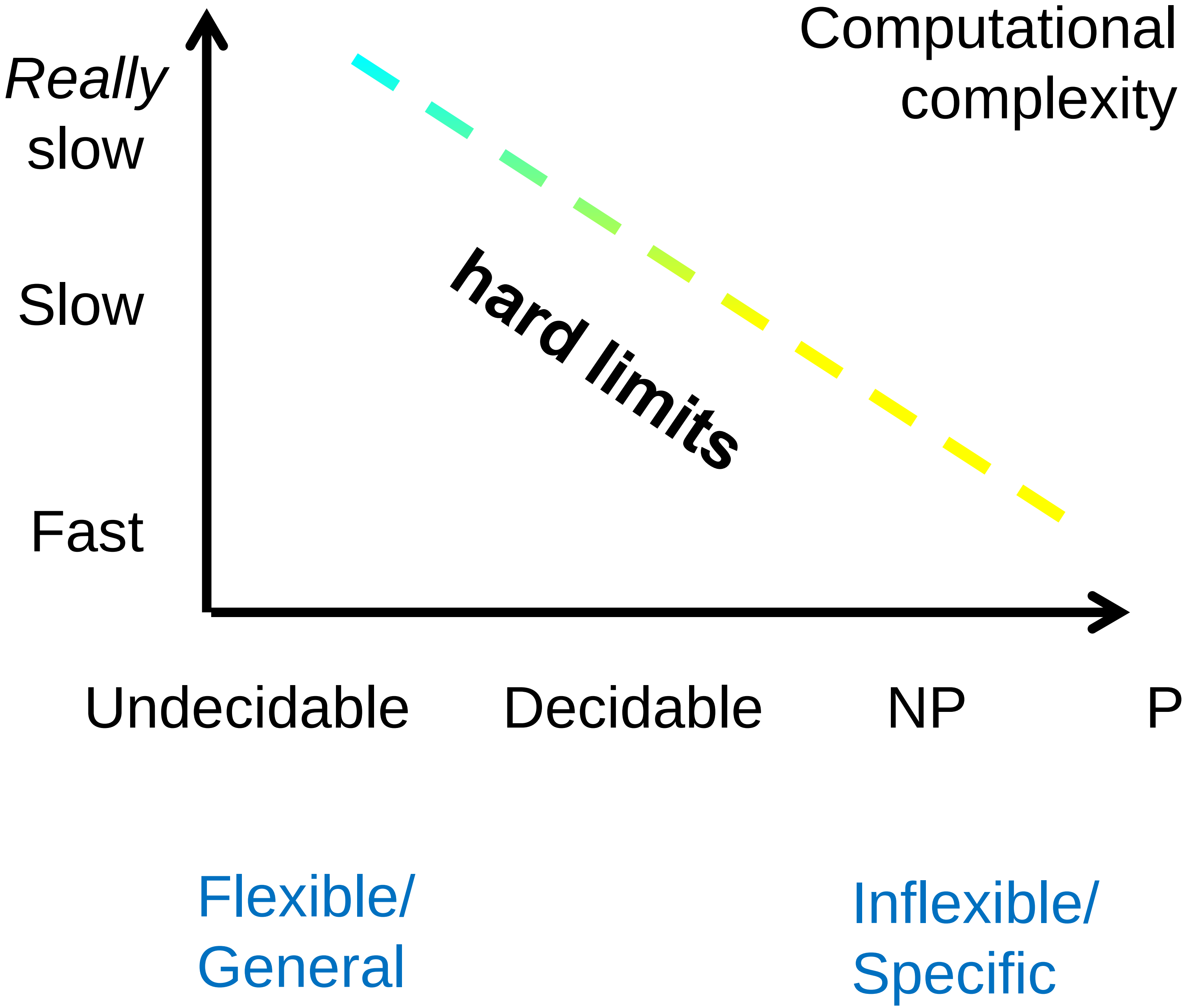
$$= \begin{cases} \text{halt if } H^*(H^*) \text{ loops forever} \\ \text{loop forever otherwise} \end{cases}$$

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.

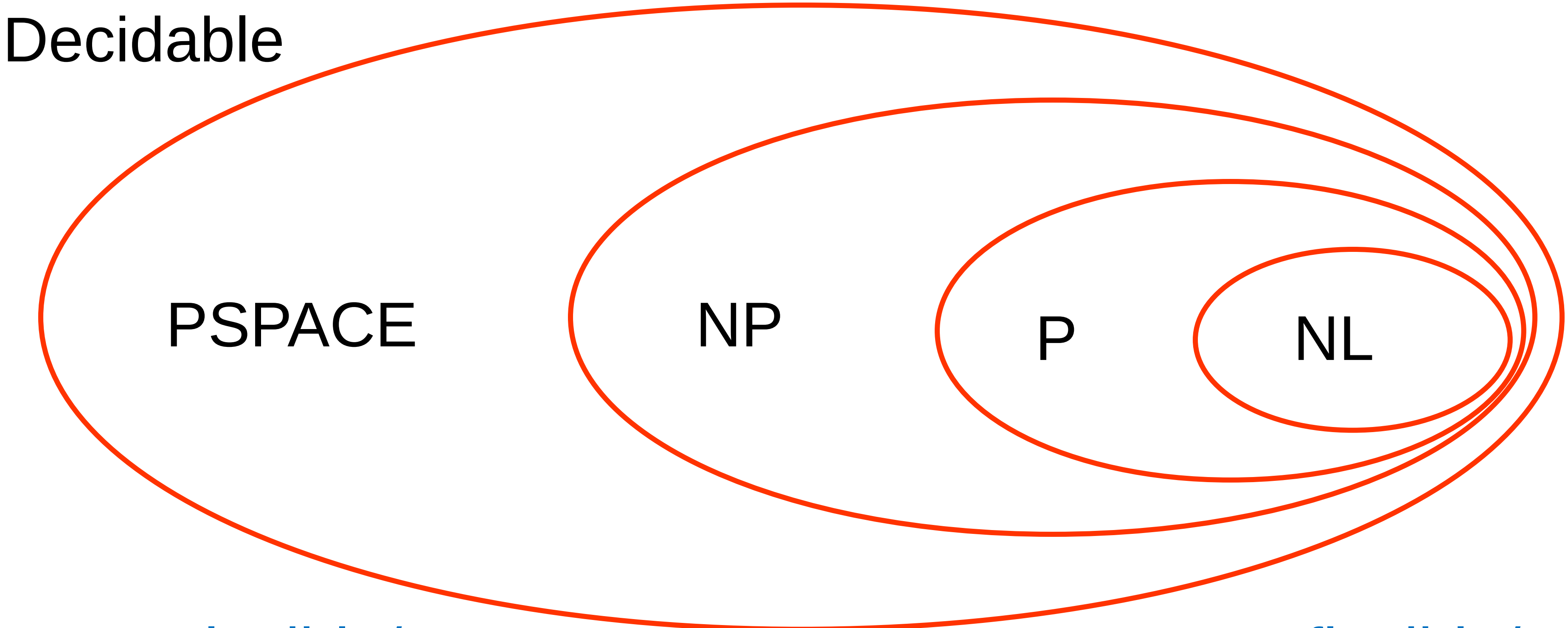

Computational complexity
Really slow
Slow
Fast
hard limits
Undecidable
Decidable
NP
P
Flexible/ General
Inflexible/ Specific

Computational complexity

$\text{PSPACE} \subset \text{NP} \subset \text{P} \subset \text{NL}$

$\text{PSPACE} \neq \text{NL}$

Space is powerful and/or cheap.

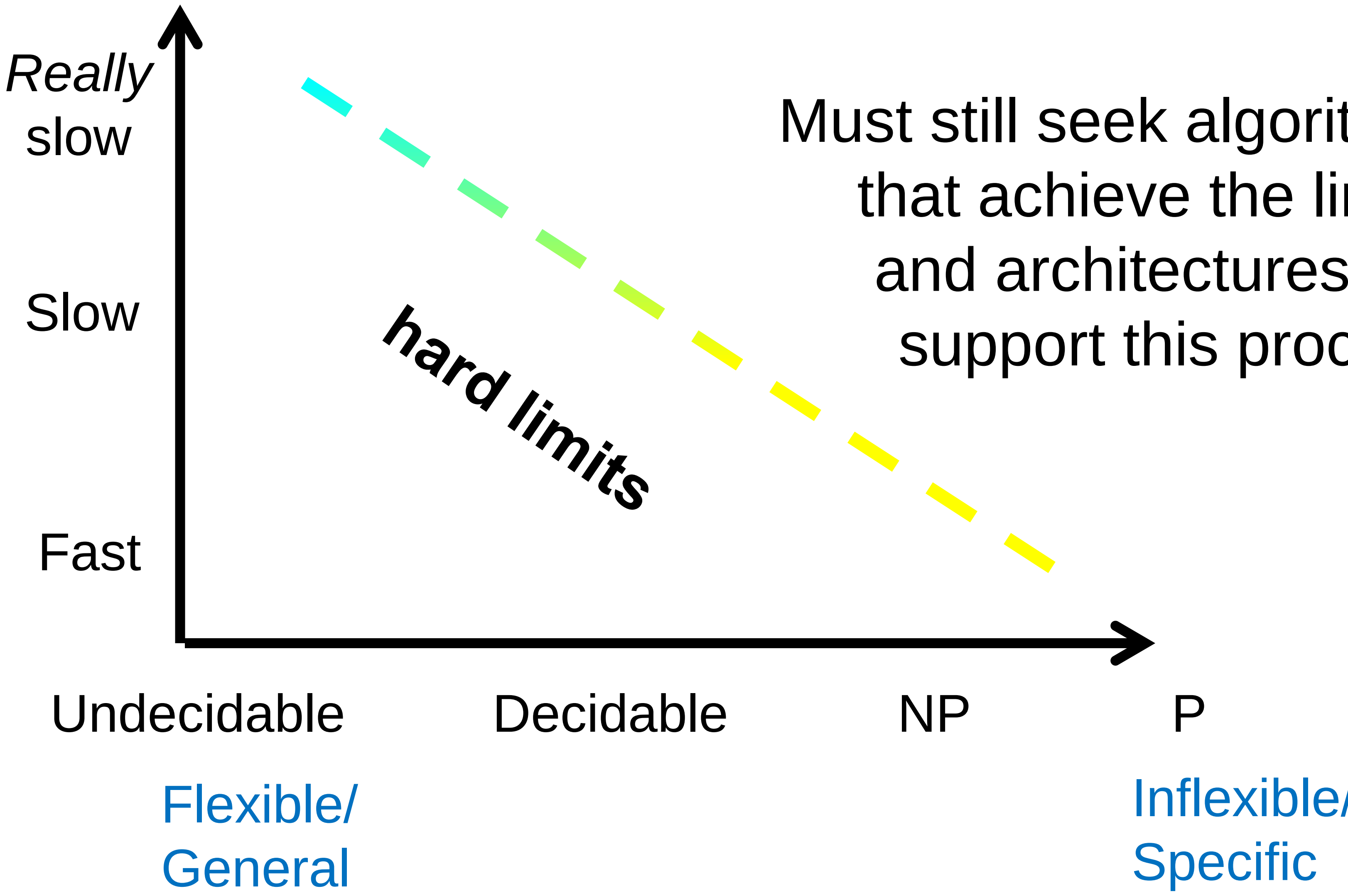


Flexible/
General

Inflexible/
Specific

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

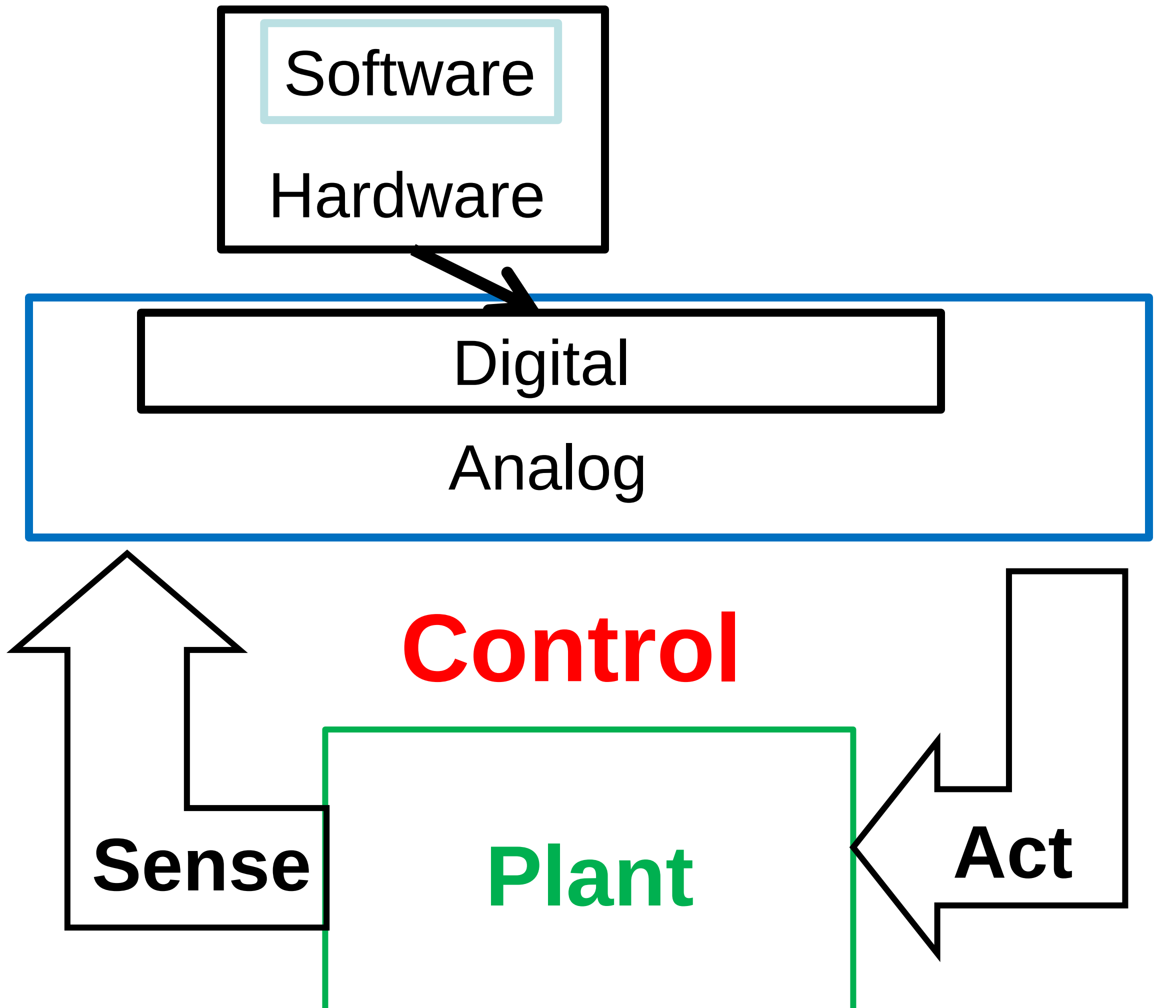
Must still seek algorithms that achieve the limits, and architectures that support this process.



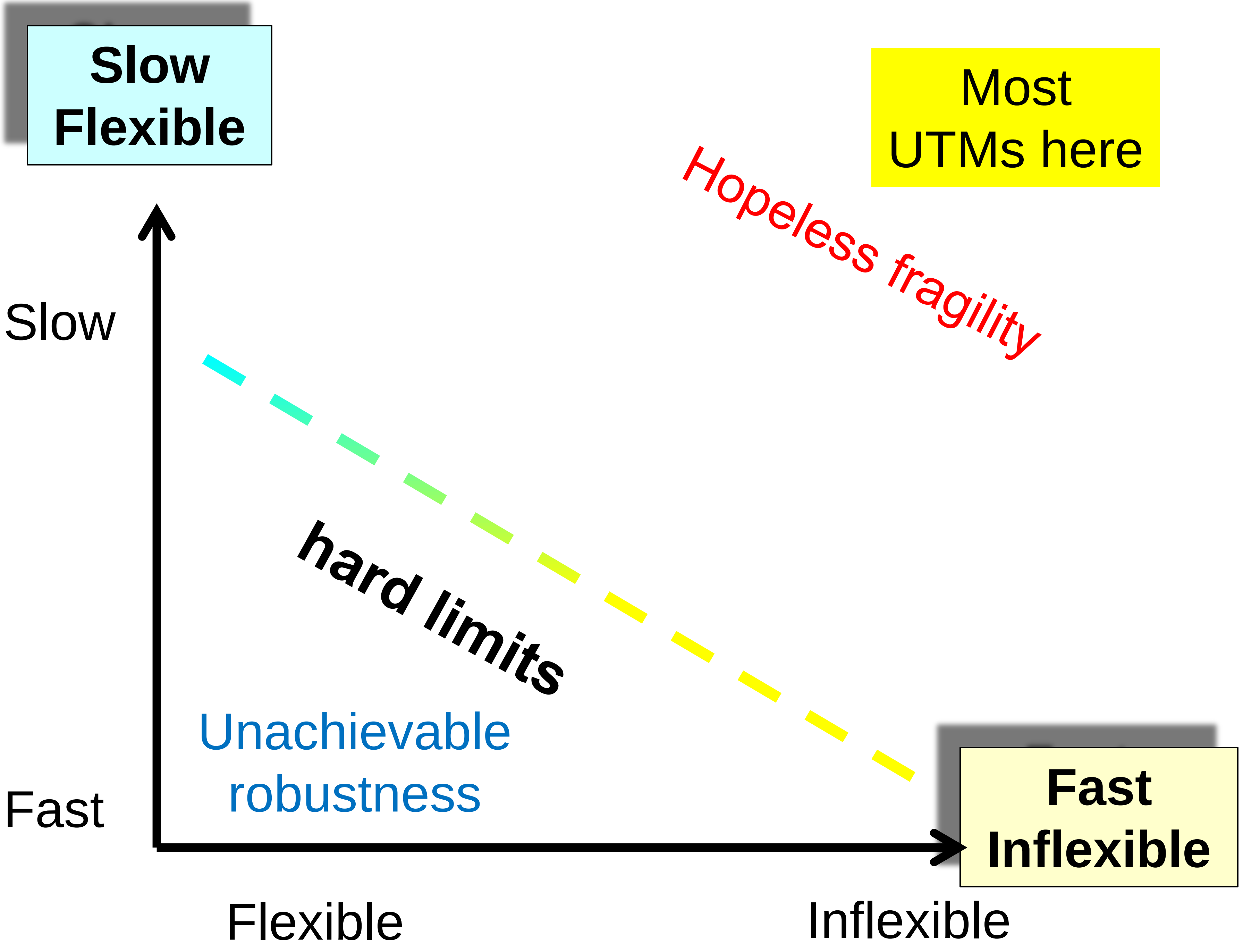
Compute

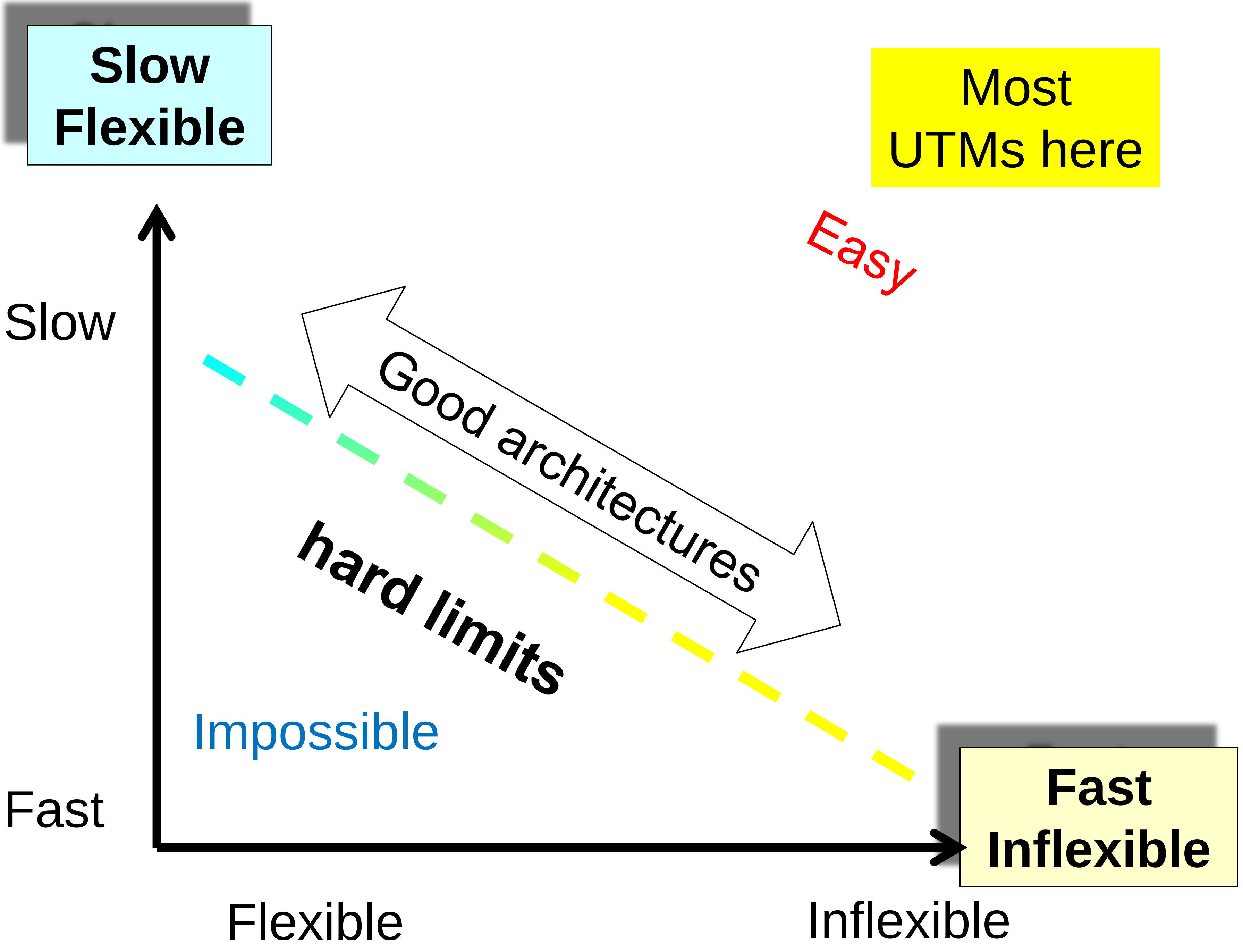
Computational complexity of
- ***Designing*** control algorithms
- ***Implementing*** control algorithms

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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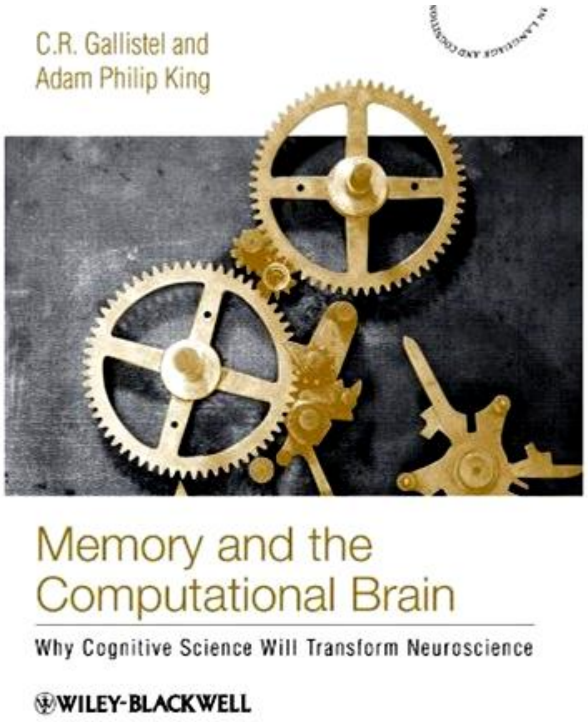
- **Most crucial:**
  - UTMs differ ***vastly*** in speed, usability, and programmability
  - You can fix bugs but it is hard to automate finding/avoiding them

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)

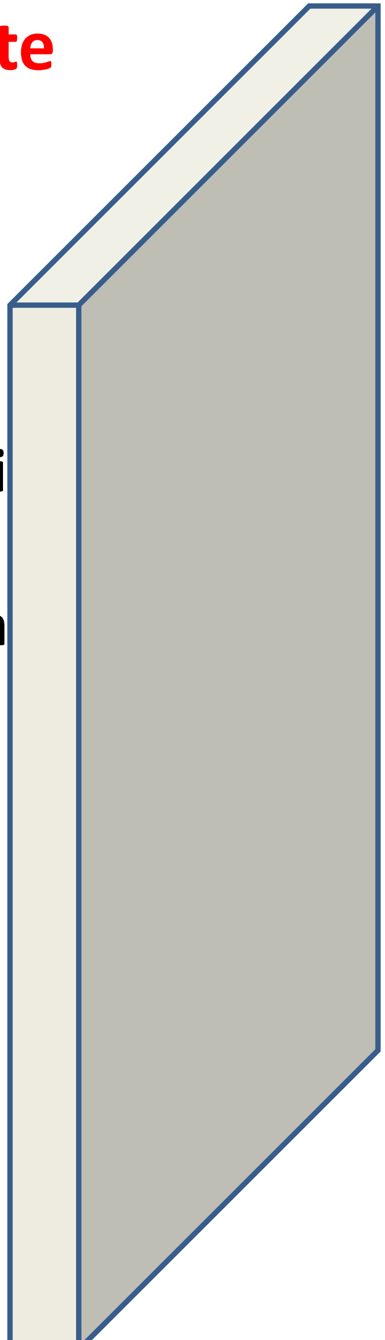
Compute

Turing

Delay i
most
importa

Bode

Control,



Communicate

Shannon

Delay is
least
important

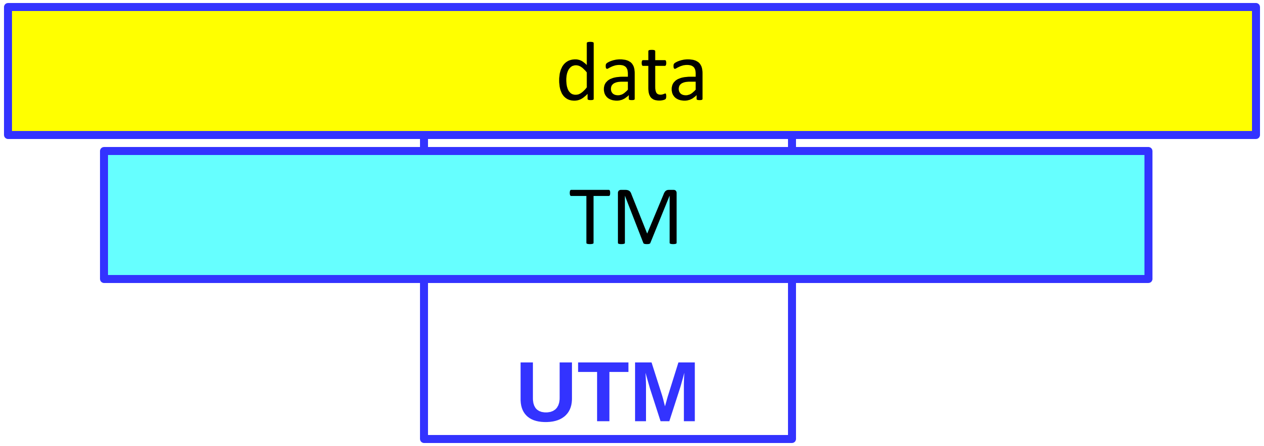
Carnot

Boltzmann

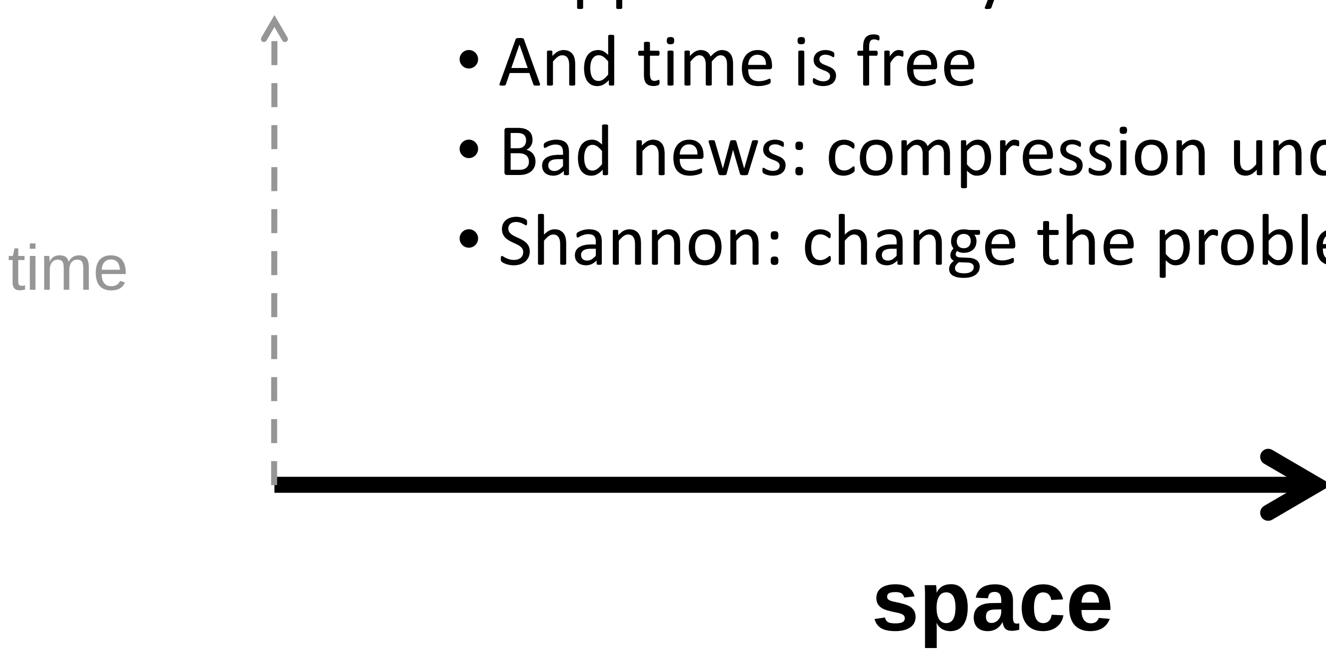
Heisenberg

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

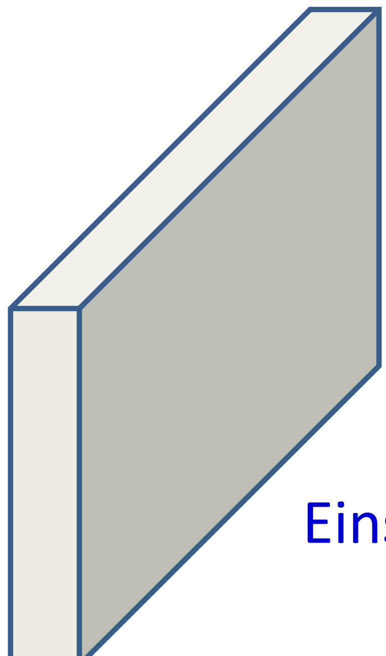
Lowering the barrier

Shannon

Delay is *most* important

New progress!

Delay is ~~*least*~~ important



Carnot

Boltzmann

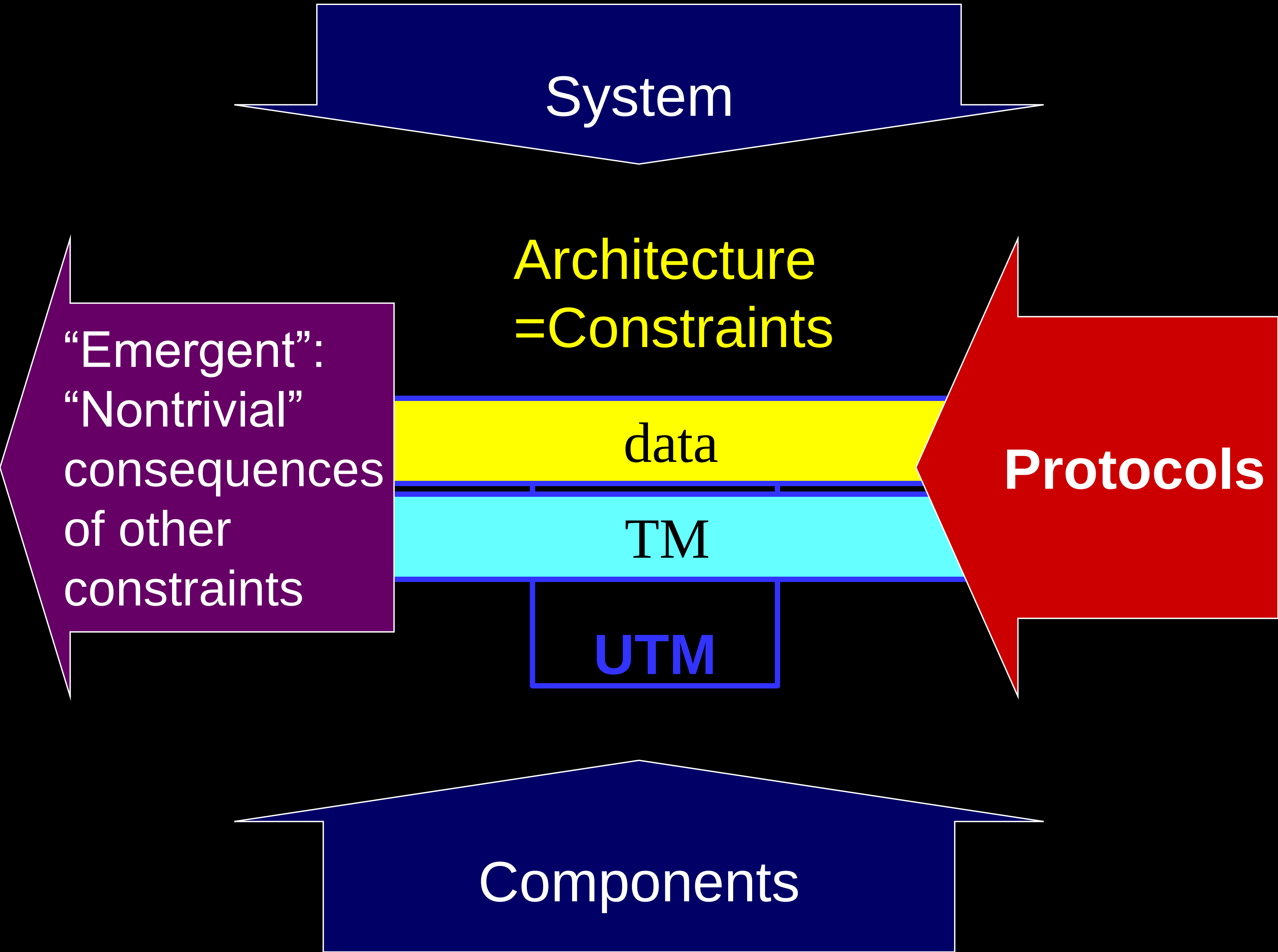
Bode

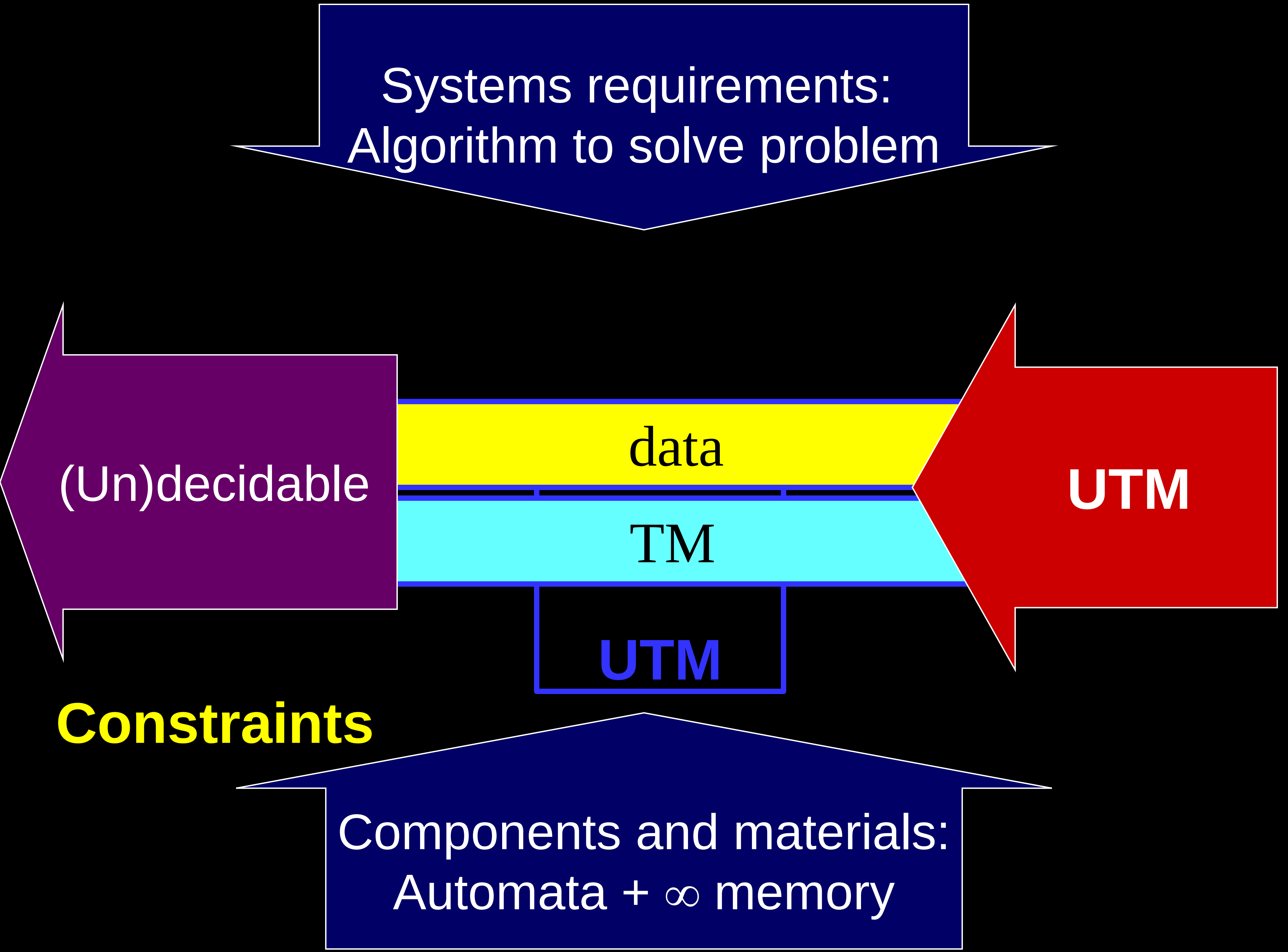
Heisenberg

Control, OR

Einstein

Physics


System
Architecture
=Constraints
"Emergent":
"Nontrivial"
consequences
of other
constraints
data
TM
UTM
Protocols
Components

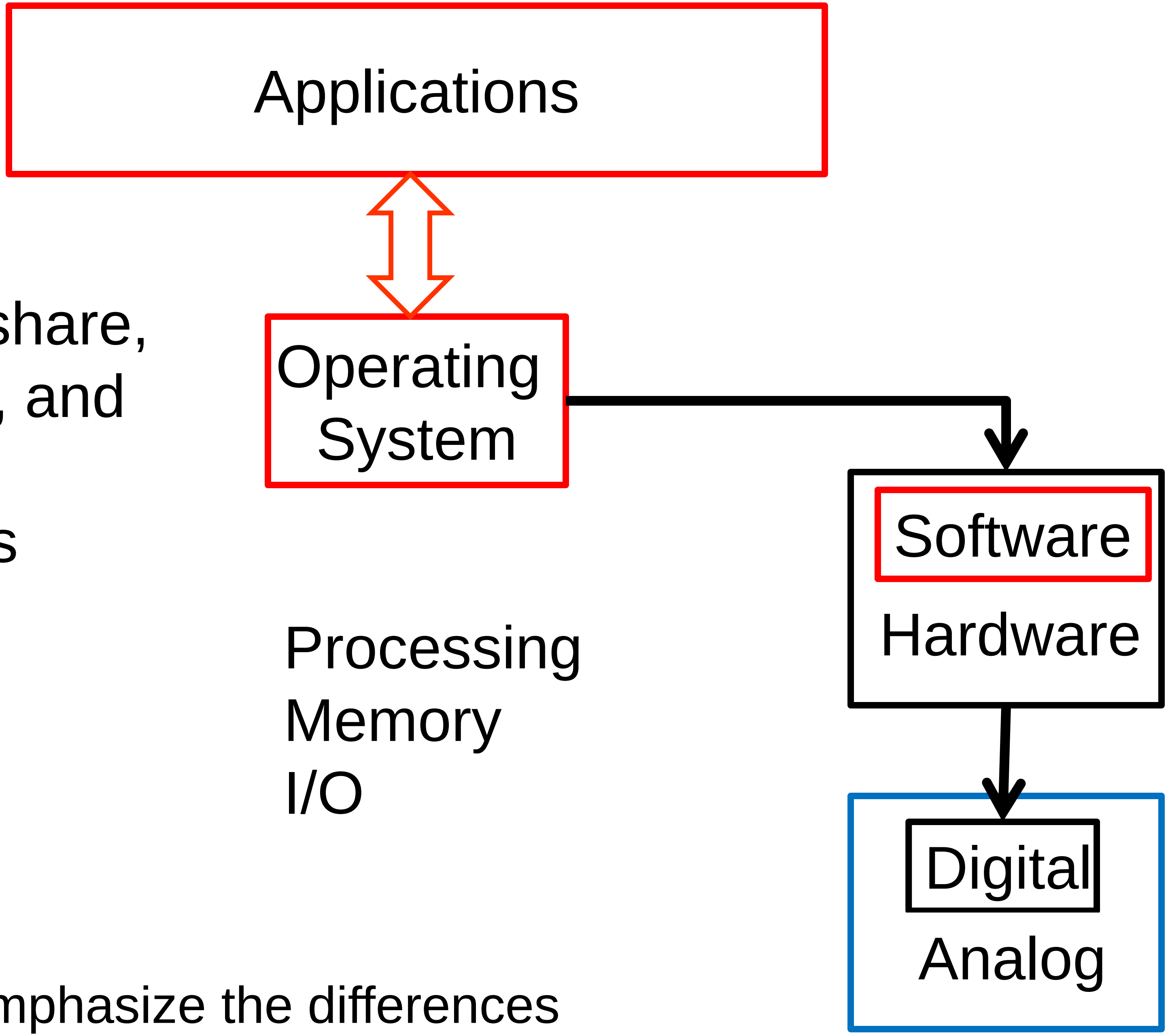


Systems requirements:
Algorithm to solve problem
(Un)decidable
data
TM
UTM
UTM
Constraints
Components and materials:
Automata + ∞ memory

Universal architectures

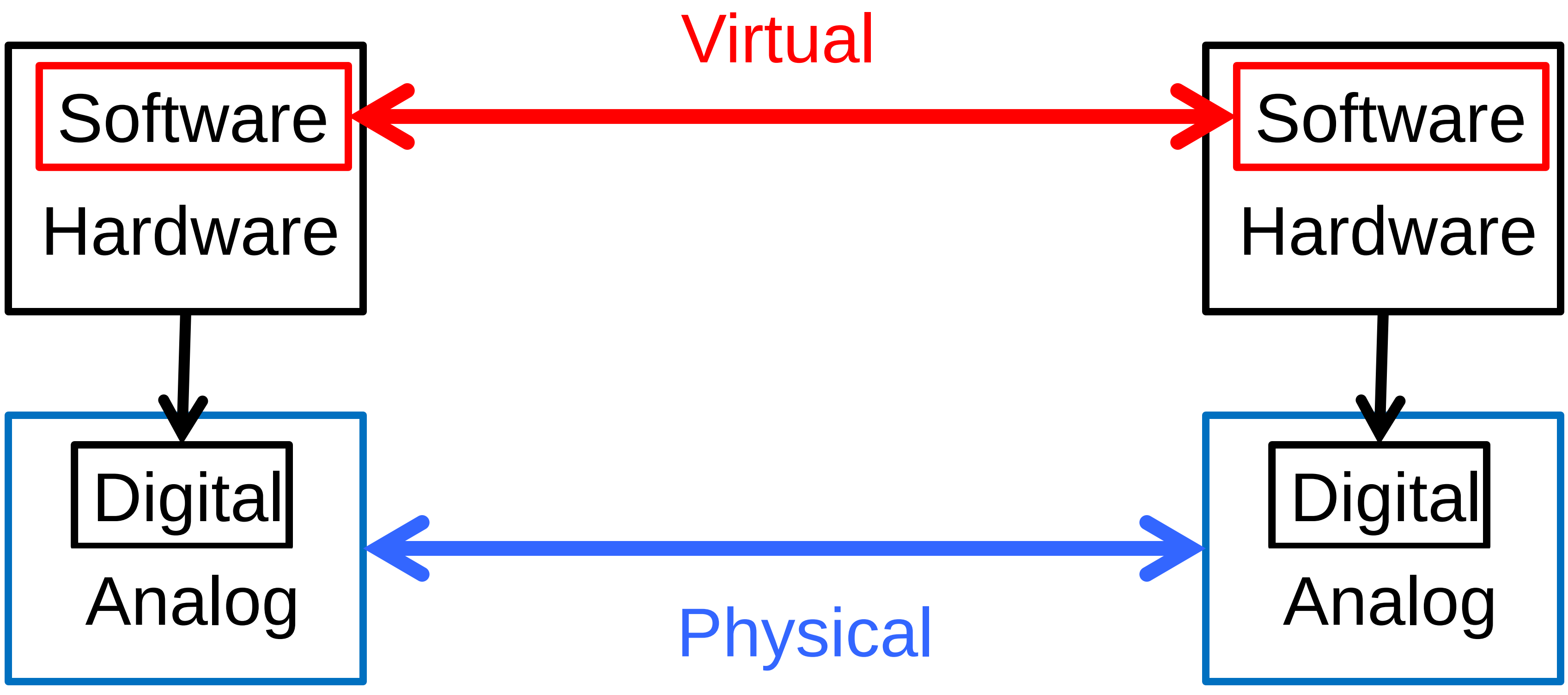
What can go wrong?

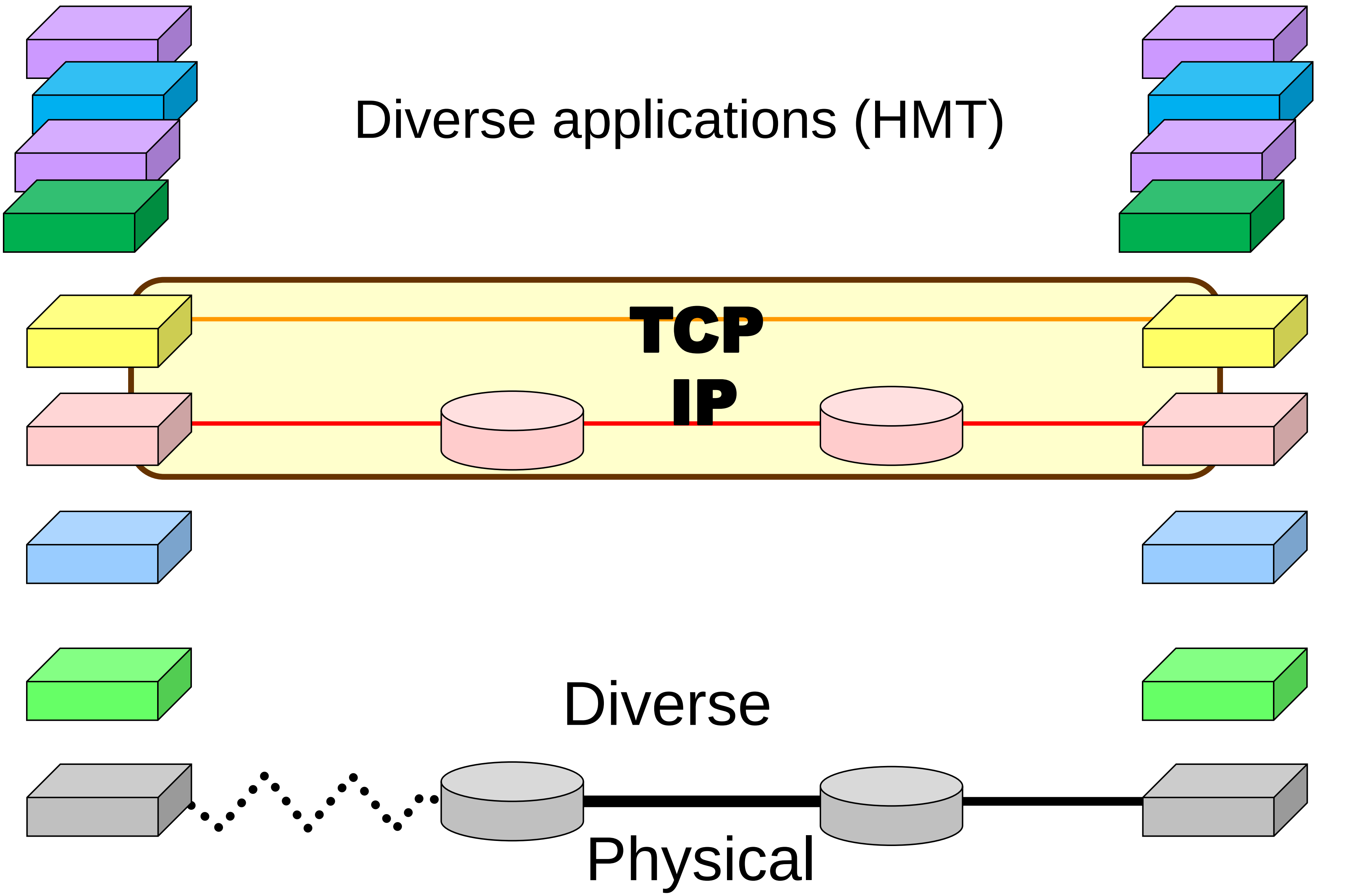
Control, share, virtualize, and manage resources



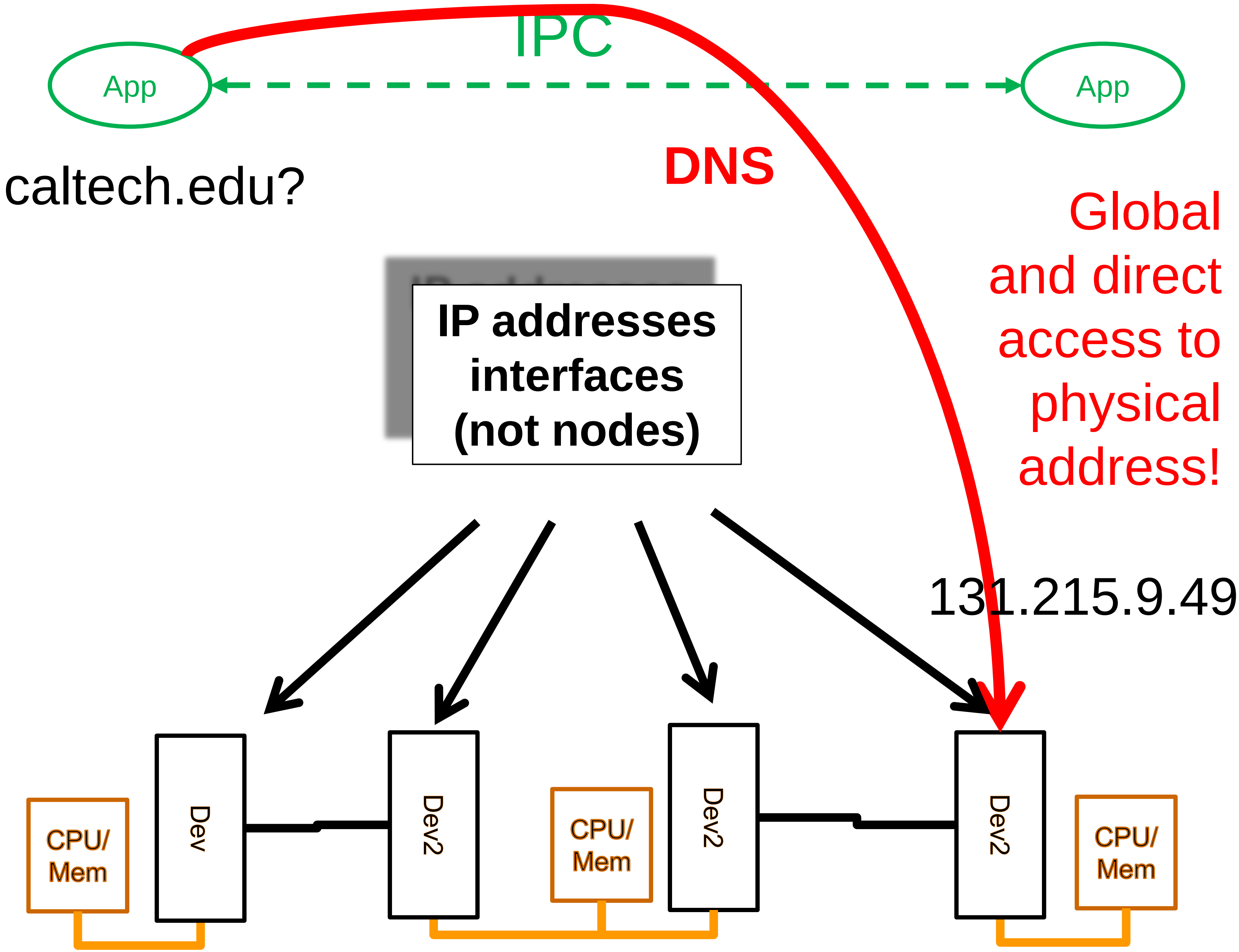
Want to emphasize the differences between these two types of layering.

Networking

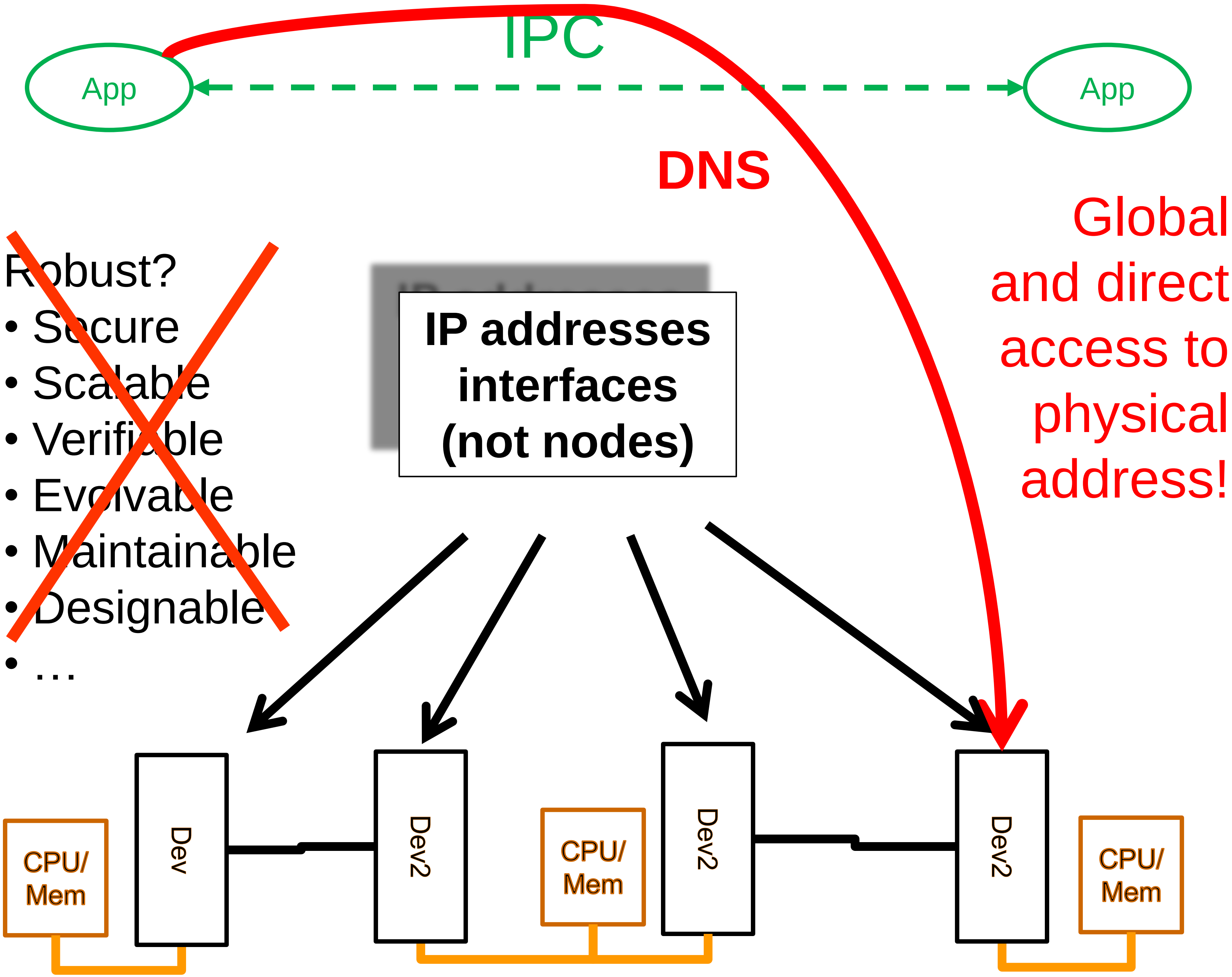

Virtual
Software
Hardware
Software
Hardware
Digital
Analog
Digital
Analog
Physical



Diverse applications (HMT)
TCP
IP
Diverse
Physical



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



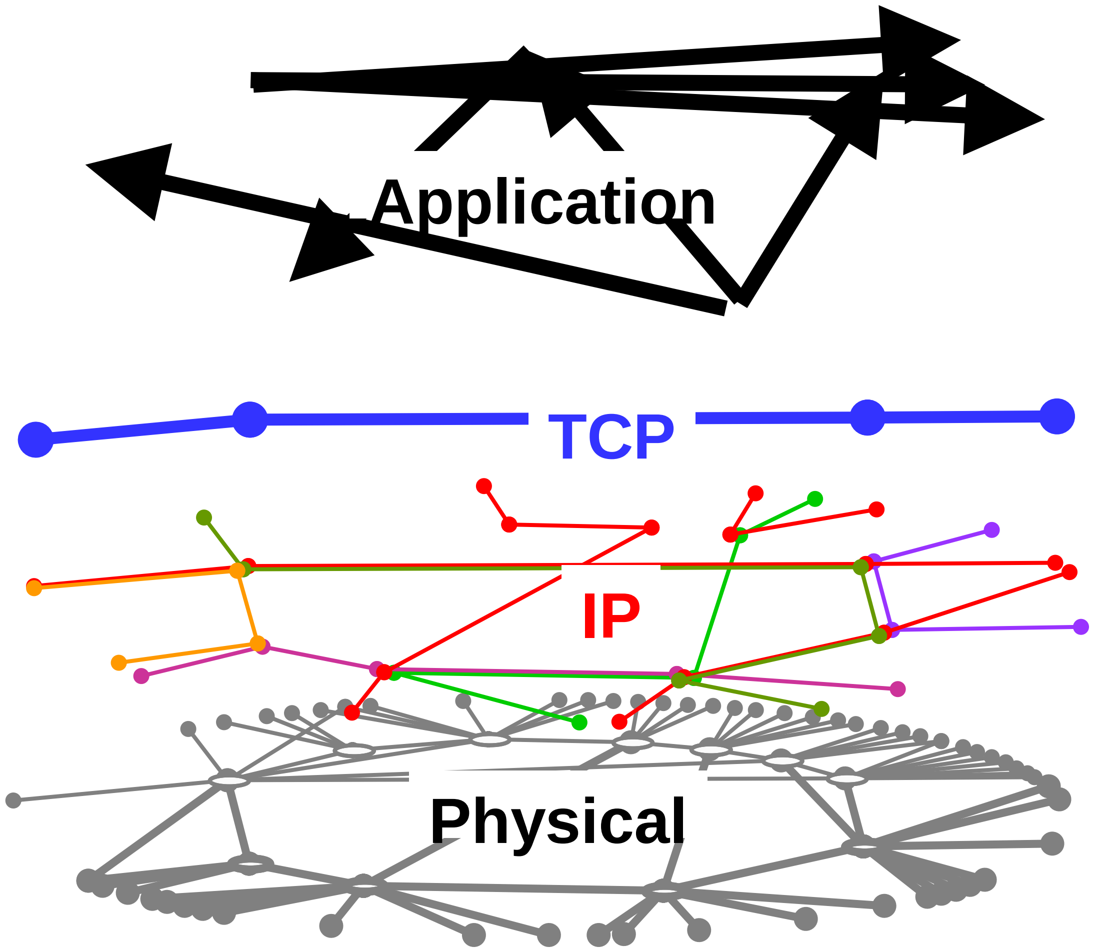
App
IPC
App
DNS
Global and direct access to physical address!
Robust?
• Secure
• Scalable
• Verifiable
• Evolvable
• Maintainable
• Designable
• …
IP addresses interfaces (not nodes)
CPU/ Mem
Dev
Dev2
CPU/ Mem
Dev2
Dev2
CPU/ Mem

Naming and addressing need to have ***scope*** and

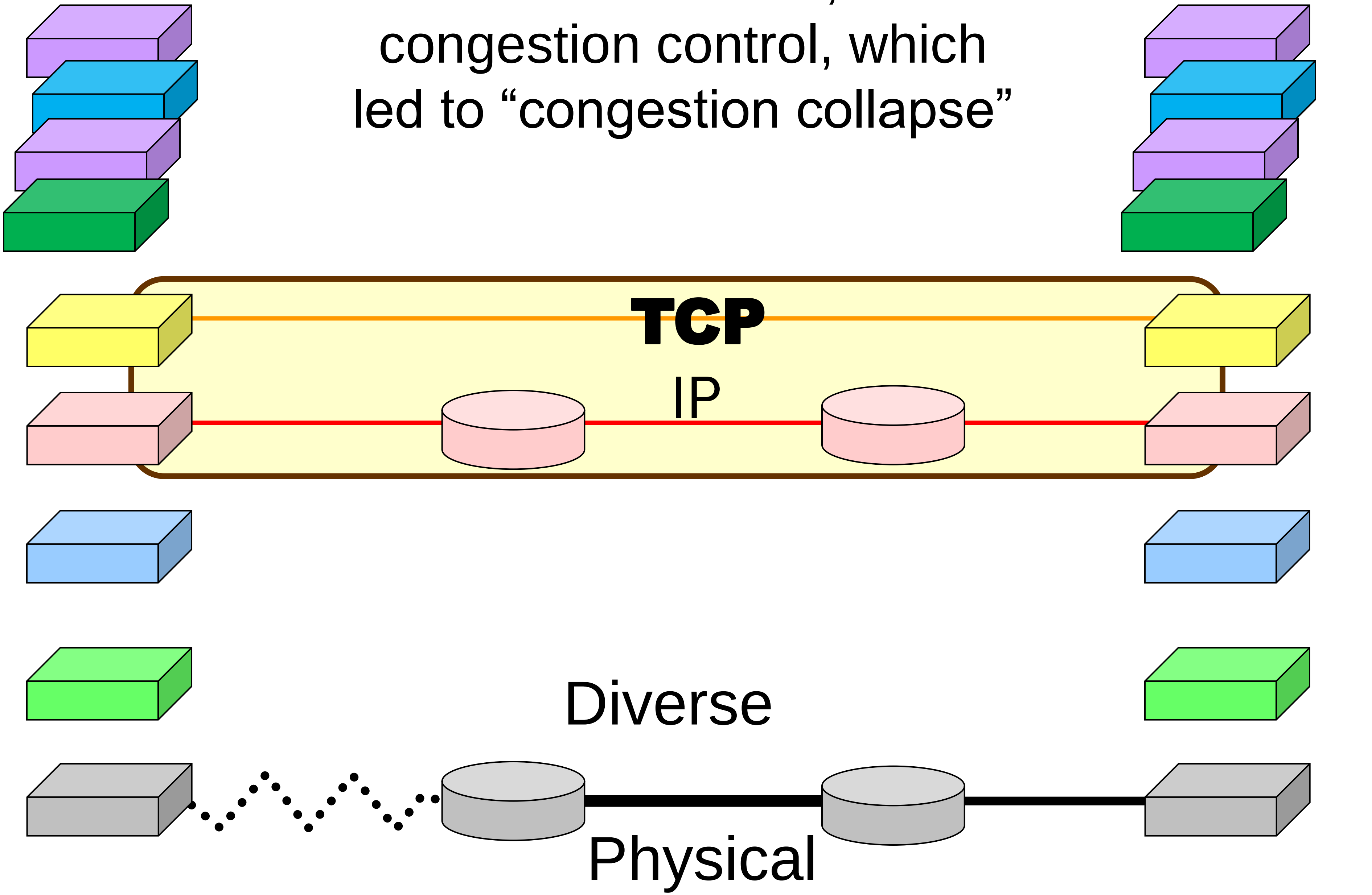
- resolved within layer
- translated between layers
- not exposed outside of layer

Related “issues”

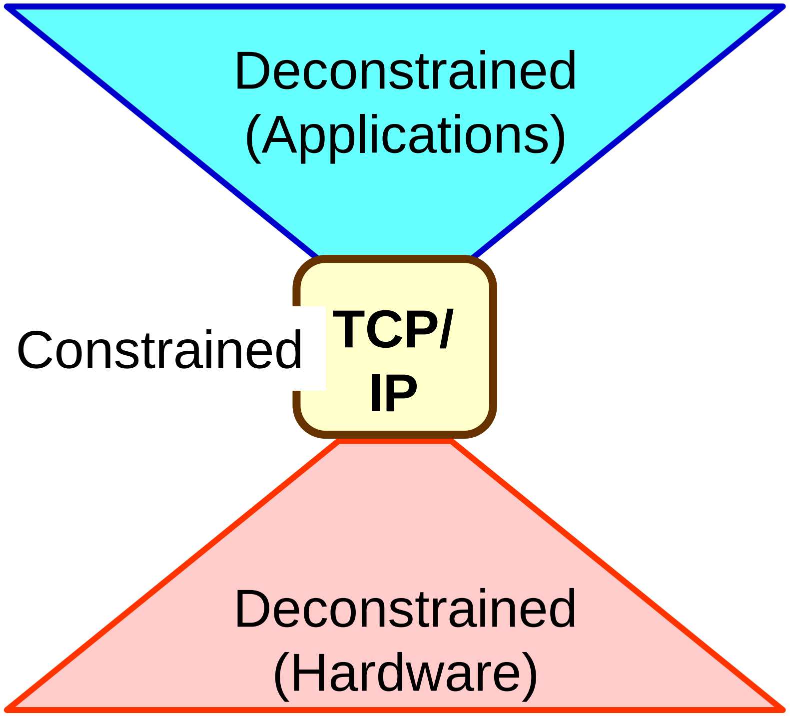
- VPNs
- NATS
- Firewalls
- Multihoming
- Mobility
- Routing table size
- Overlays
- …



Until late 1980s, no congestion control, which led to “congestion collapse”



Original design challenge?



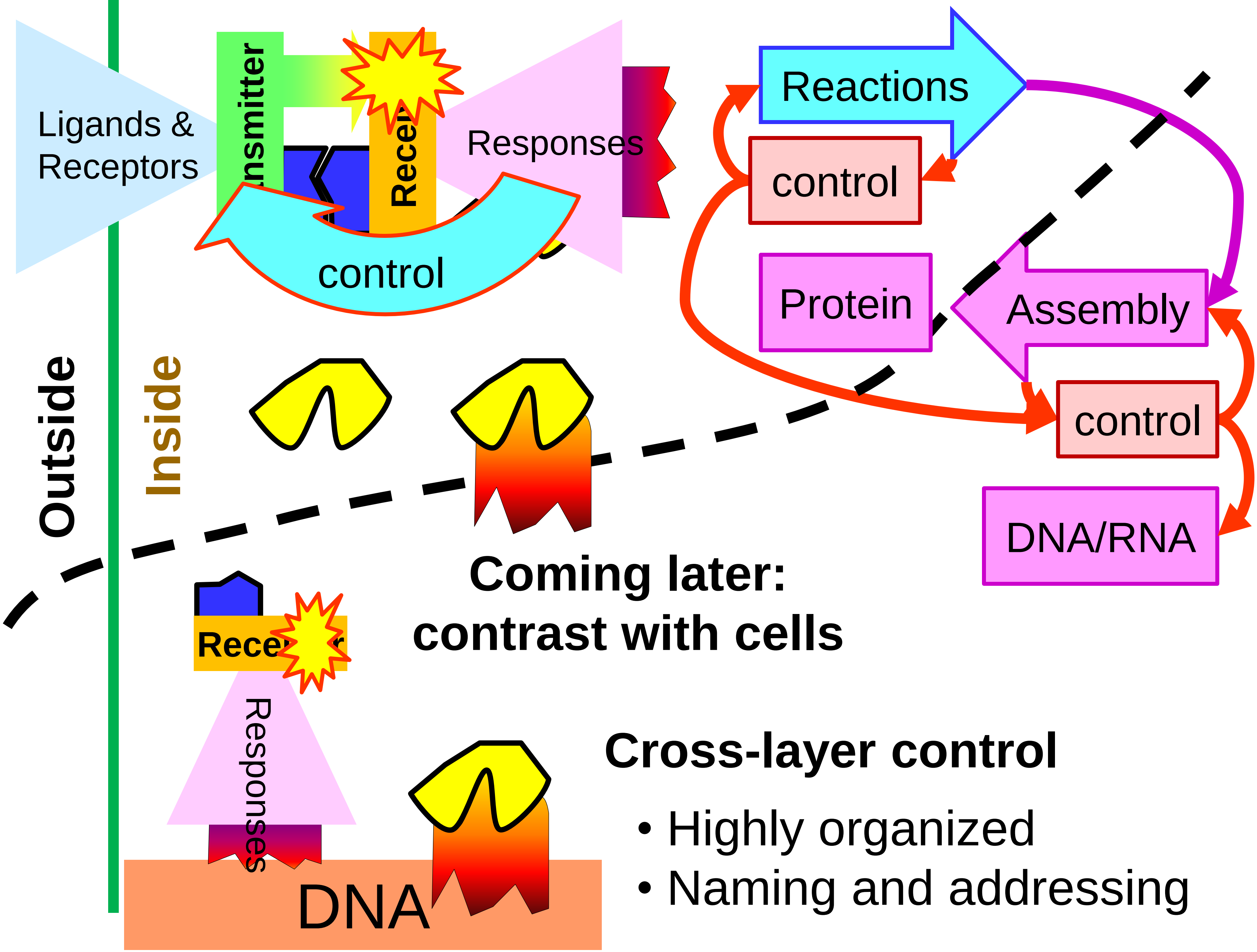
Networked OS

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

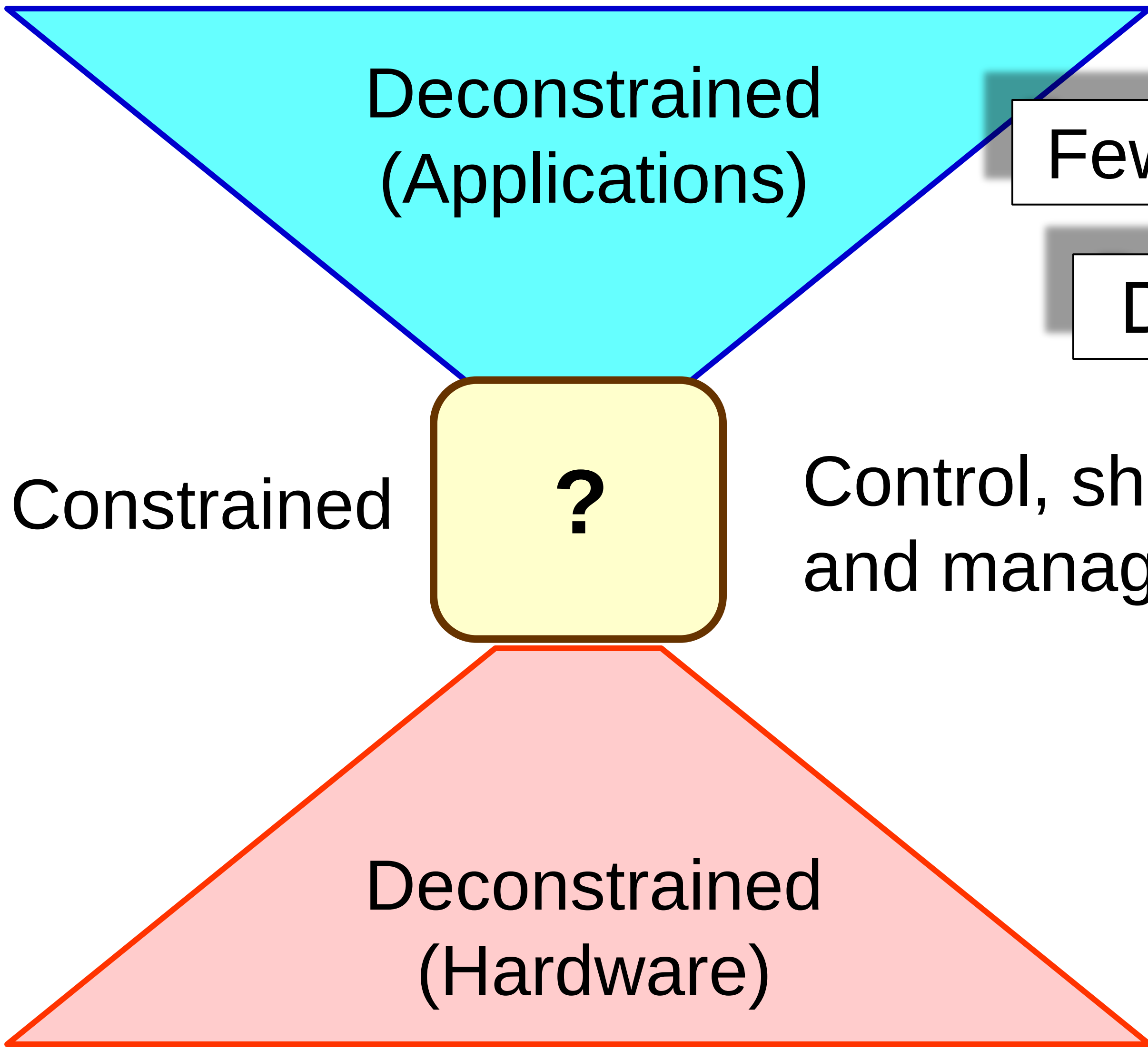
Facilitated wild evolution

Created

- whole new ecosystem
- completely opposite


Ligands &
Receptors
Responses
control
Reactions
control
Protein
Assembly
control
DNA/RNA
Outside
Inside
Coming later:
contrast with cells
Responses
DNA
Cross-layer control
• Highly organized
• Naming and addressing

Next layered architectures



Few global variables

Don't cross layers

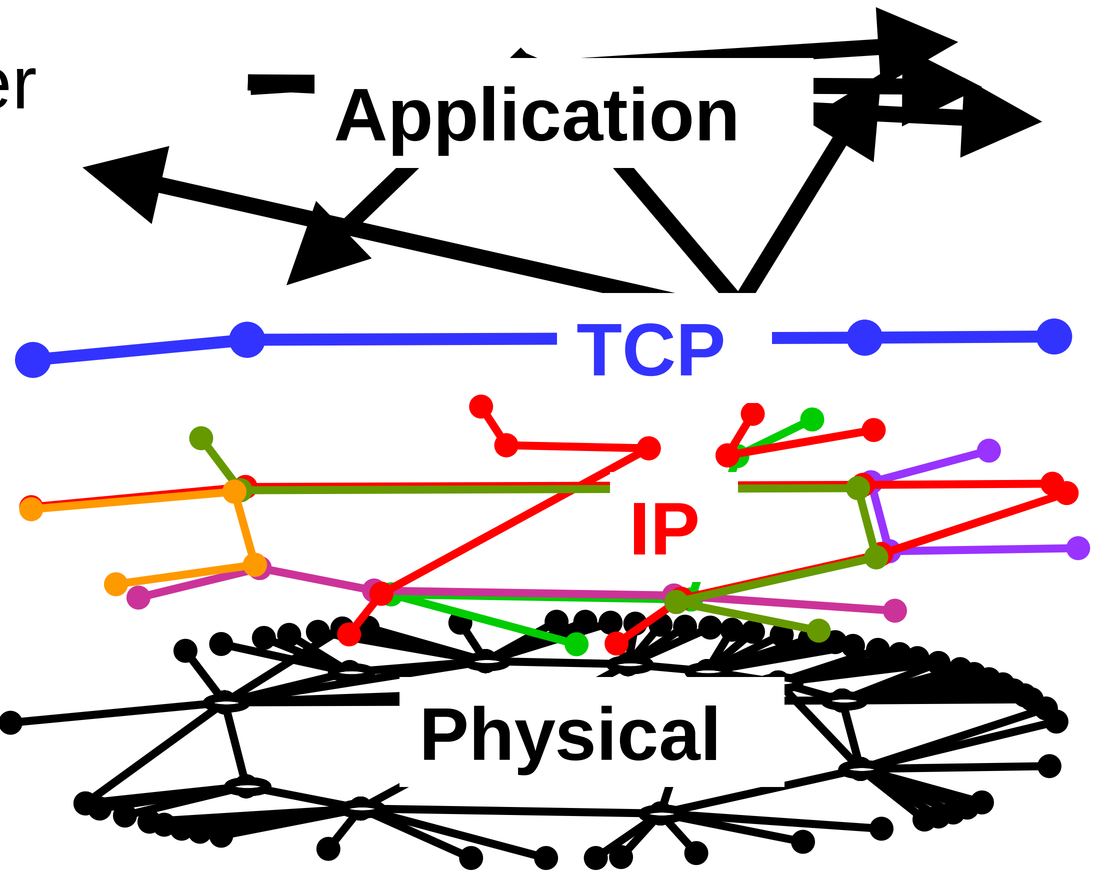
Control, share, virtualize, and manage resources

Comms
Memory, storage
Latency
Processing
Cyber-physical

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

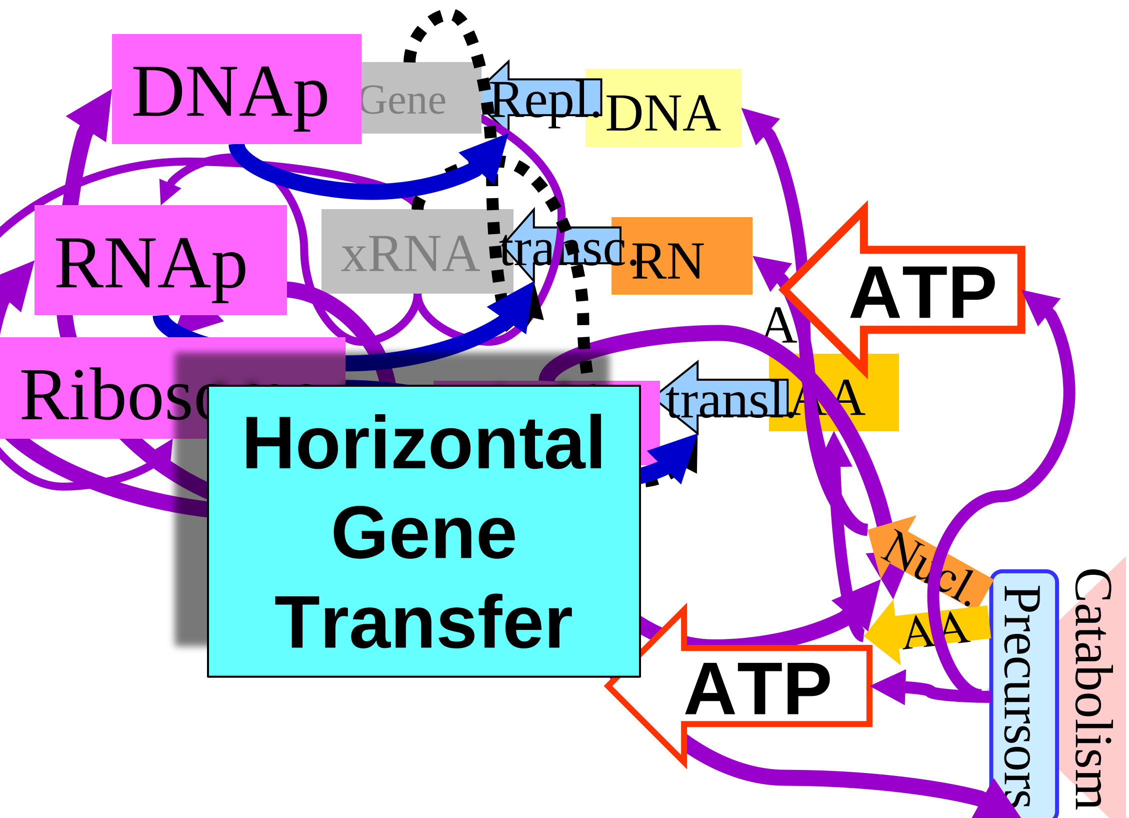
Mathematics and the Internet: A Source of Enormous Confusion and Great Potential

Walter Willinger, David Alderson, and John C. Doyle

Who and what

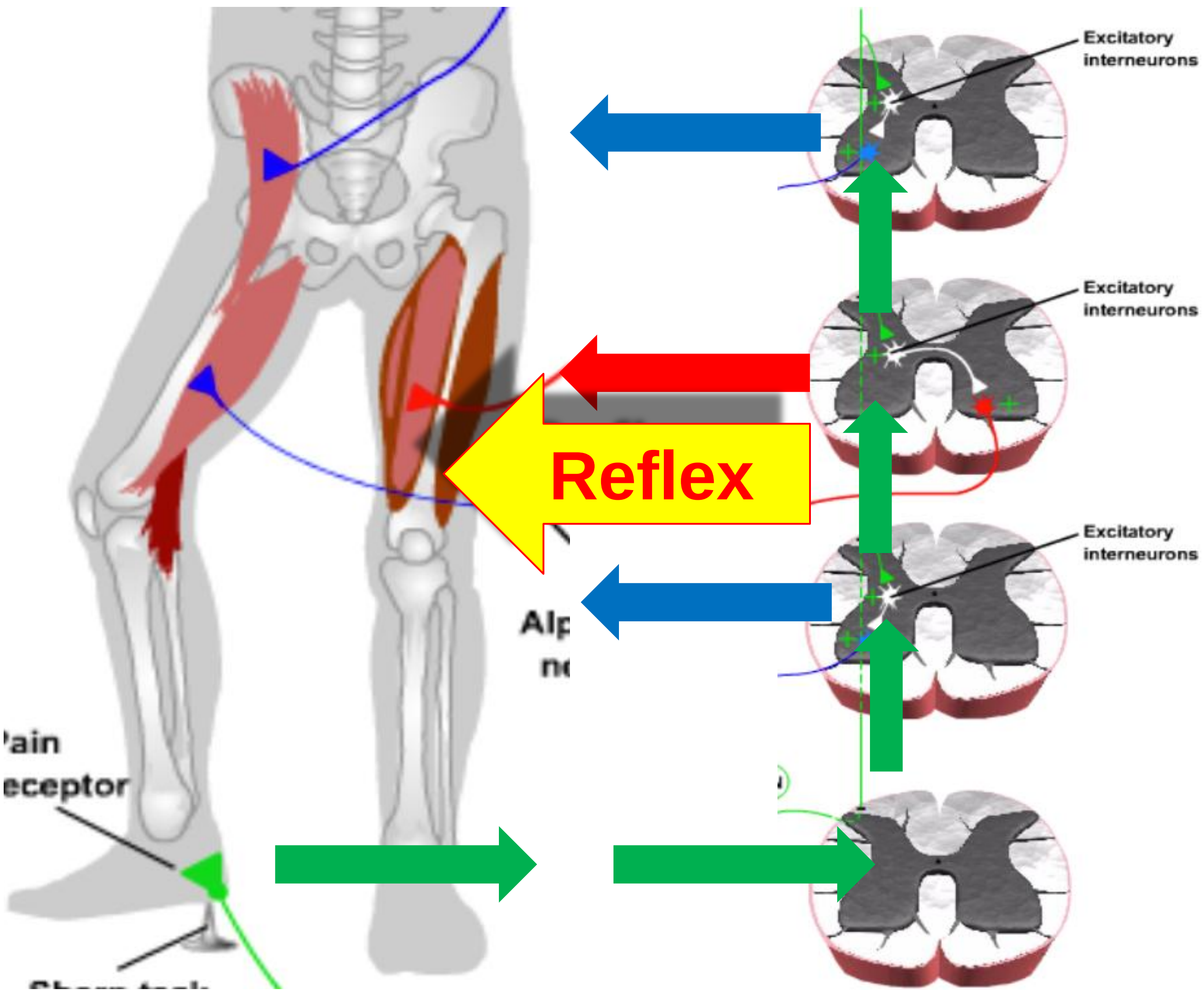
Sequence ~100 E Coli (*not* chosen randomly)

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



See slides on bacterial biosphere

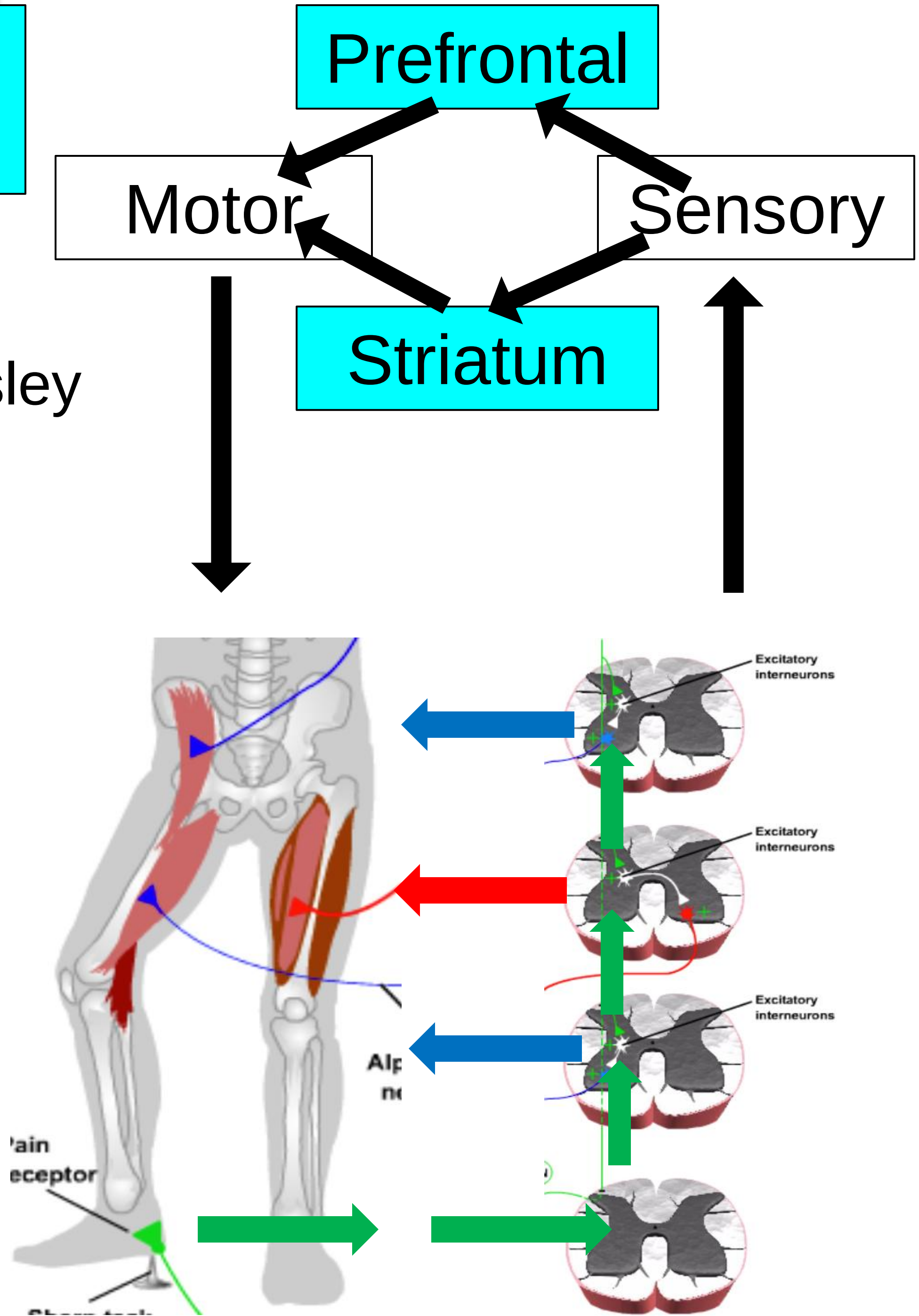
Neuro motivation



Fast
Inflexible

Slow
Flexible

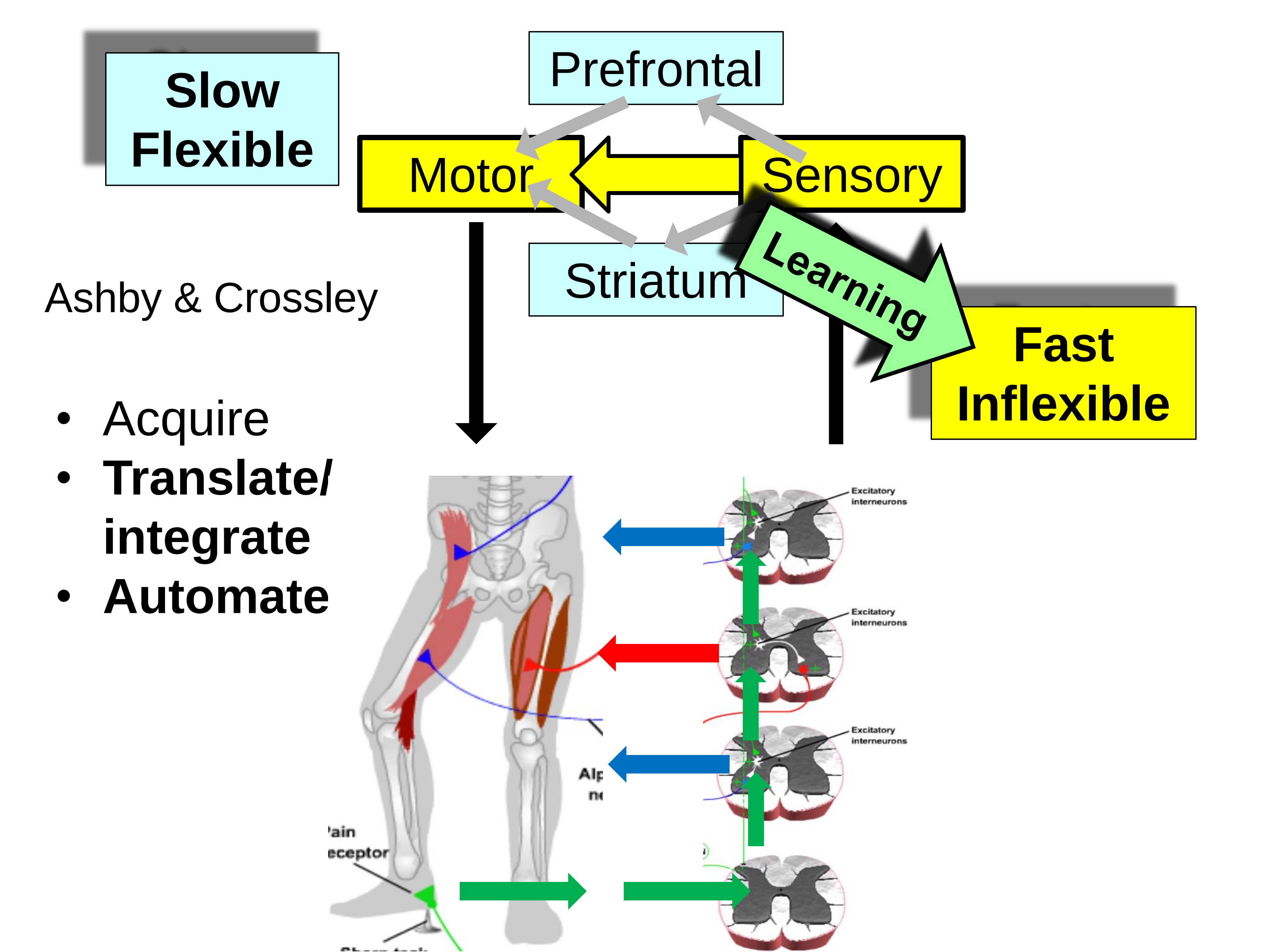
Learning

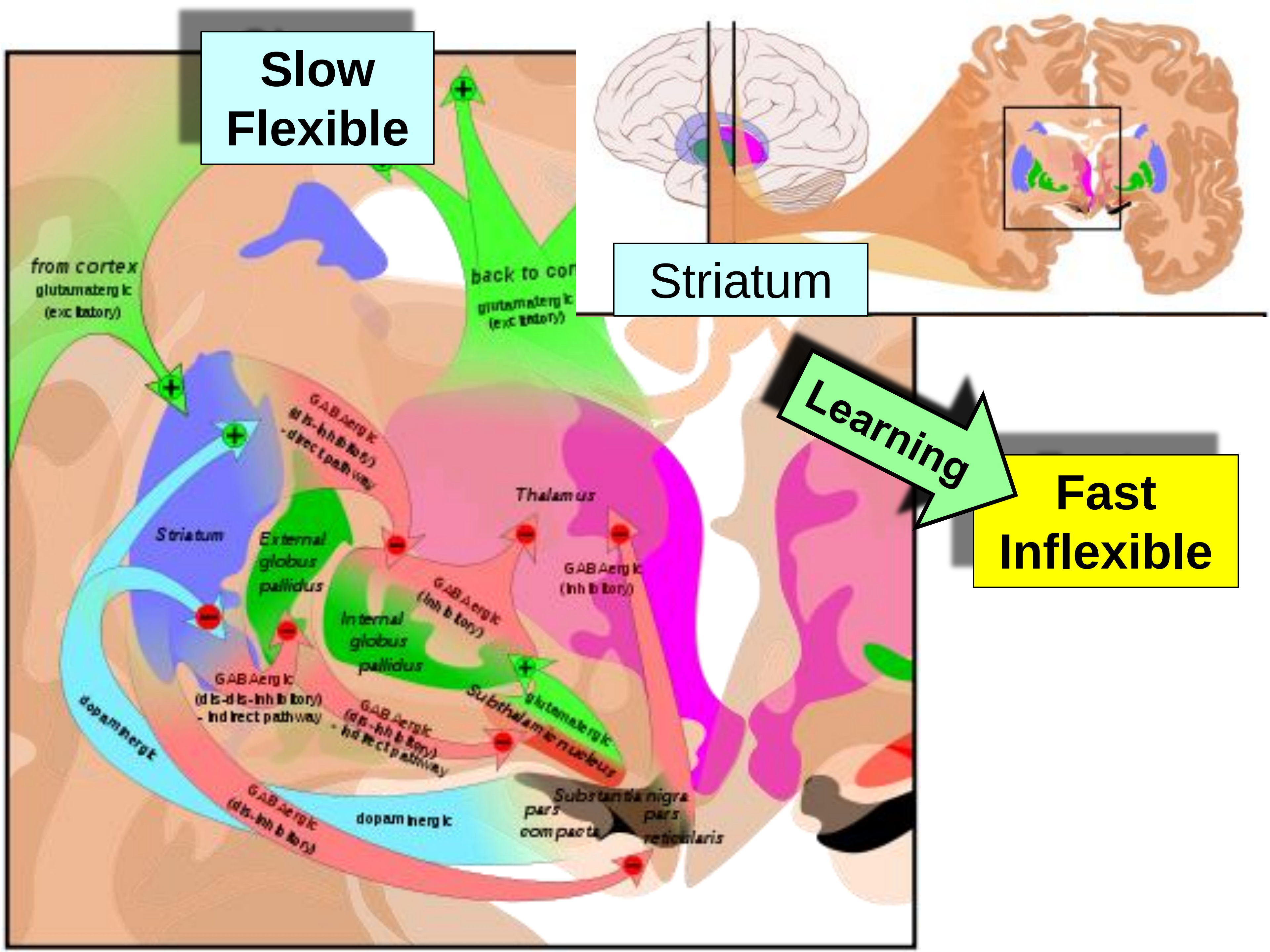


Ashby & Crossley

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

Thanks to
Bassett & Grafton

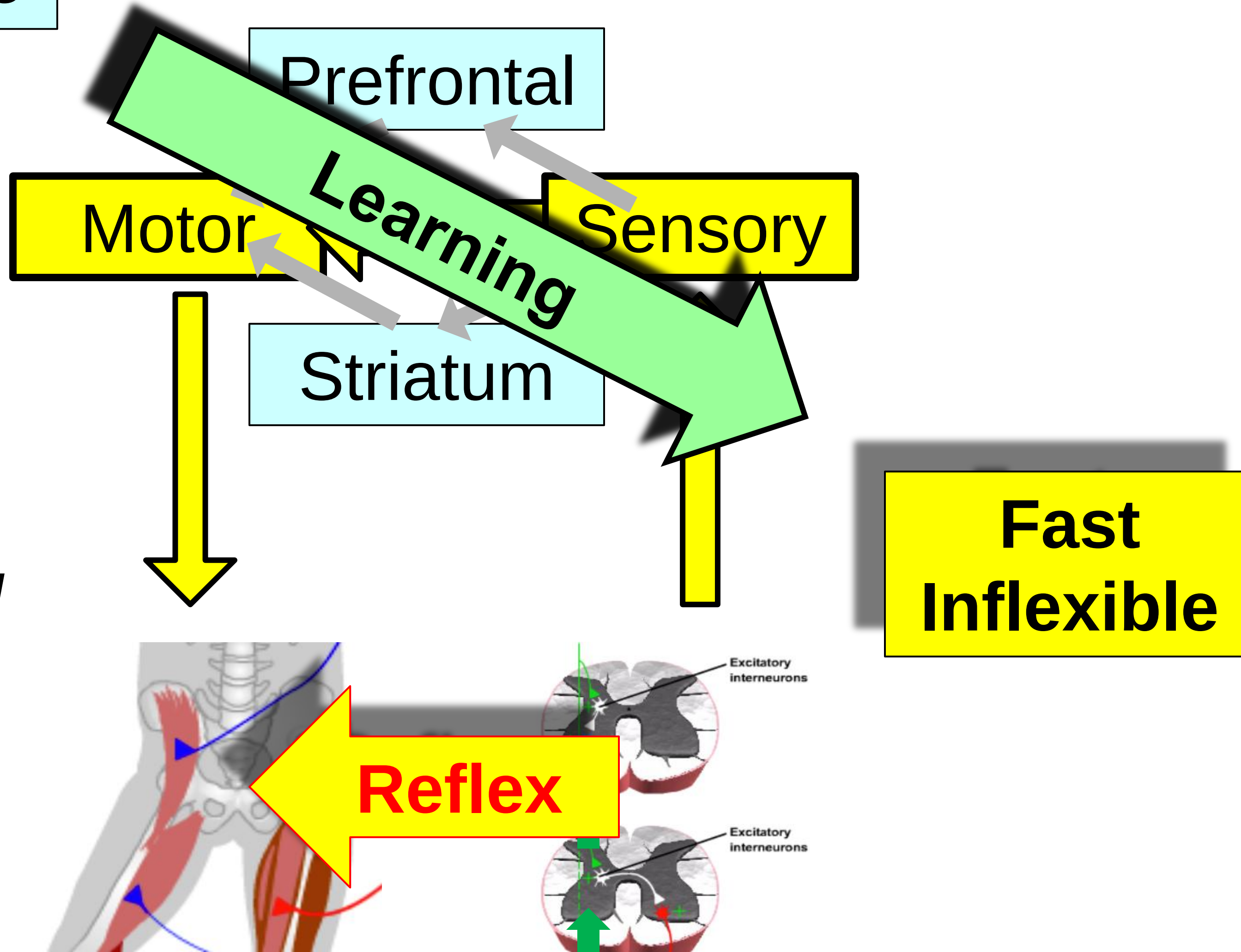

Slow
Flexible
Prefrontal
Motor
Sensory
Striatum
Learning
Fast
Inflexible
Ashby & Crossley
• Acquire
• Translate/ integrate
• Automate
Excitatory interneurons
Excitatory interneurons
Excitatory interneurons



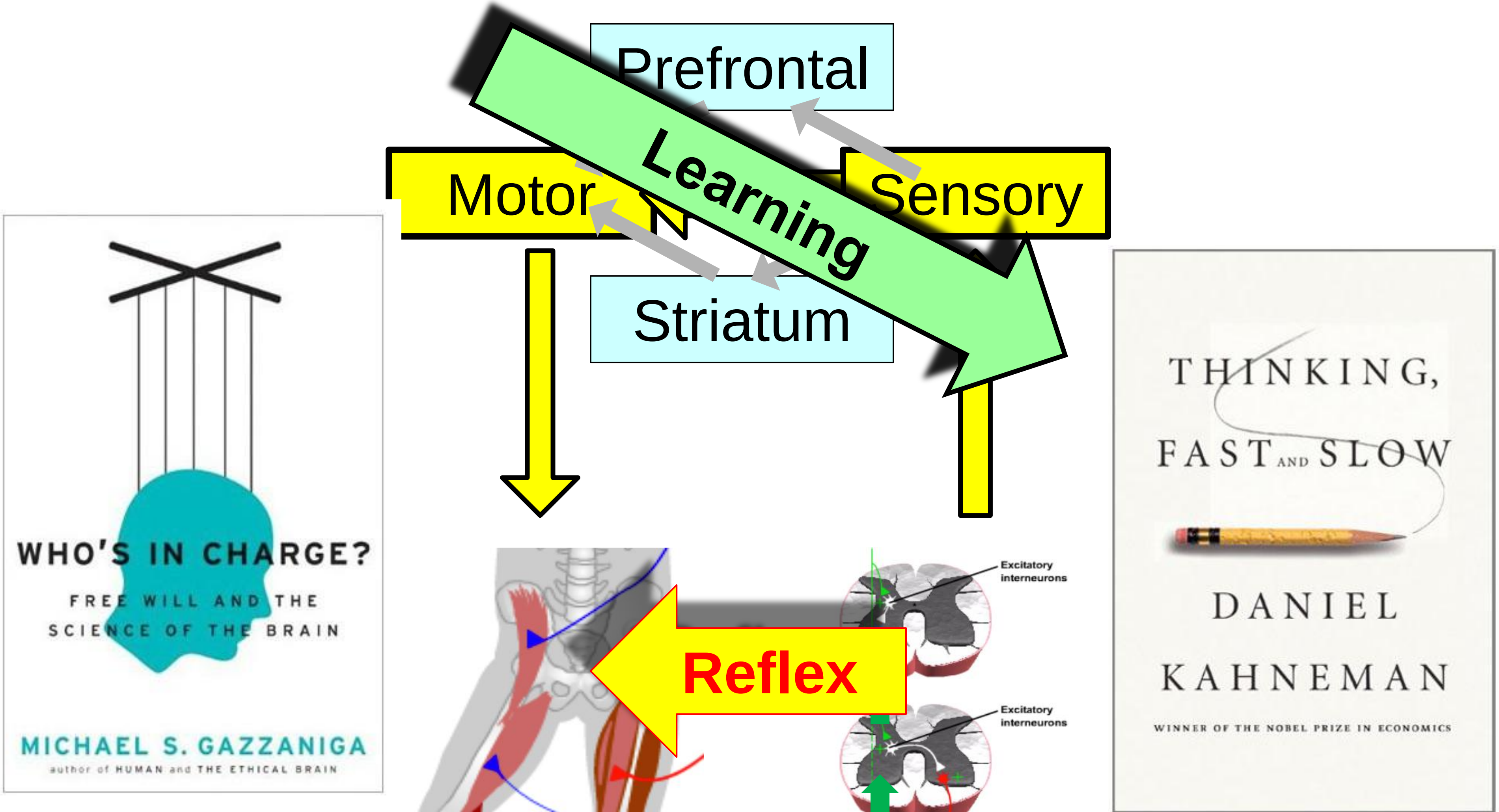
Slow
Flexible
Striatum
Learning
Fast
Inflexible
from cortex
glutamatergic
(excitatory)
back to cor
glutamatergic
(excitatory)
GABAergic
(dis-inhibitory)
- direct pathway
Thalamus
Striatum
External
globus
pallidus
GABAergic
(inhibitory)
GABAergic
(inhibitory)
Internal
globus
pallidus
GABAergic
(dis-dis-inhibitory)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

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

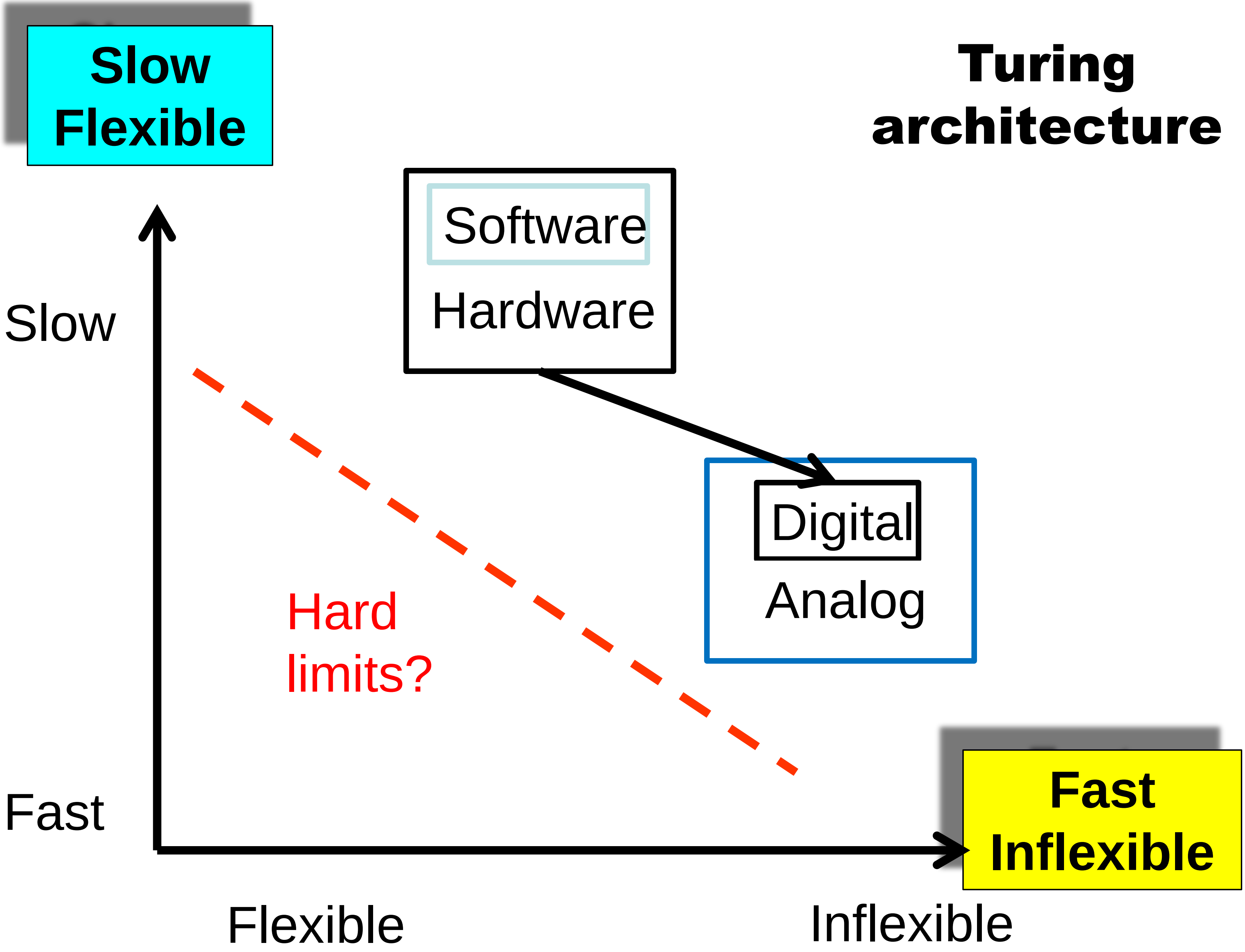
Slow
Flexible



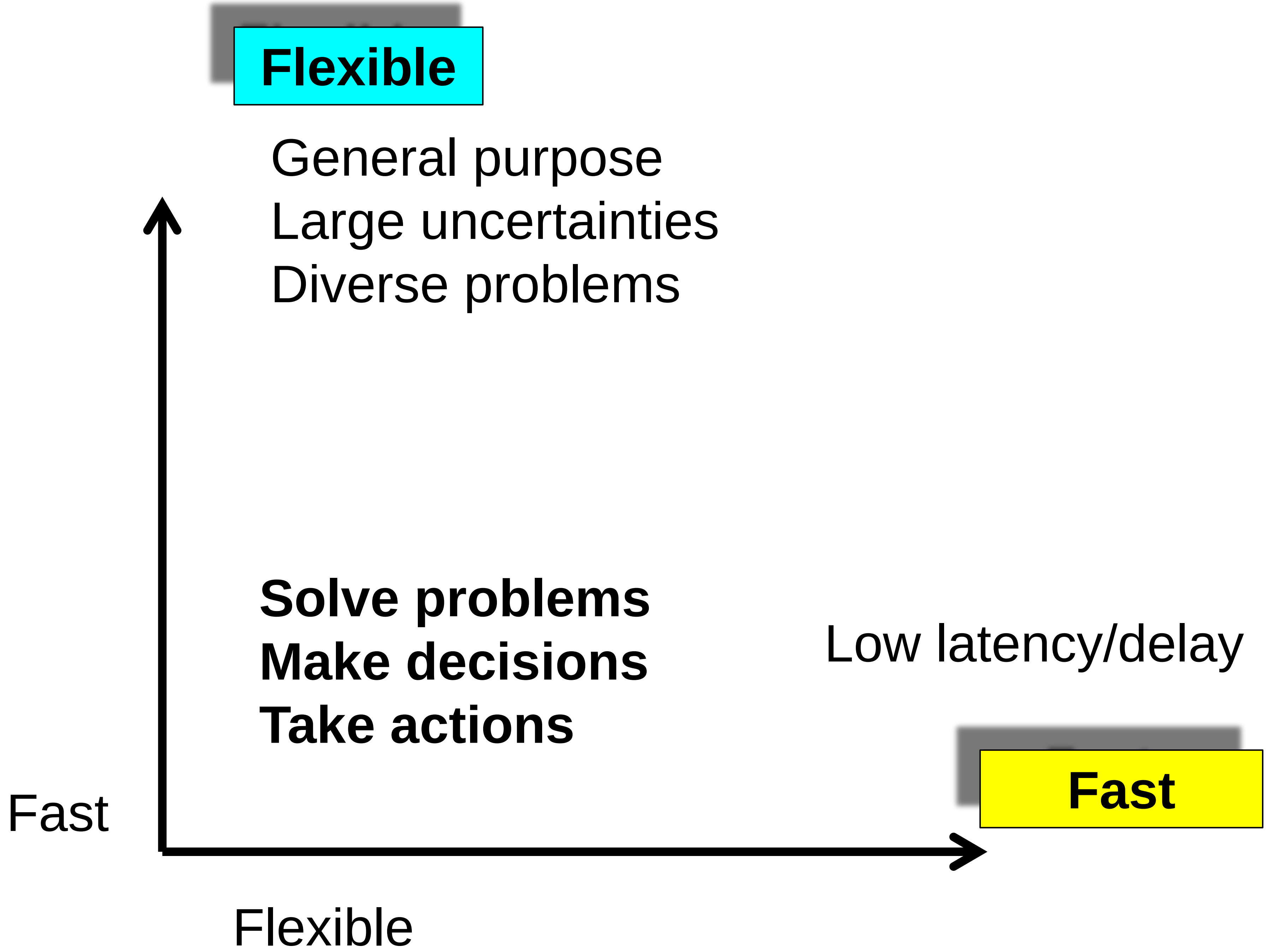
- **Acquire**
- **Translate/ integrate**
- **Automate**

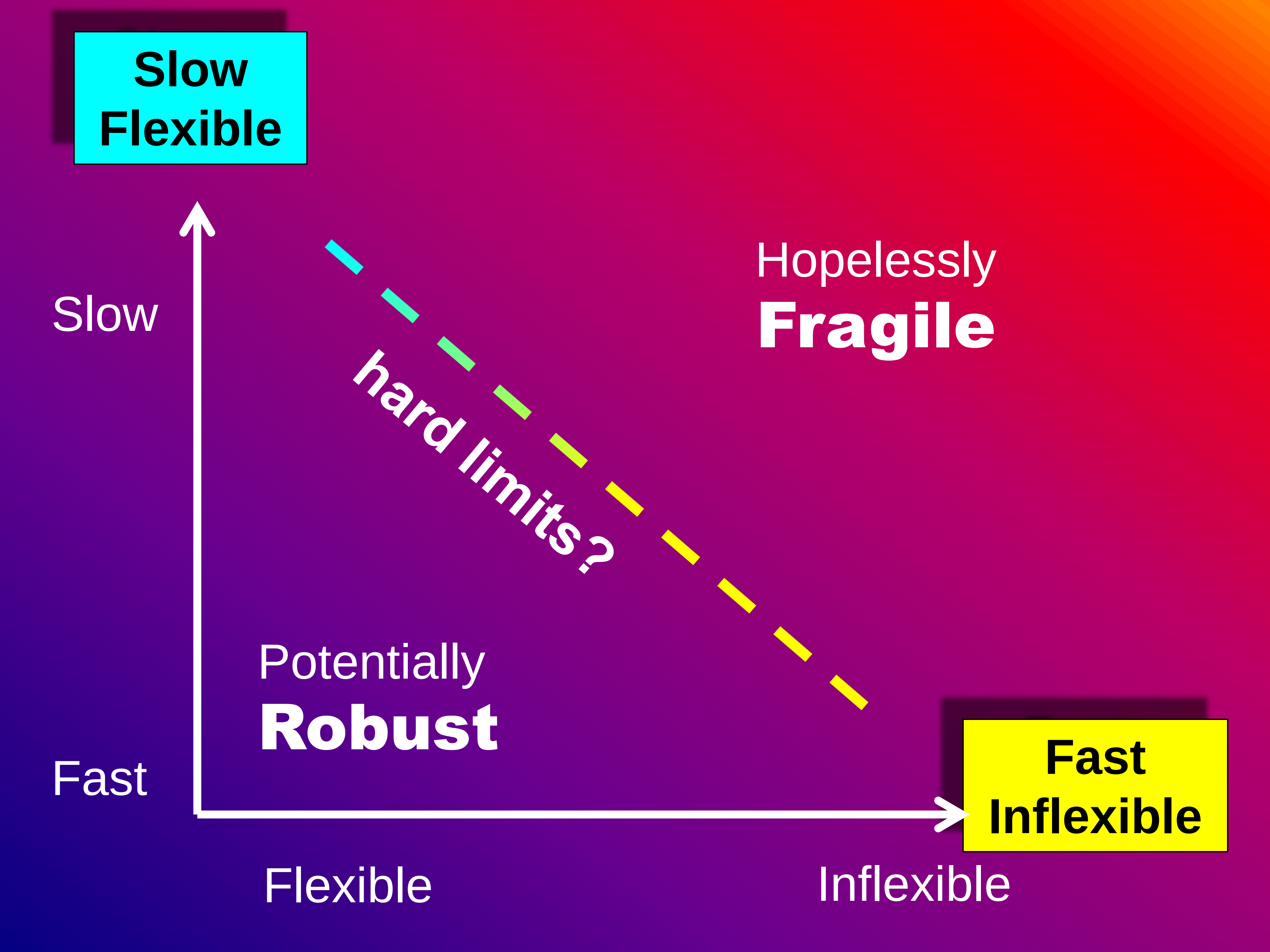


Prefrontal
Motor
Sensory
Learning
Striatum
Reflex
Excitatory interneurons
Excitatory interneurons
WHO'S IN CHARGE?
FREE WILL AND THE SCIENCE OF THE BRAIN
MICHAEL S. GAZZANIGA
author of HUMAN and THE ETHICAL BRAIN
THINKING, FAST AND SLOW
DANIEL KAHNEMAN
WINNER OF THE NOBEL PRIZE IN ECONOMICS



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


Flexible
General purpose
Large uncertainties
Diverse problems
Solve problems
Make decisions
Take actions
Low latency/delay
Fast
Fast
Flexible


Slow
Flexible
Slow
Fast
Hopelessly
Fragile
hard limits?
Potentially
Robust
Fast
Inflexible
Flexible
Inflexible

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?

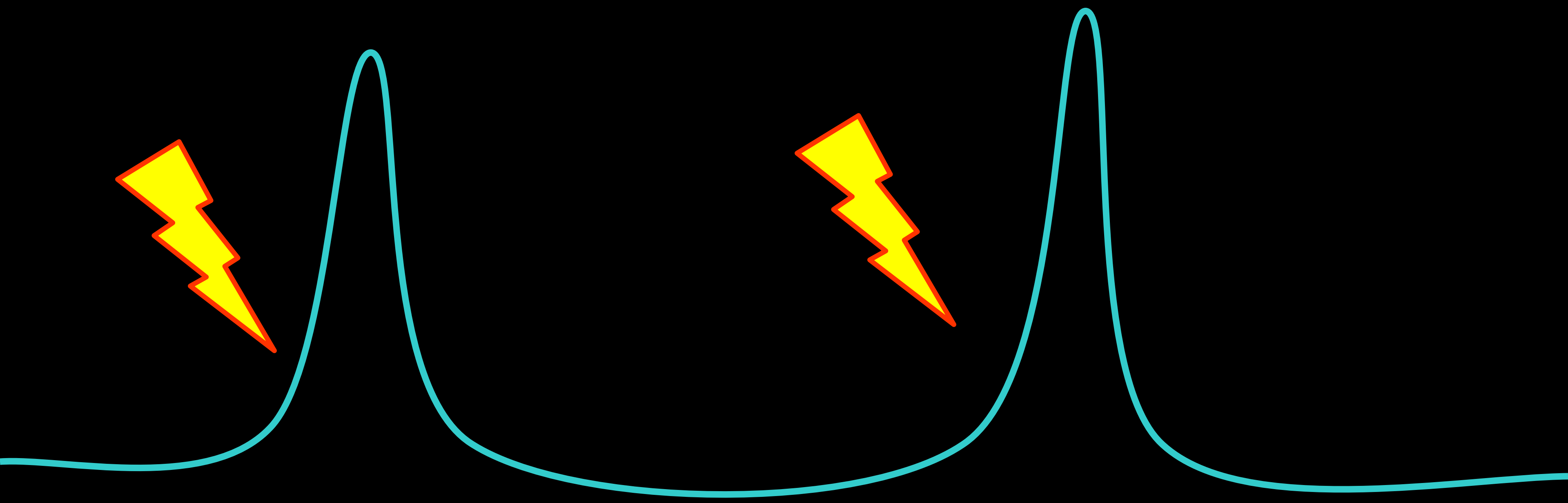
Robust	Fragile
☺ Metabolism	☹ Obesity, diabetes
☺ Regeneration & repair	☹ Cancer
☺ Healing wound /infect	☹ AutoImmune/Inflame
☹ Fat accumulation	☹ Fat accumulation
☹ Insulin resistance	☹ Insulin resistance
☹ Proliferation	☹ Proliferation
☹ Inflammation	☹ Inflammation

What's the difference?

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

☹ Fat accumulation
☹ Insulin resistance
☹ Proliferation
☹ Inflammation

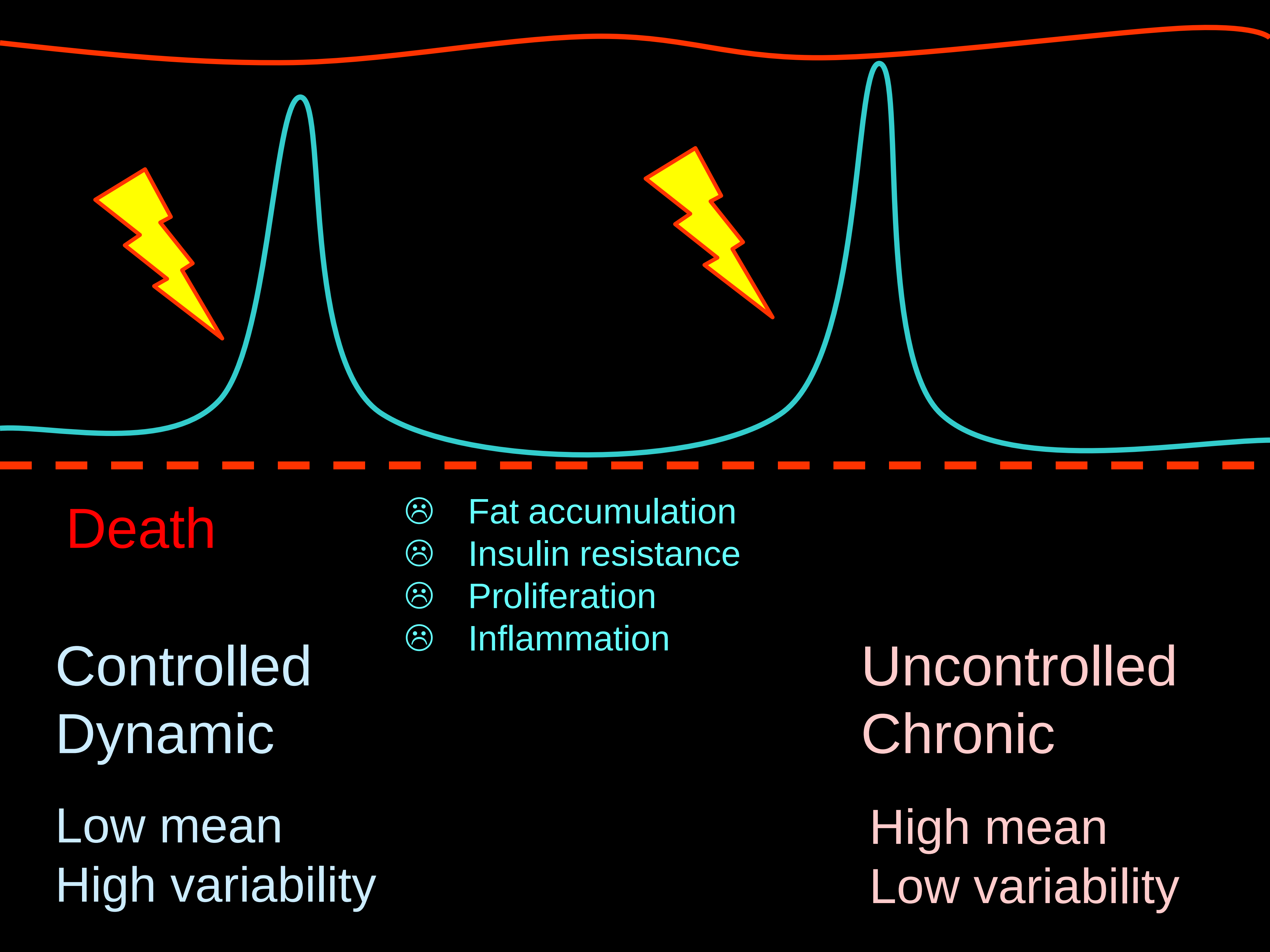
Controlled	Uncontrolled
Dynamic	Chronic



- ☹ 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	Fragile
☺ Metabolism	☹ Obesity, diabetes
☺ Regeneration & repair	☹ Cancer
☺ Healing wound /infect	☹ AutoImmune/Inflame
☹ Fat accumulation	☹ Fat accumulation
☹ Insulin resistance	☹ Insulin resistance
☹ Proliferation	☹ Proliferation
☹ Inflammation	☹ Inflammation

Controlled
Dynamic

Low mean
High variability

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

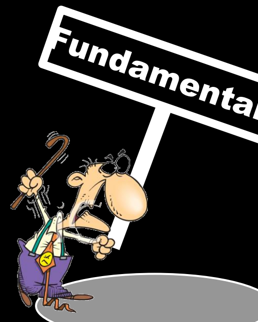
☹ Proliferation

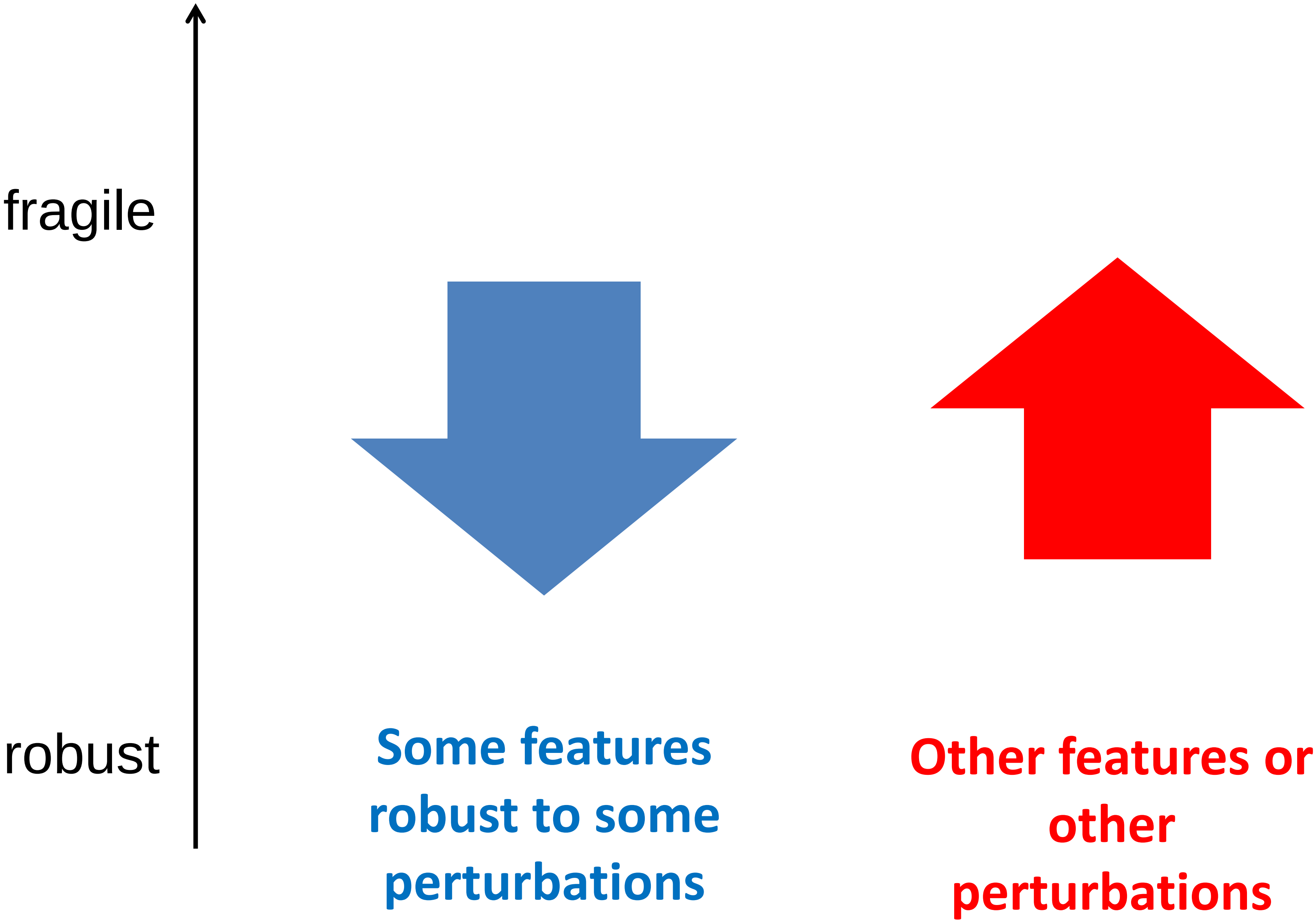
☹ Inflammation

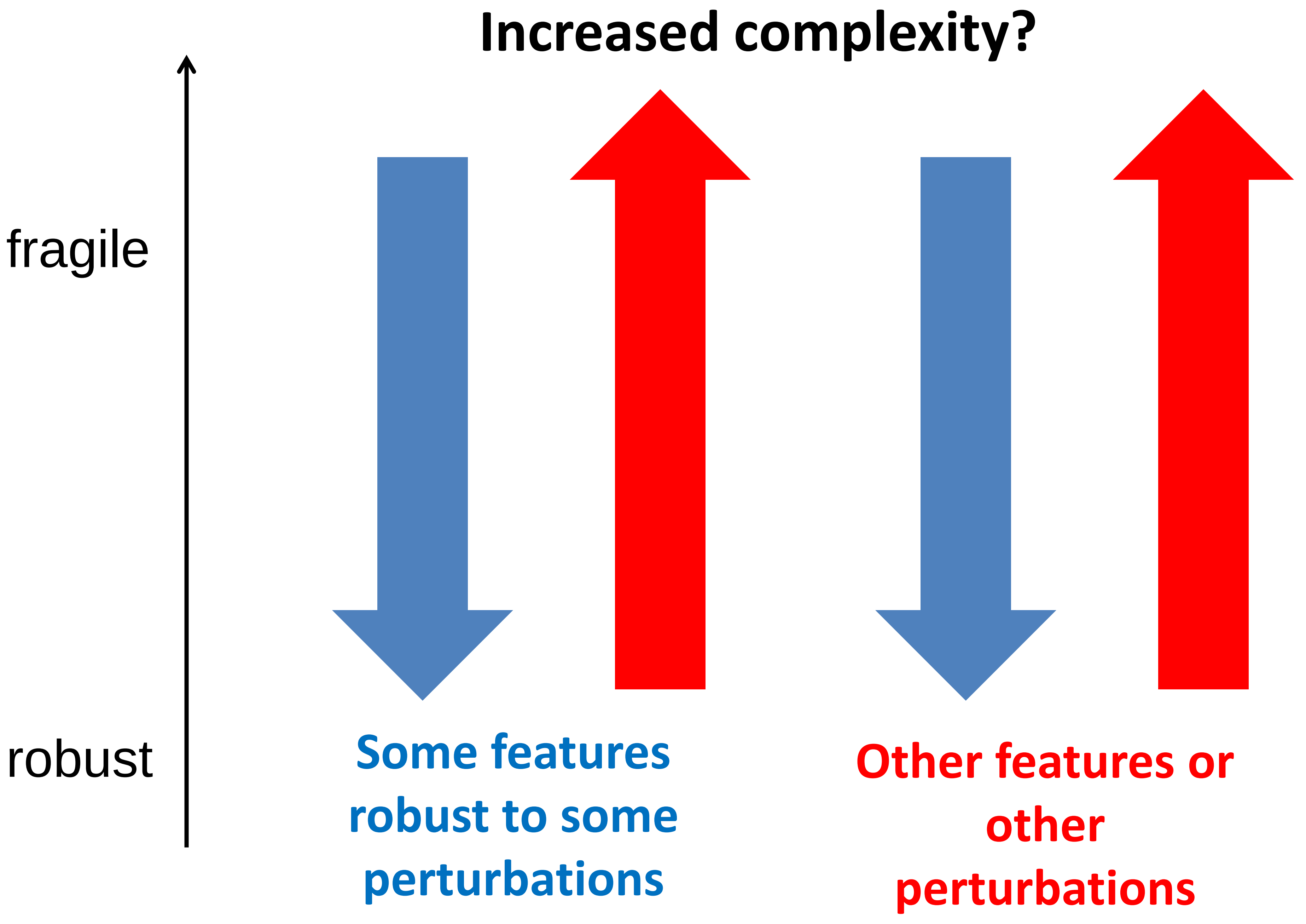
- Fragility ← Hijacking, side effects, unintended…
- Of mechanisms evolved for robustness
- Complexity ← control, robust/fragile tradeoffs
- Math: robust/fragile constraints (“conservation laws”)

Both

Accident or necessity?

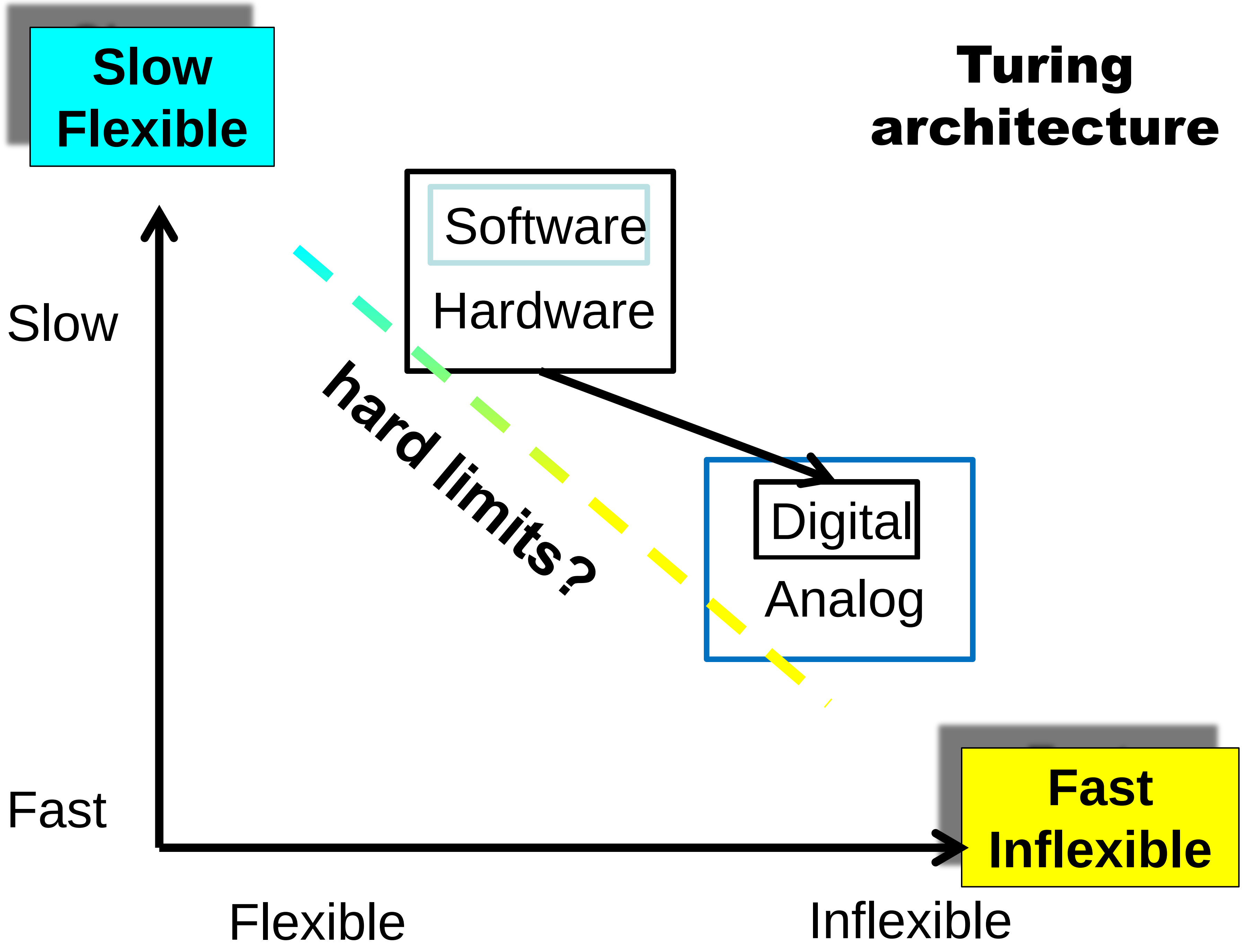



fragile
robust
Some features robust to some perturbations
Other features or other perturbations

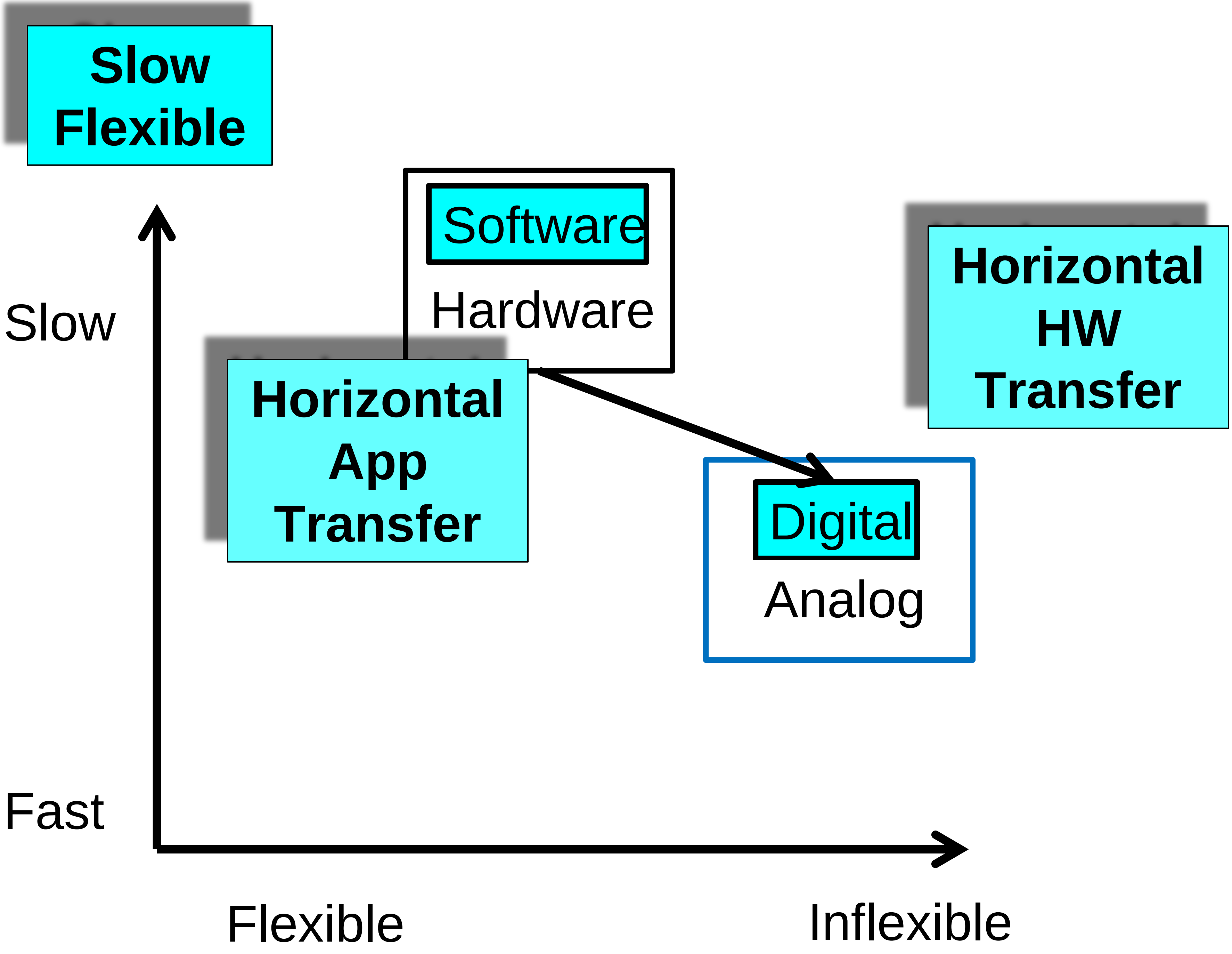

Increased complexity?
fragile
robust
Some features robust to some perturbations
Other features or other perturbations

Robust		Fragile
Modular	*and*	Distributed
Simple	~~***xor***~~	Complex
Plastic		Frozen
Evolvable		Frozen

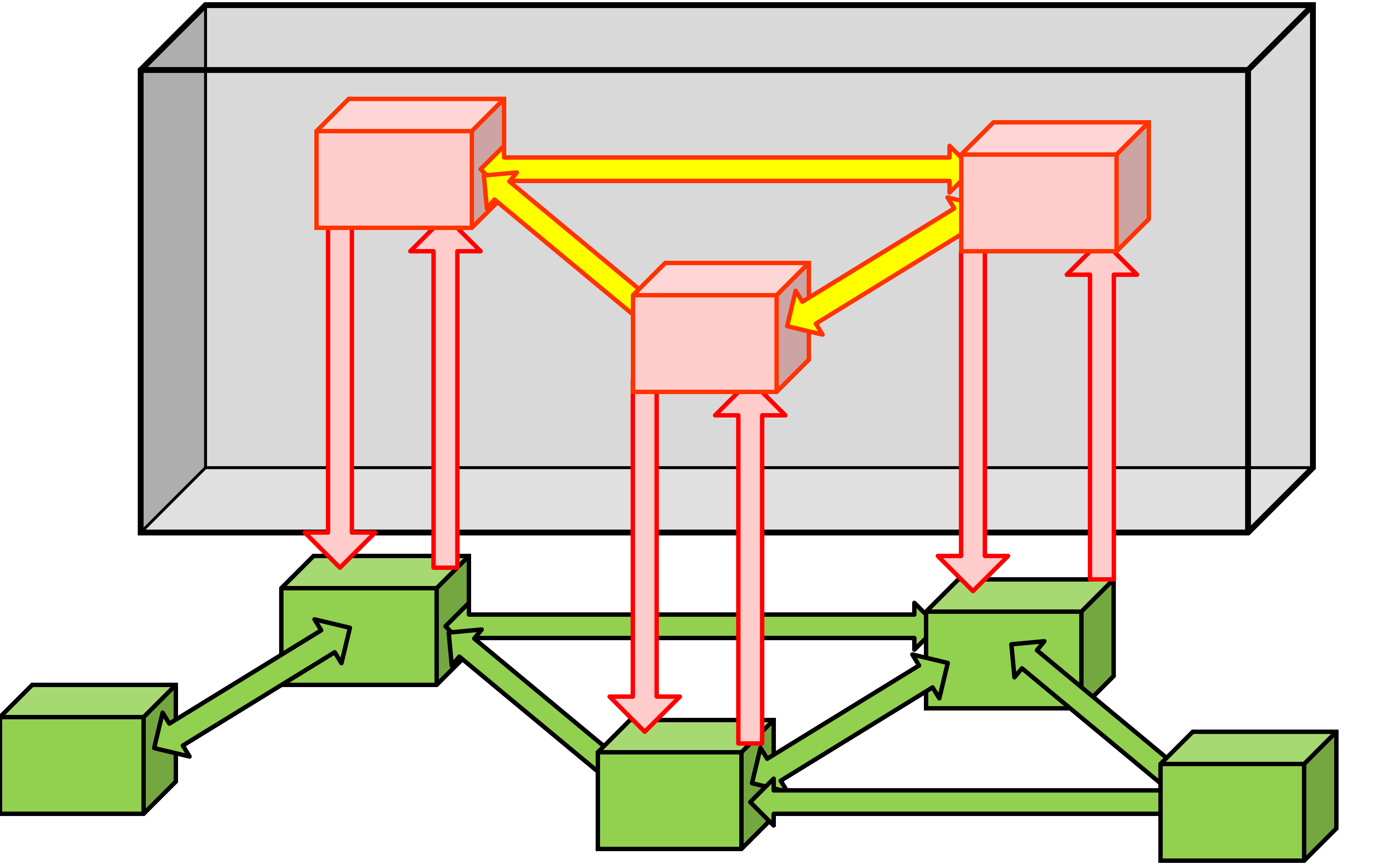
tradeoffs

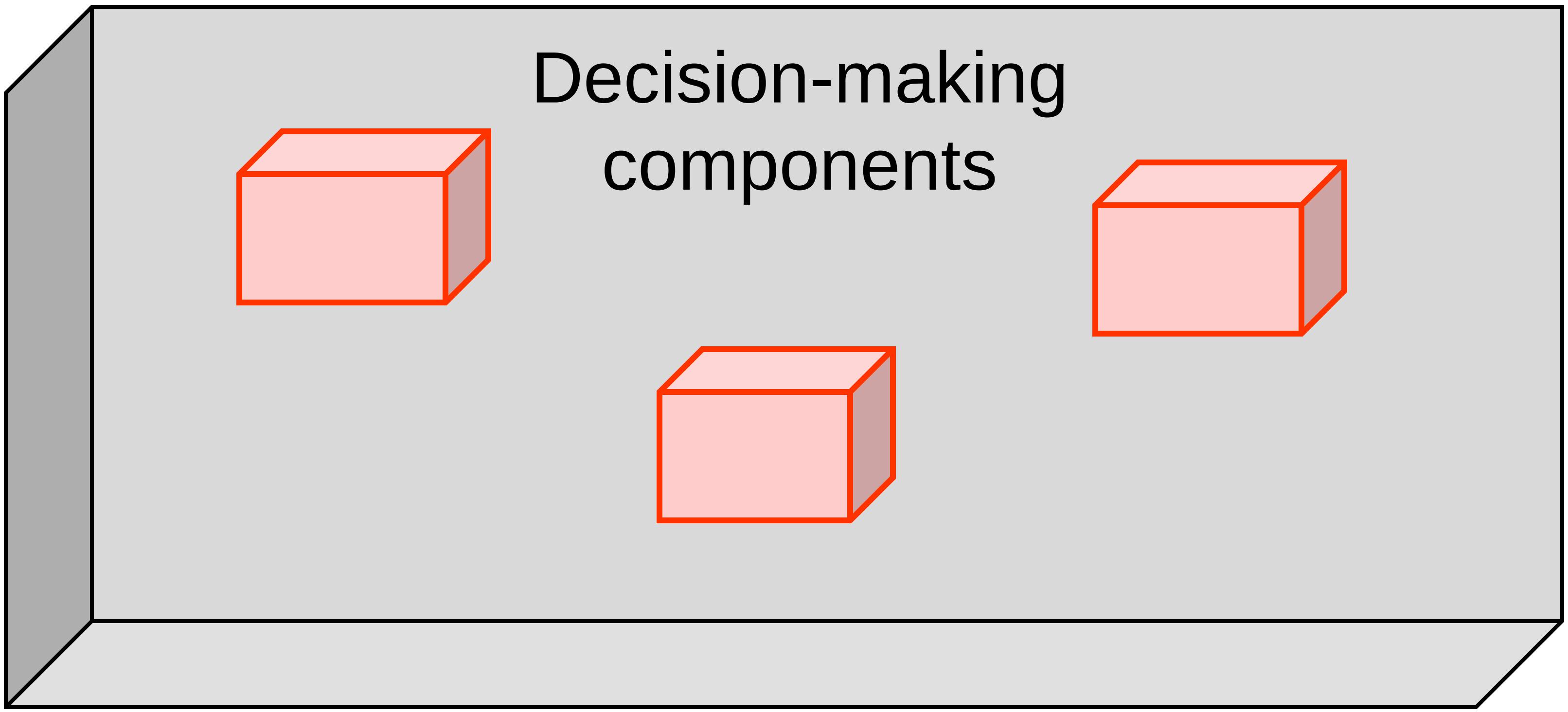


Slow
Flexible
Turing
architecture
Software
Hardware
hard limits?
Digital
Analog
Slow
Fast
Fast
Inflexible
Flexible
Inflexible

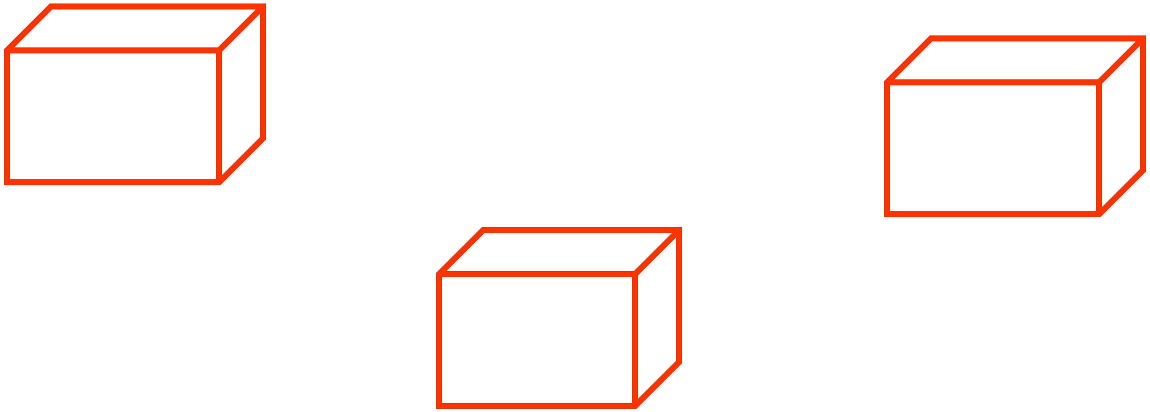

Slow
Flexible
Software
Hardware
Horizontal
HW
Transfer
Slow
Horizontal
App
Transfer
Digital
Analog
Fast
Flexible
Inflexible

Cyber-physical: decentralized control with internal delays.

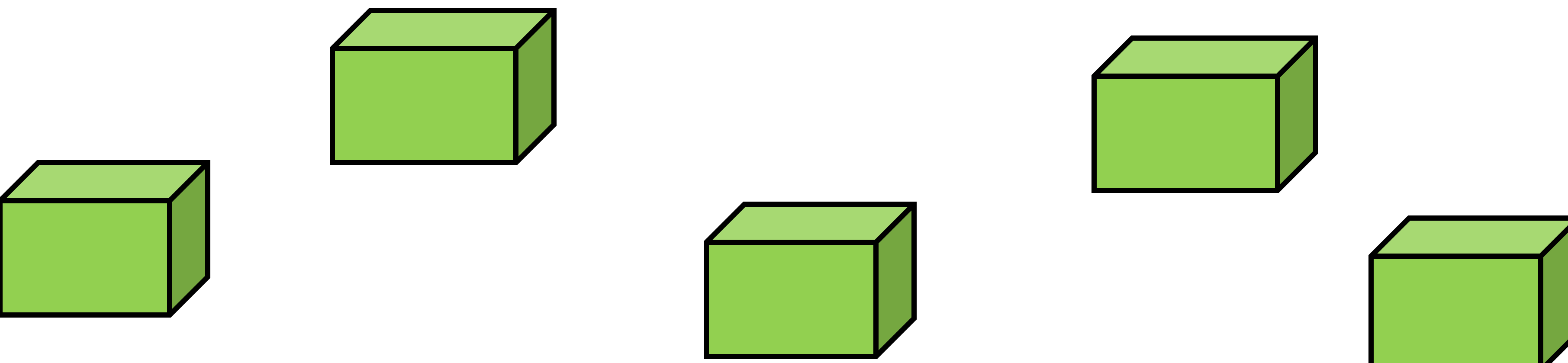




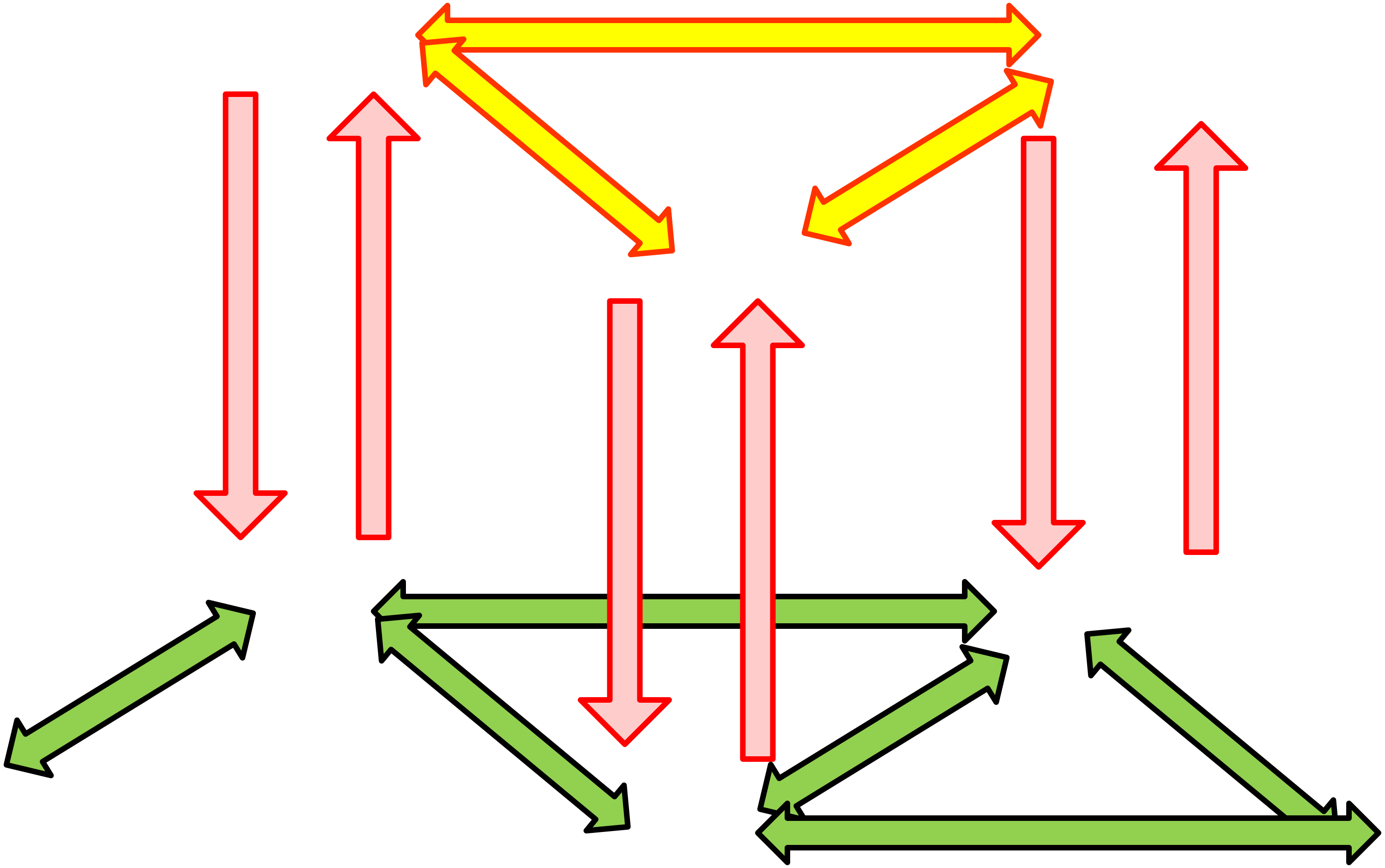
Decentralized, but initially assume computation is fast and memory is abundant.



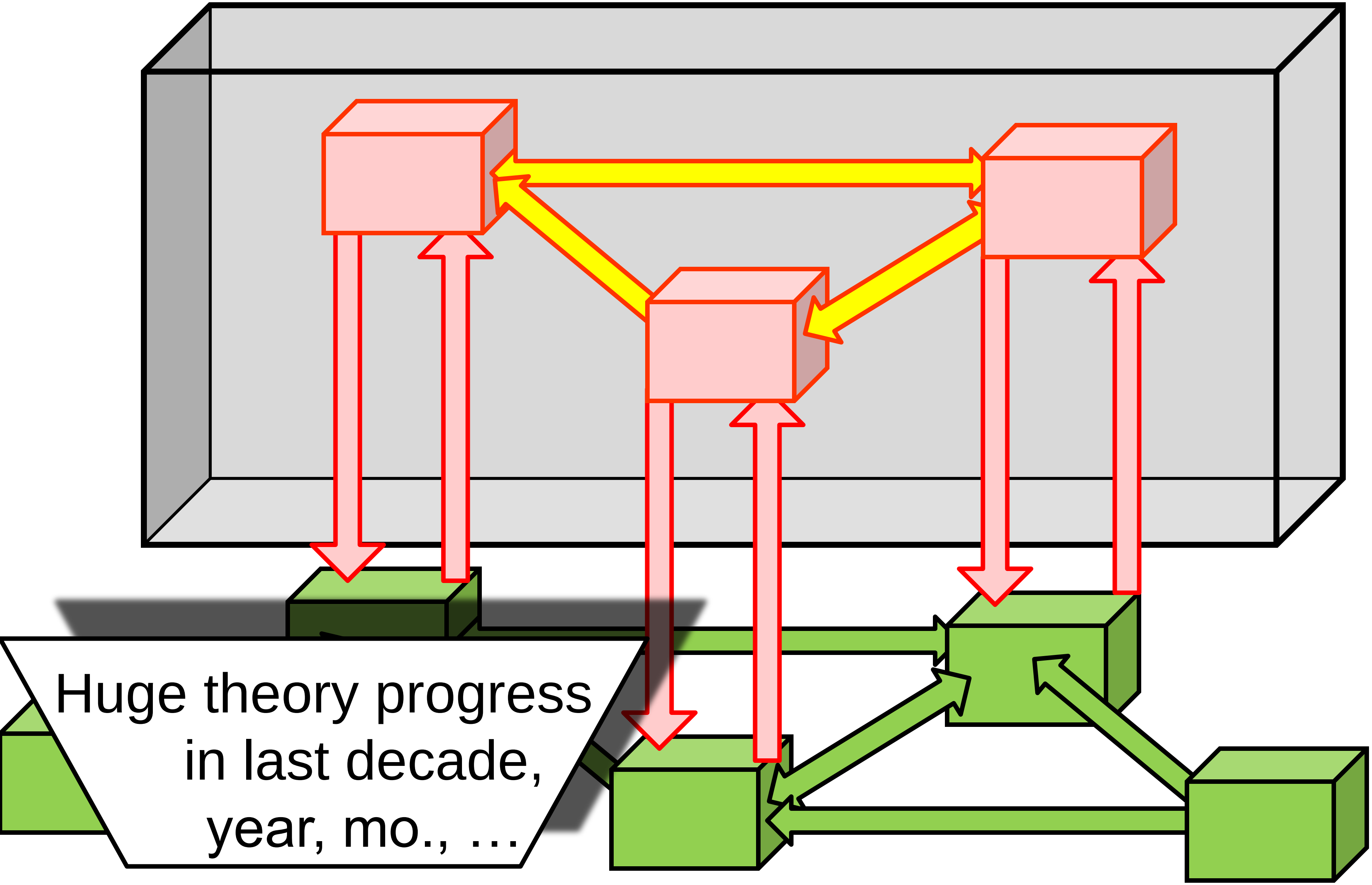
Plant is also distributed with its own component dynamics



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

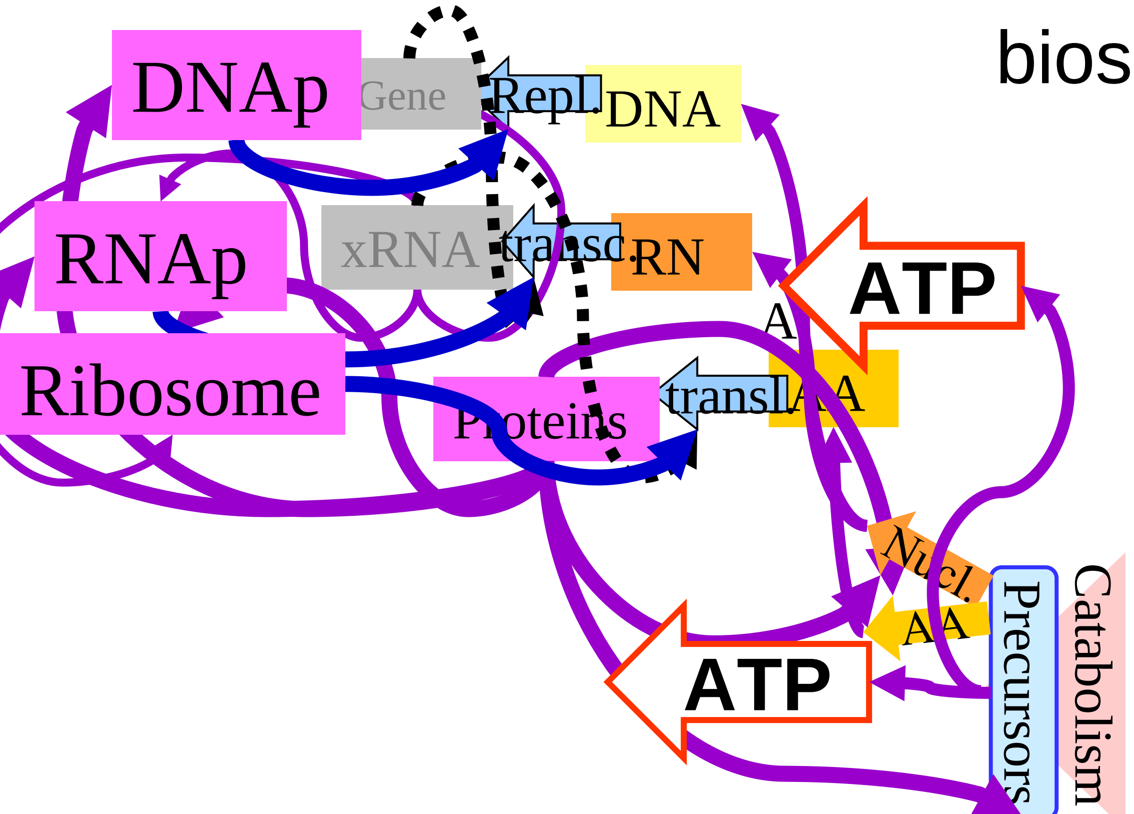


Going beyond black box: control is decentralized with internal delays.



The best case study so far

Layered architecture of the bacterial biosphere



Not done here in detail, see slides elsewhere

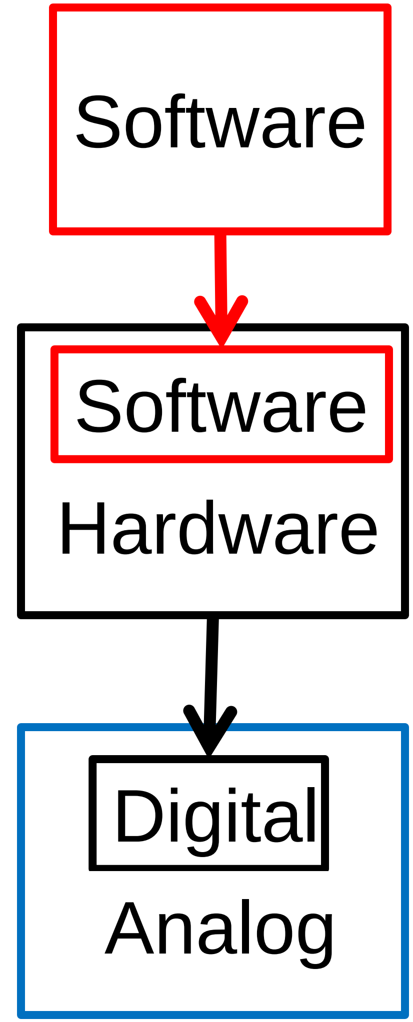
How?

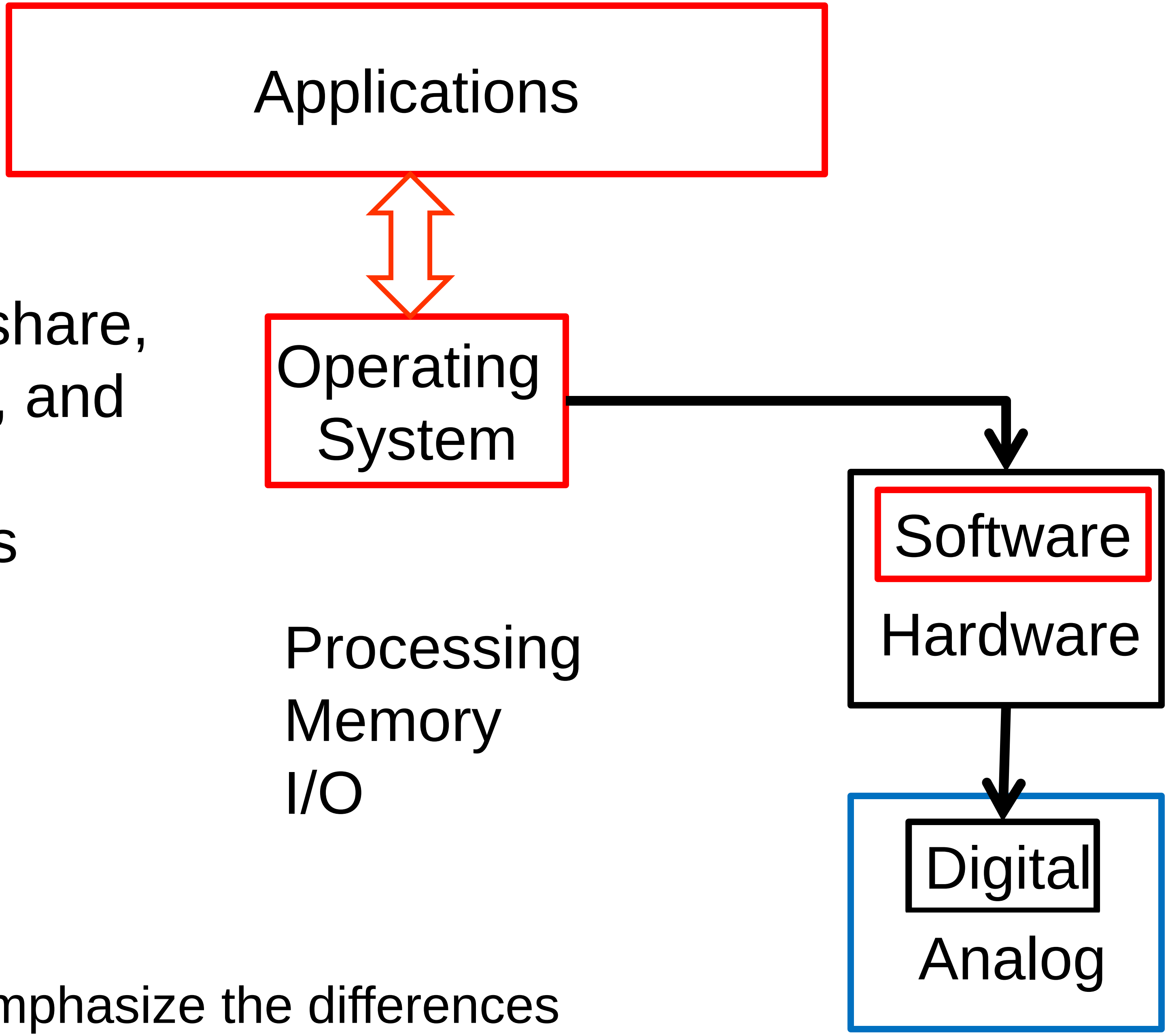
Universal architectures

Slow execution
Flexible reprogramming

Faster execution
Less flexible

Modern technology gives lots of intermediate alternatives.

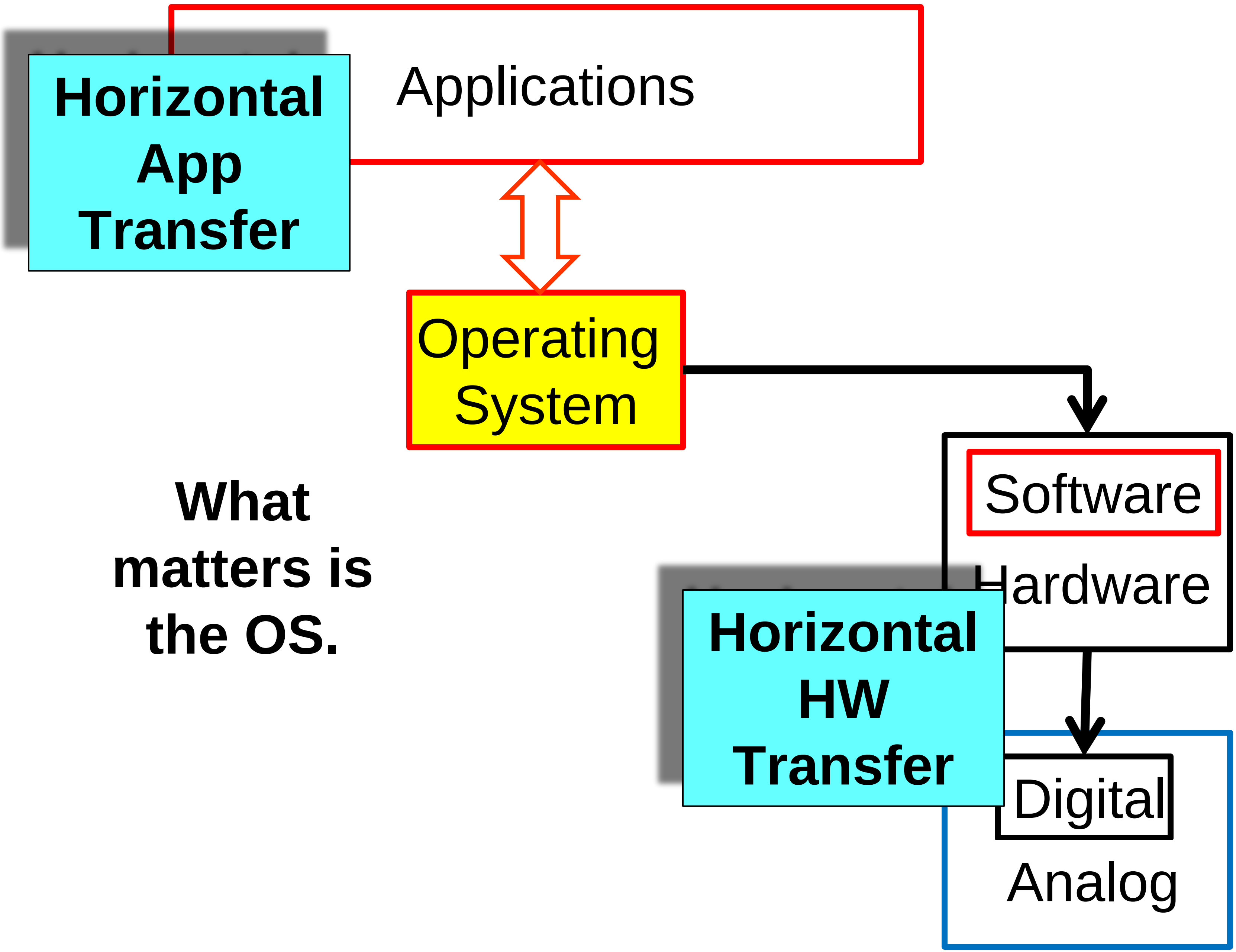


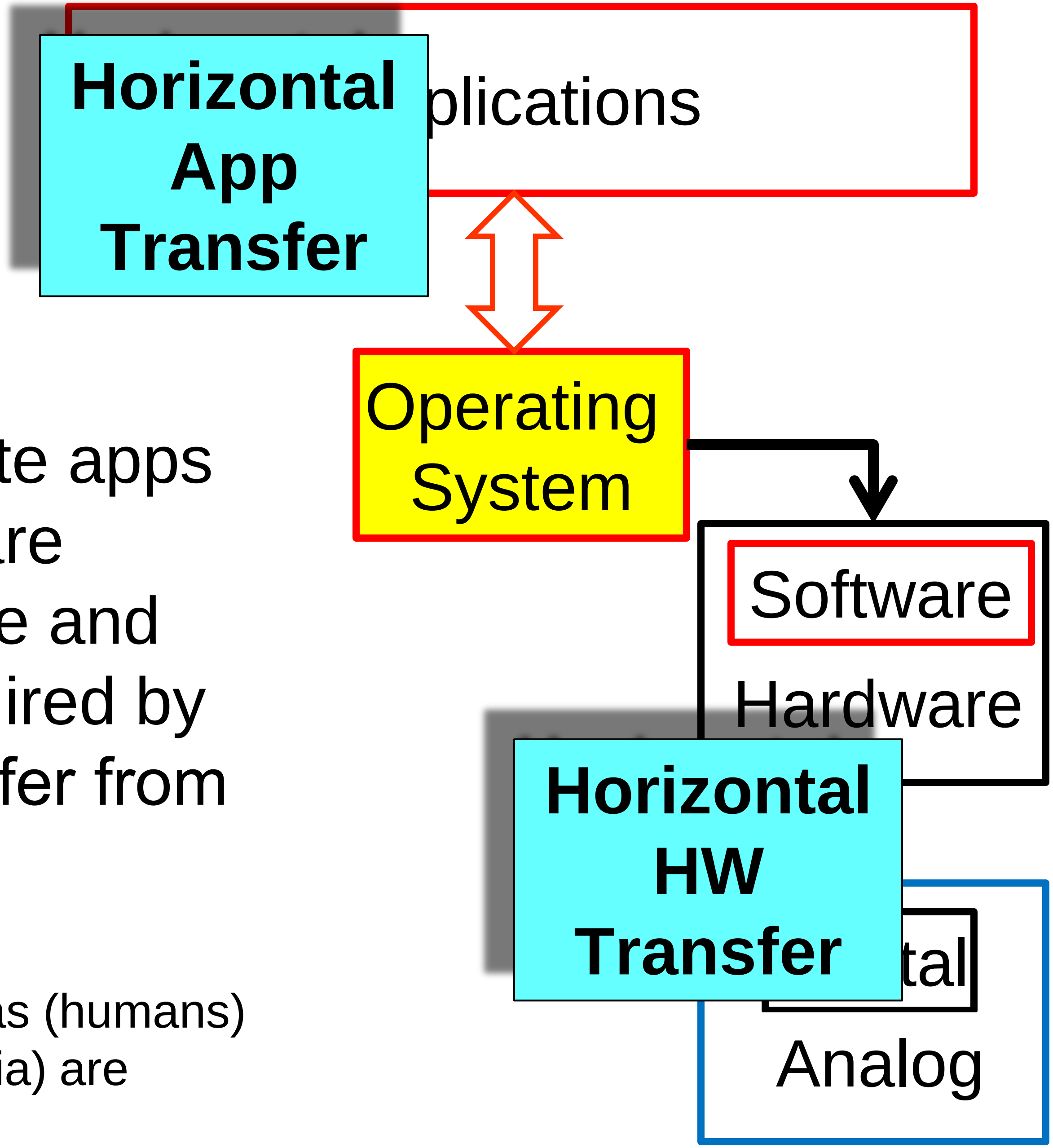


Control, share, virtualize, and manage resources

Processing
Memory
I/O

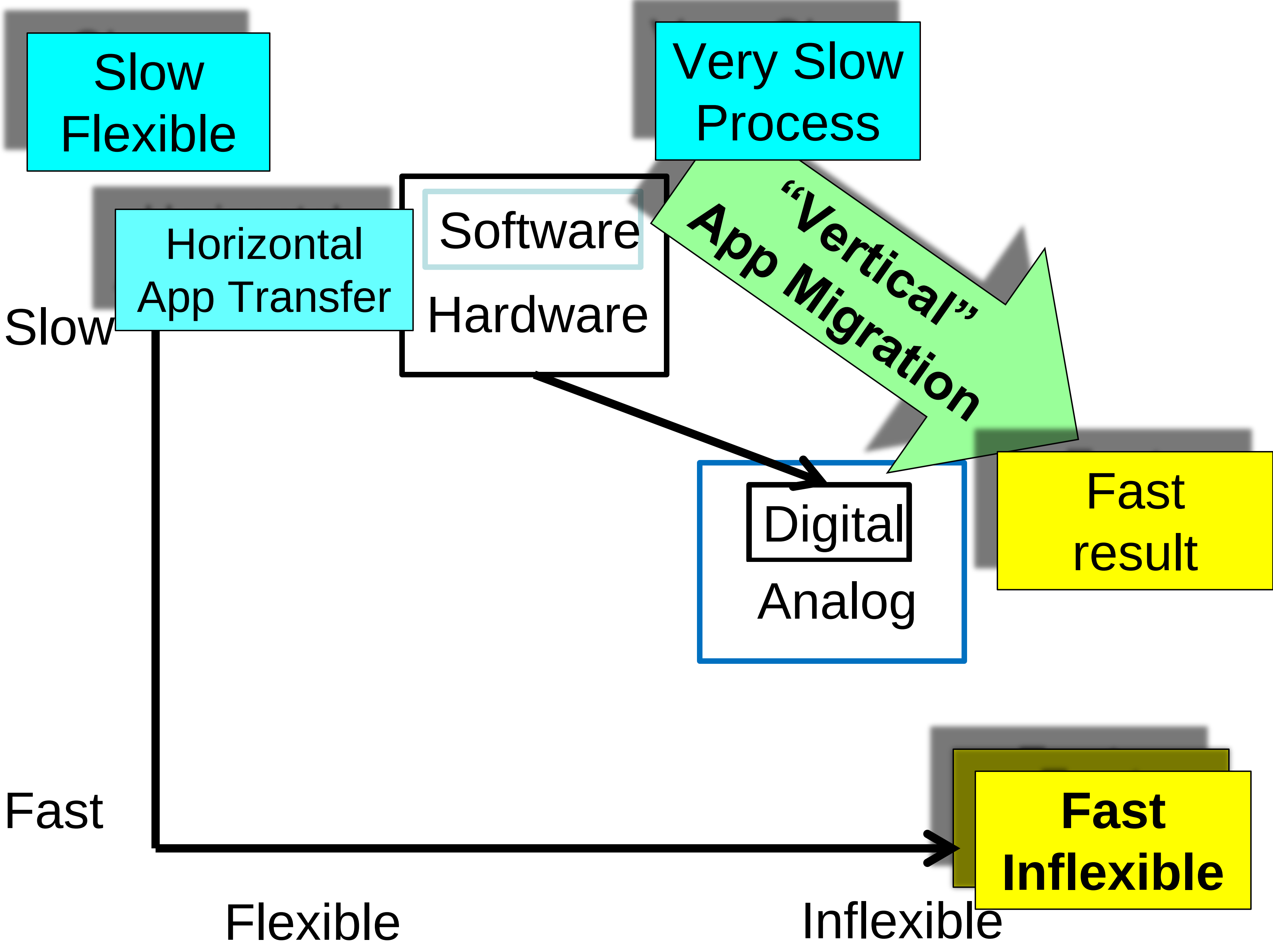
Want to emphasize the differences between these two types of layering.

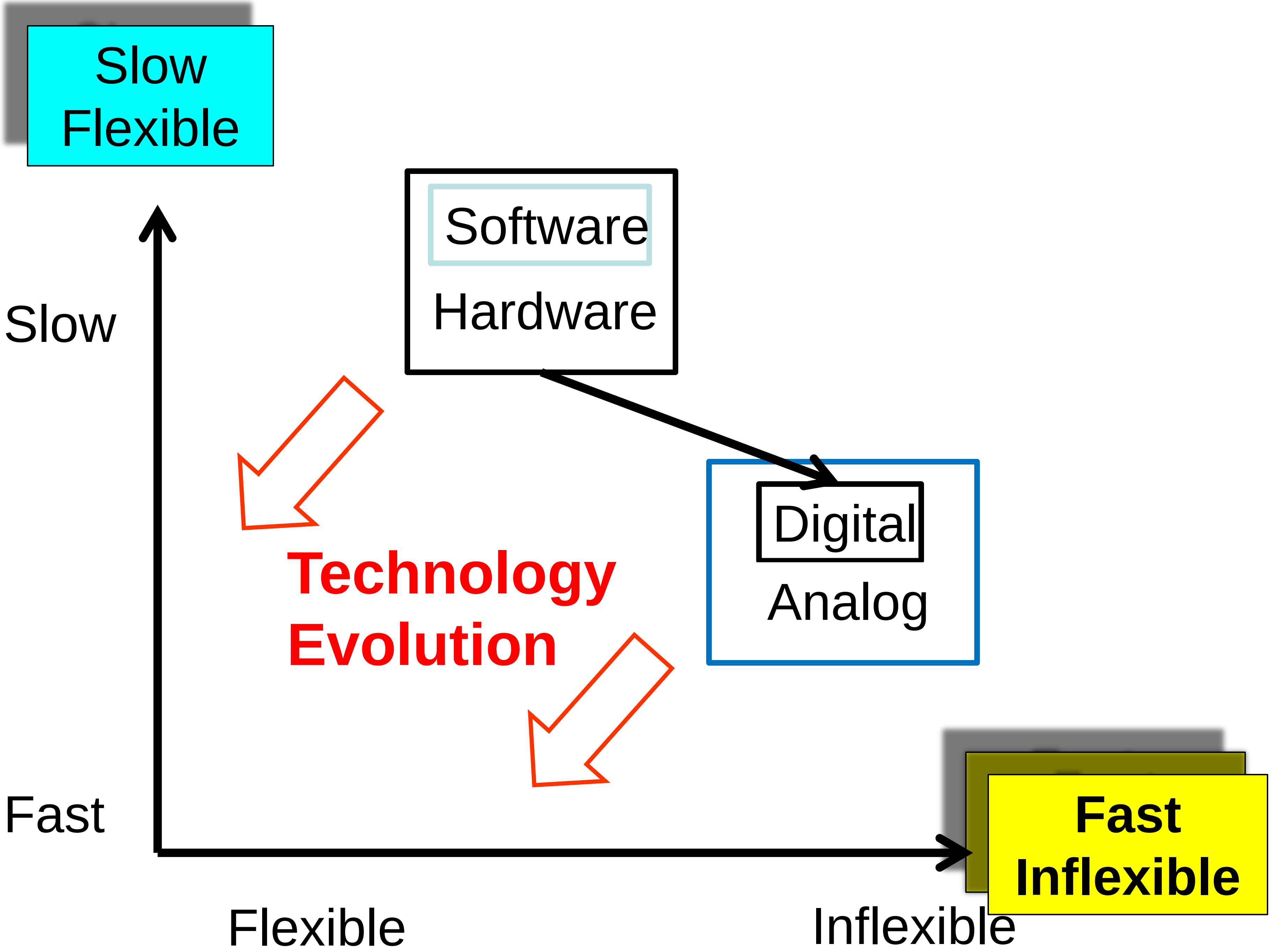

Applications
Horizontal App Transfer
Operating System
What matters is the OS.
Software
Hardware
Horizontal HW Transfer
Digital
Analog

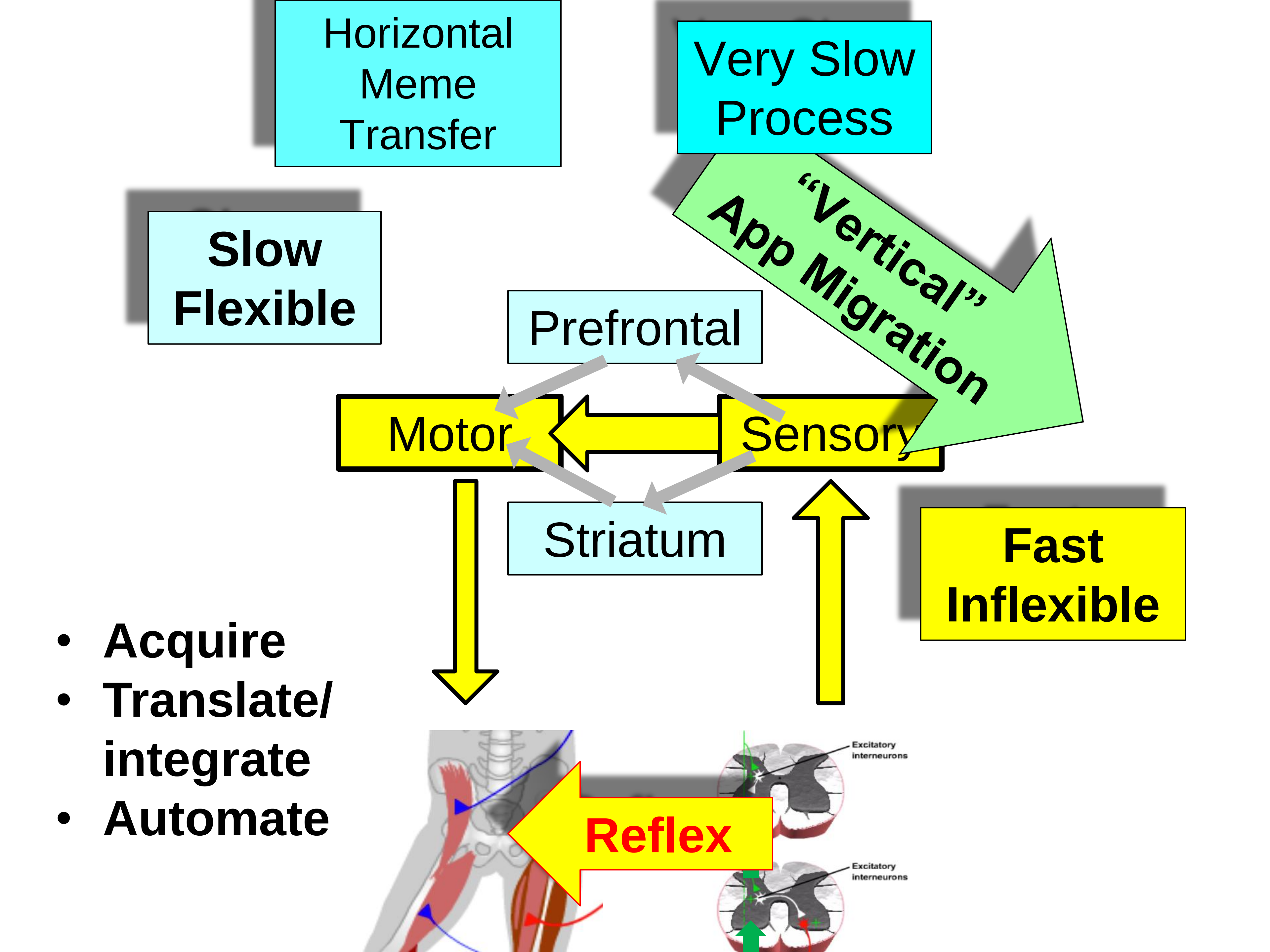


- Some people write apps and build hardware
- But most software and hardware is acquired by "horizontal" transfer from others

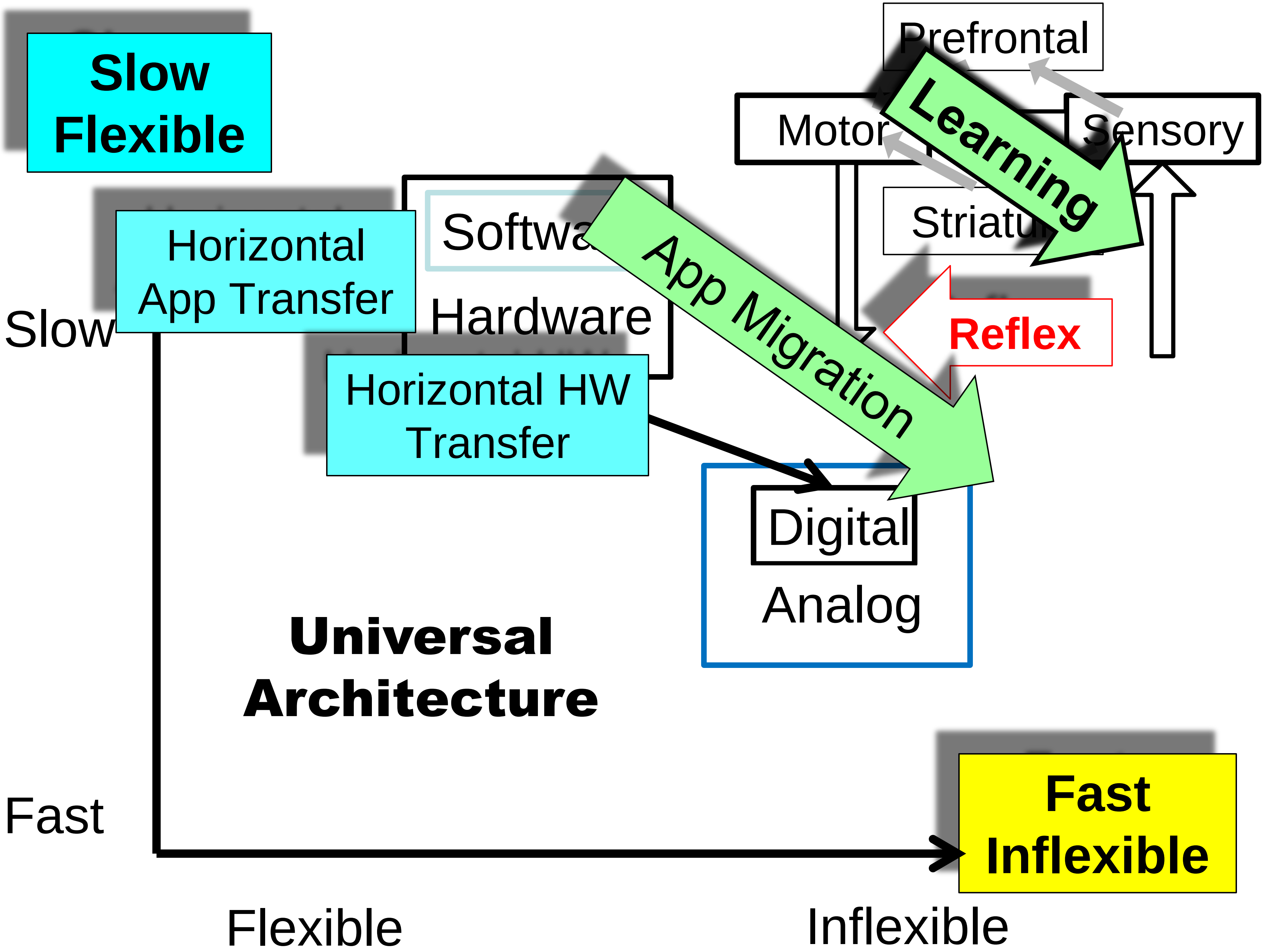
- Similarly, most new ideas (humans) and new genes (bacteria) are acquired horizontally

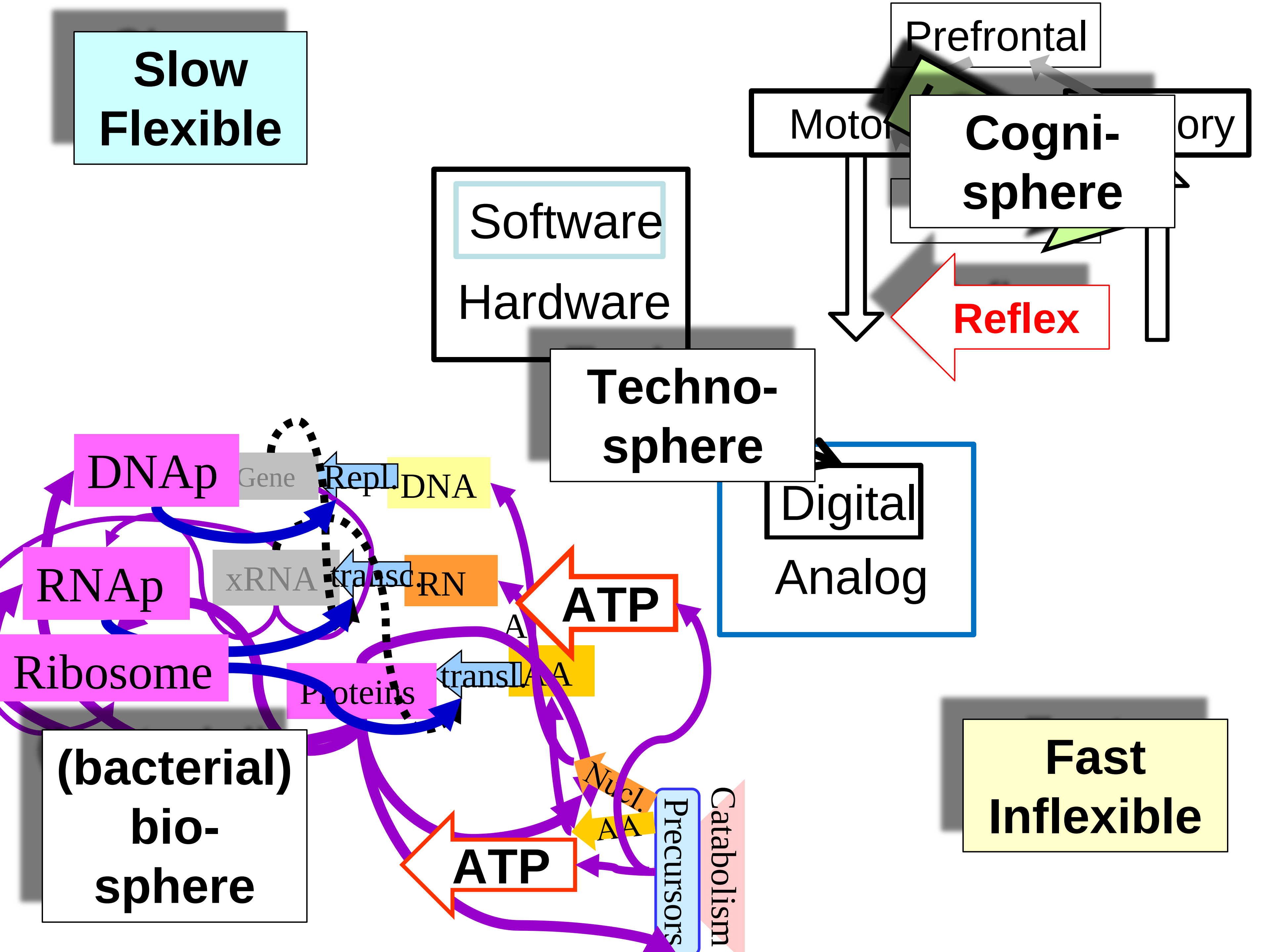

Slow
Flexible
Very Slow
Process
Horizontal
App Transfer
Software
Hardware
"Vertical"
App Migration
Slow
Digital
Analog
Fast
result
Fast
Fast
Inflexible
Flexible
Inflexible


Slow
Flexible
Software
Hardware
Slow
Digital
Analog
Technology
Evolution
Fast
Fast
Inflexible
Flexible
Inflexible

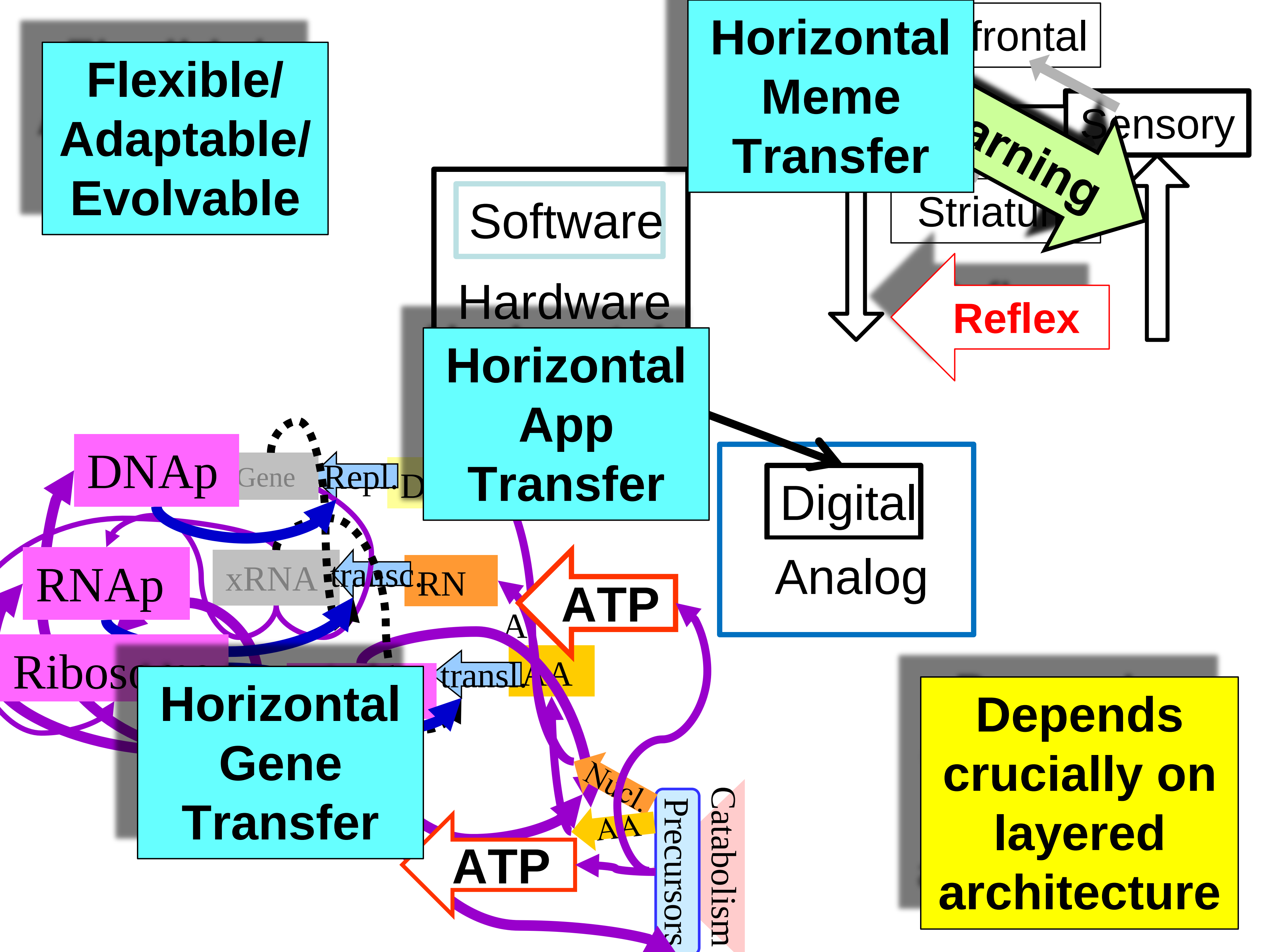


Horizontal Meme Transfer
Very Slow Process
Slow Flexible
"Vertical" App Migration
Prefrontal
Motor
Sensory
Striatum
Fast Inflexible
• Acquire
• Translate/ integrate
• Automate
Reflex
Excitatory interneurons
Excitatory interneurons


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



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



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

Horizontal Meme Transfer

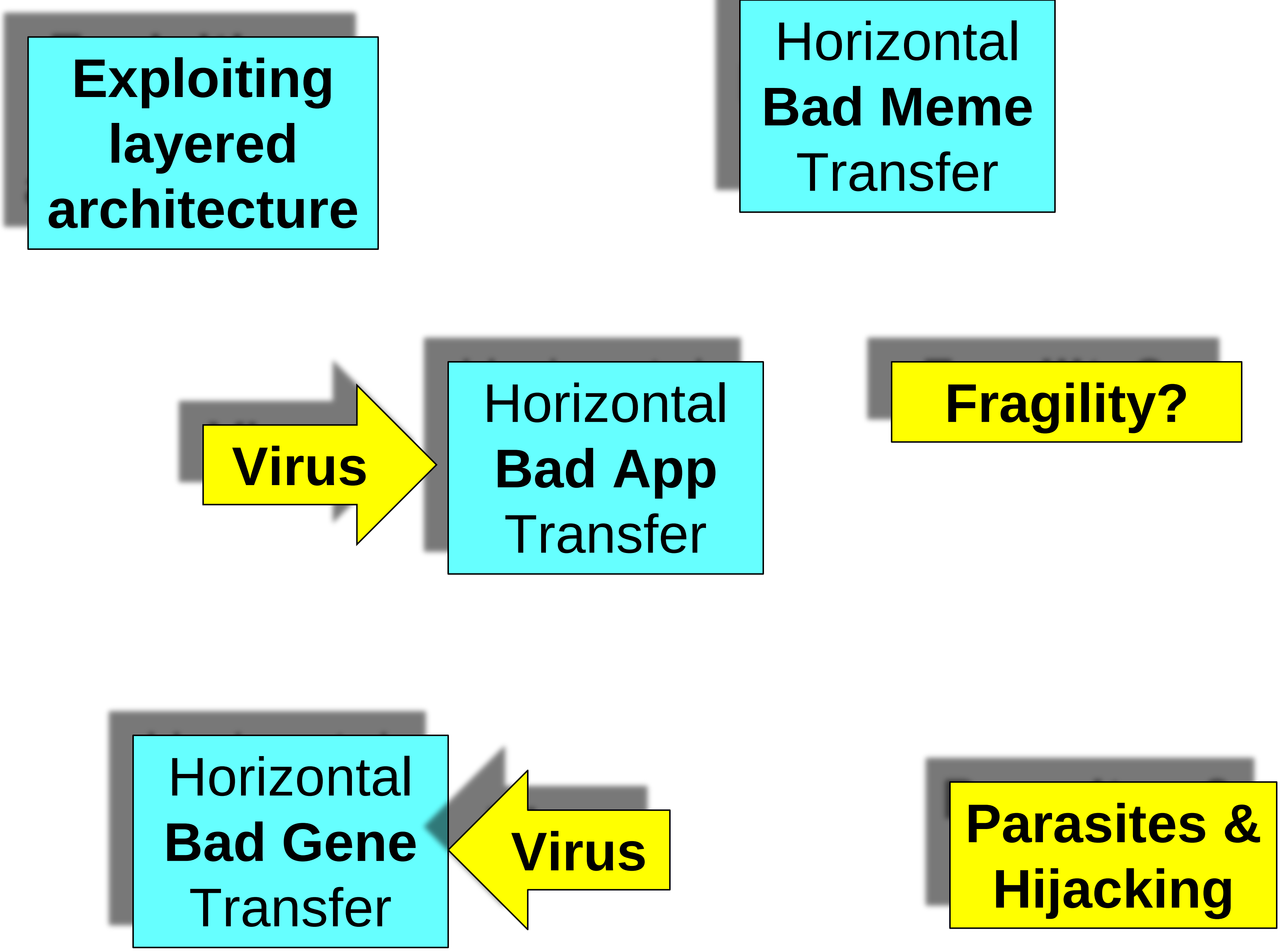
Horizontal App Transfer

Horizontal Gene Transfer

Most

- software and hardware
- new ideas (humans)
- new genes (bacteria)

is acquired by “horizontal” transfer,
though sometimes it is evolved locally


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

Depends crucially on layered architecture

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

Horizontal Meme Transfer

- Acquire
- Translate/ integrate
- Automate

Horizontal App Transfer

Amazingly Flexible/ Adaptable

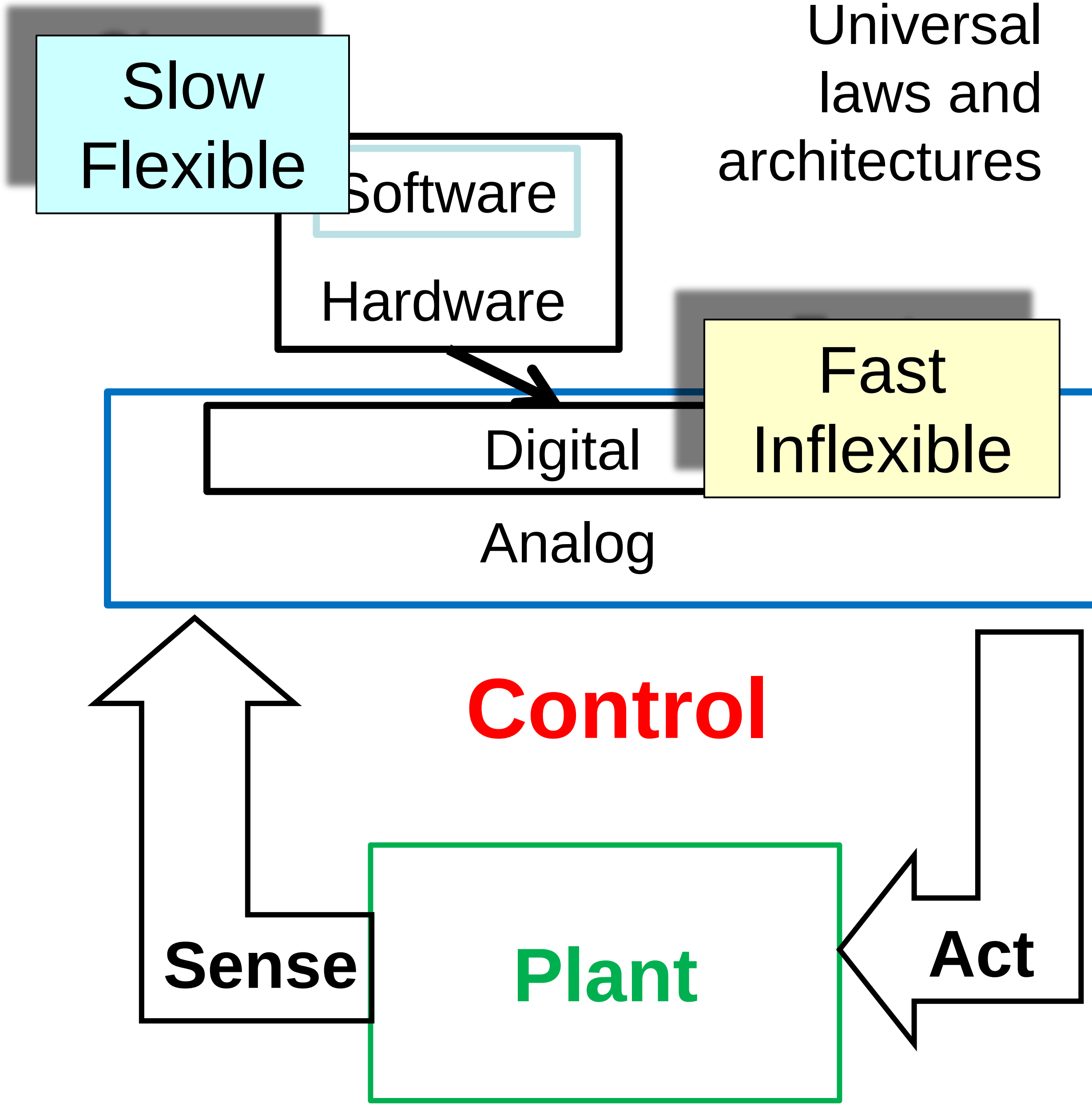
Horizontal Gene Transfer

Compute

Turing

Universal
laws and
architectures

Delay is *even more* important



Bode

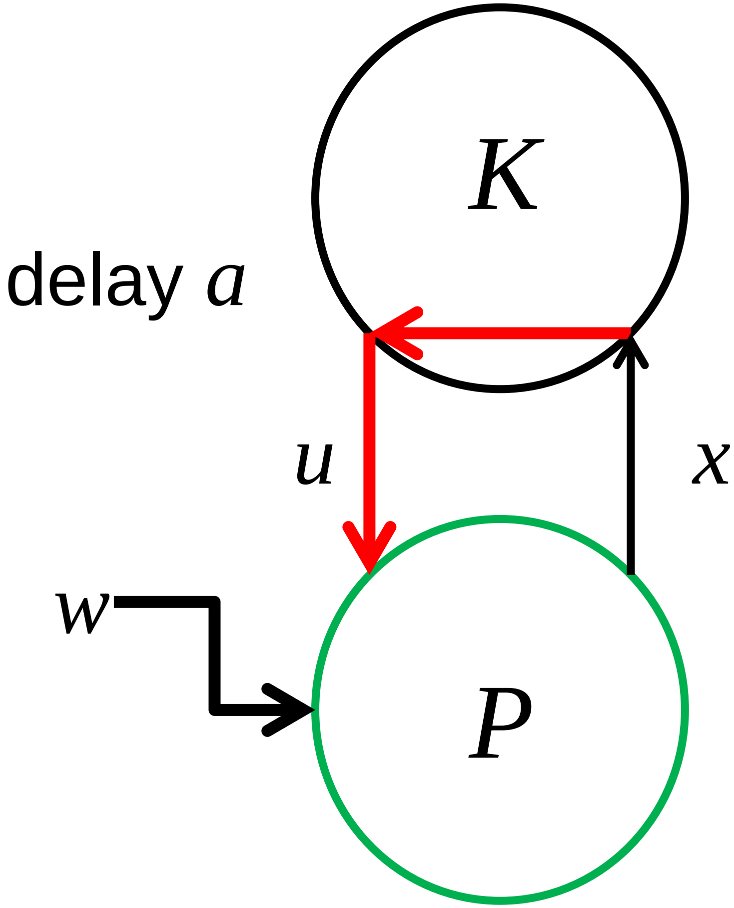
Control

Compute

Turing

Why

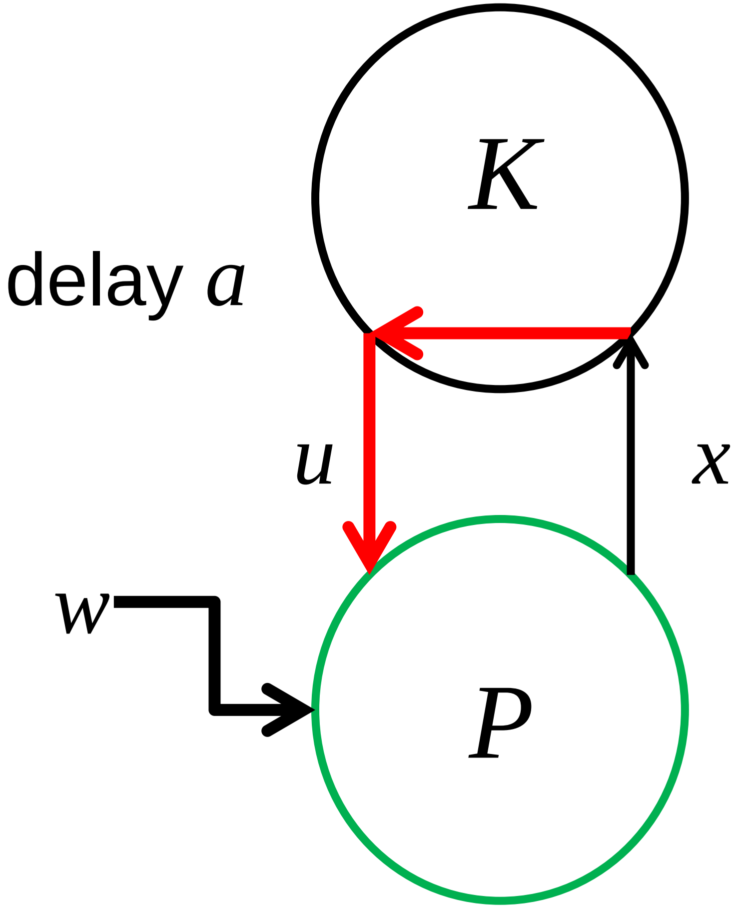
Necessity



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

delay a

$$p > 1$$



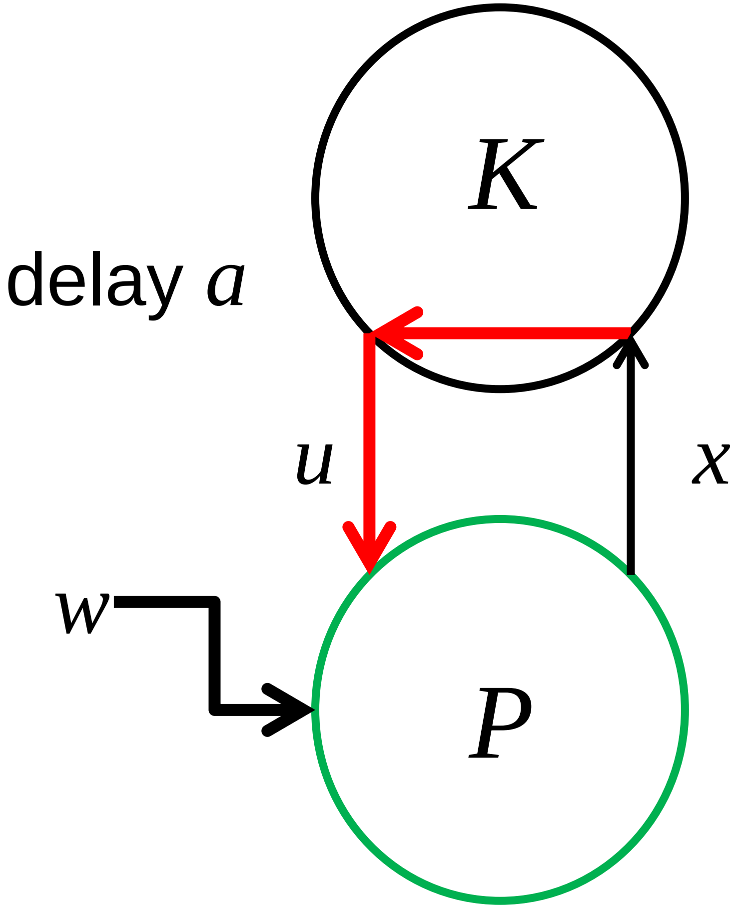
No delay or
no uncertainty

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

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

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

$$p > 1$$



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

$$p > 1$$

No delay or
no uncertainty

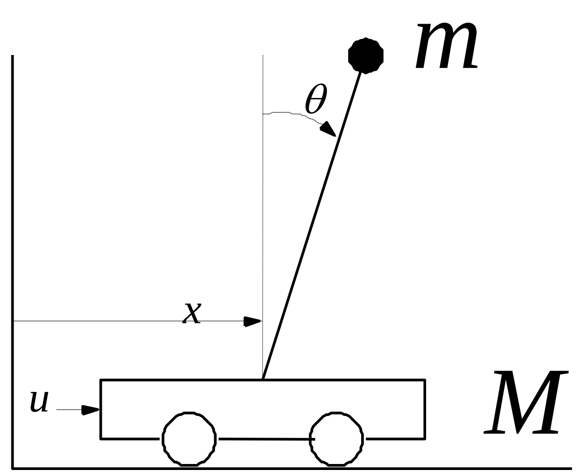
$$u_{t-a} = -\left(px_t + w_t\right)$$

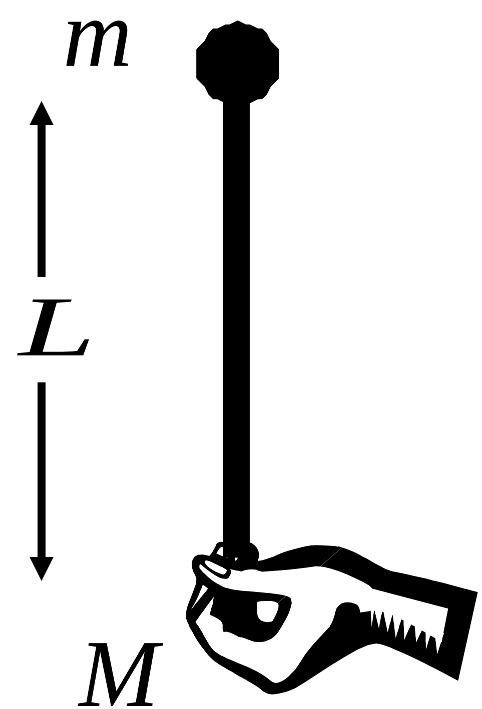
$$\Rightarrow \|x\| \approx 0 \quad \|u\| \approx \|w\|$$

With delay ***and***
uncertainty

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

Linearized pendulum on a cart





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

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

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

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

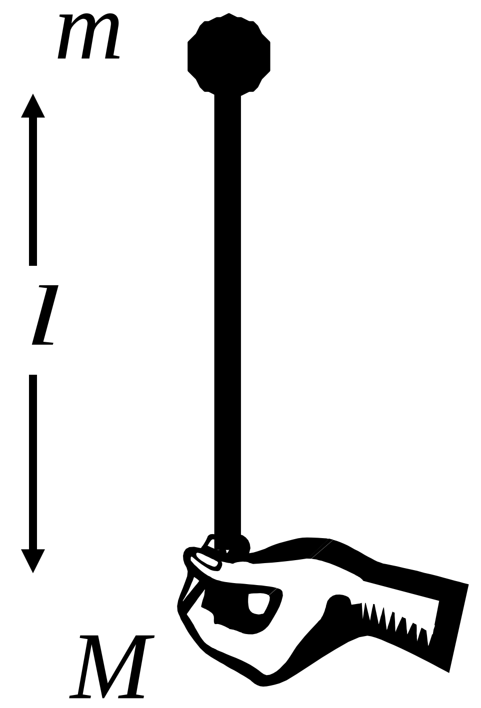
$$y=x+\alpha l\sin\theta$$

linearize

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

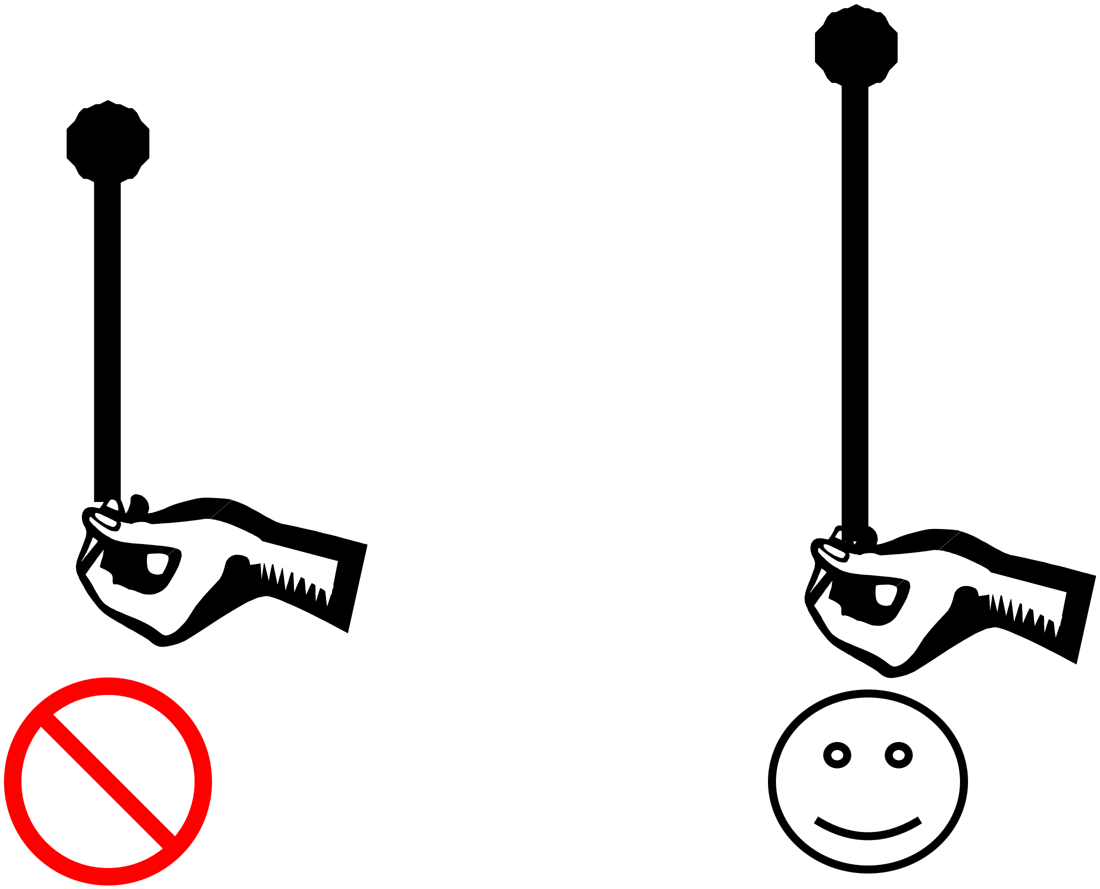
$$\ddot{x}+l\ddot{\theta}\pm g\theta=0$$

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



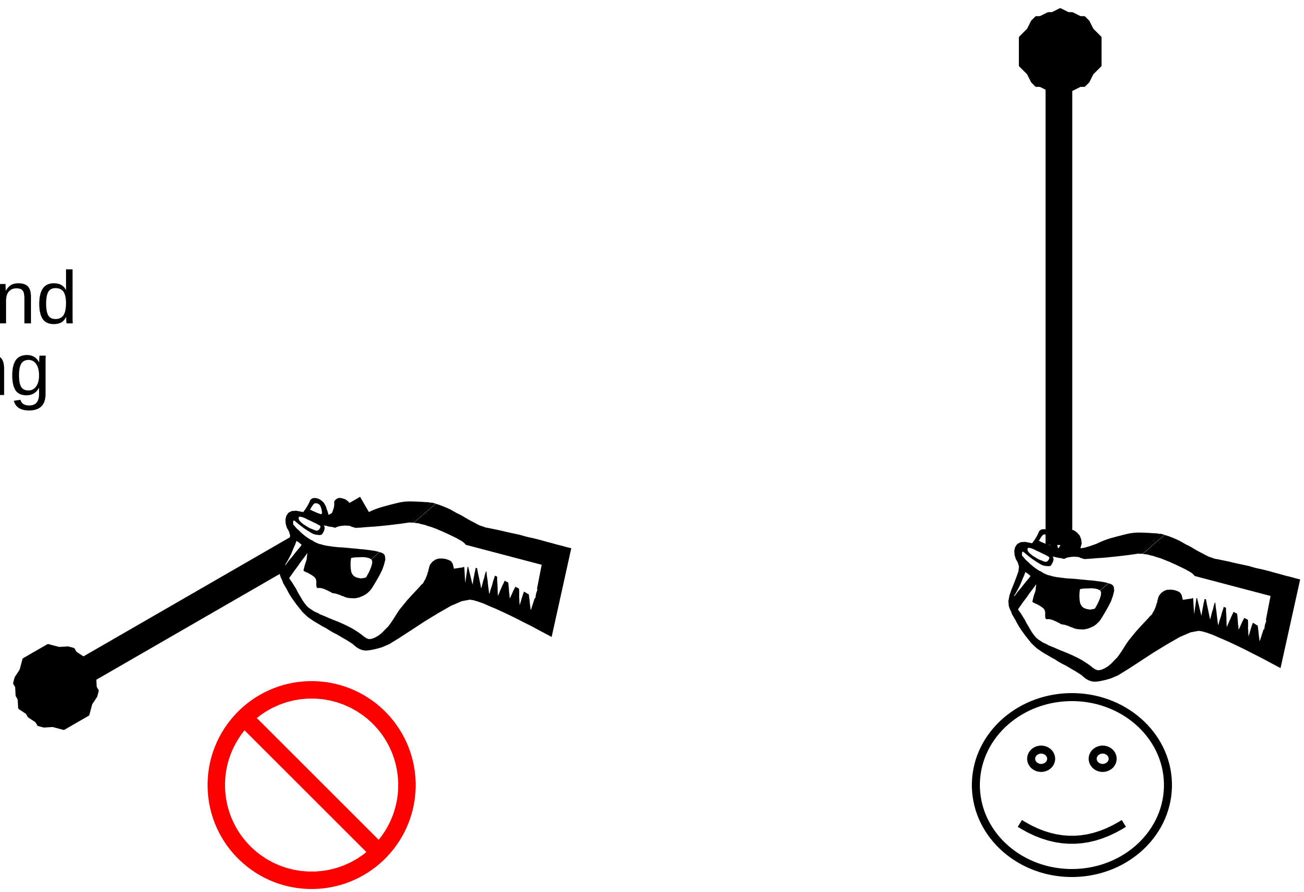
Robust

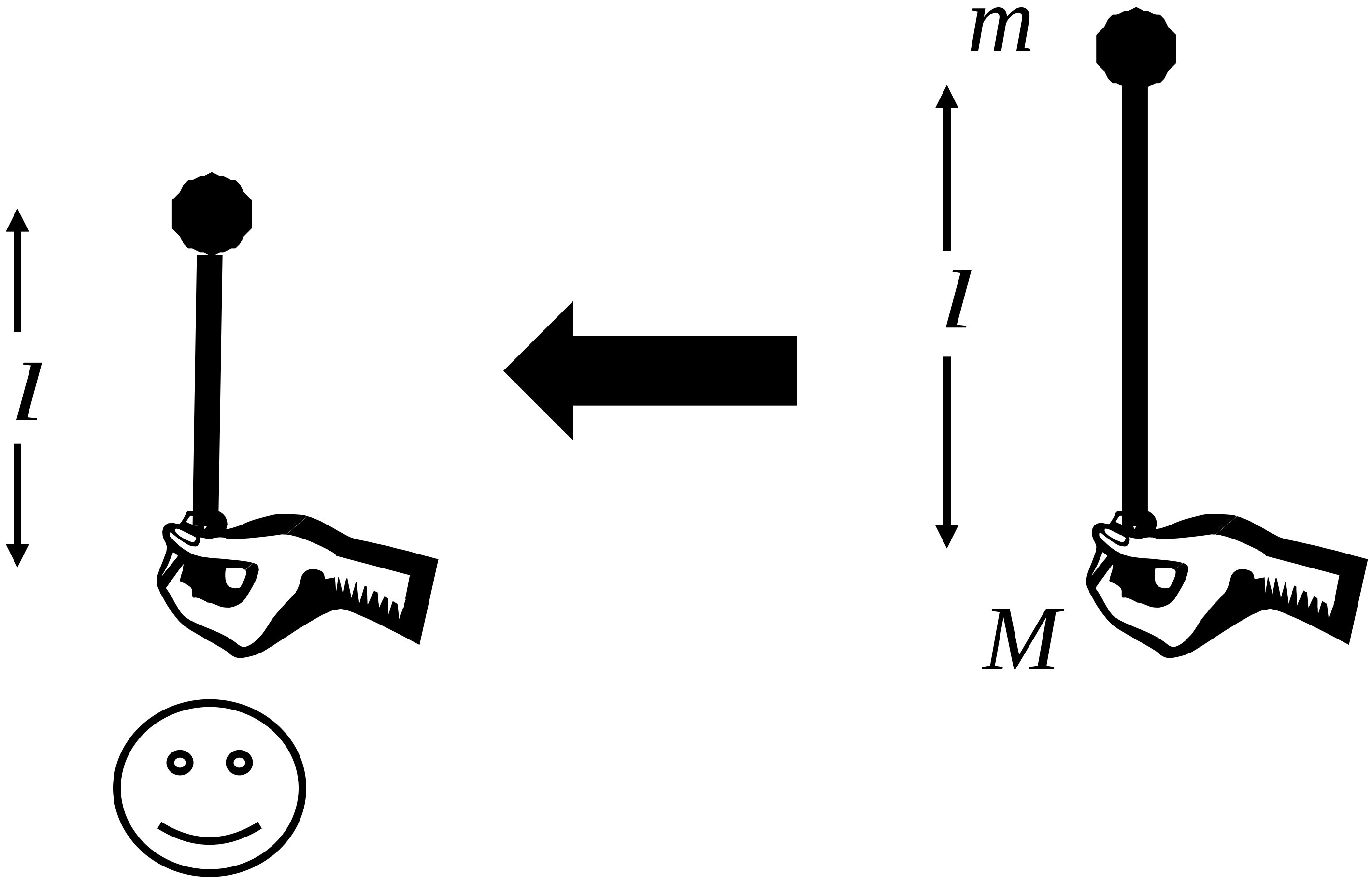
=agile and balancing



Robust

=agile and balancing





Efficient=length of pendulum (artificial)

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

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

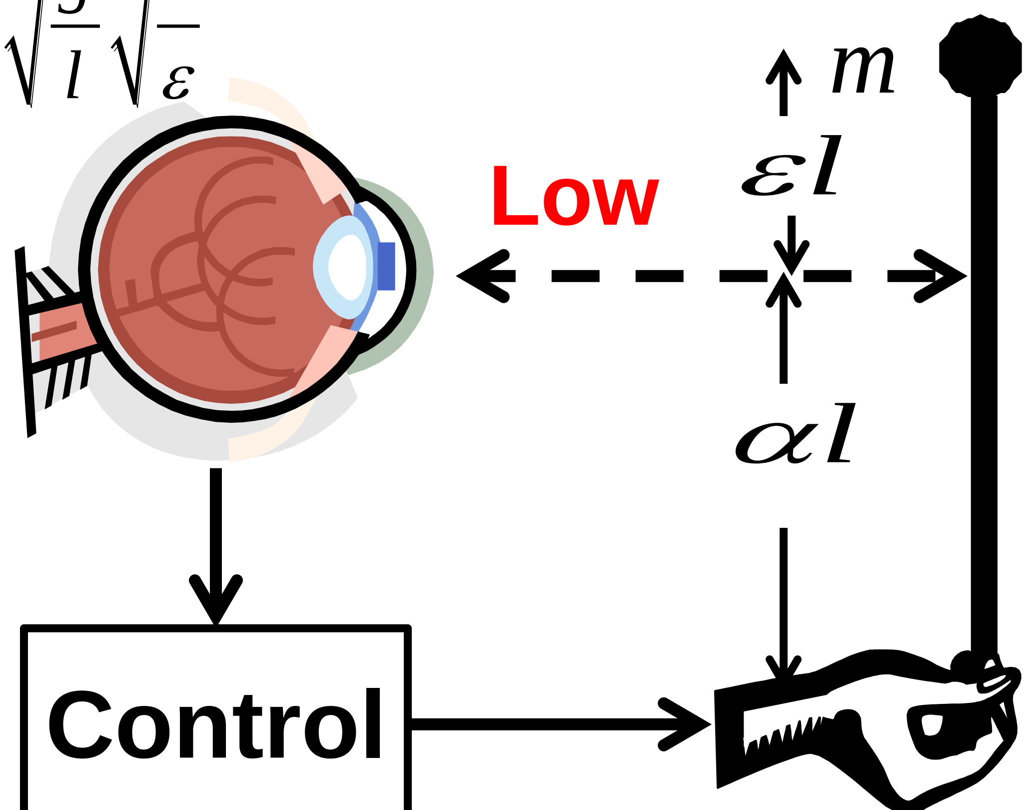
$$p = \sqrt{\frac{g}{l}}\sqrt{1+r} \quad r = \frac{m}{M} \quad z = \sqrt{\frac{g}{l}}\sqrt{\frac{1}{\varepsilon}}$$

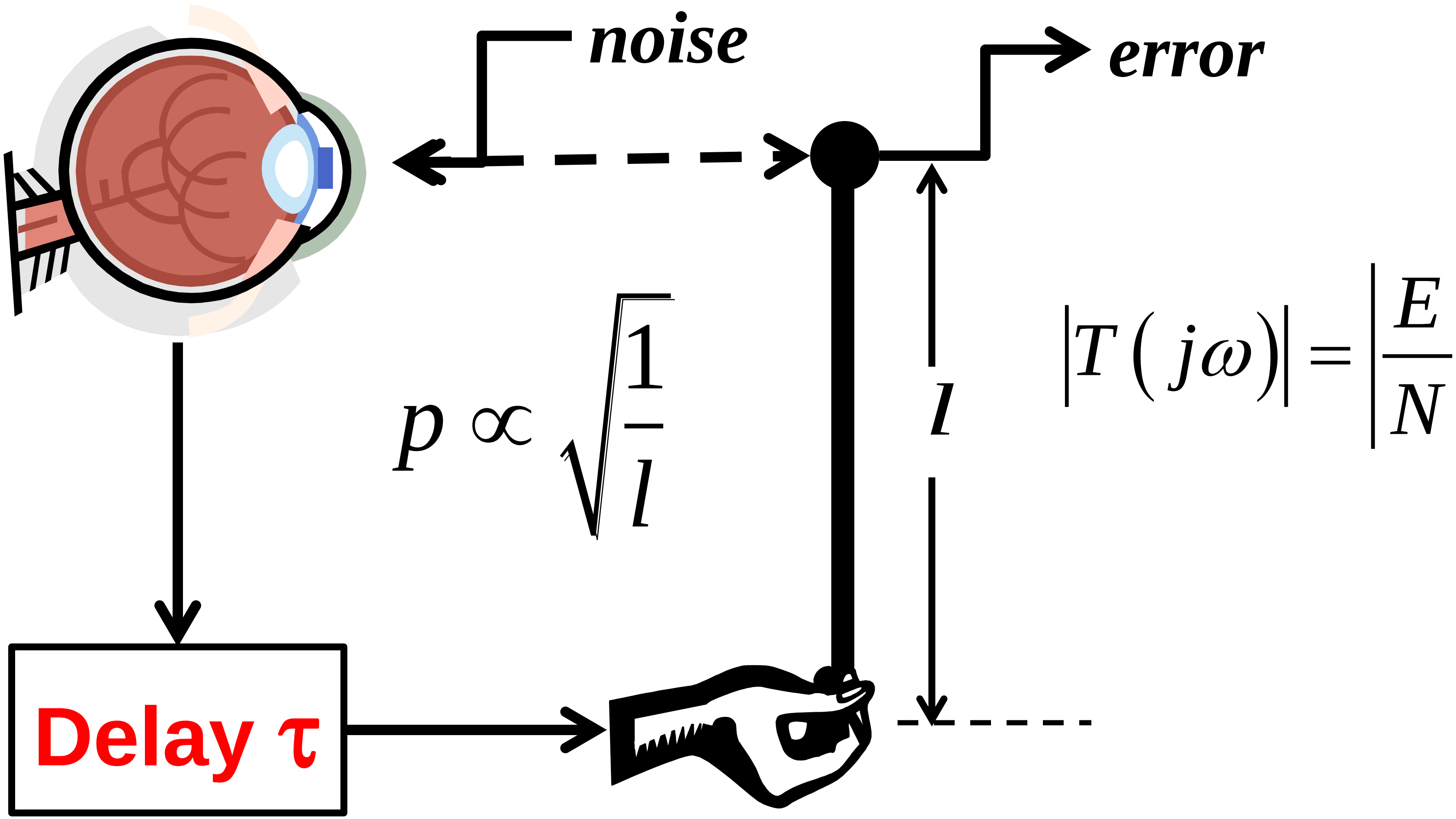
transform+
algebra

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

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

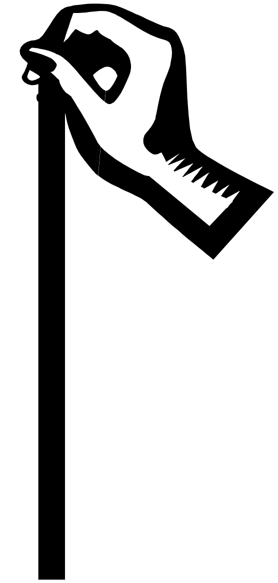
$$y = x + \alpha l \theta$$





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

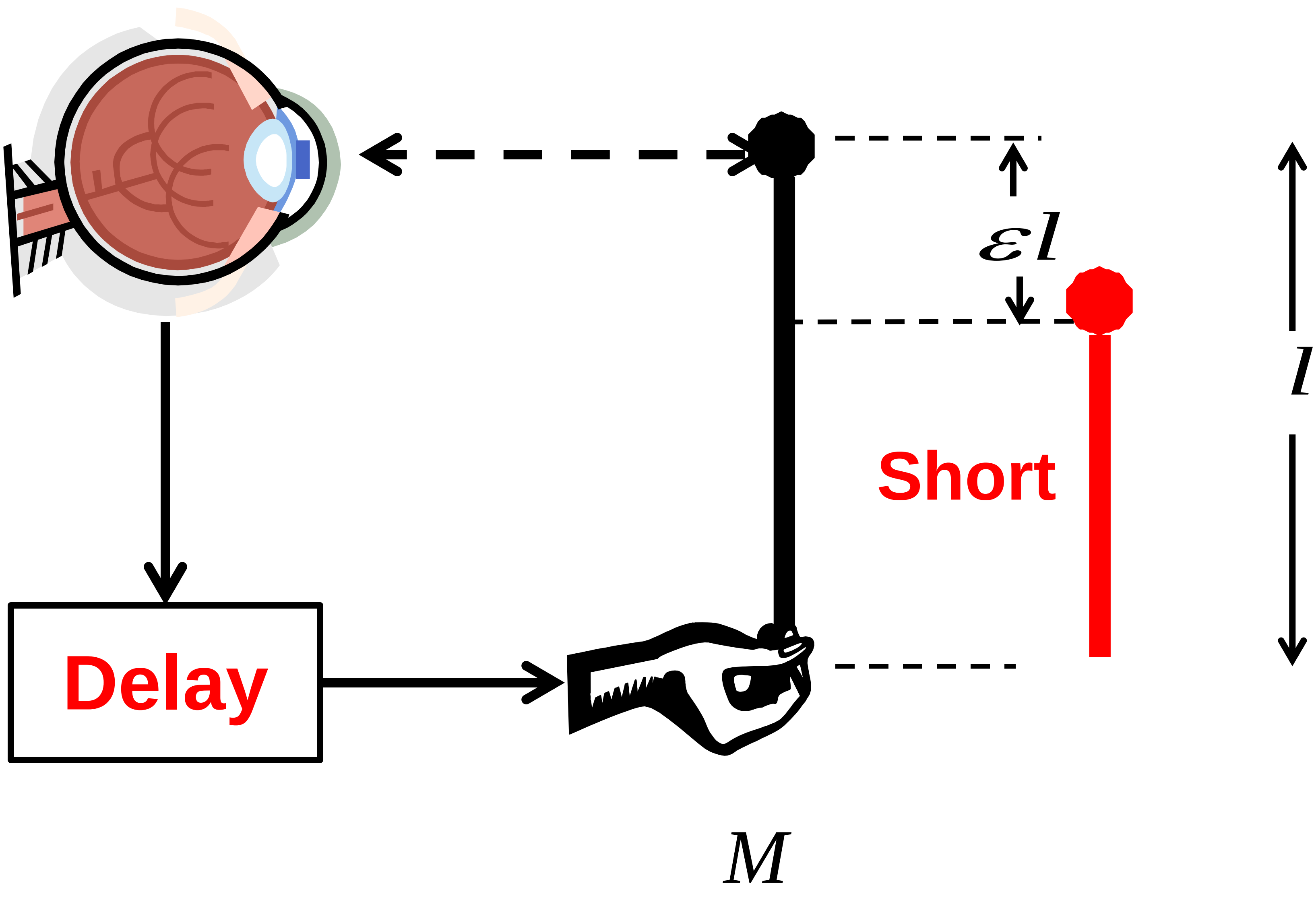
$$\frac{1}{\pi}\int_0^{\infty} \ln\left|T(j\omega)\right| d\omega \ge 0$$



Easy, even with eyes closed
No matter what the length

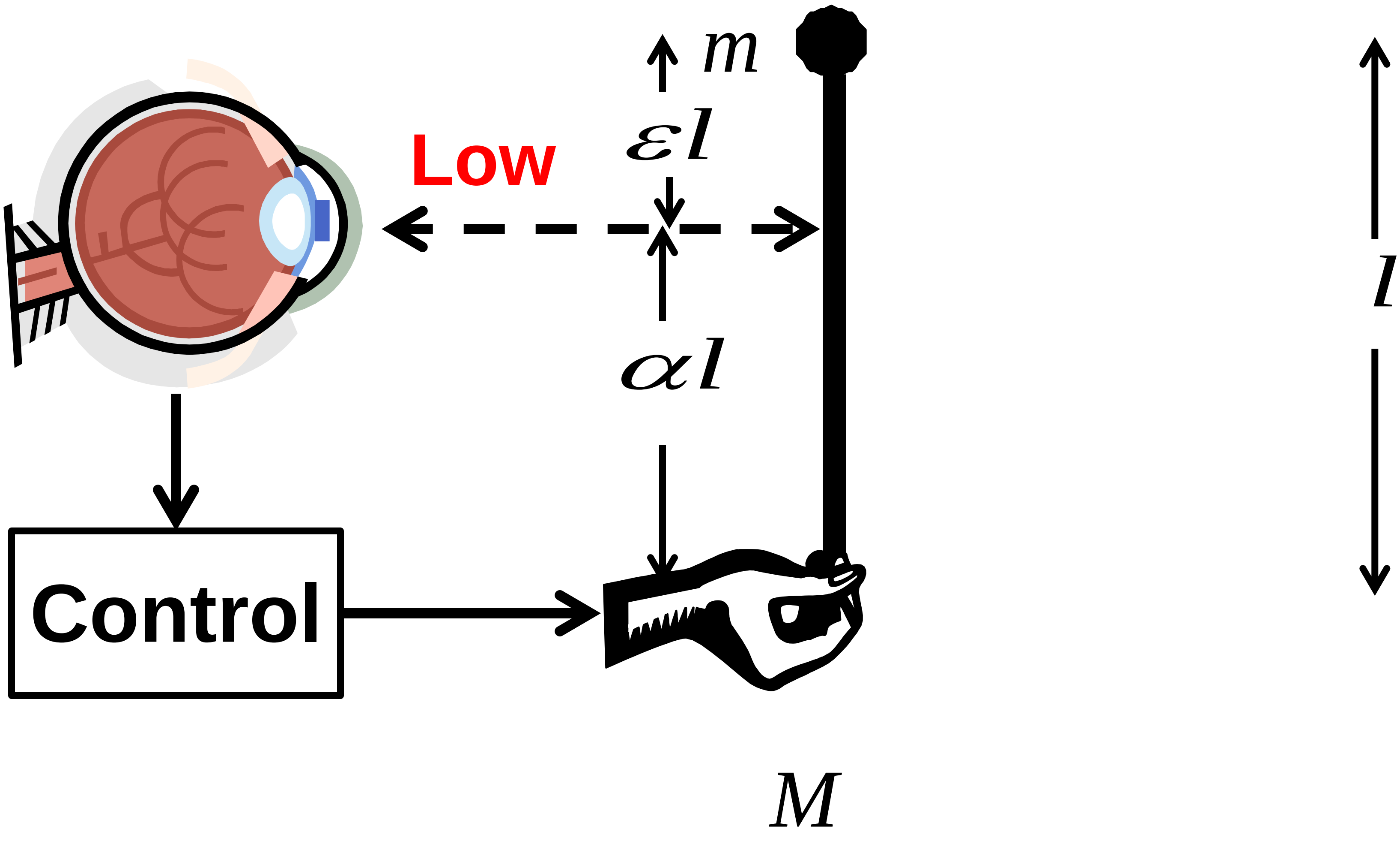
Proof: Standard UG control theory:
Easy calculus, easier contour integral,
easiest Poisson Integral formula

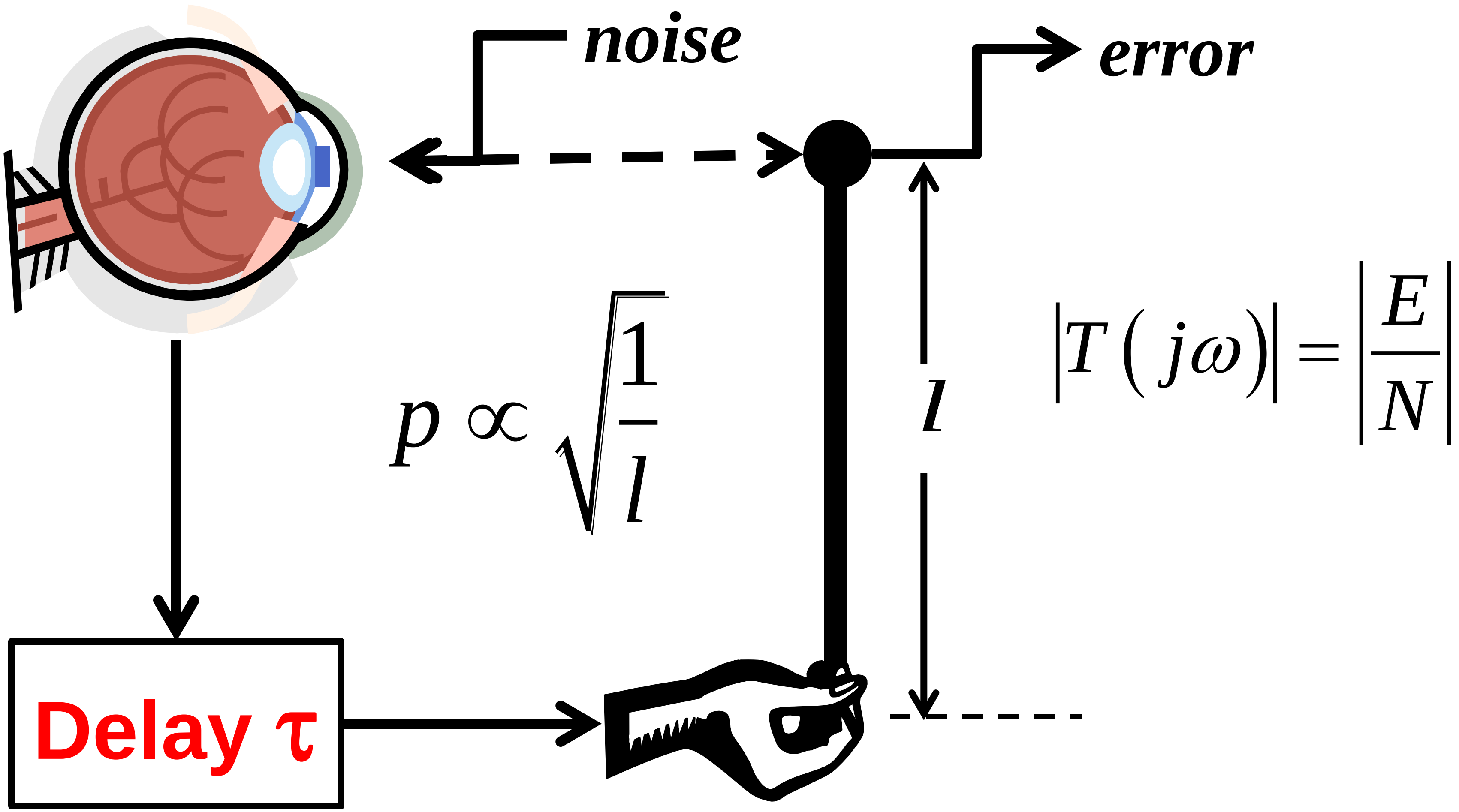
Harder if delayed or short



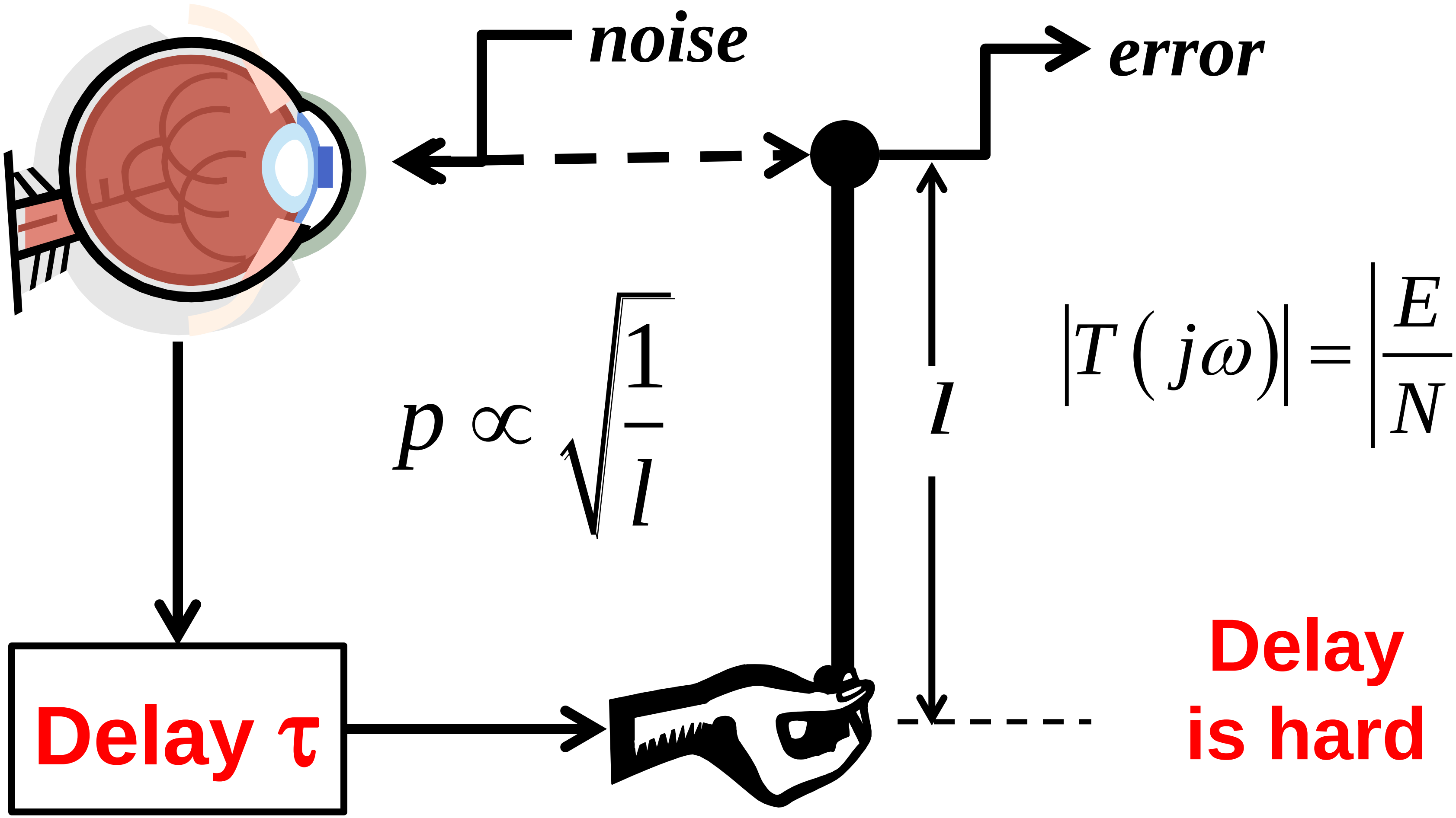
Also harder if sensed low

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

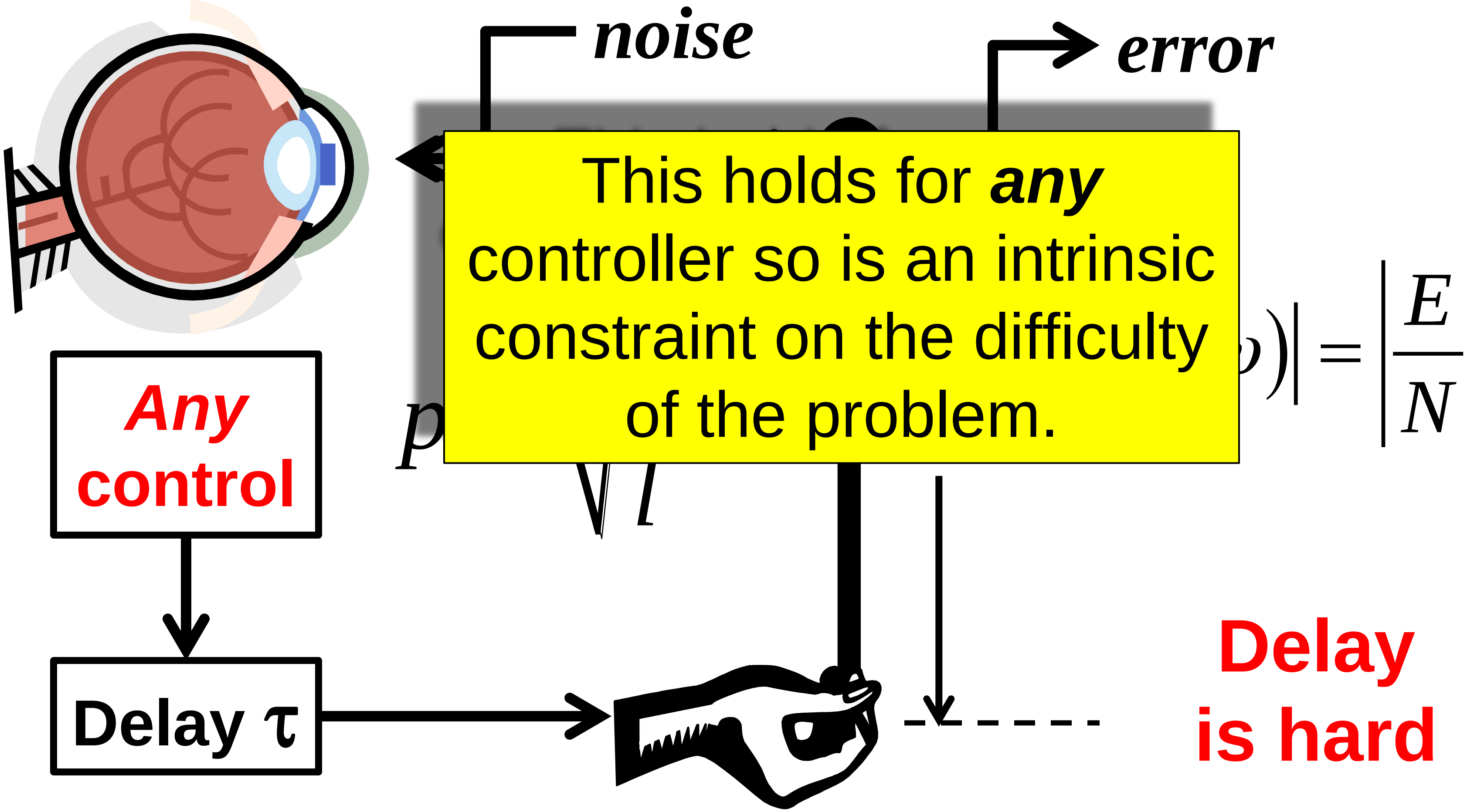




noise
error
Delay τ
l
$p \propto \sqrt{\frac{1}{l}}$
$|T(j\omega)| = \left|\frac{E}{N}\right|$



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

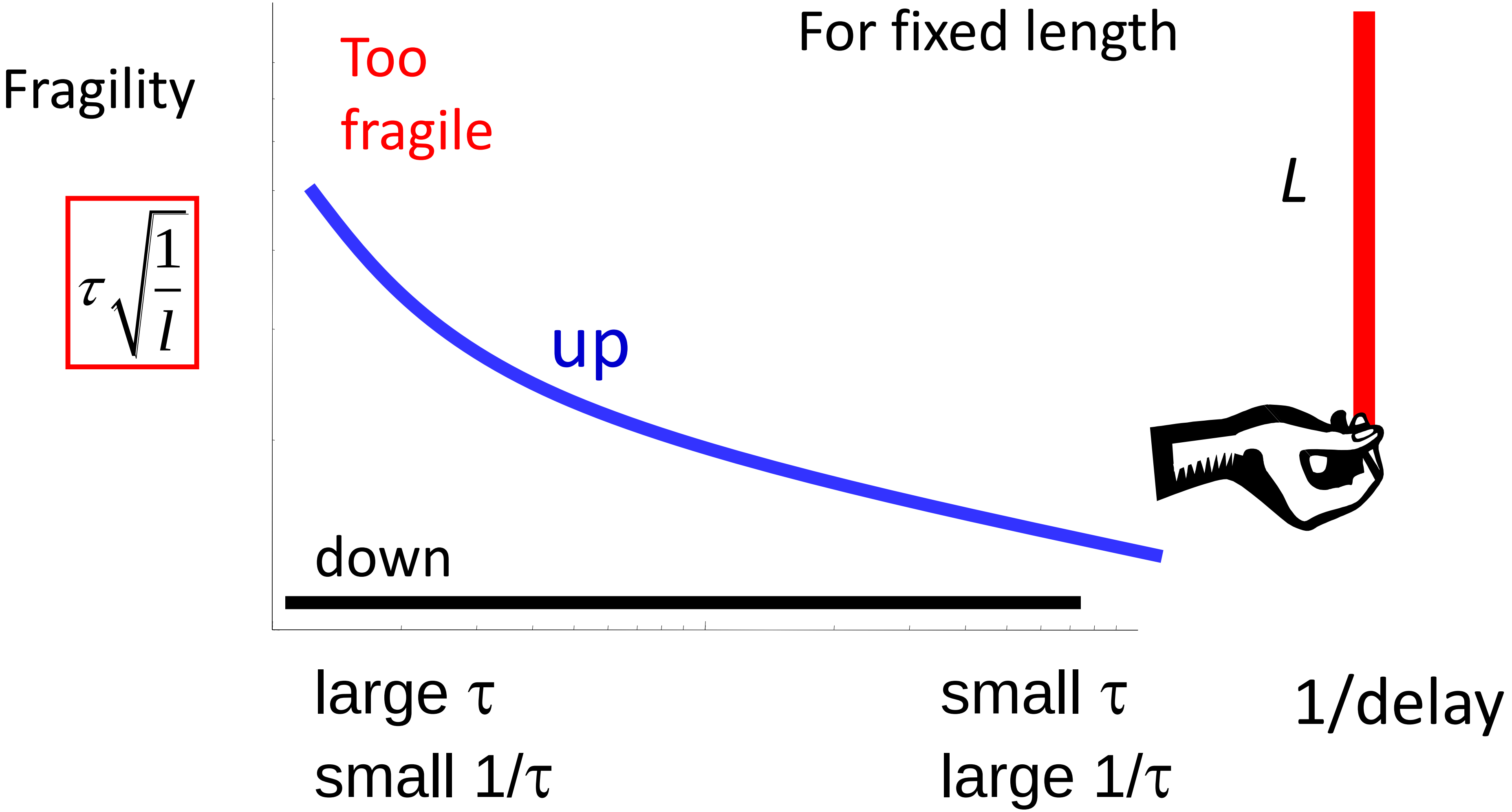


This holds for ***any*** controller so is an intrinsic constraint on the difficulty of the problem.

Delay is hard

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

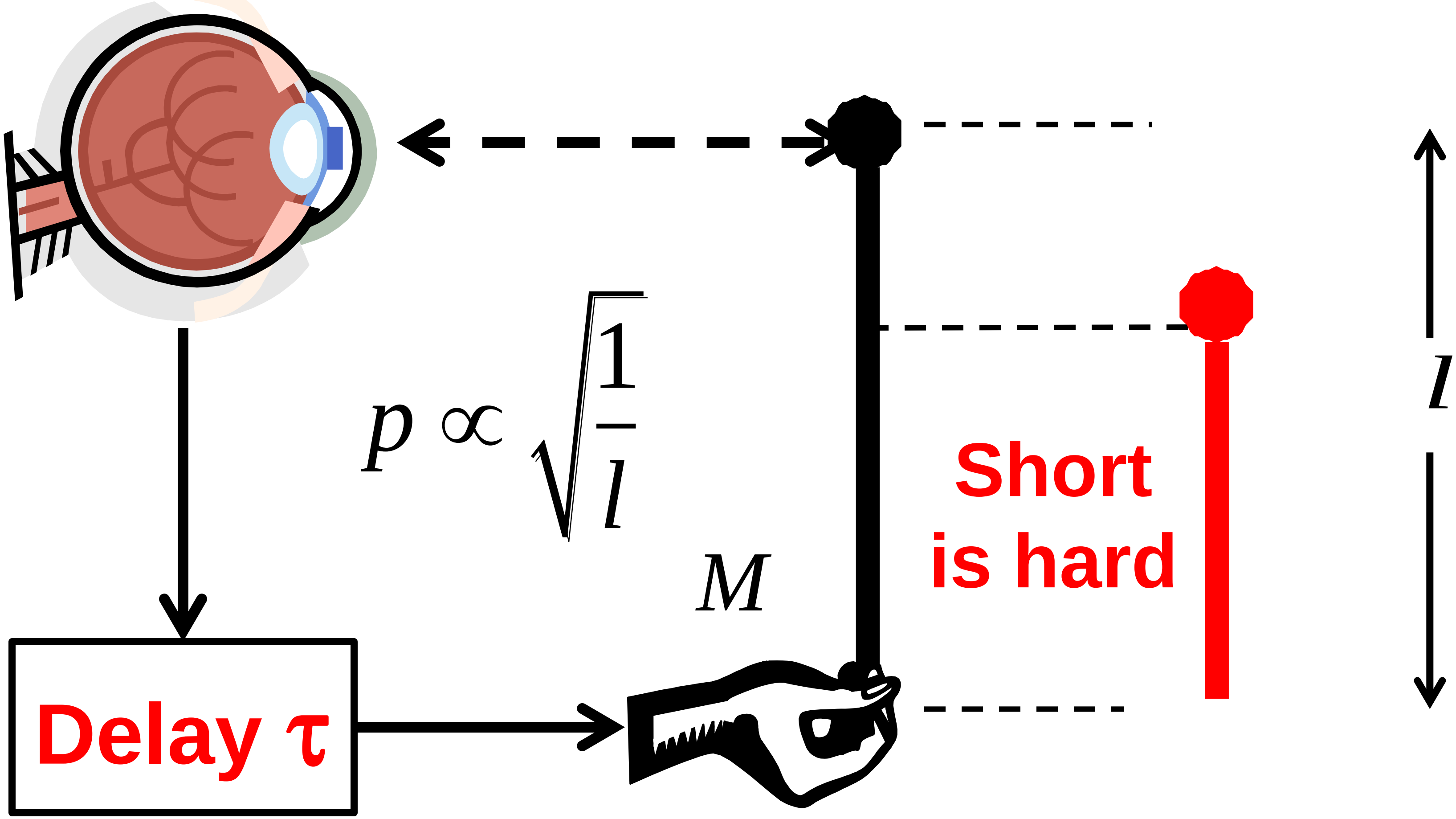
$$\frac{1}{\pi}\int_0^\infty \ln\left|T(j\omega)\right| \frac{2p}{p^2+\omega^2} d\omega \geq p\tau \propto \tau\sqrt{\frac{1}{l}}$$



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

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 $1/\tau$



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

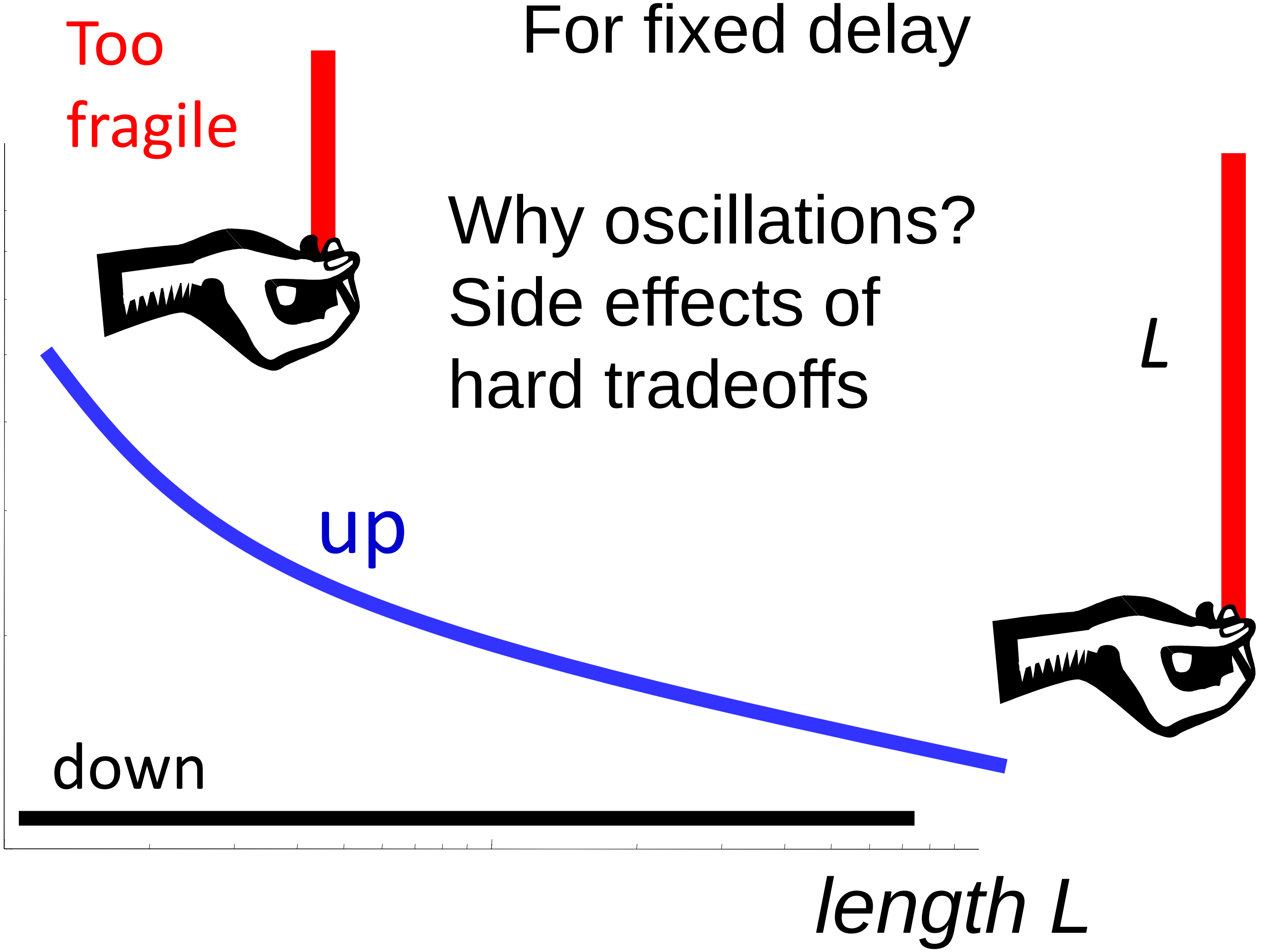
$$\frac{1}{\pi}\int_0^\infty \ln\left|T(j\omega)\right|\frac{2p}{p^2+\omega^2}d\omega \geq \ln\left|T_{mp}(p)\right| = p\tau \propto \tau\sqrt{\frac{1}{l}}$$

For fixed delay

Why oscillations?
Side effects of
hard tradeoffs

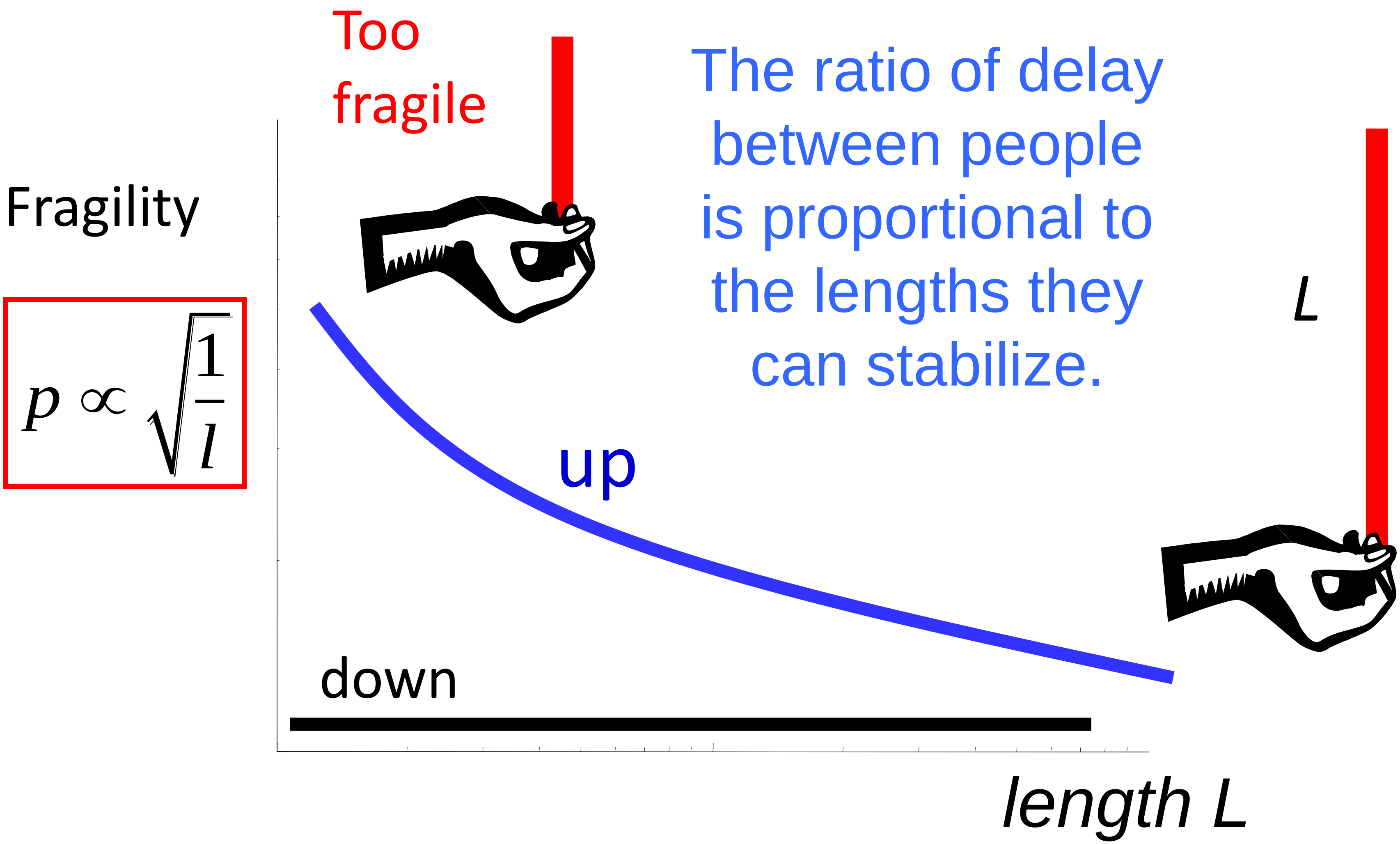
Fragility

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



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

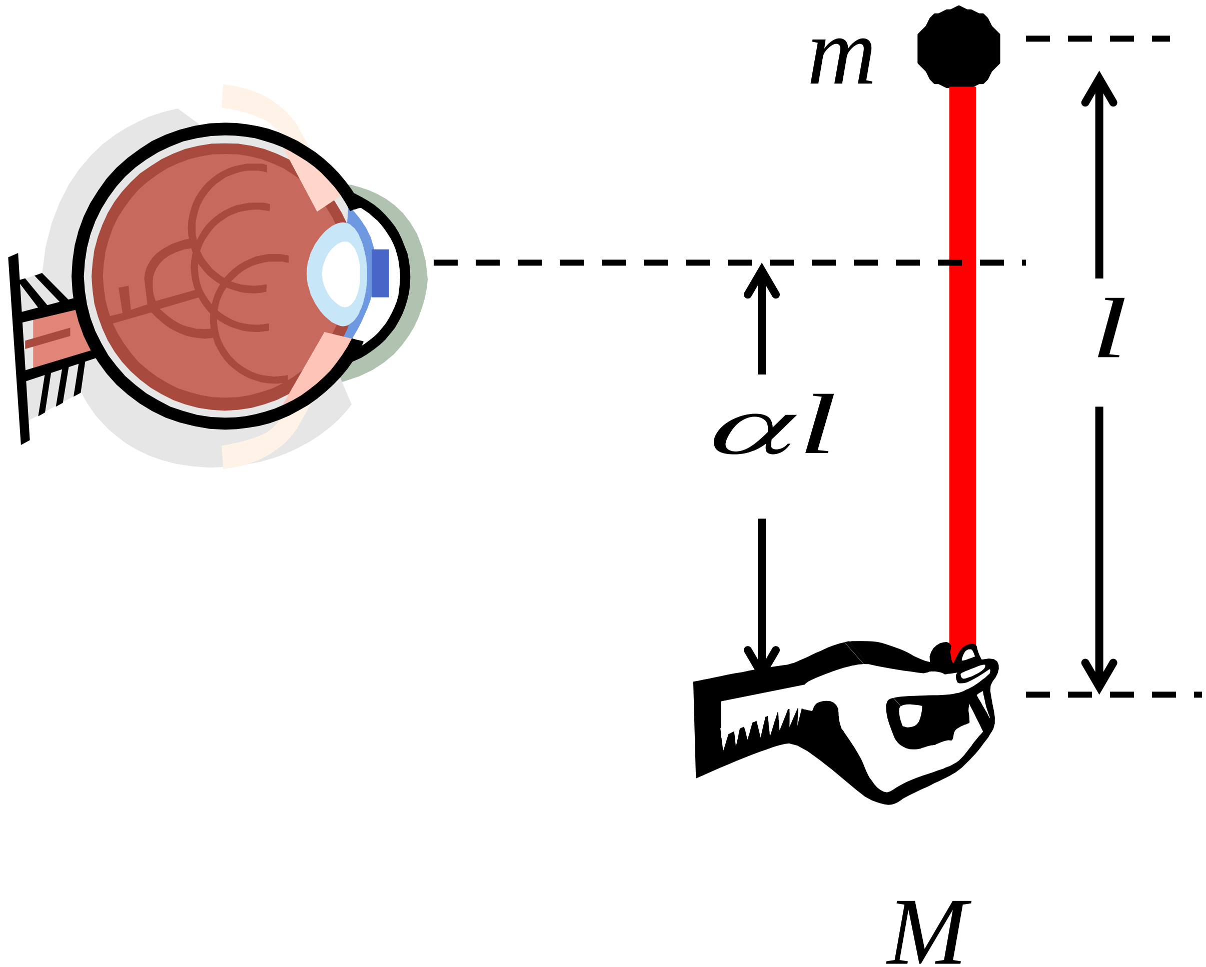
The ratio of delay between people is proportional to the lengths they can stabilize.



Eyes moved down is harder

(RHP zero)

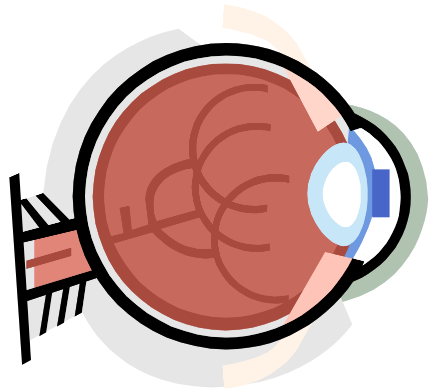
Similar to delay

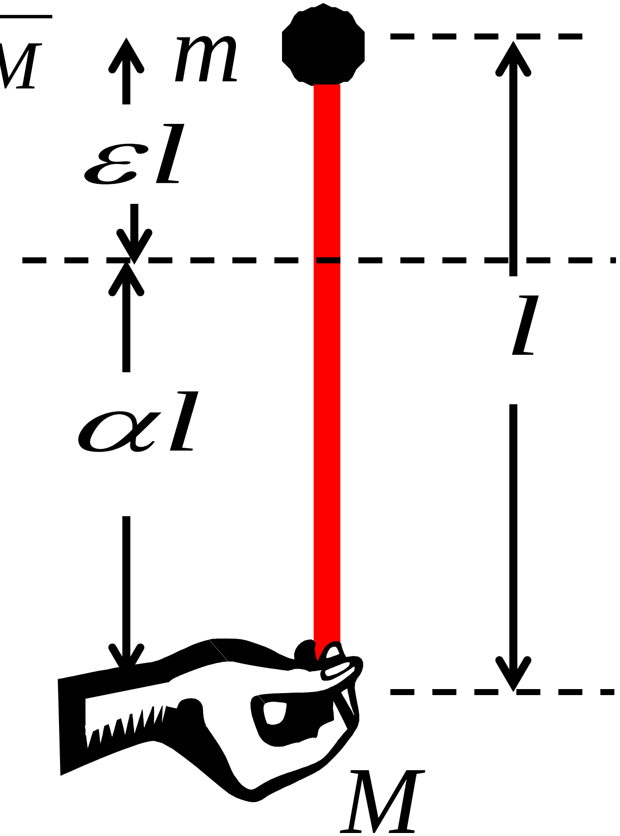


$$r = \frac{m}{M}$$

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

Units $\Rightarrow M = g = 1$





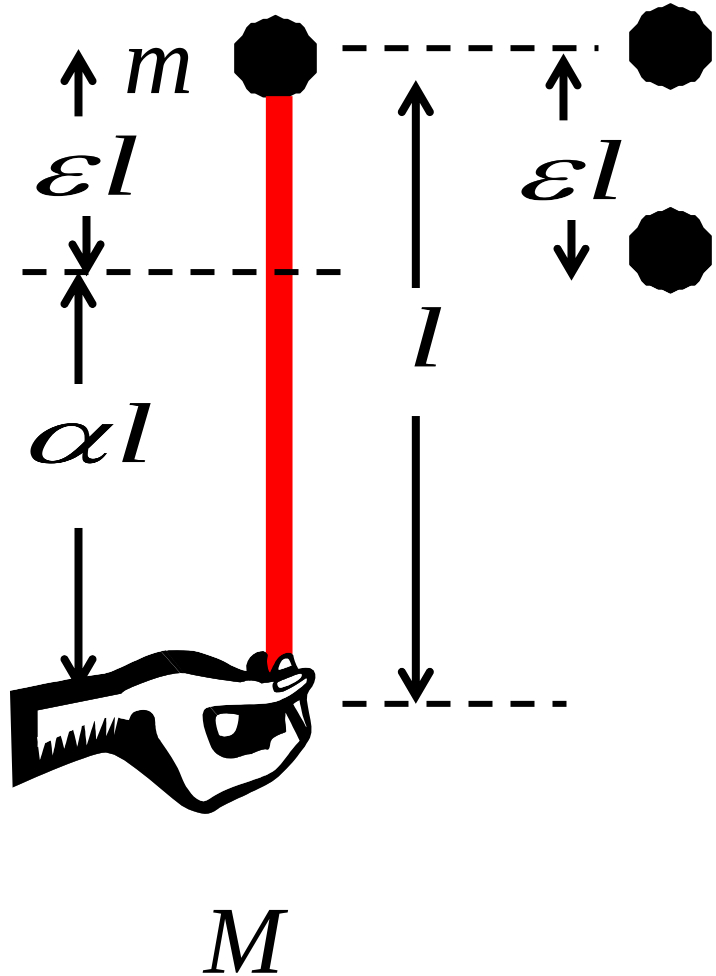
$$y = x + \alpha l \theta = \frac{\varepsilon l s^2 \pm g}{s^2\left(l s^2 \pm g\right)} \qquad \varepsilon = 1 - \alpha$$

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

Compare

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

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



Move eyes

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

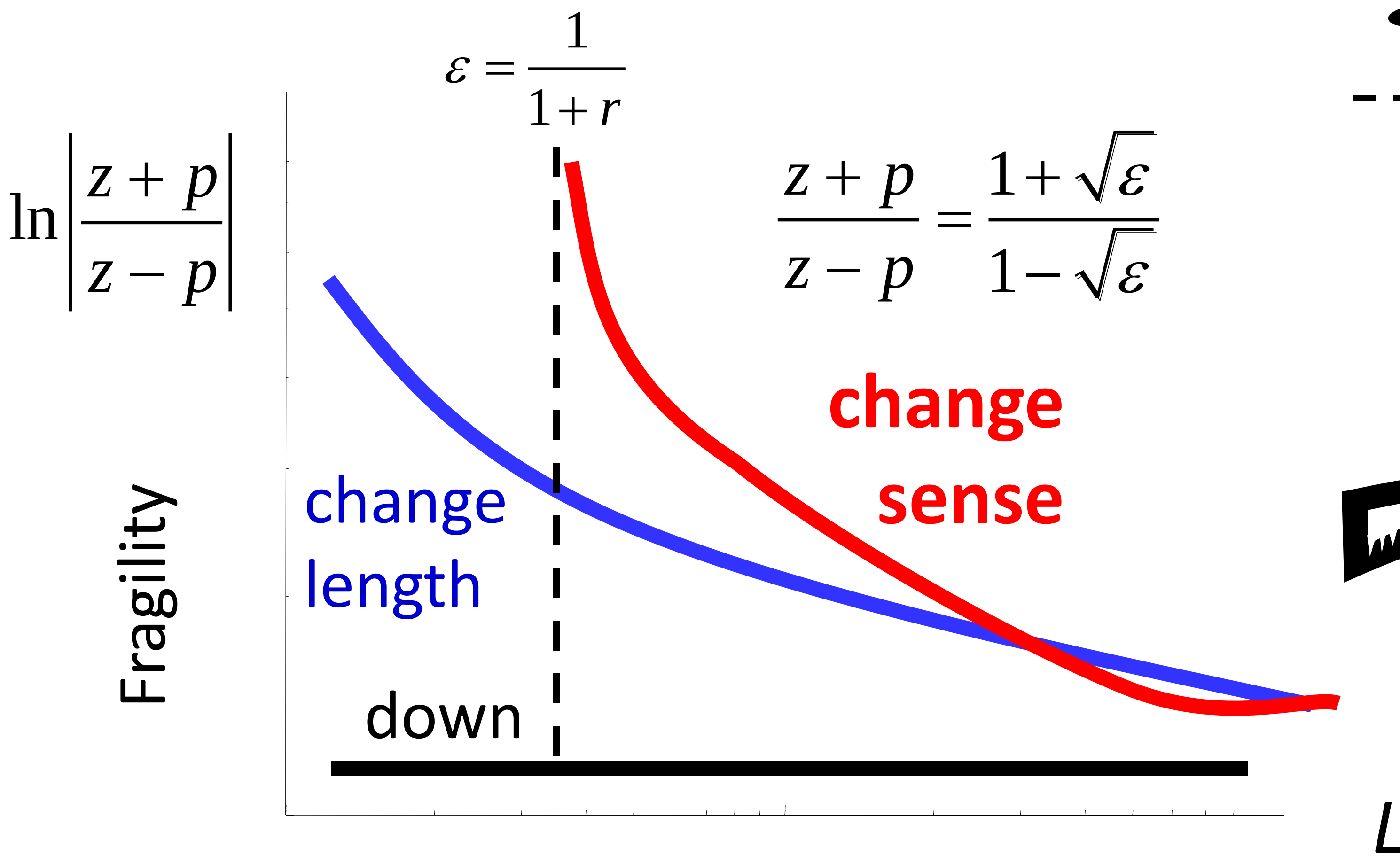
$$p=z\Rightarrow 1+r=\frac{1}{\varepsilon}\Rightarrow\varepsilon=\frac{1}{1+r}$$

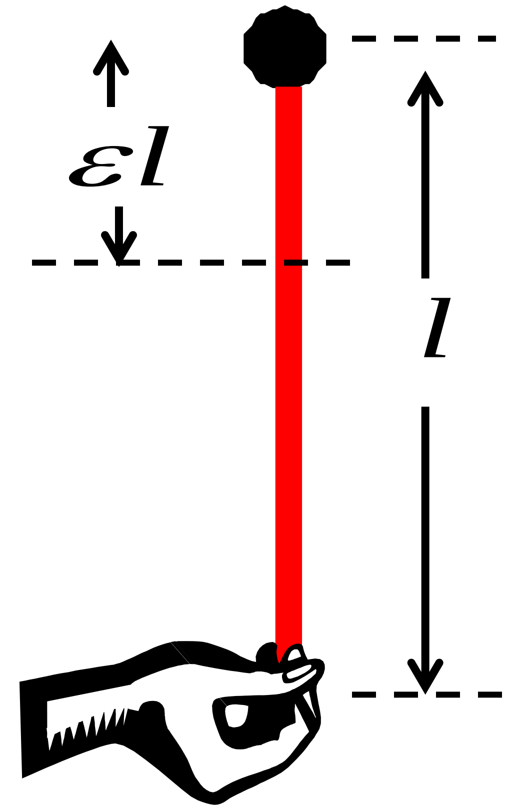
$$p\left(1+\frac{1}{3}\frac{p^2}{z^2}\right)=\sqrt{\frac{g}{l}}\sqrt{1+r}\left(1+\frac{1}{3}\varepsilon\right)=p\left(1+\frac{\varepsilon}{3}\right)$$

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

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

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

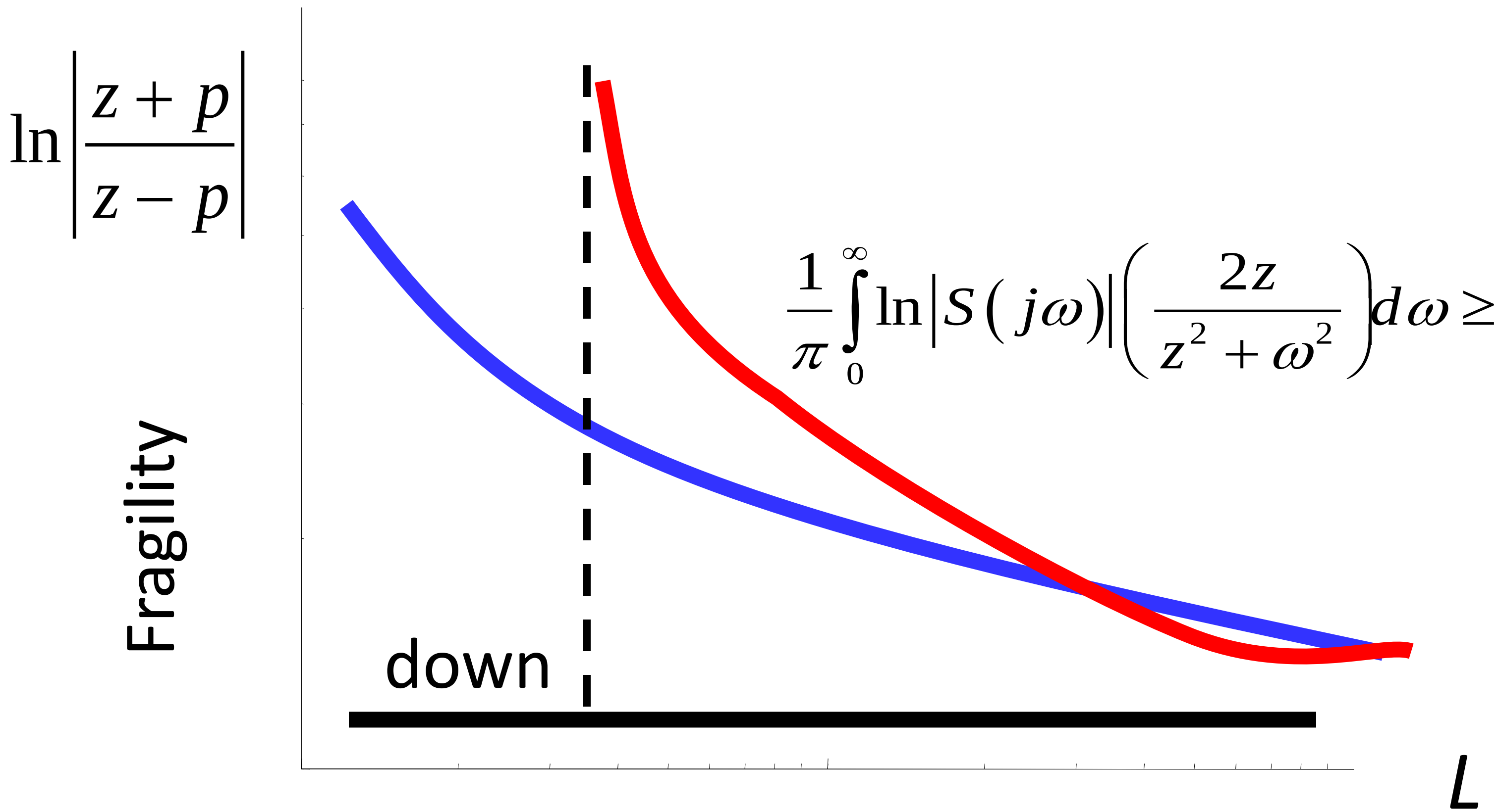




This is a cartoon, but can be made precise.

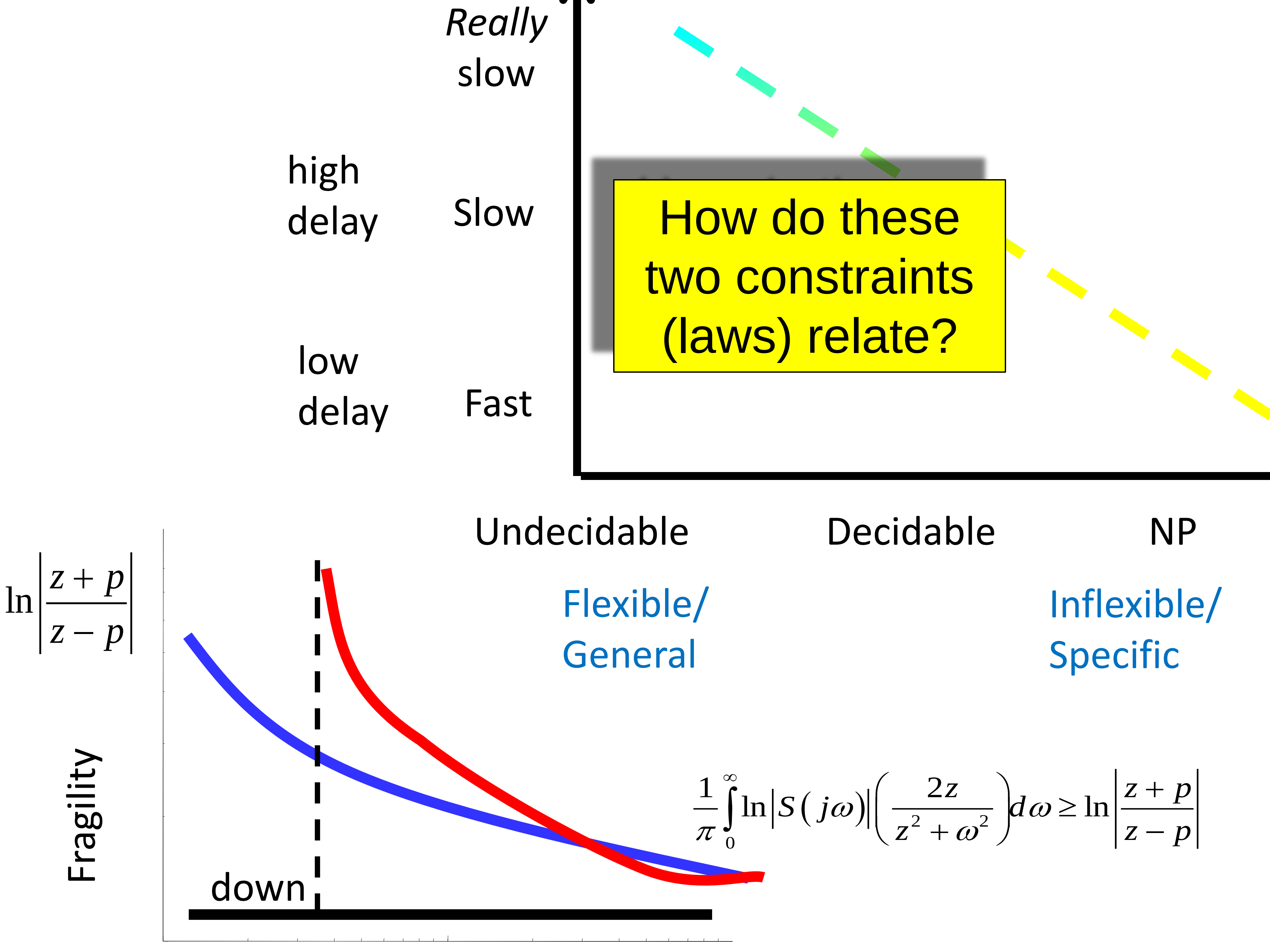
Hard limits on the ***intrinsic*** robustness of control ***problems***.

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



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

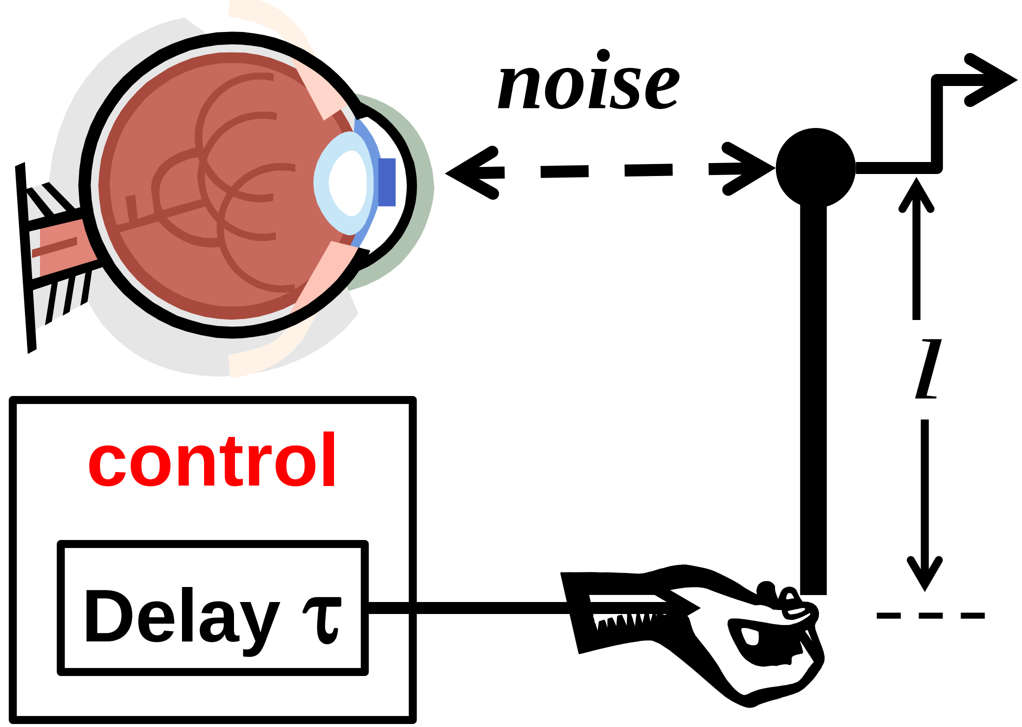
This is a cartoon, but can be made precise.



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

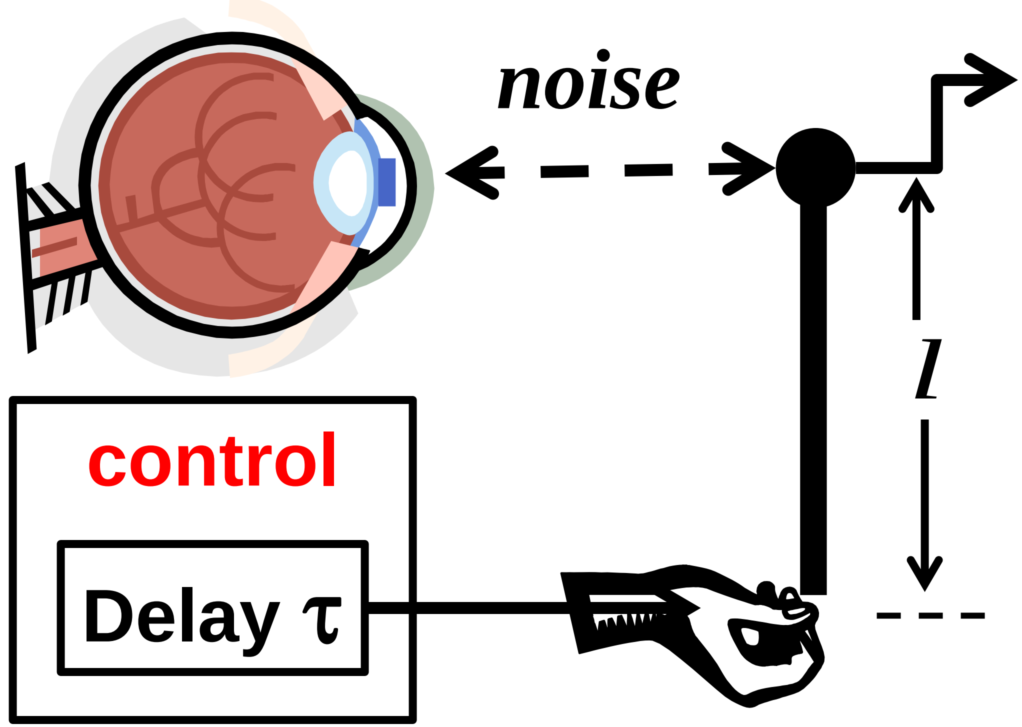
$$\frac{1}{\pi}\int_0^\infty \ln\left|S(j\omega)\right|\left(\frac{2z}{z^2+\omega^2}\right)d\omega \geq \ln\left|\frac{z+p}{z-p}\right|$$

Delay comes from sensing, communications, computing, and actuation.
Delay limits robust performance.



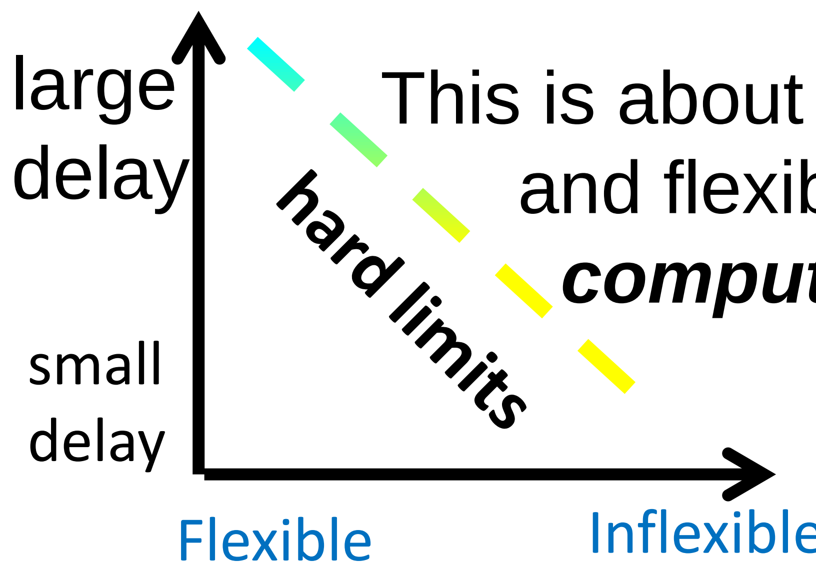
$$\frac{1}{\pi}\int_0^\infty \ln\left|T(j\omega)\right| \frac{2p}{p^2+\omega^2} d\omega \geq \ln\left|T_{mp}(p)\right| = p\tau \propto \tau\sqrt{\frac{1}{l}}$$

How do these two constraints (laws) relate?

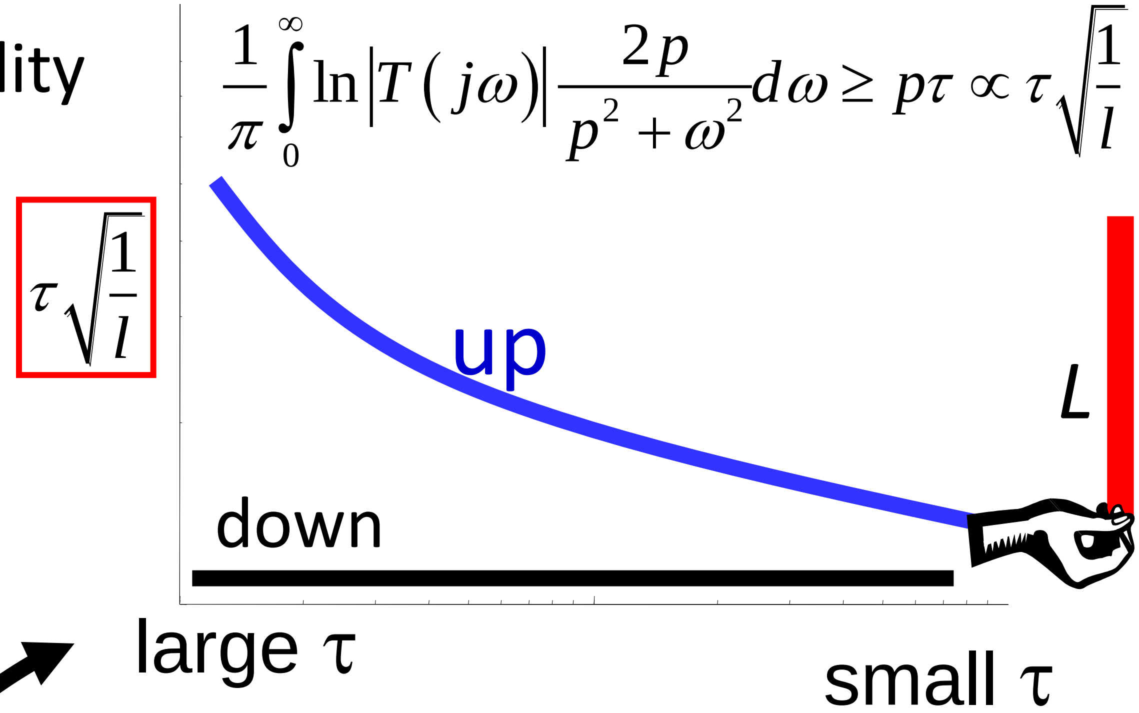


Computation delay adds to total delay.

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

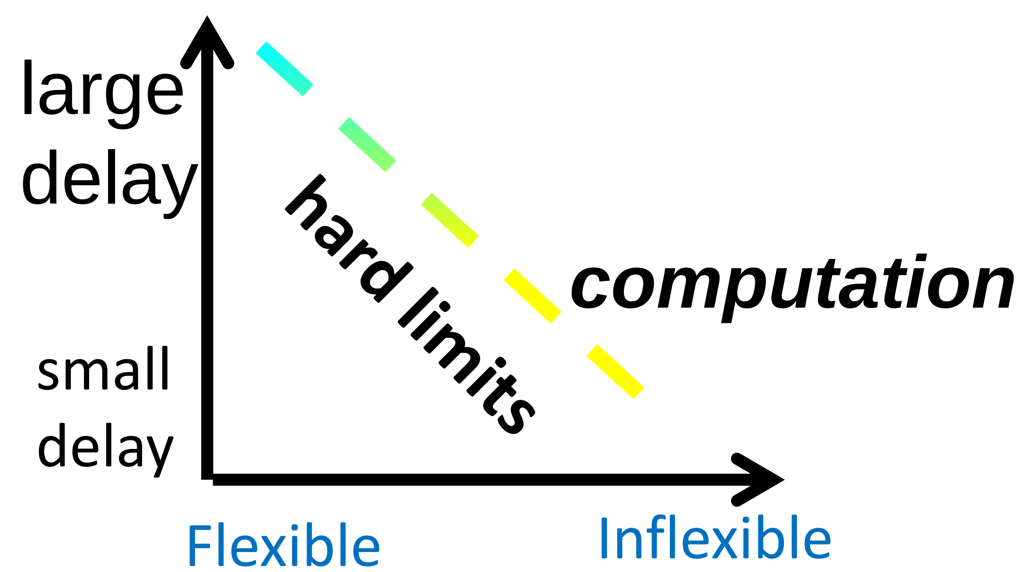


Computation is a component in control.



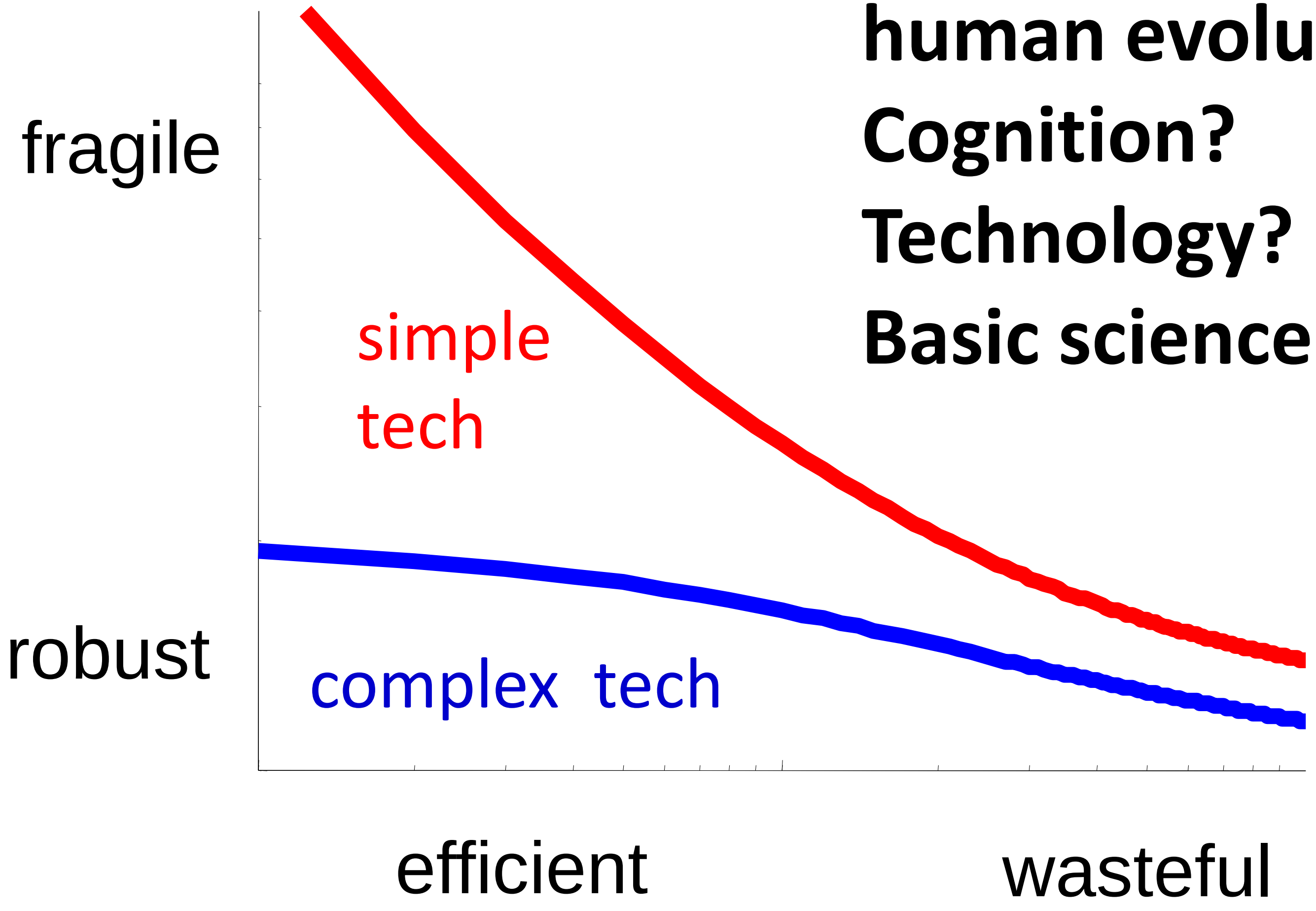
Delay makes control hard.

Computation delay adds to total delay.



Computation is a component in control.

How general is this picture?



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

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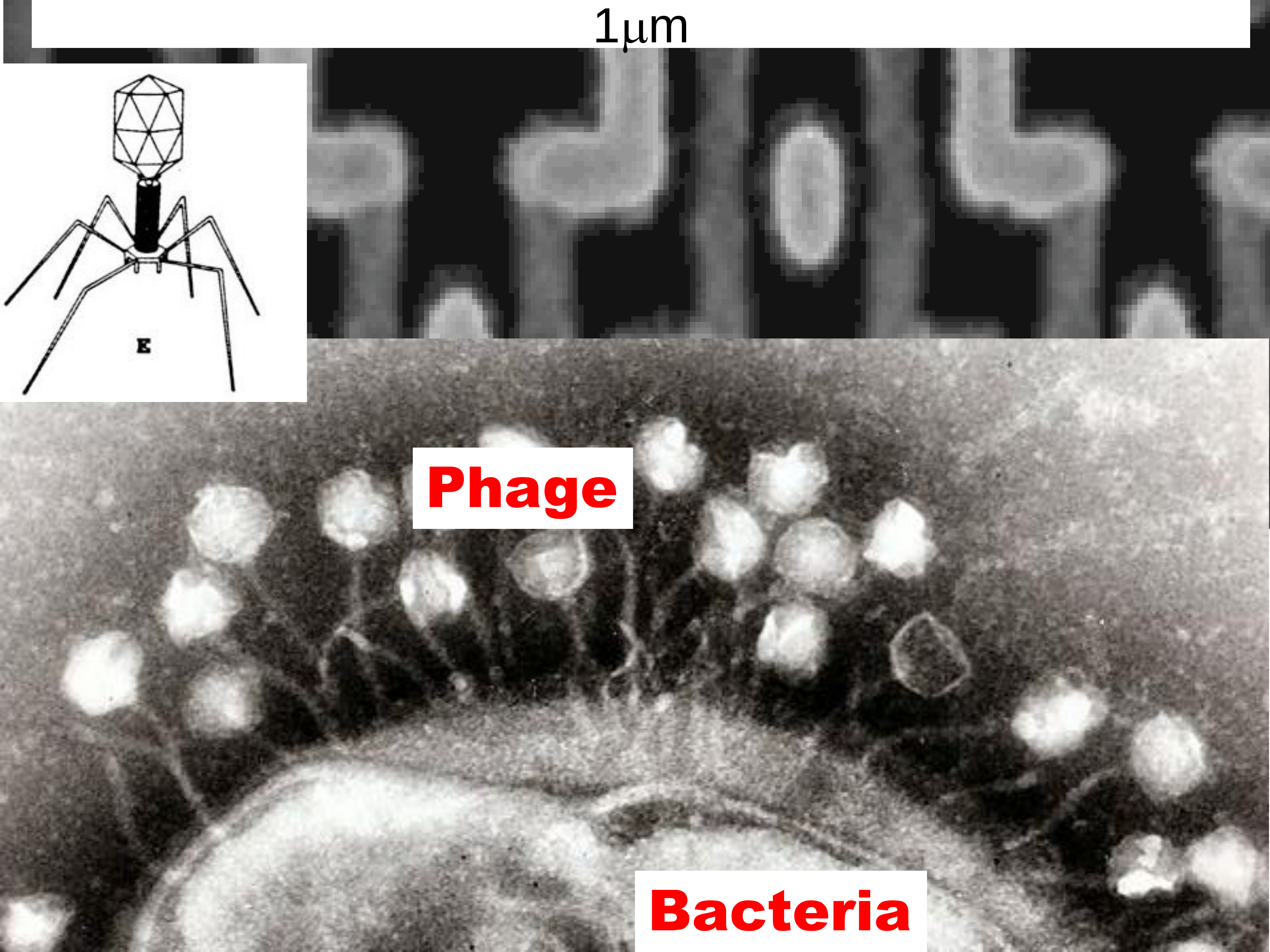
Viruses' Life History: Towards a Mechanistic Basis of a Trade-Off between Survival and Reproduction among Phages

Marianne De Paepe, François Taddei*

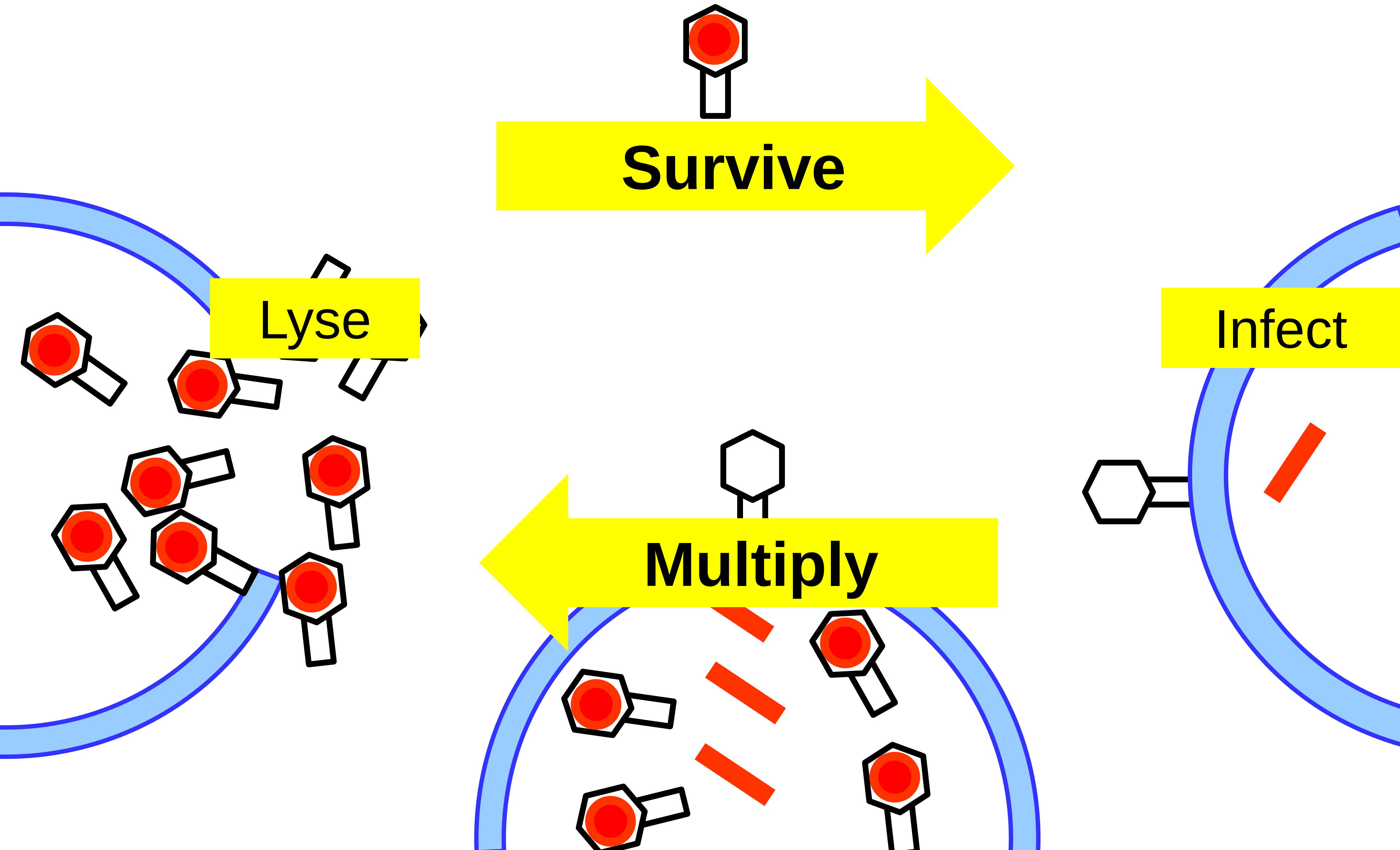
Laboratoire de Genetique Moleculaire, Evolutive et Medicale, University of Paris 5, INSERM, Paris, France

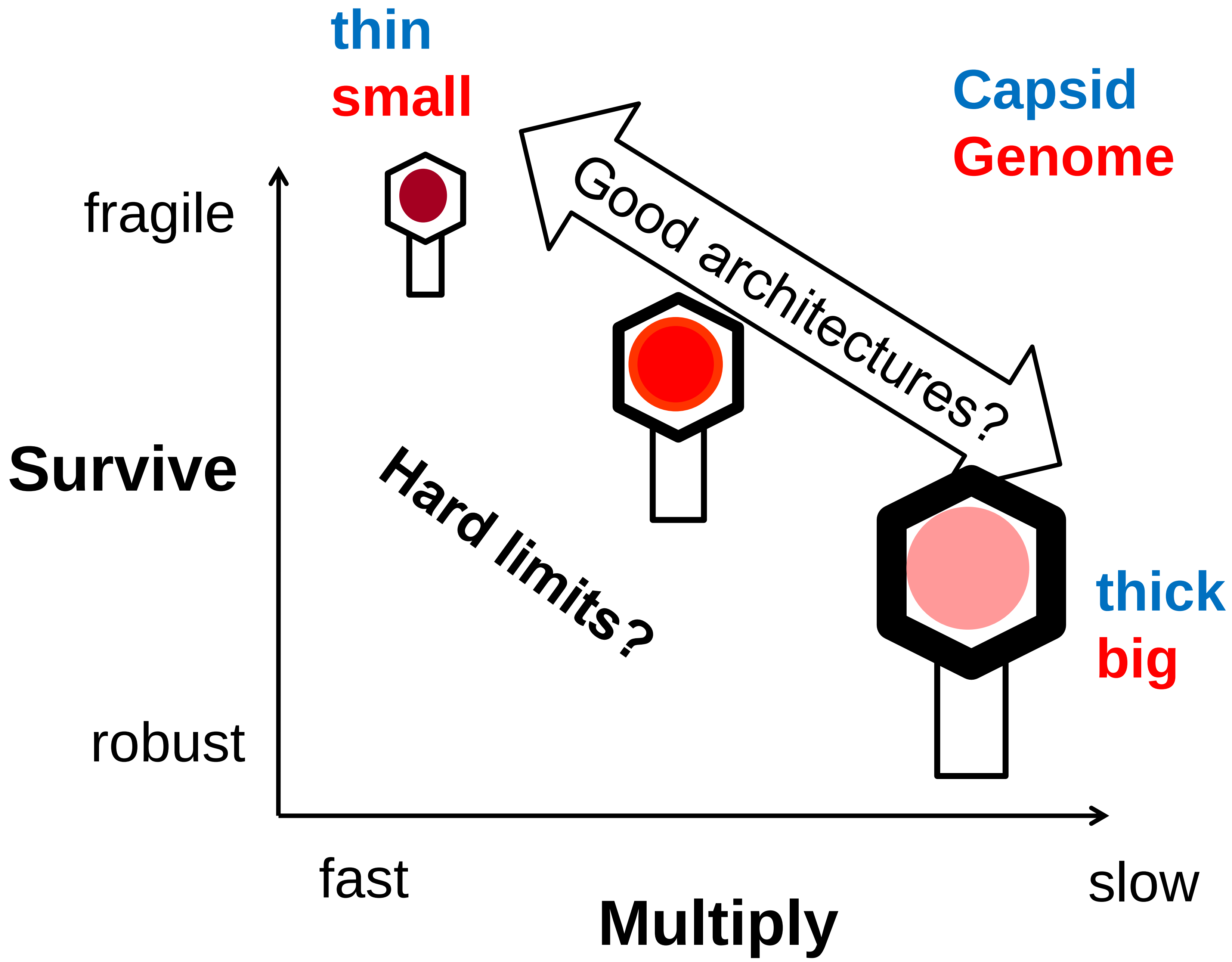
July 2006 | Volume 4 | Issue 7 | e193

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

Science
AAAS

Most important paper so far.

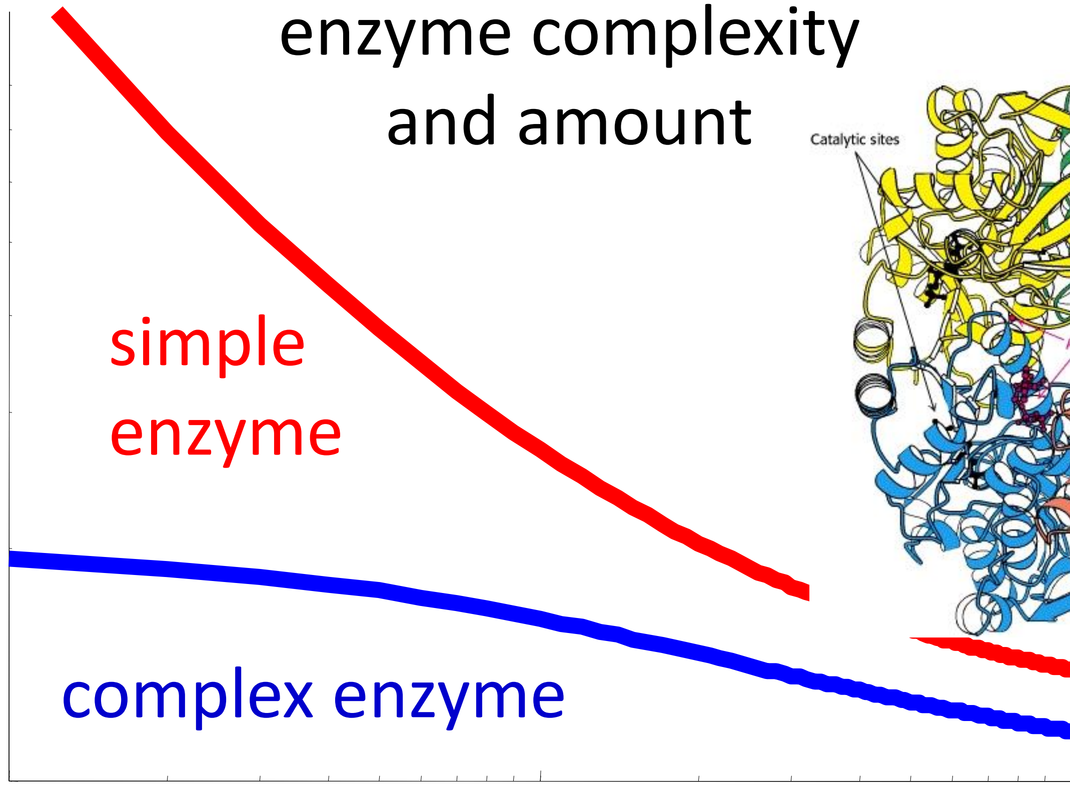
Theorem!

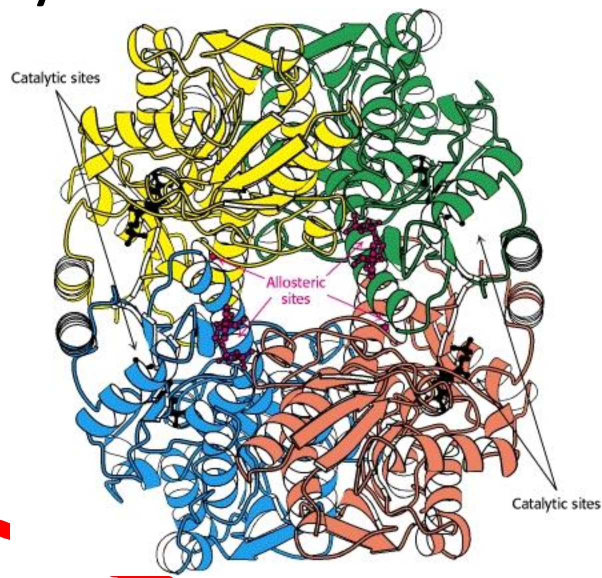
$$\frac{1}{\pi}\int_0^\infty \ln|S(j\omega)|\left(\frac{z}{z^2+\omega^2}\right)d\omega \ge \ln\left|\frac{z+p}{z-p}\right|$$

z and p functions of enzyme complexity and amount

Fragility

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



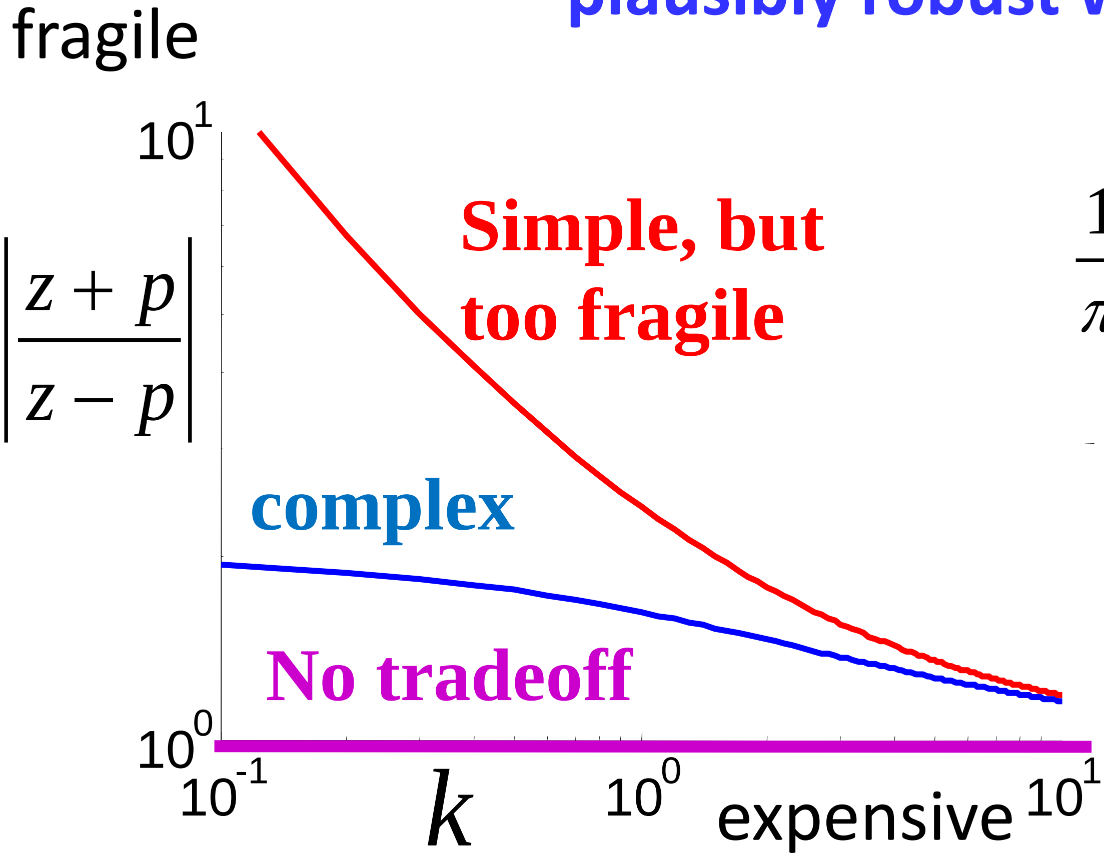


Enzyme amount

Savageaumics

Hard tradeoff in glycolysis is

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

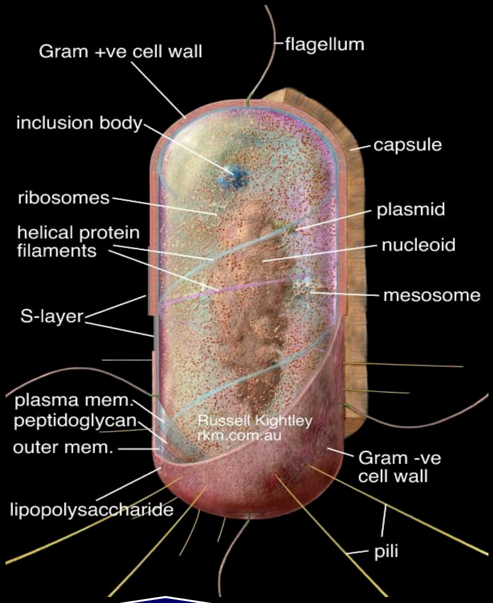


$$\frac{1}{\pi}\int_0^\infty \ln\left|S(j\omega)\right|\left(\frac{z}{z^2+\omega^2}\right)d\omega \geq \ln\left|\frac{z+p}{z-p}\right|$$

System

"Emergent": "Nontrivial" consequences of other constraints

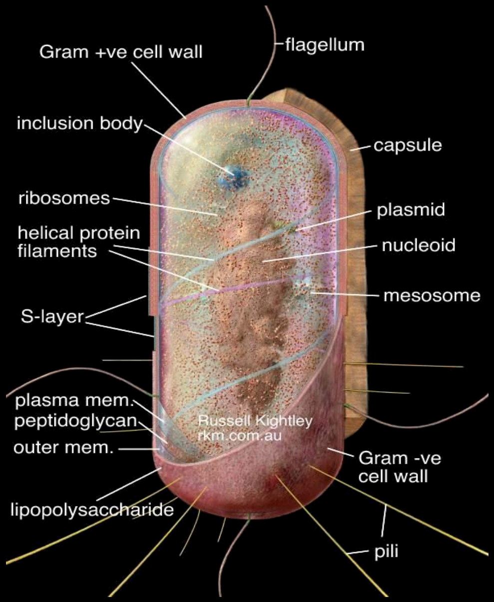
Architecture =Constraints



Protocols

Components

Systems requirements: Survive in hostile environments



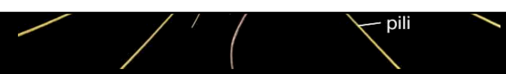
Constraints

Components and materials: “Chemistry”

Constrained (“conserved”):

Moieties

1. NAD
2. Adenylate
3. Carbon
4. phosphate
5. oxygen
6. Oxidized state of metabolites
7. Reduced state of metabolites
8. High energy potential release



Constraints

Components and materials:
“Chemistry”

Bacterial biosphere

- carriers: ATP, NADH, etc
- Precursors, …
- Enzymes
- Translation
- Transcription
- Replication
- …

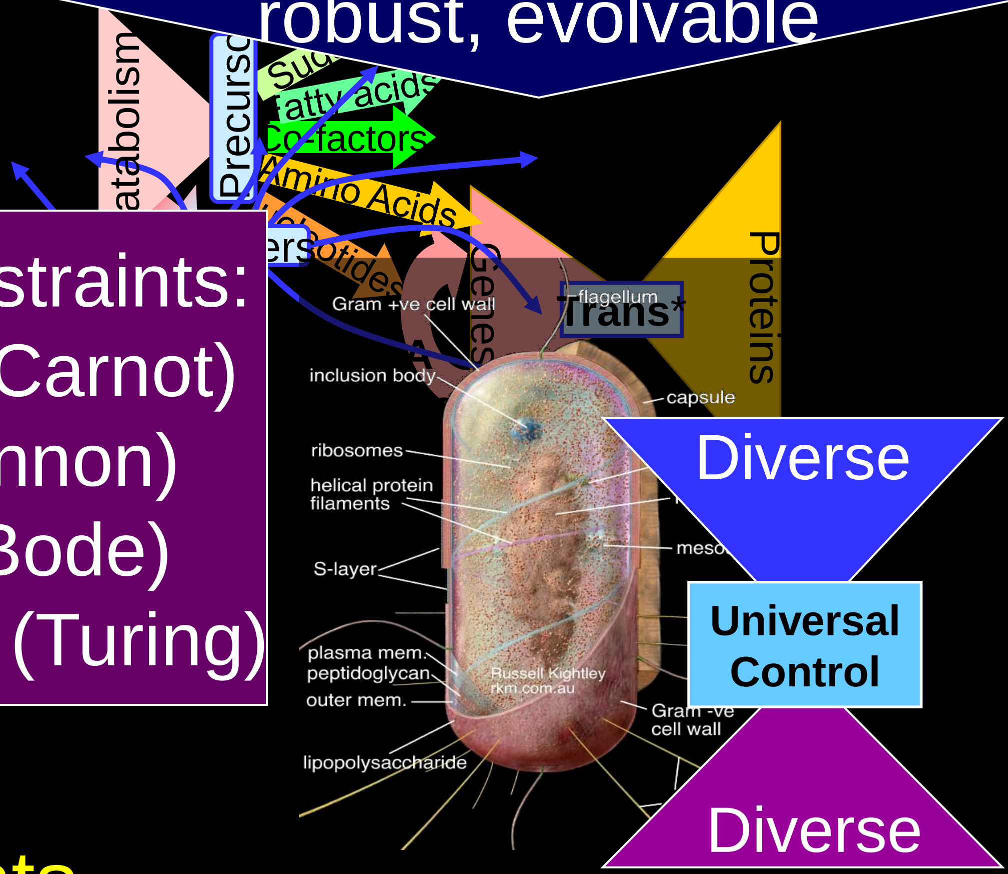
Protocols

Architecture = protocols
= “constraints that deconstrain”

Systems requirements: functional, efficient, robust, evolvable

Hard constraints:
Thermo (Carnot)
Info (Shannon)
Control (Bode)
Compute (Turing)

Protocols



Constraints

Components and materials: Energy, moieties

Systems requirements: functional, efficient, robust, evolvable

Constrained ("conserved"):

Moieties

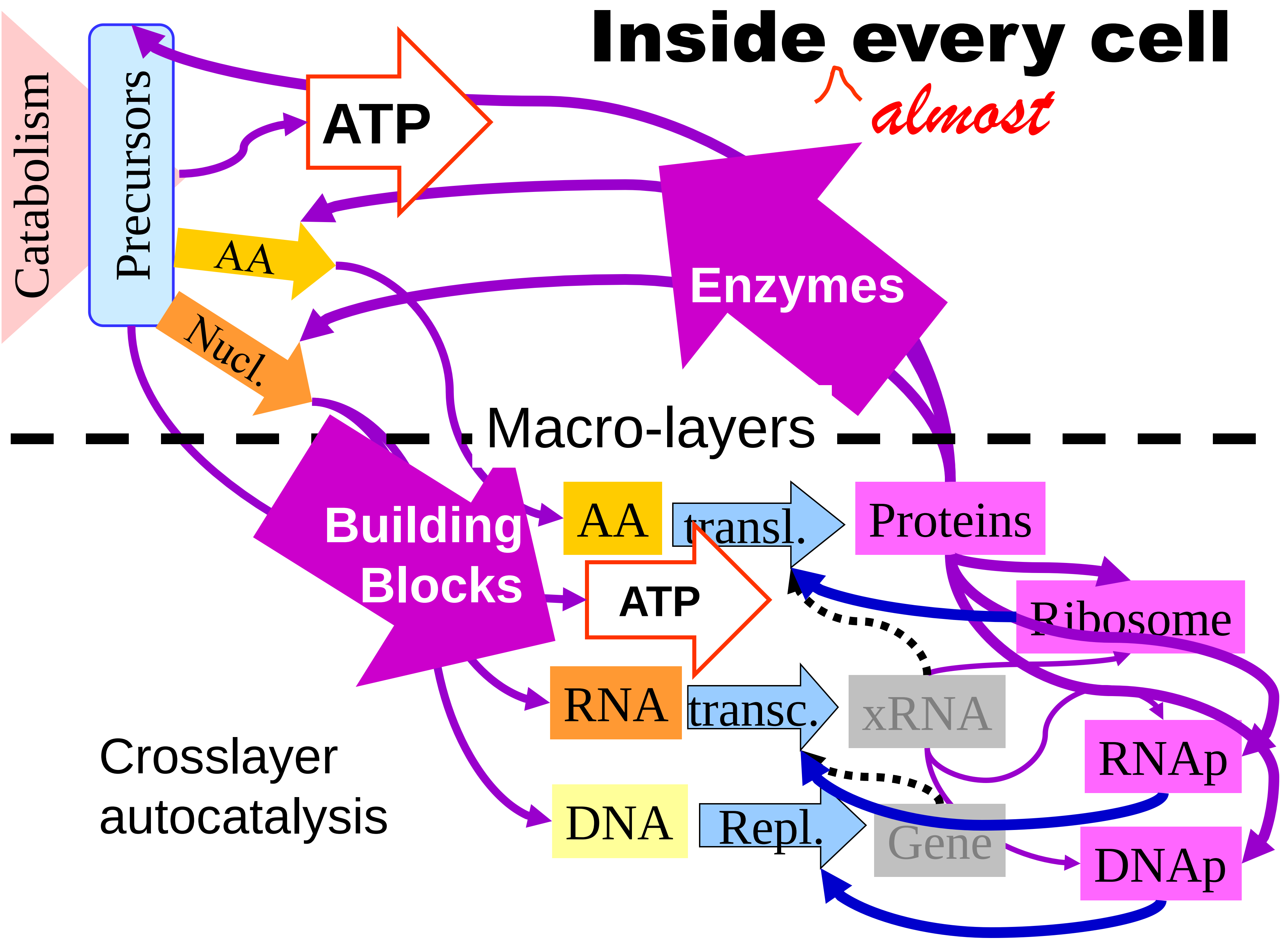
1. NAD
2. Adenylate
3. Carbon
4. phosphate
5. oxygen
6. Oxidized state of metabolites
7. Reduced state of metabolites
8. High energy potential release

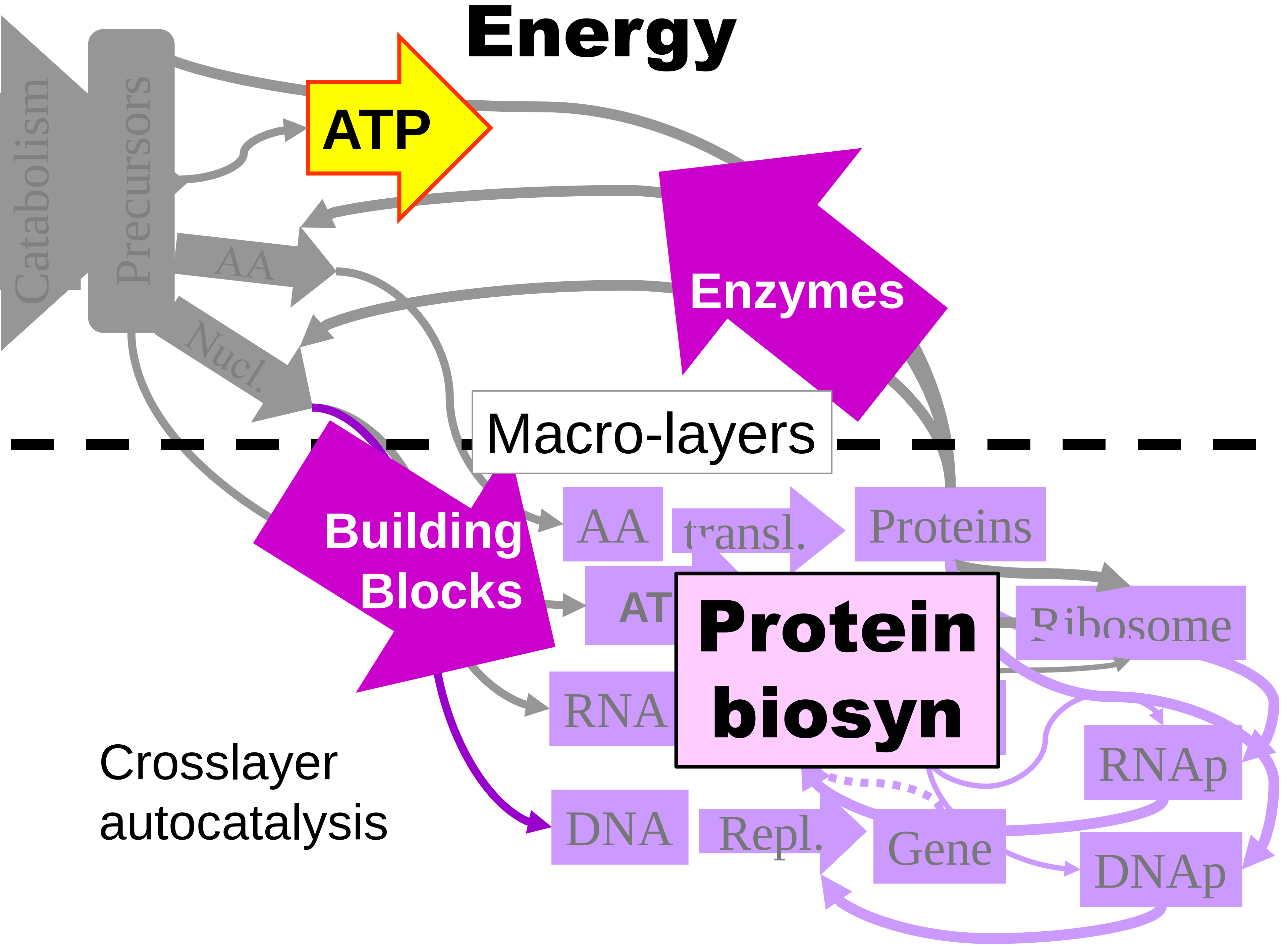
$$\frac{1}{\pi}\int_0^\infty \ln\left|S(j\omega)\right|\left(\frac{z}{z^2+\omega^2}\right)d\omega \geq \ln\left|\frac{z+p}{z-p}\right|$$

Constraints

Protocols

Components and materials: Energy, moieties


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


Energy
ATP
Catabolism
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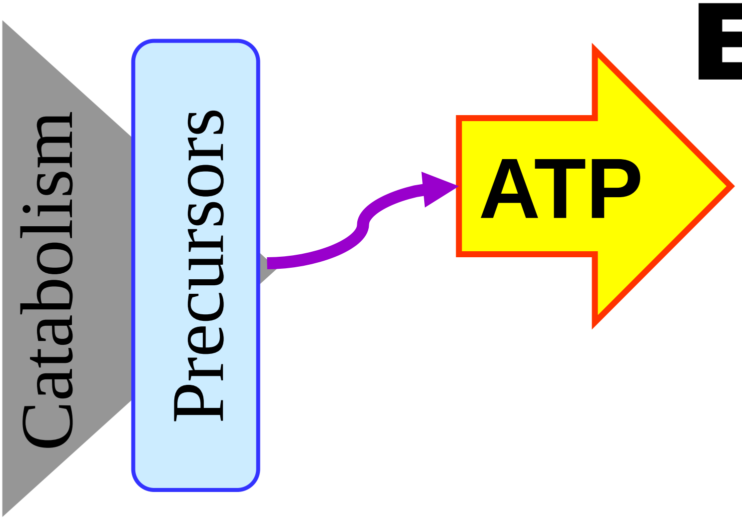
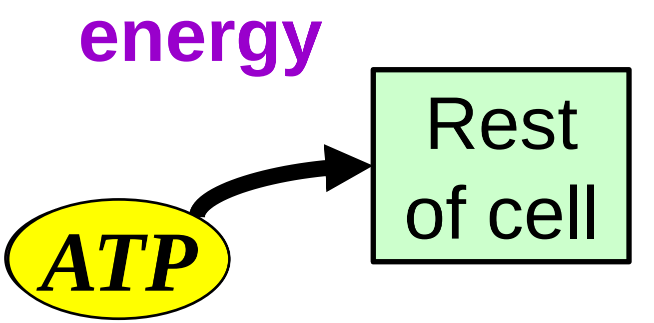
Macro-layers
Building
Blocks
AA
transl.
Proteins
Ribosome
RNA
Protein
biosyn
RNAp
DNA
Repl.
Gene
DNAp
Crosslayer
autocatalysis

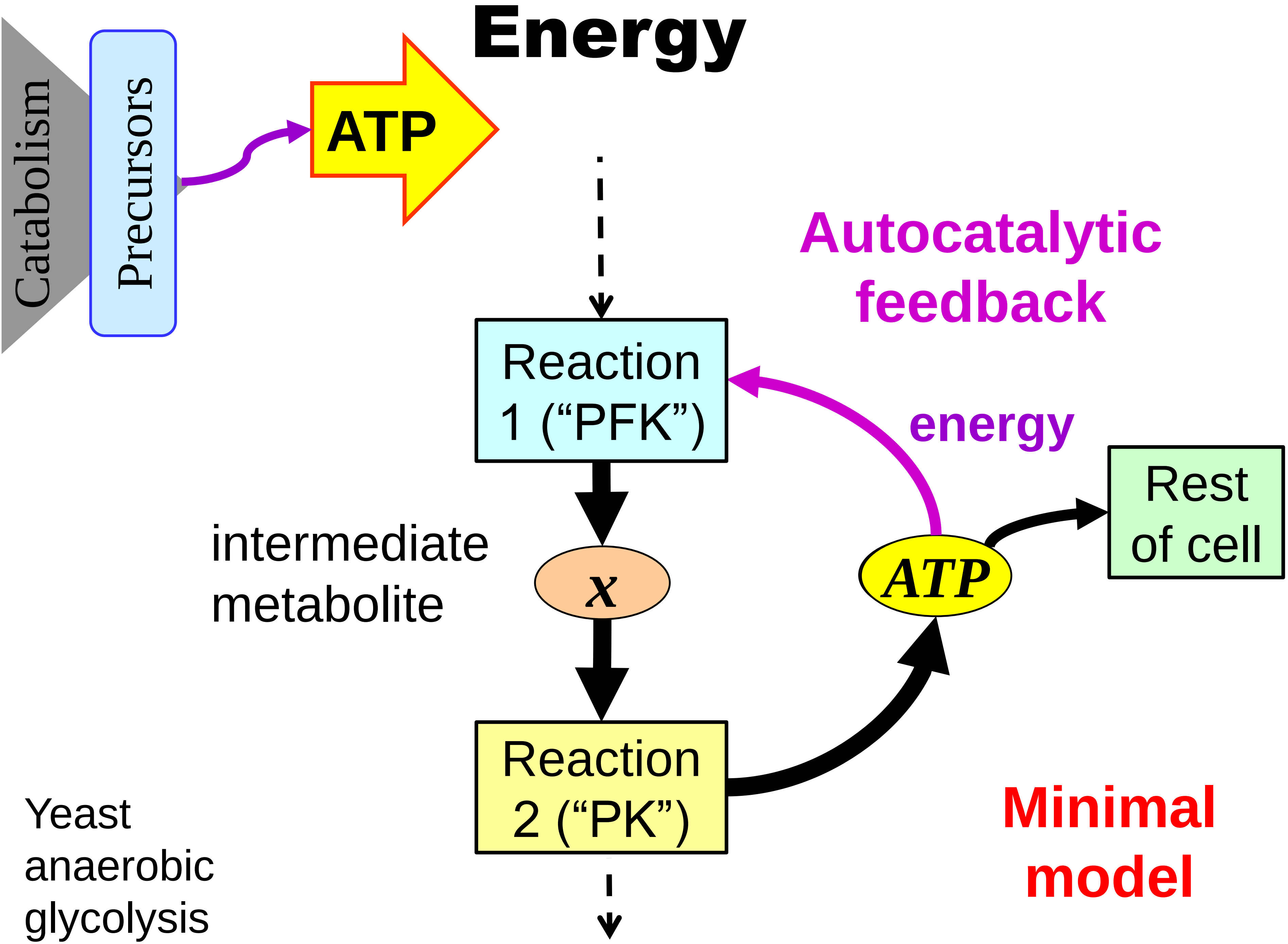
Energy





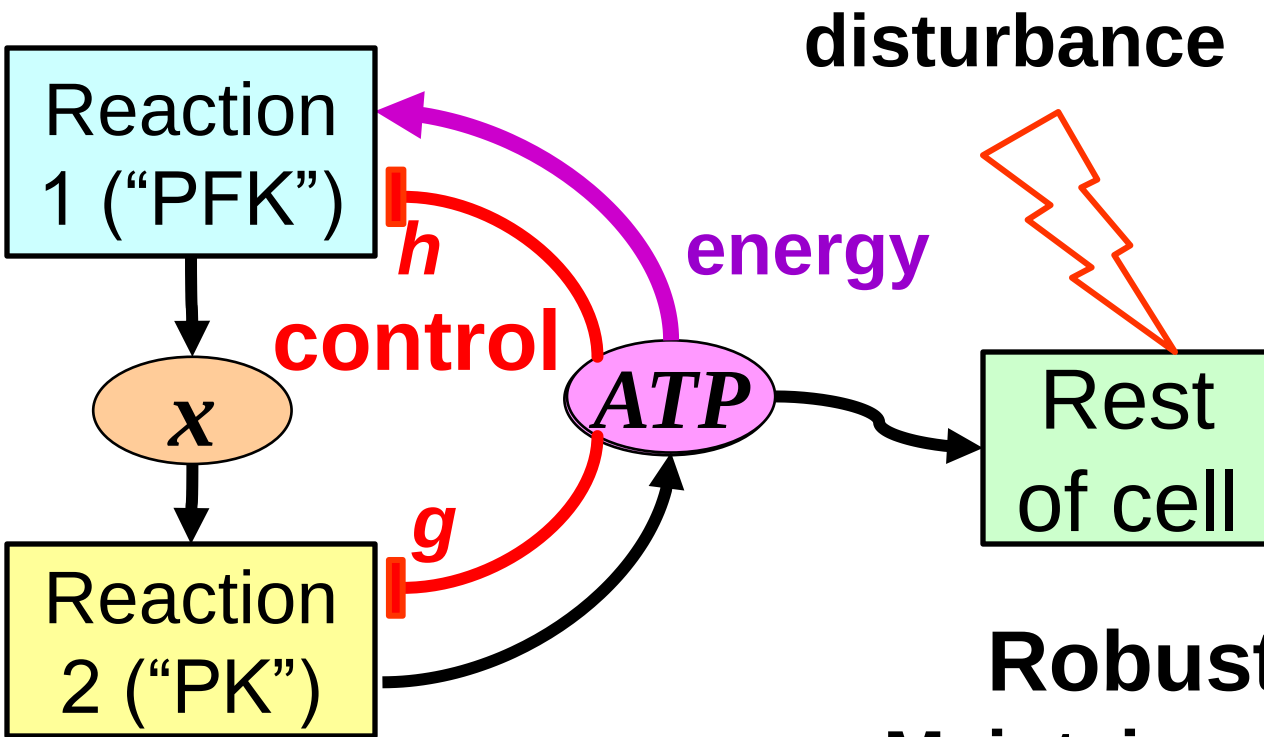
Yeast
anaerobic
glycolysis

**Minimal
model**



Energy
Catabolism
Precursors
ATP
Autocatalytic feedback
Reaction 1 ("PFK")
energy
Rest of cell
intermediate metabolite
x
ATP
Reaction 2 ("PK")
Yeast anaerobic glycolysis
Minimal model

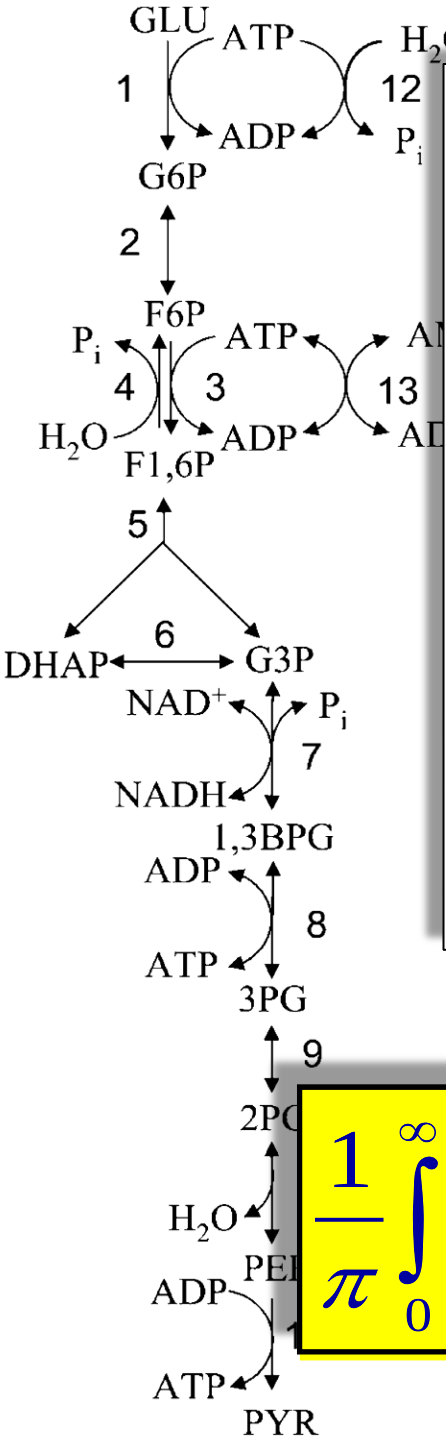
control feedback



Robust =
Maintain energy
(ATP concentration)
despite demand fluctuation

Tight control creates “weak linkage” between power supply and demand

(P1) Total NAD moiety: $[NAD^+] + [NADH]$



Constrained ("conserved"):

Moieties

1. NAD
2. Adenylate
3. Carbon
4. phosphate
5. oxygen

6. Oxidized state of metabolites
7. Reduced state of metabolites
8. High energy potential release

[F1,6P] + [DHAP] +

[2PG] + [PEP] + [PYR]

HAP] + [G3P] +

+ [PEP] +

DP] + $[P_i]$

$P_i] + [H_2O]$

] +

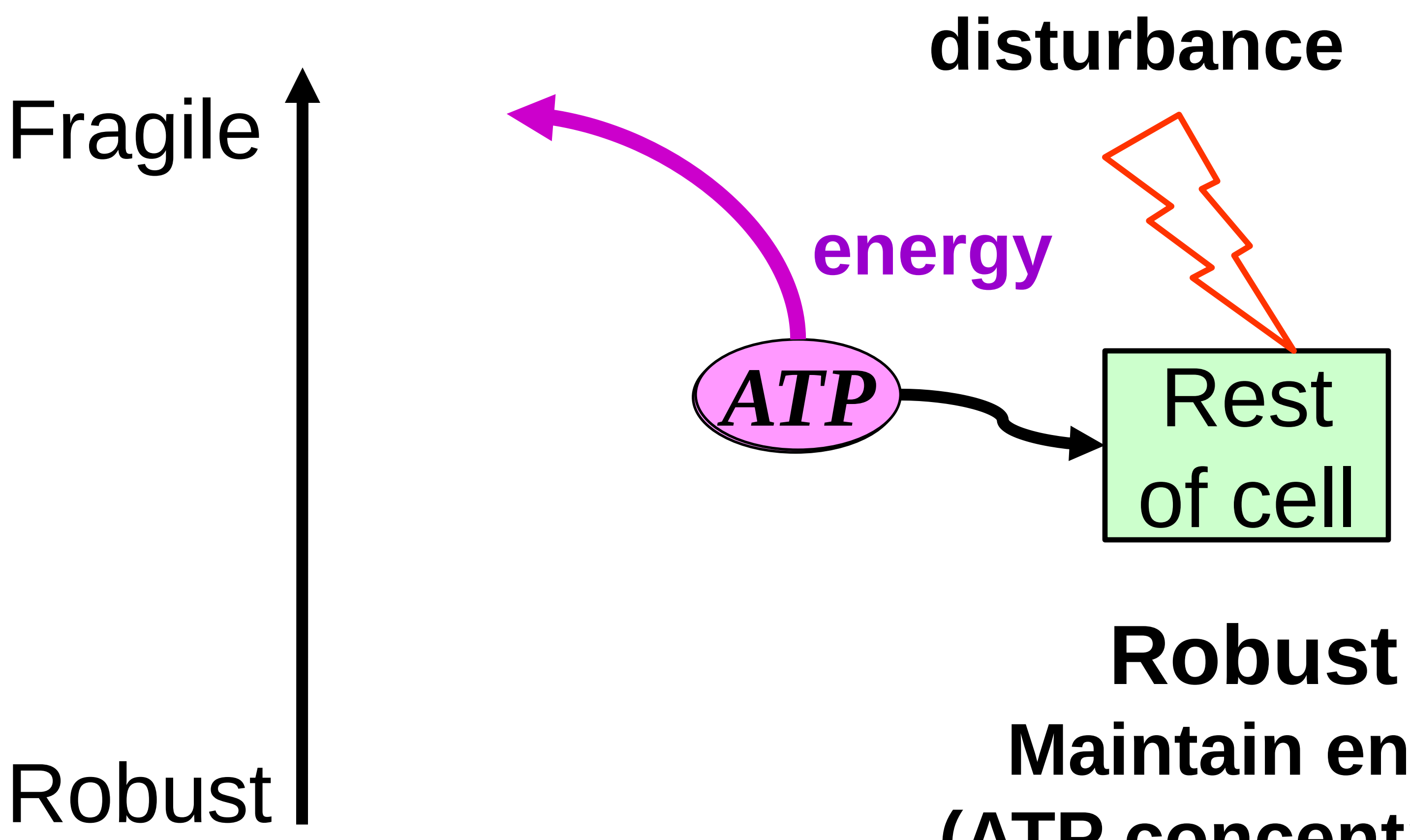
+ [PEP] + [PYR] + $[NAD^+]$

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

] +

+ [PYR] + [ADP] + 2[AMP] + $[H_2O]$

Hard tradeoff in glycolysis

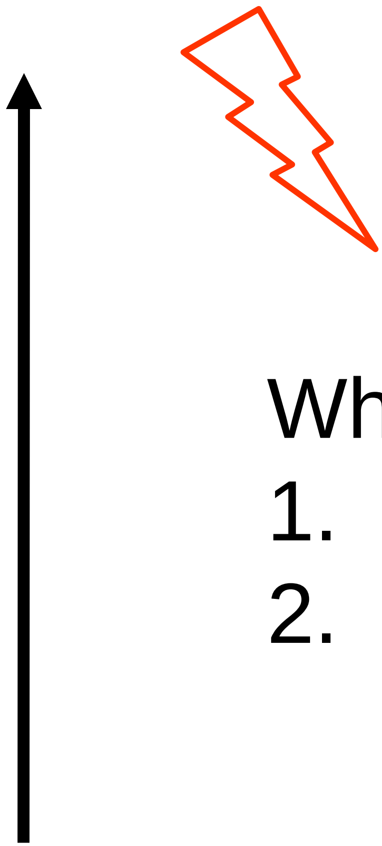


Robust =
Maintain energy (ATP concentration) despite demand fluctuation

disturbance

Accurate vs sloppy

Fragile



Robust

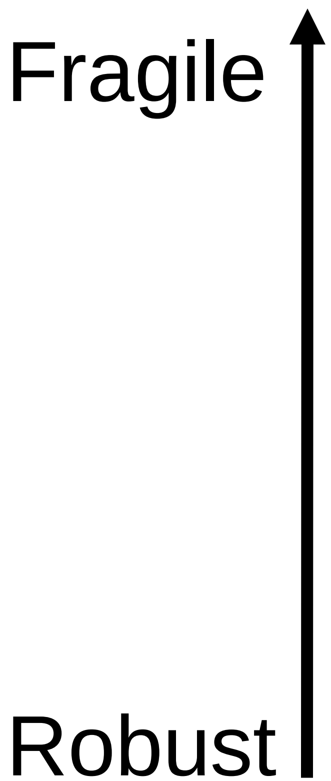
What makes this hard?

1. Instability (autocatalysis)
2. Delay (enzyme amount)

Robust

≈Disturbance rejection

≈ Accurate



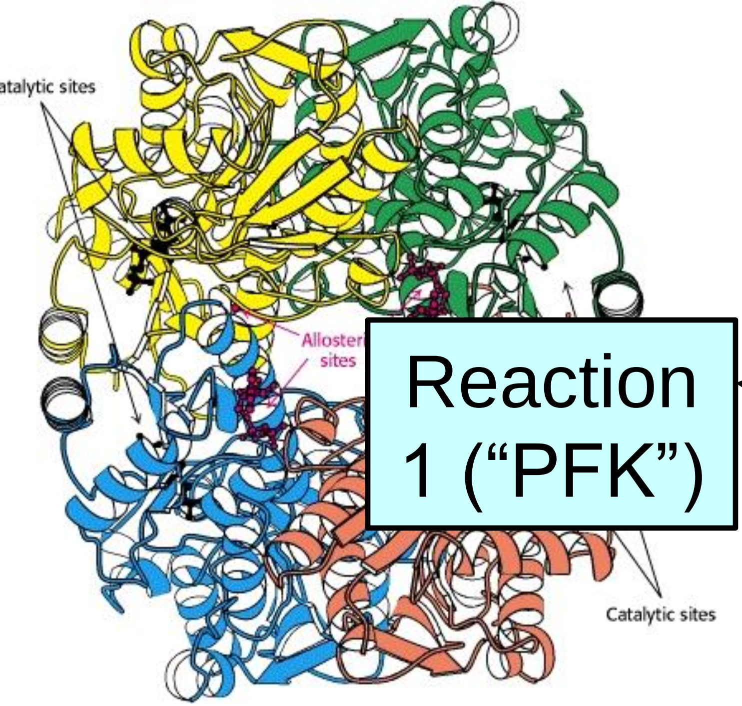
What makes this hard?

1. Instability
2. Delay

The CNS must cope with both

Today's important point

enzymes catalyze reactions



Reaction 1 (“PFK”)

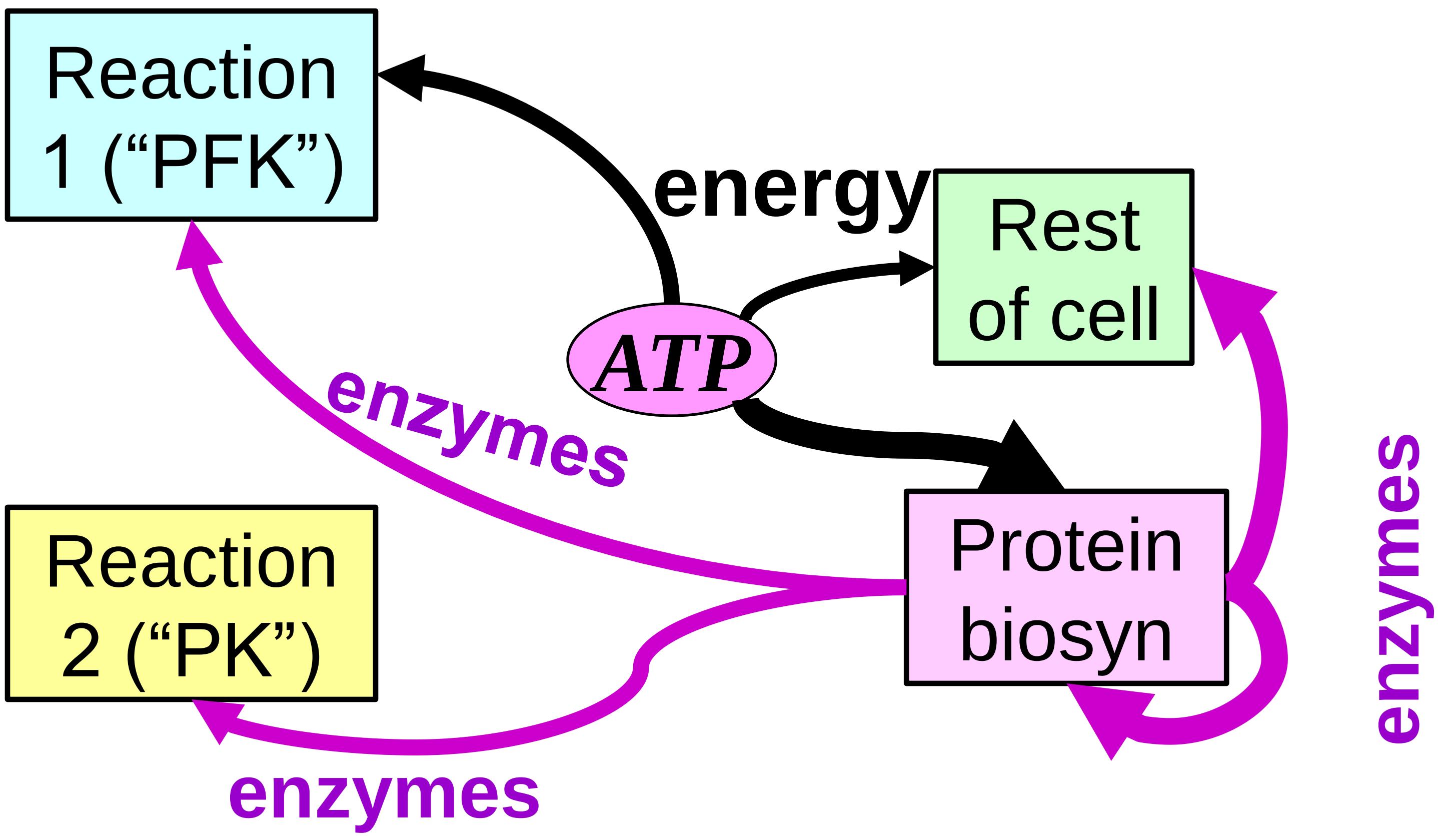
energy

ATP

Rest of cell

Reaction 2 (“PK”)

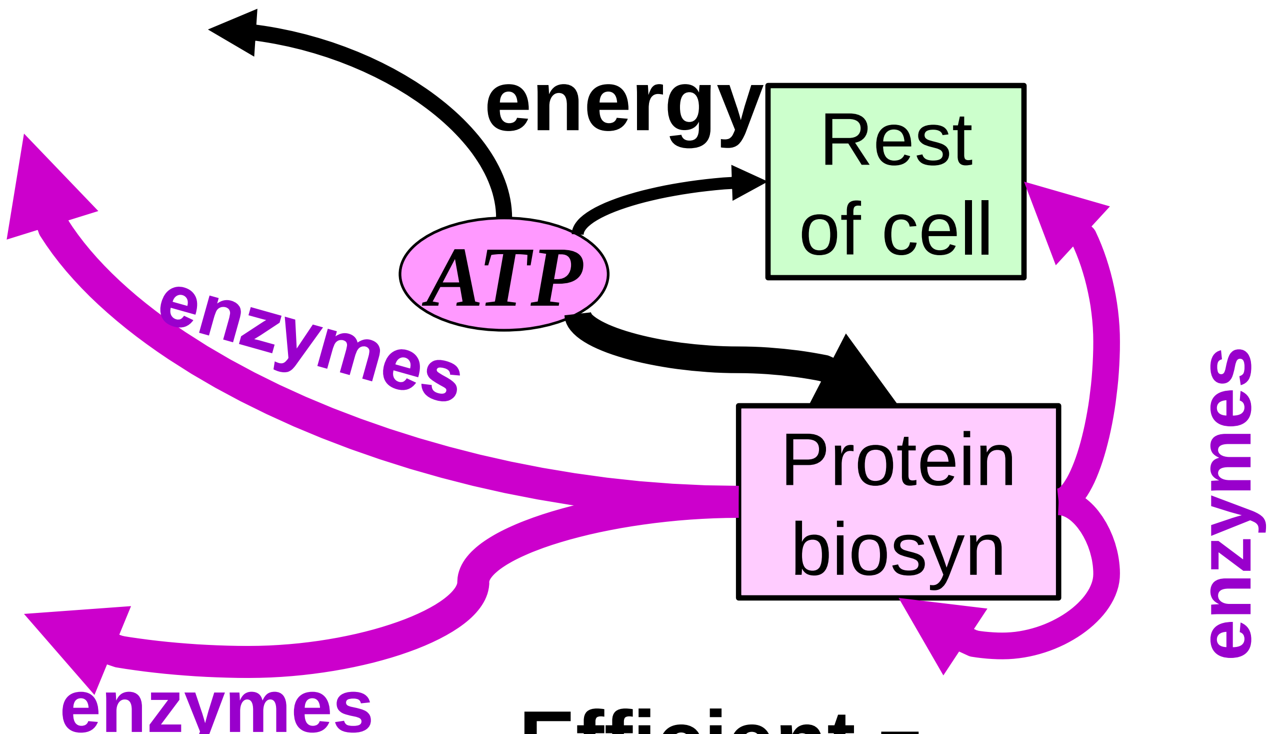
enzymes catalyze reactions, another source of autocatalysis



Efficient =
low metabolic overhead
≈ low enzyme amount

enzymes catalyze reactions, another source of autocatalysis

reaction rates ∝ enzyme amount



Can't make too many enzymes here, need to supply rest of the cell.

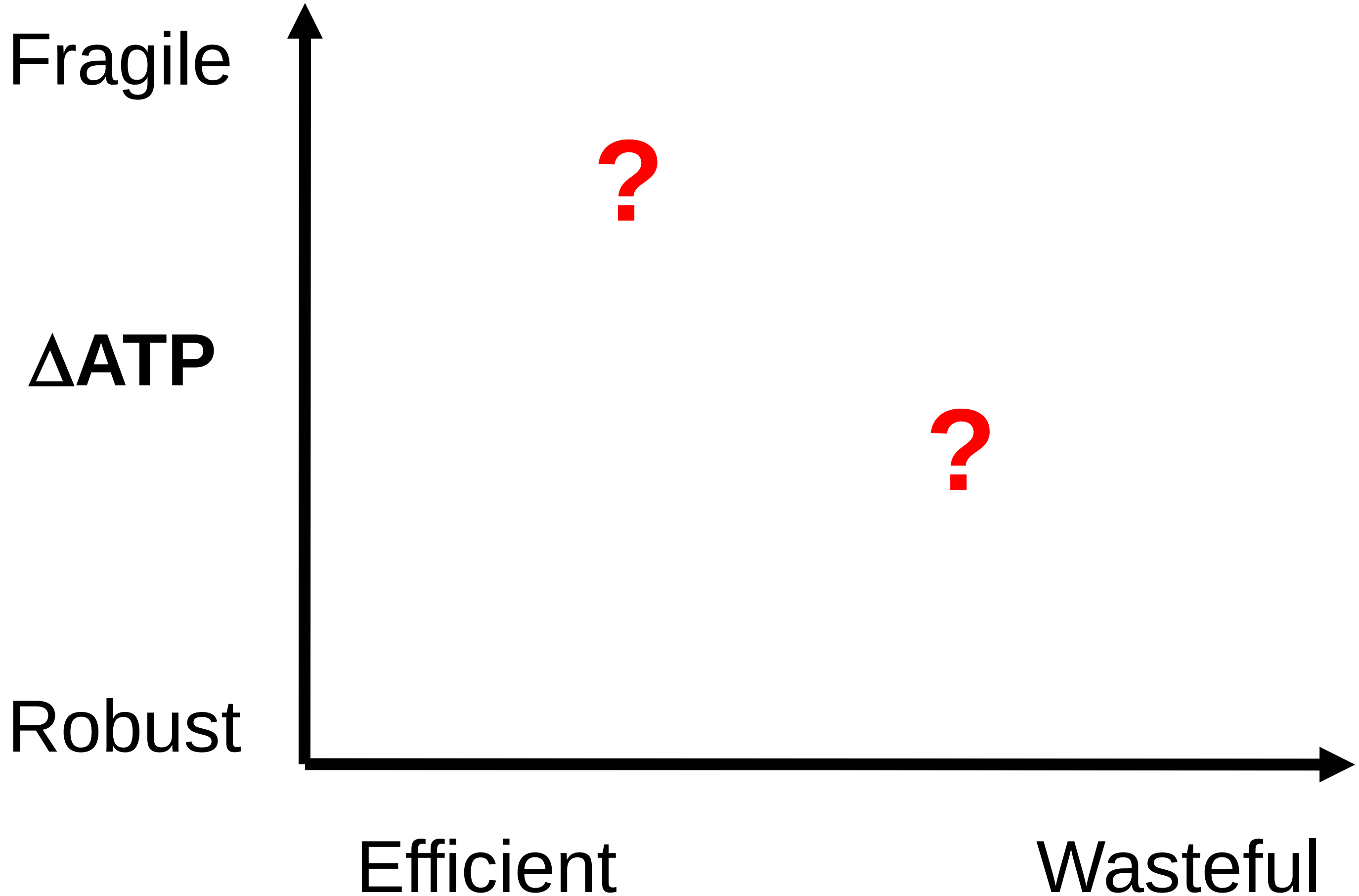
Efficient =

low metabolic overhead

≈ low enzyme amount

(⇒ slow reactions)

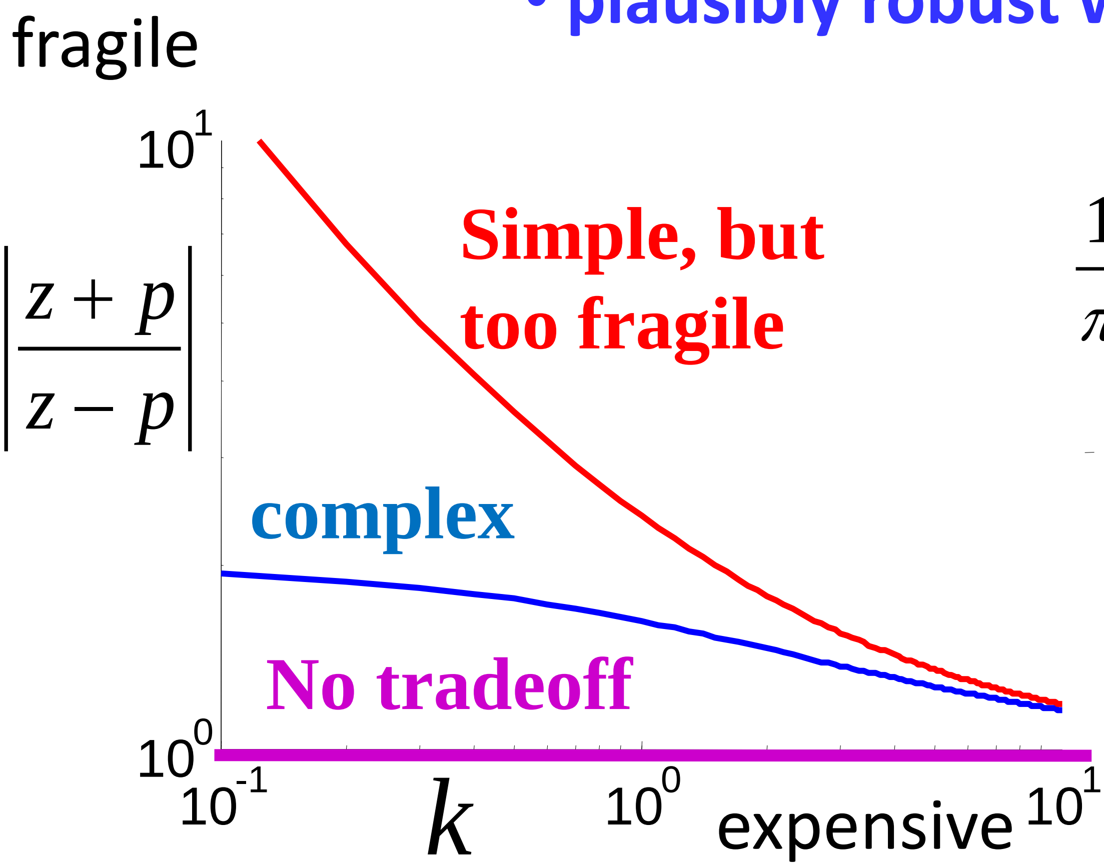
Robust =
Maintain ATP



Efficient =
low enzyme amount
(⇒ slow reactions)

Hard tradeoff in glycolysis is

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



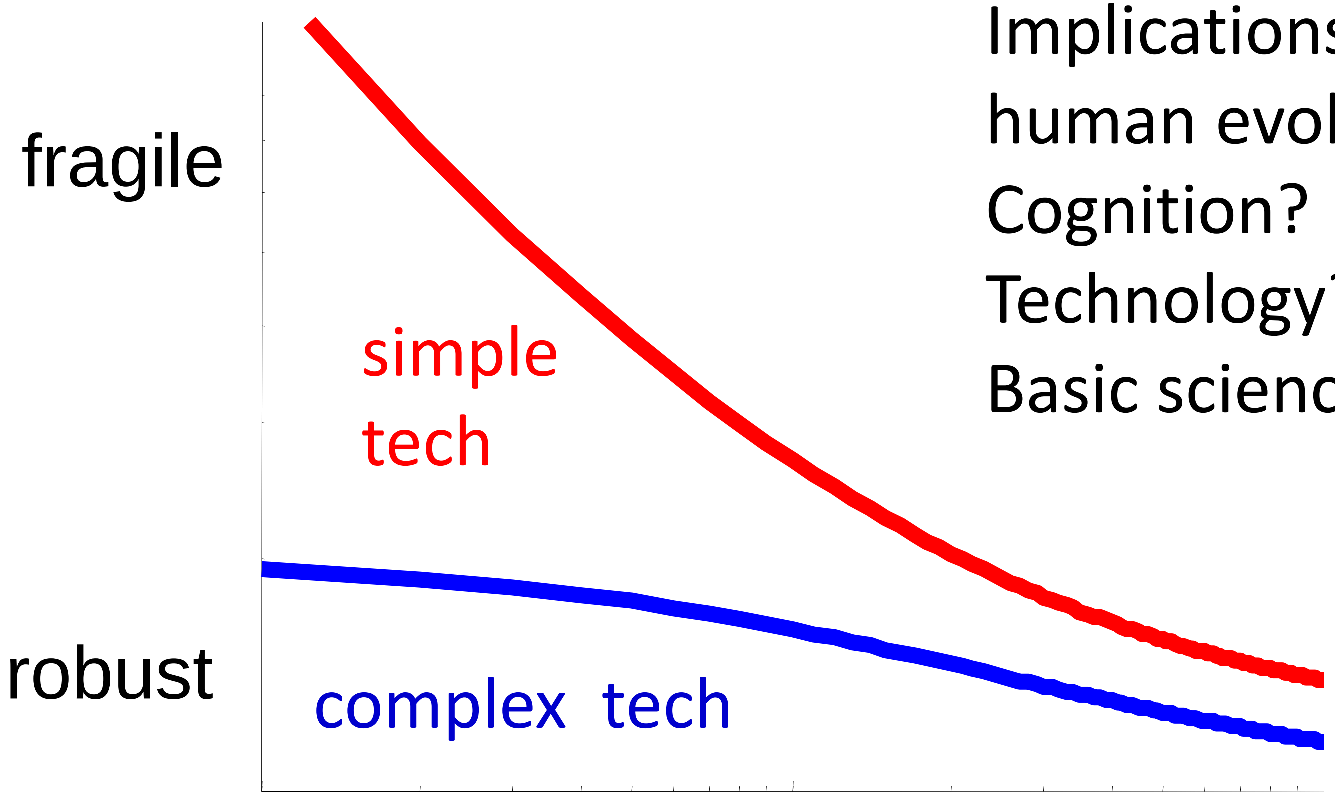
$$\frac{1}{\pi}\int_0^\infty \ln\left|S(j\omega)\right|\left(\frac{z}{z^2+\omega^2}\right)d\omega$$

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

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



cheap — metabolic expensive

large delay τ — small τ

fast multiply — slow

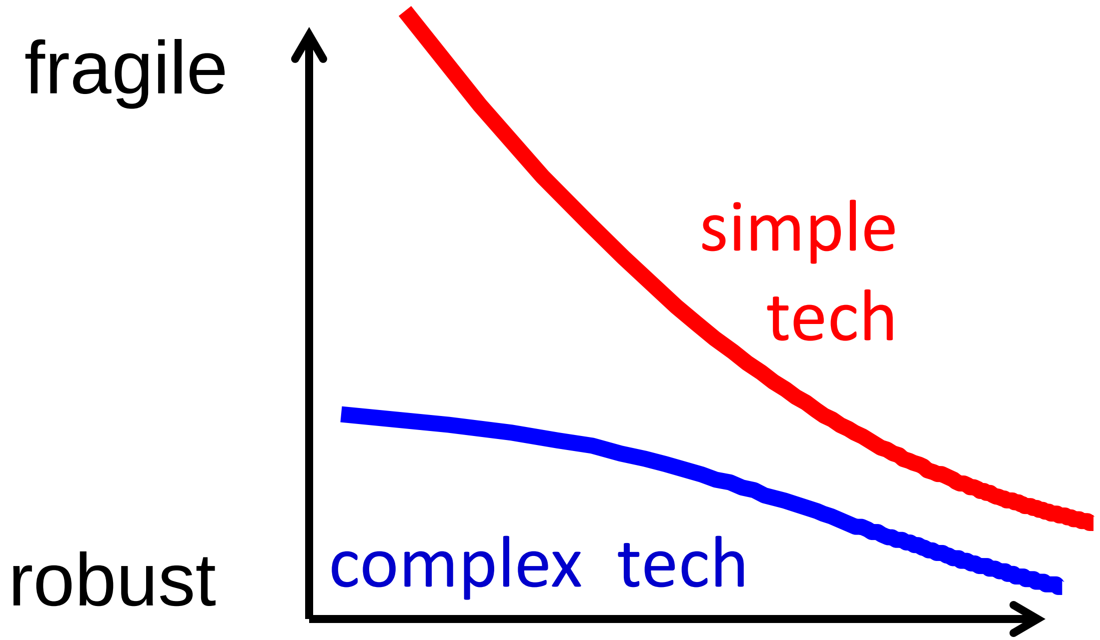
Implications for human evolution?
Cognition?
Technology?
Basic sciences?

This picture is very general

Domain specific costs/tradeoffs

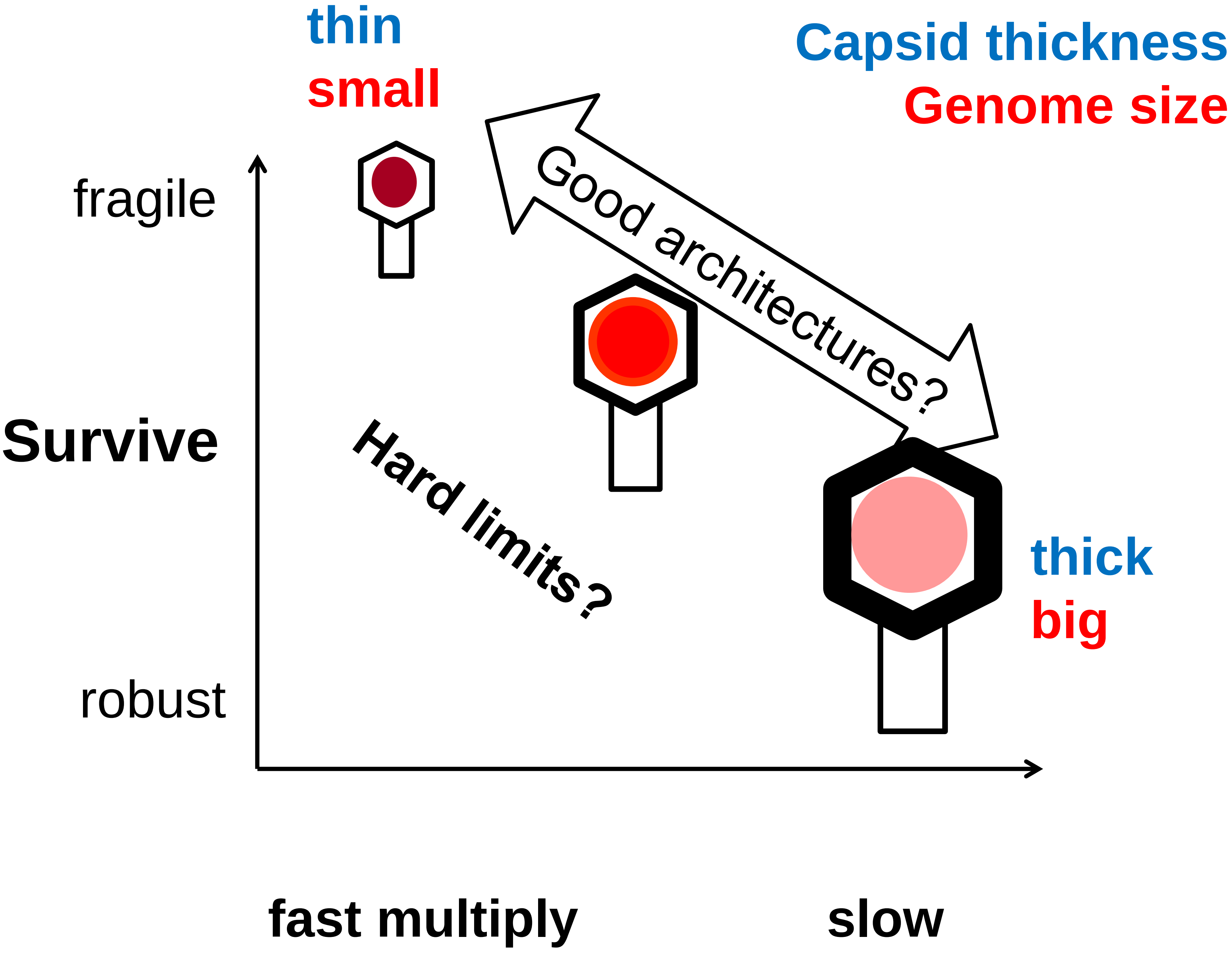
metabolic overhead	cheap	⟷	metabolic expensive
CNS reaction time τ (delay)	large τ	⟷	small τ
phage multiplication rate	fast multiply	⟷	slow

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



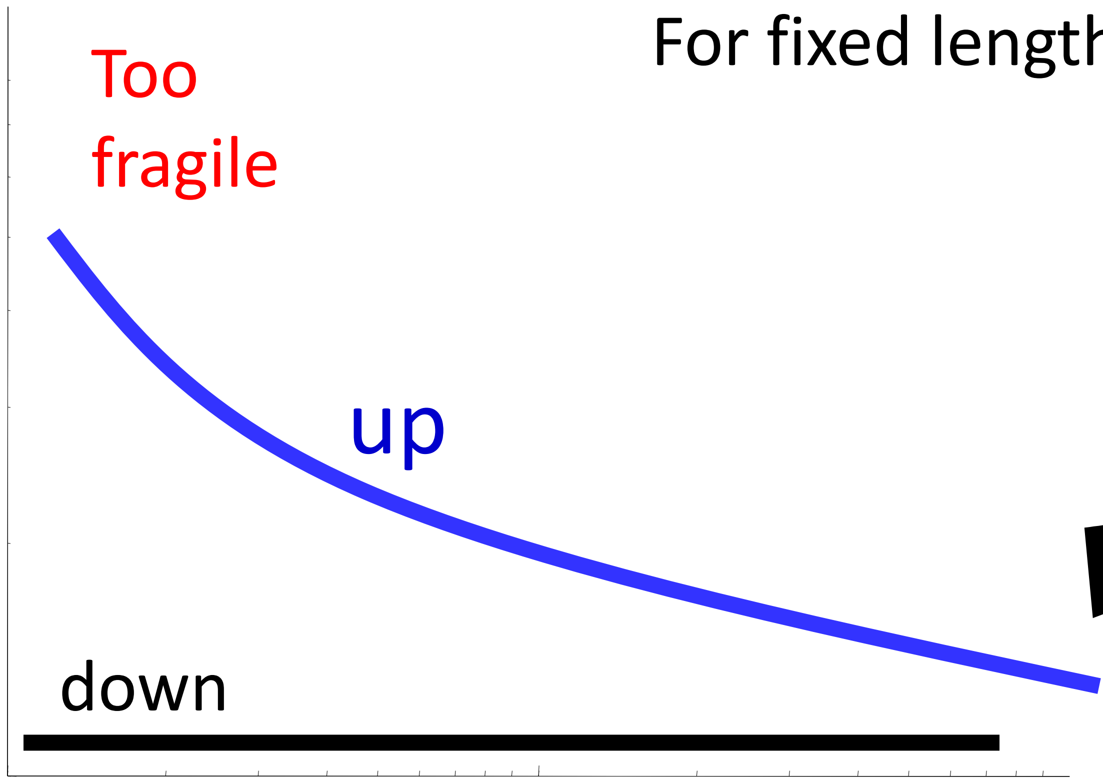
thin
small
Capsid thickness
Genome size
fragile
Good architectures?
Survive
Hard limits?
thick
big
robust
fast multiply
slow

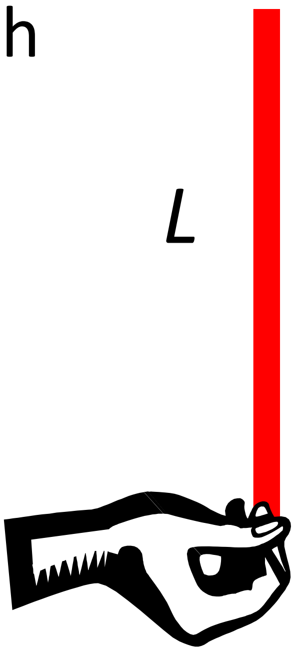
$$\frac{1}{\pi}\int_0^\infty \ln|T(j\omega)|\frac{2p}{p^2+\omega^2}d\omega \geq p\tau \propto \tau\sqrt{\frac{1}{l}}$$

For fixed length

Fragility

$$\tau\sqrt{\frac{1}{l}}$$





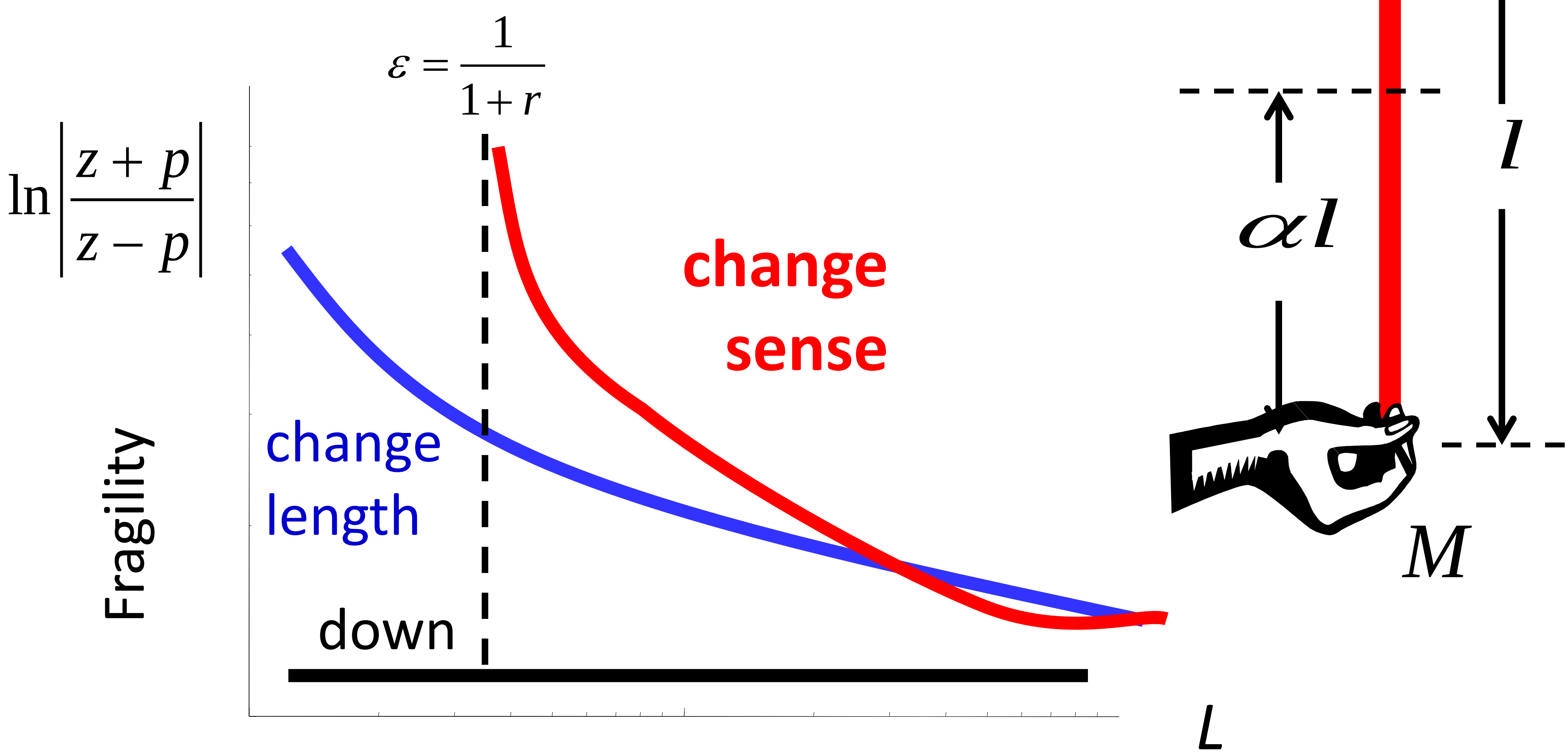
large τ
small 1/τ

small τ
large 1/τ

1/delay

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

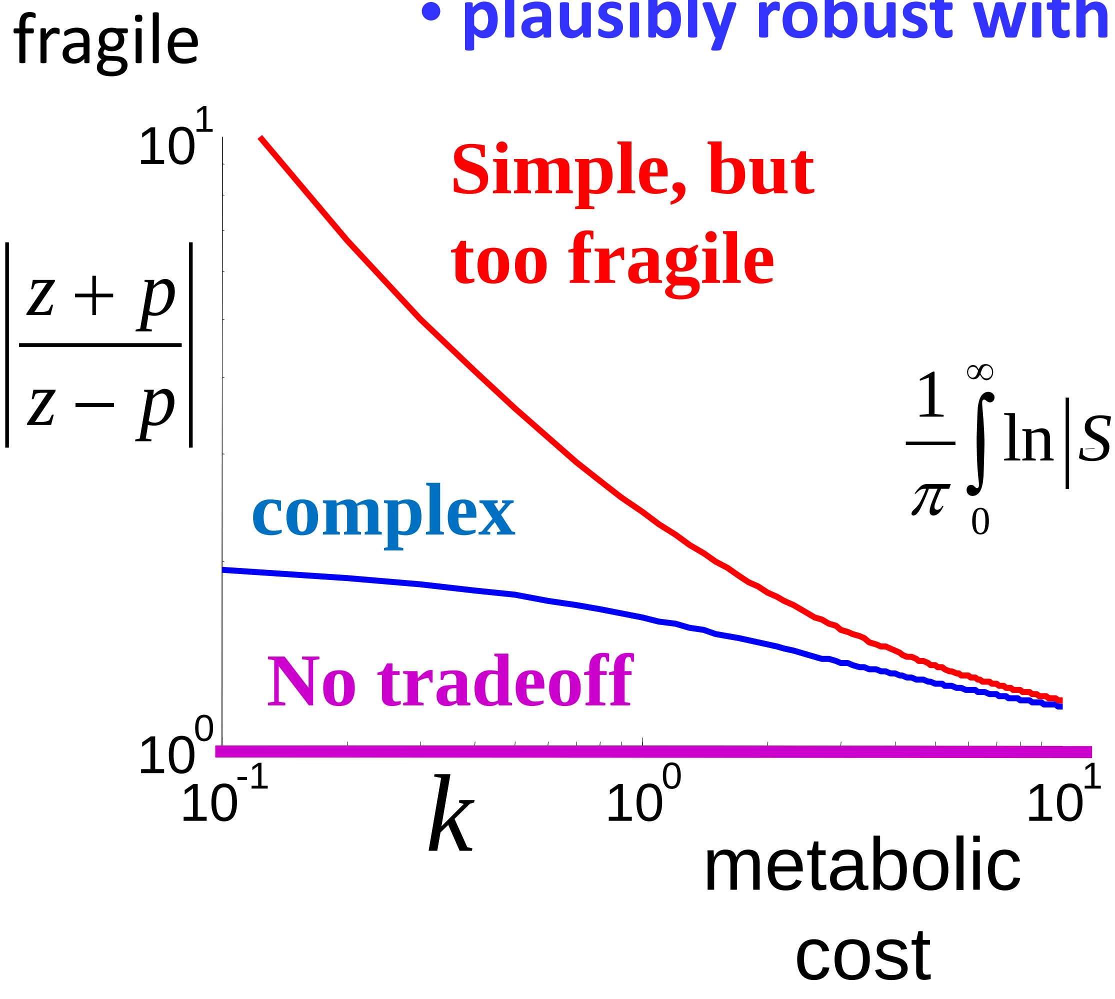
$$r = \frac{m}{M}$$



This is a cartoon, but can be made precise.

Hard tradeoff in glycolysis is

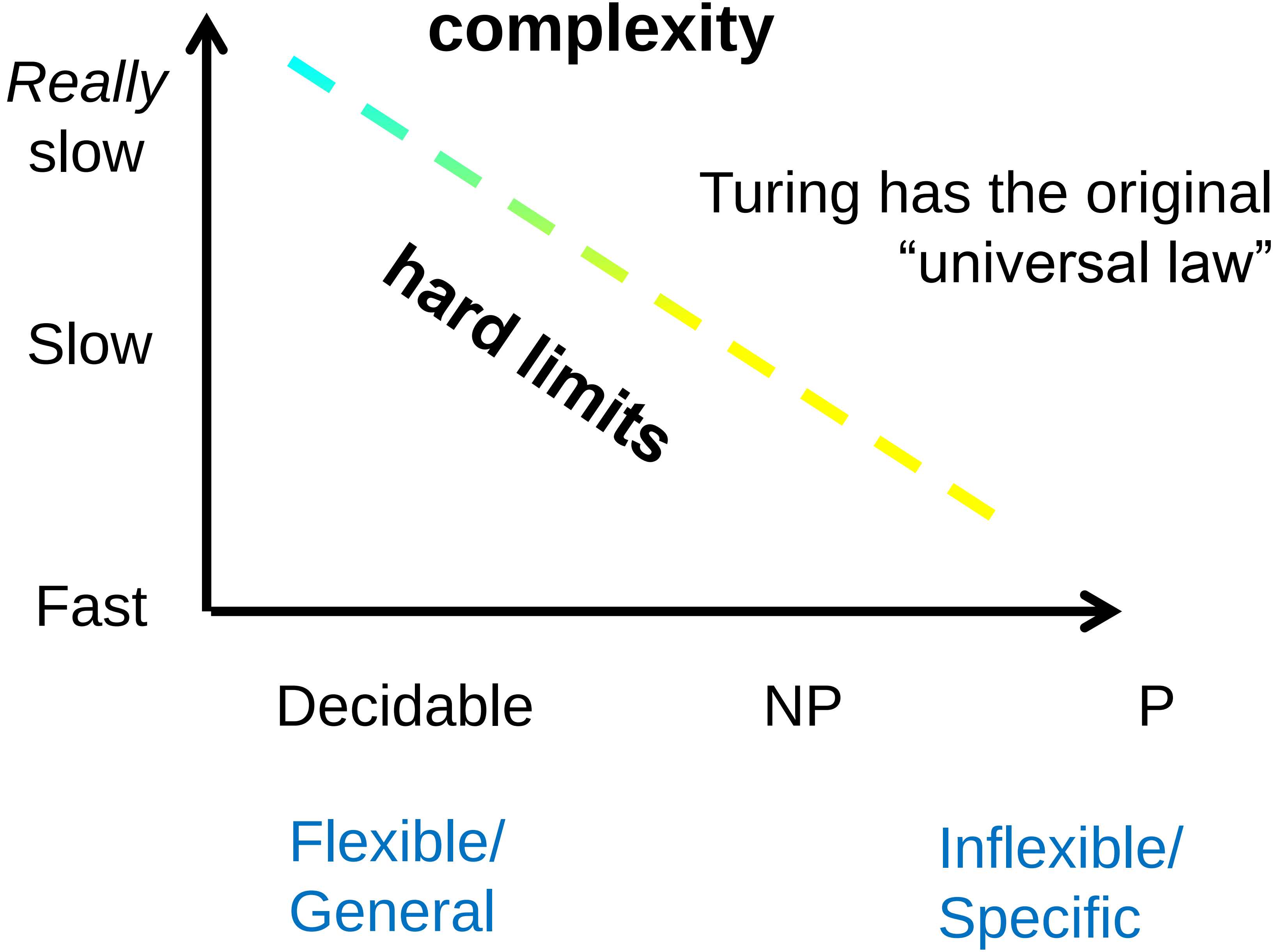
- **robustness vs efficiency**
- **absent without autocatalysis**
- **too fragile with simple control**
- **plausibly robust with complex control**



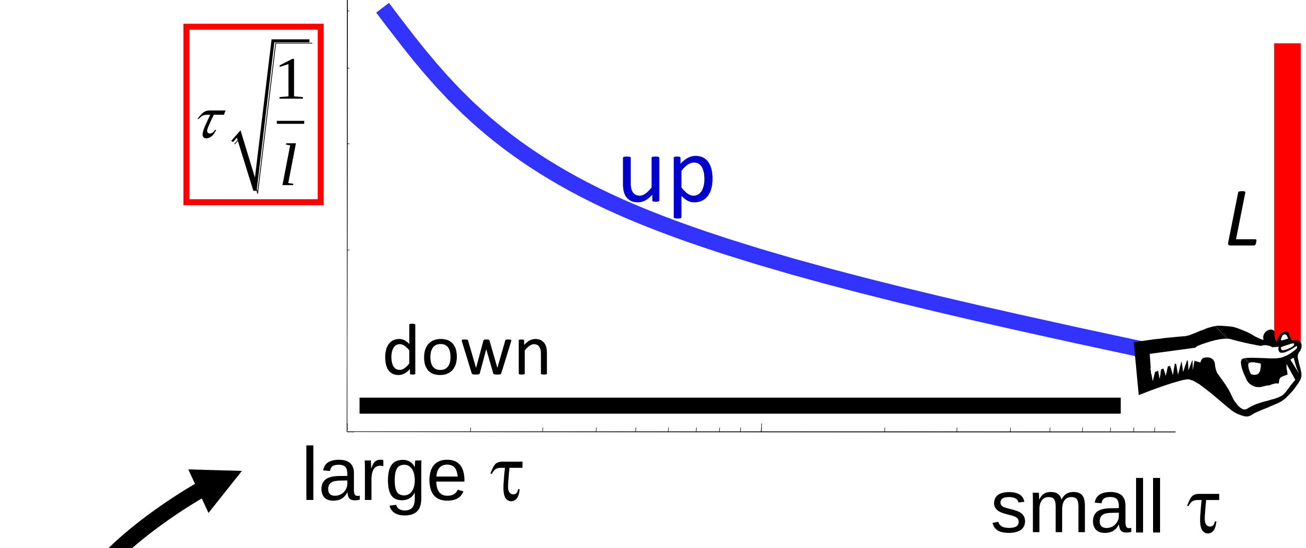
$$\frac{1}{\pi}\int_0^\infty \ln\left|S(j\omega)\right|\left(\frac{z}{z^2+\omega^2}\right)d\omega$$

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

Computational complexity



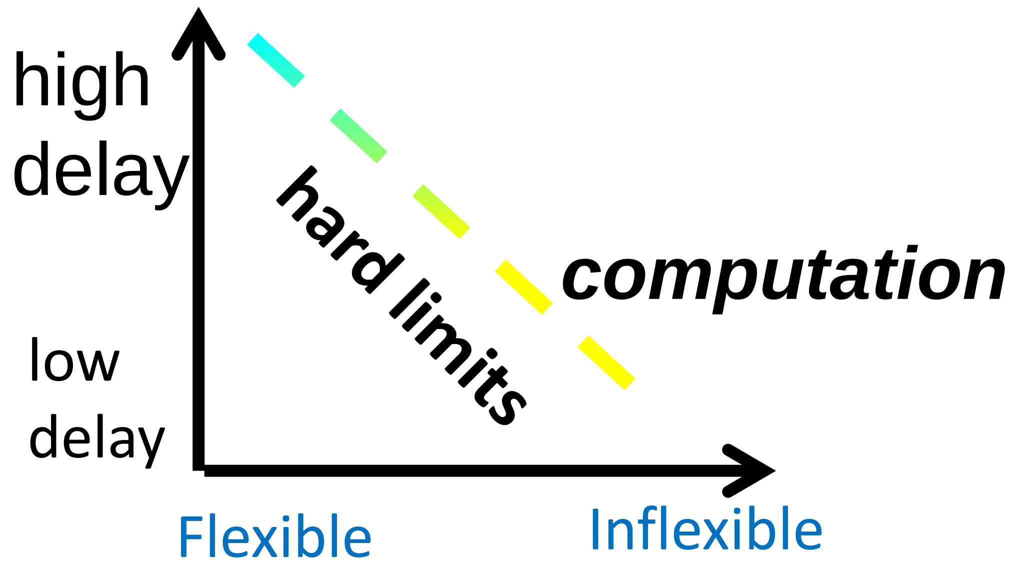
$$\frac{1}{\pi}\int_0^\infty \ln\left|T(j\omega)\right|\frac{2p}{p^2+\omega^2}d\omega \geq p\tau \propto \tau\sqrt{\frac{1}{l}}$$



Delay makes control hard.

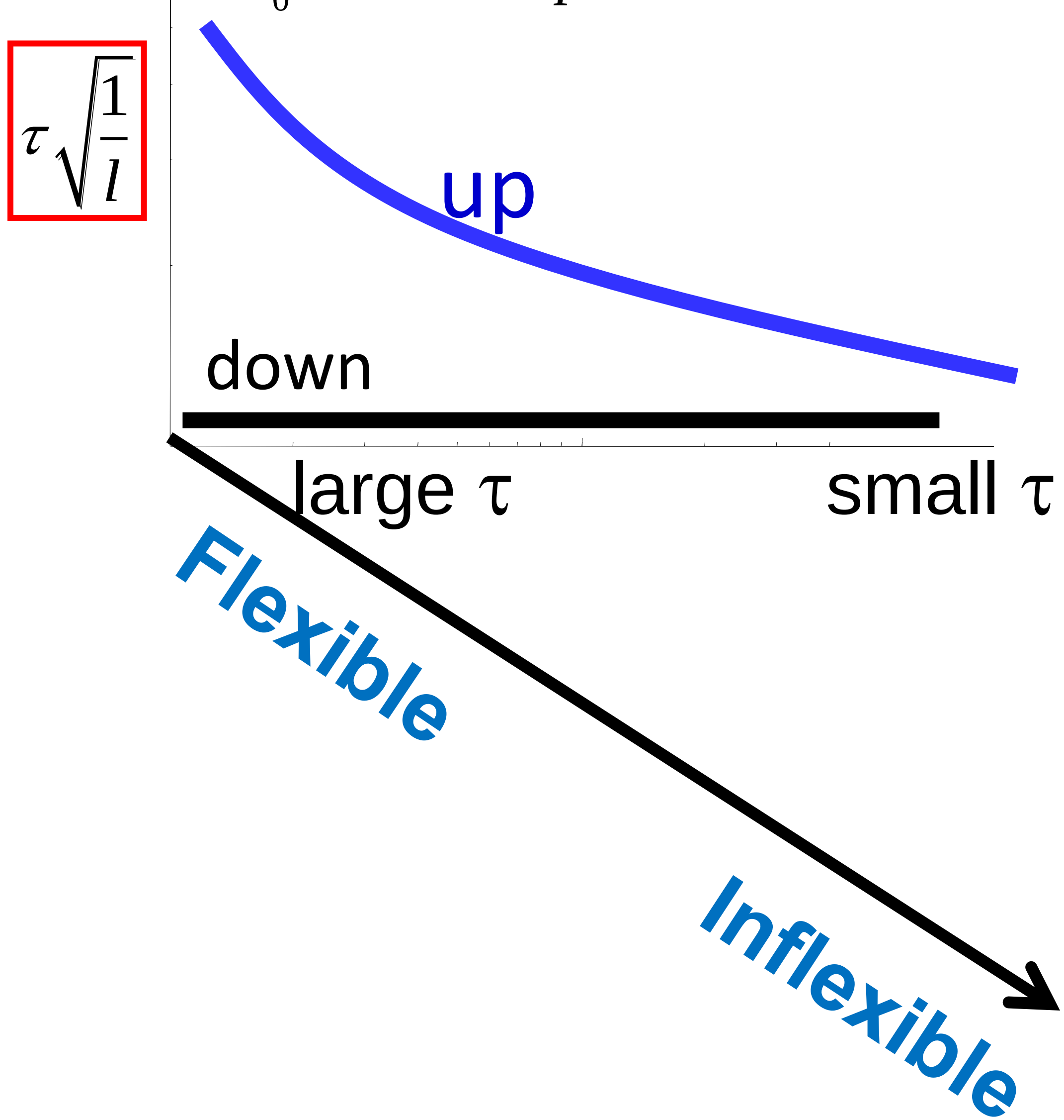
Computation delay adds to total delay.

Computation is a component in control.



Fragility

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

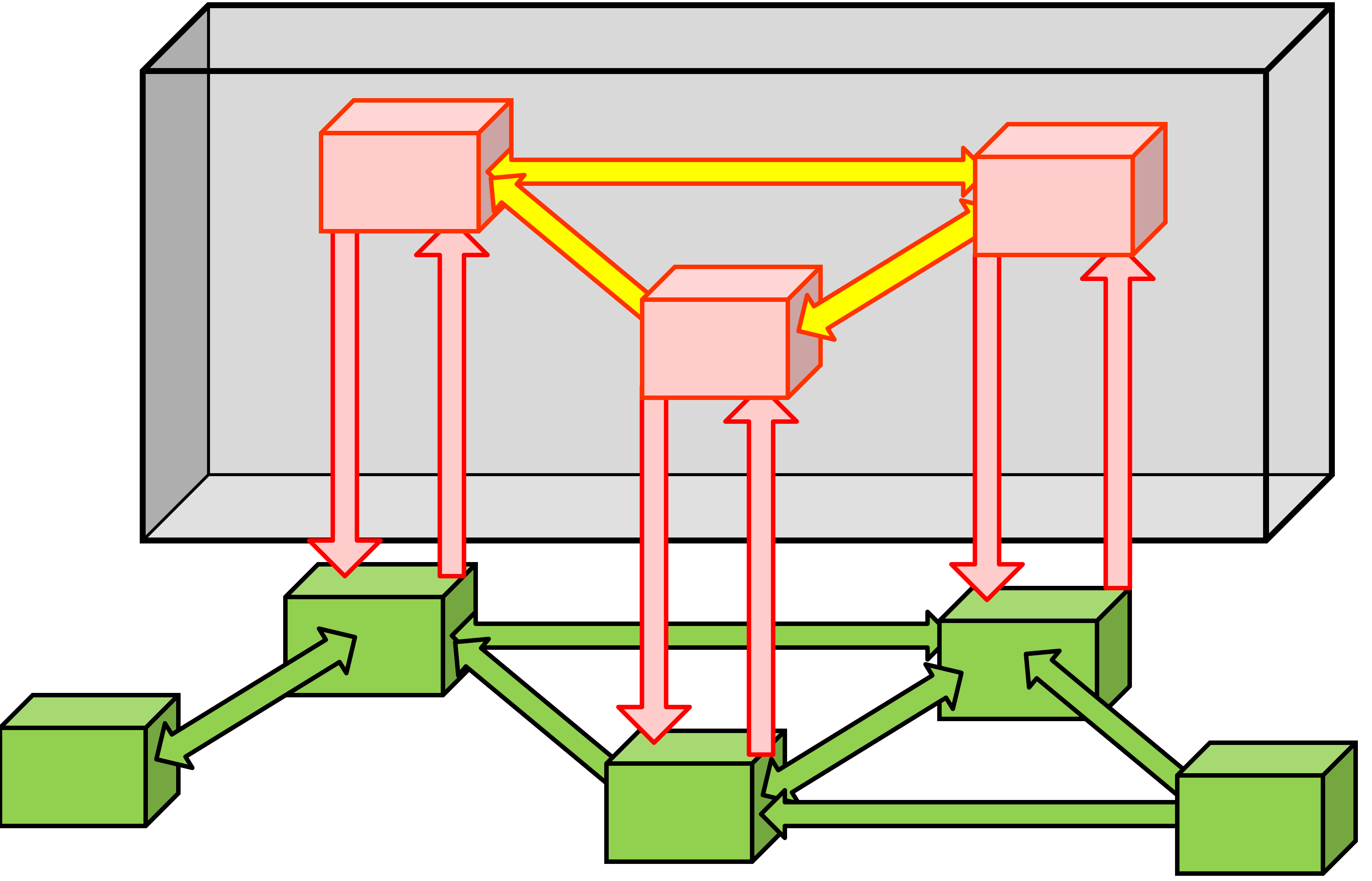


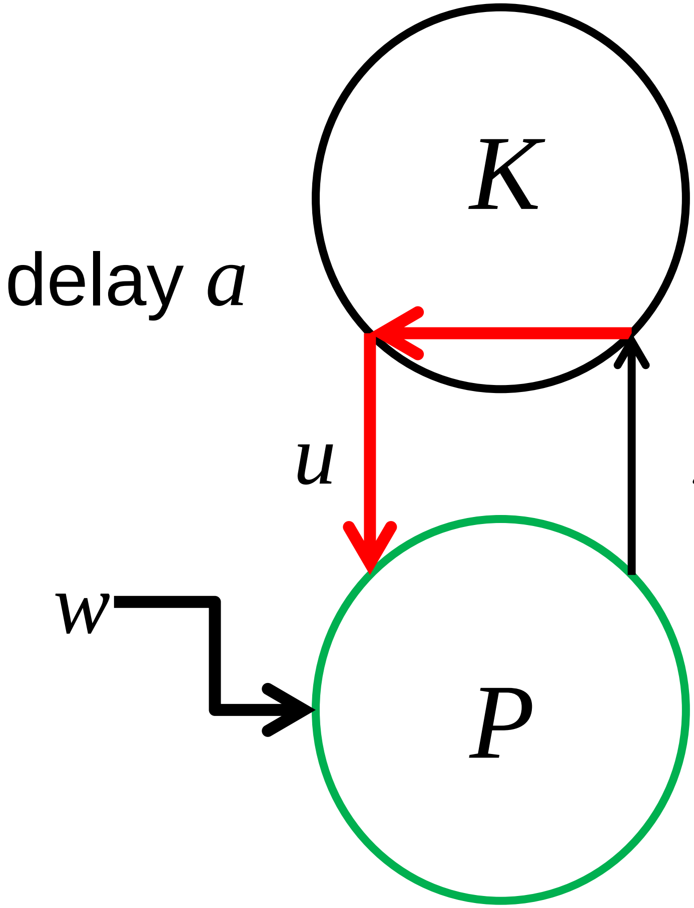
This needs formalization:

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

Large, structured uncertainty?

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





No delay or
no uncertainty

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

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

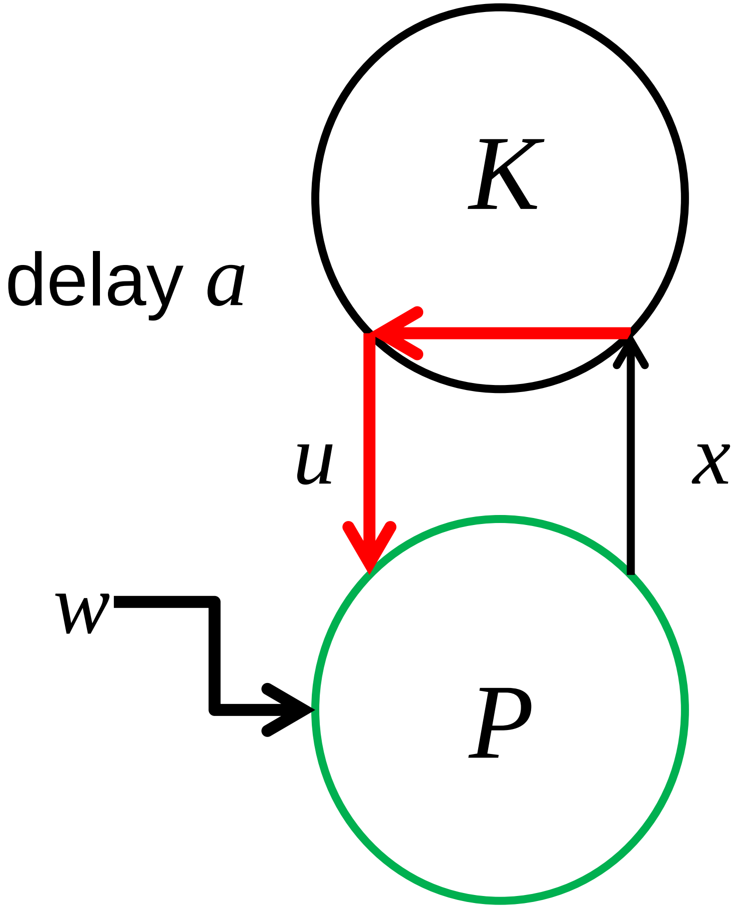
With delay ***and***
uncertainty

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

$$p > 1$$

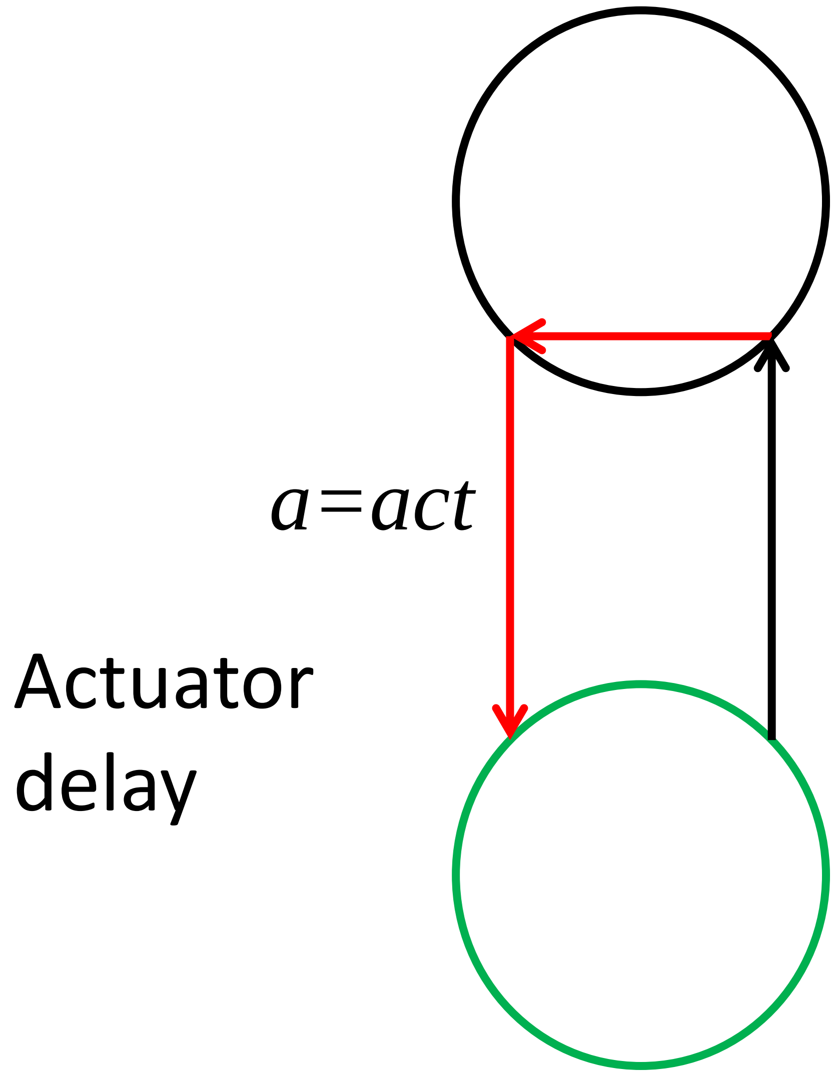
$$\Rightarrow \|x\| \approx \|u\| \approx p^a \|w\|$$

Focus on delays

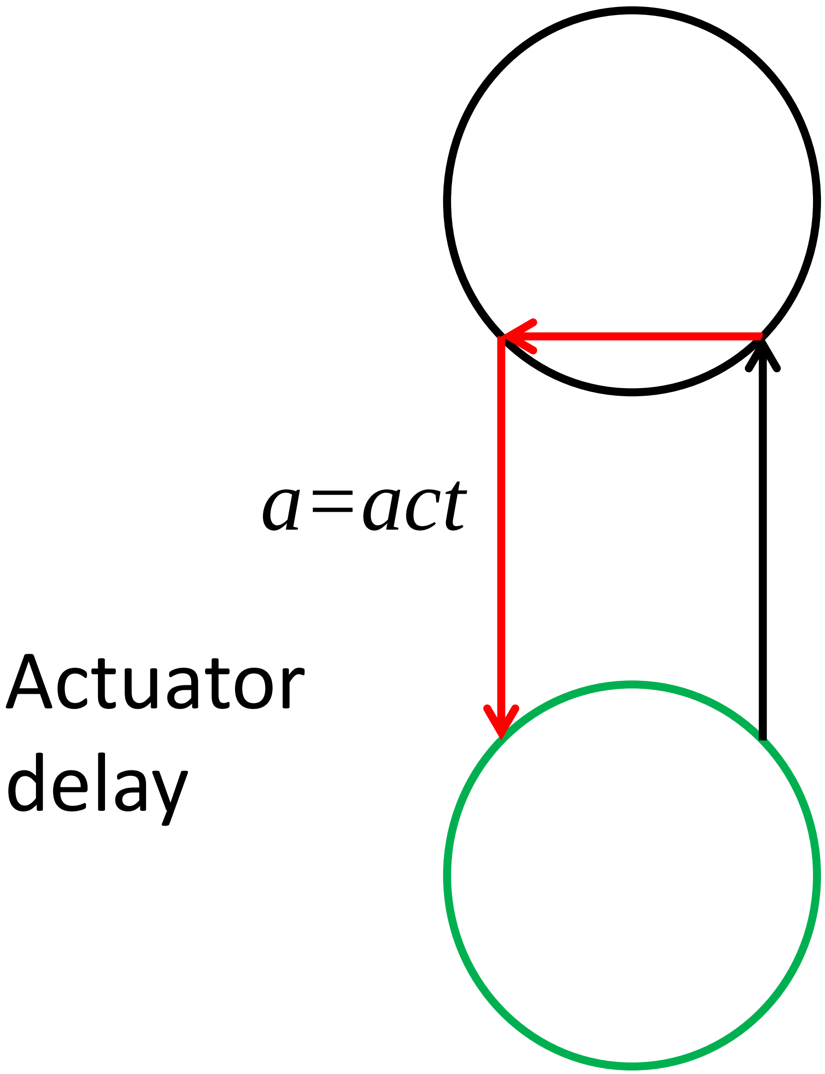


$$x_{t+1} = px_t + w_t + u_{t-a}$$

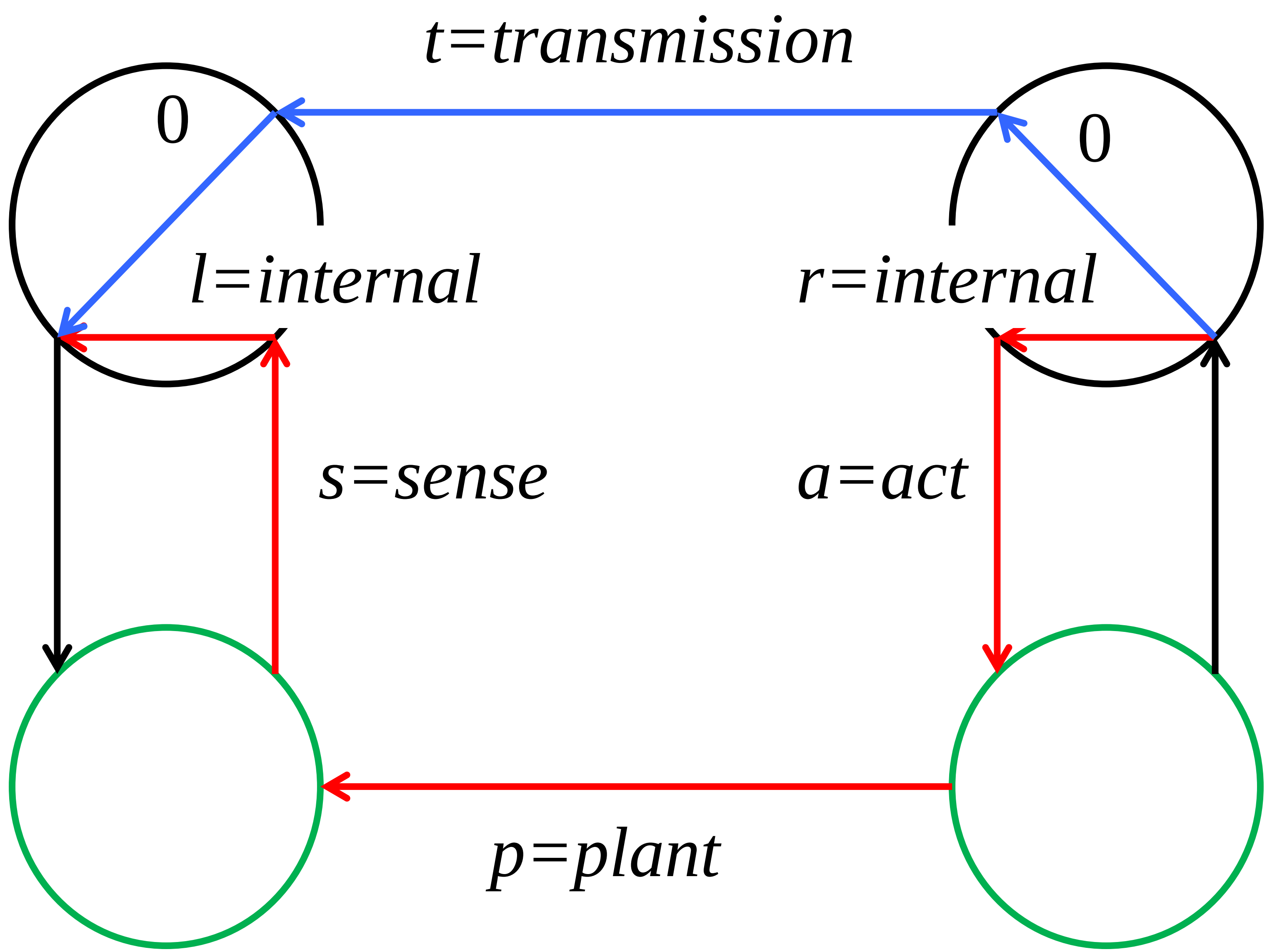
$$p > 1$$

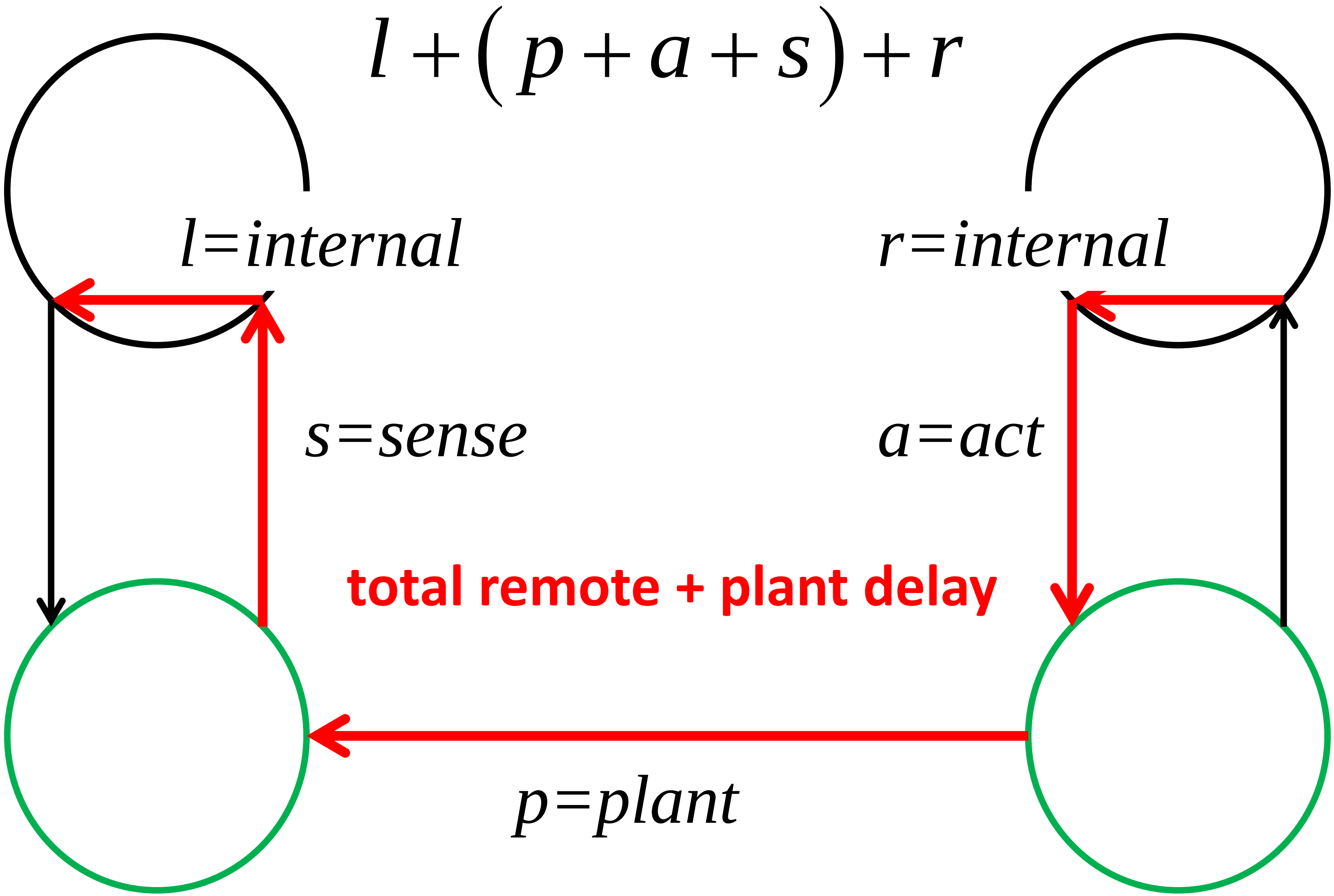


Focus on delays



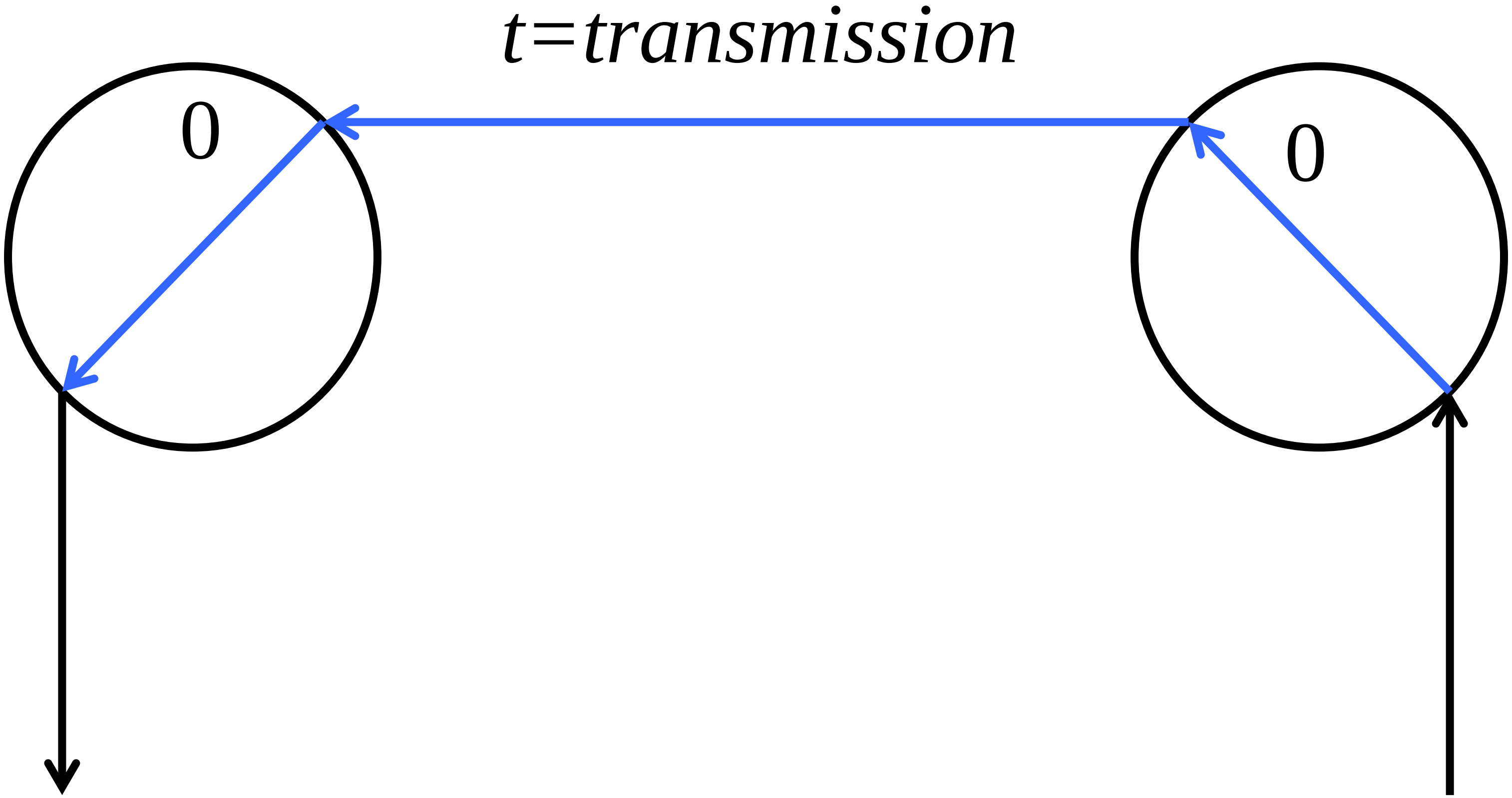
Decentralized control





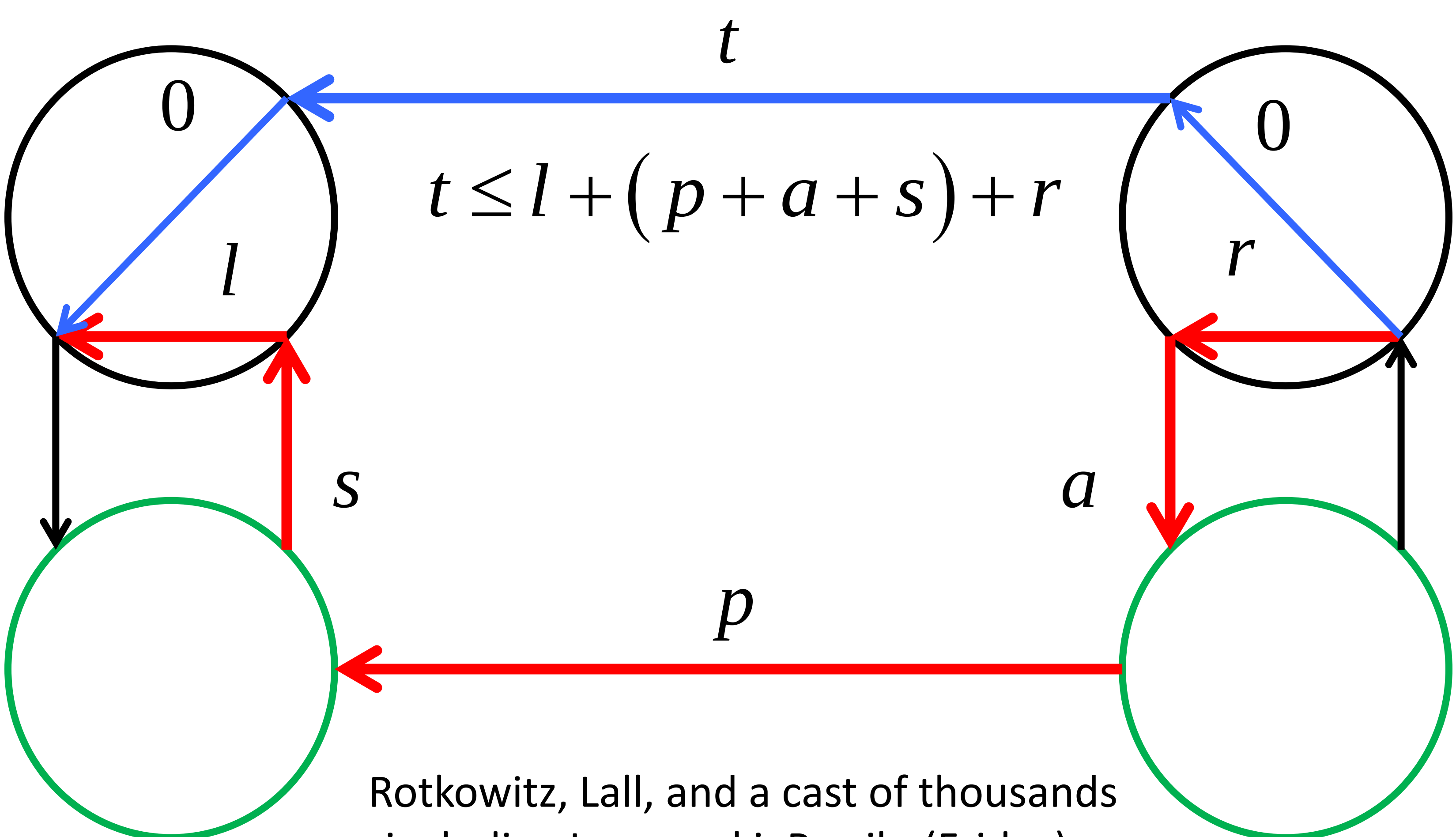
l+(p+a+s)+r
l=internal
r=internal
s=sense
a=act
total remote + plant delay
p=plant

Communications delay



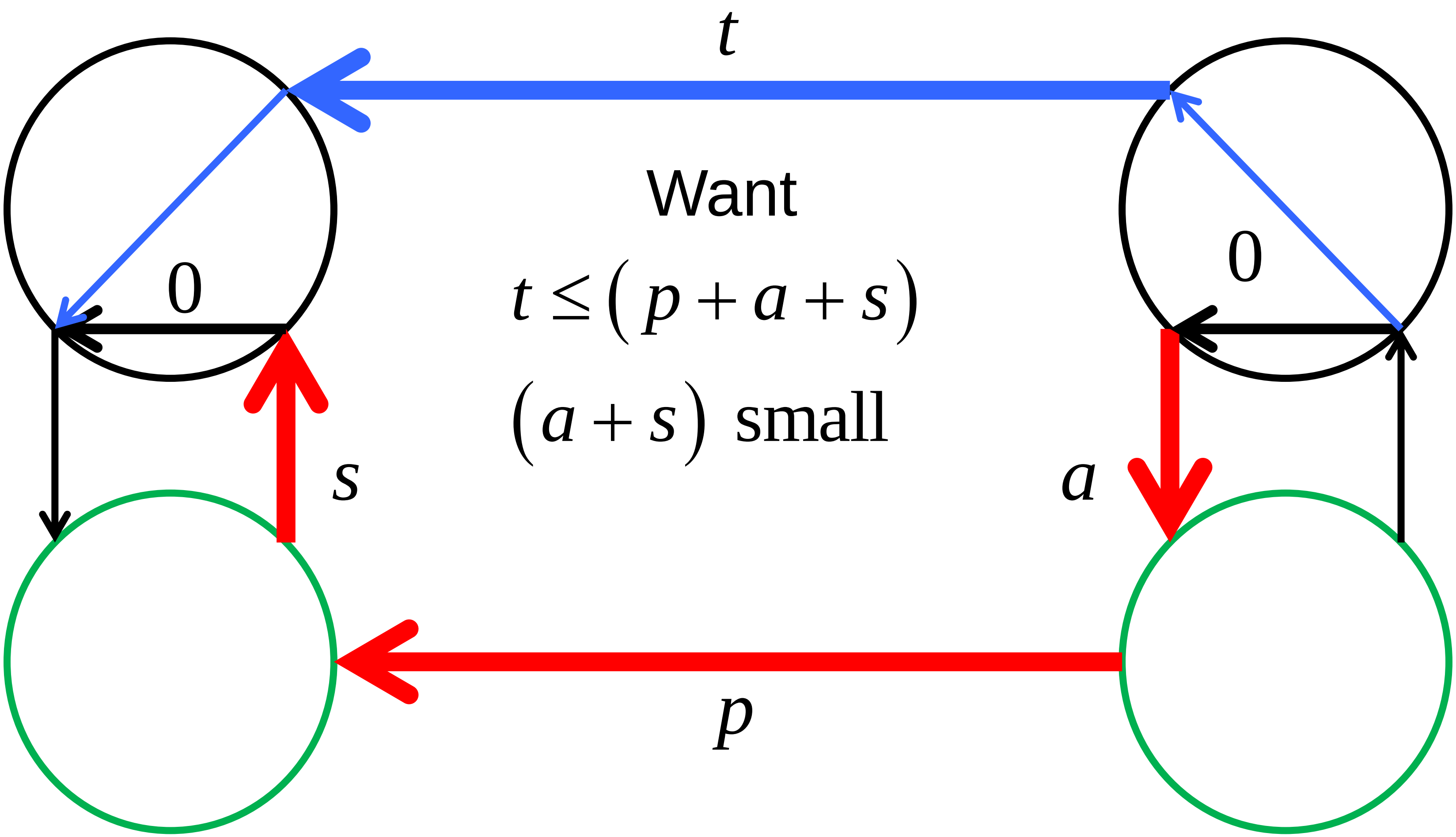
$$t \le l + (p + a + s) + r$$

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?

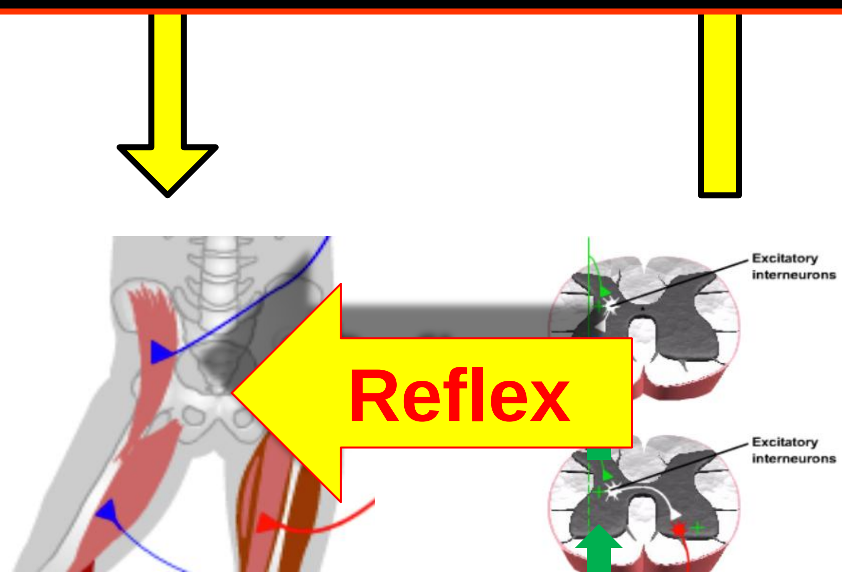


Wolpert, Grafton, etc

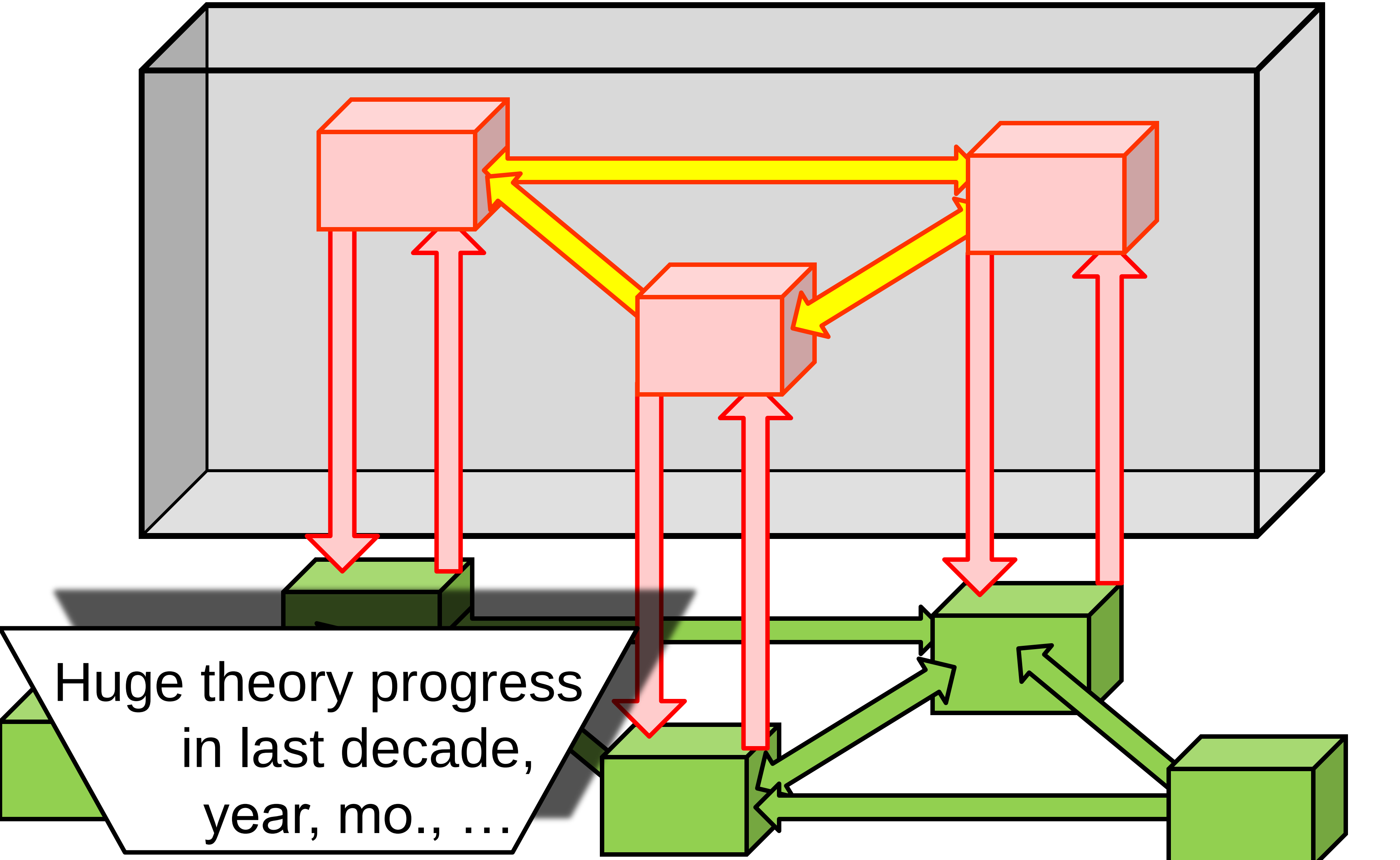
robust

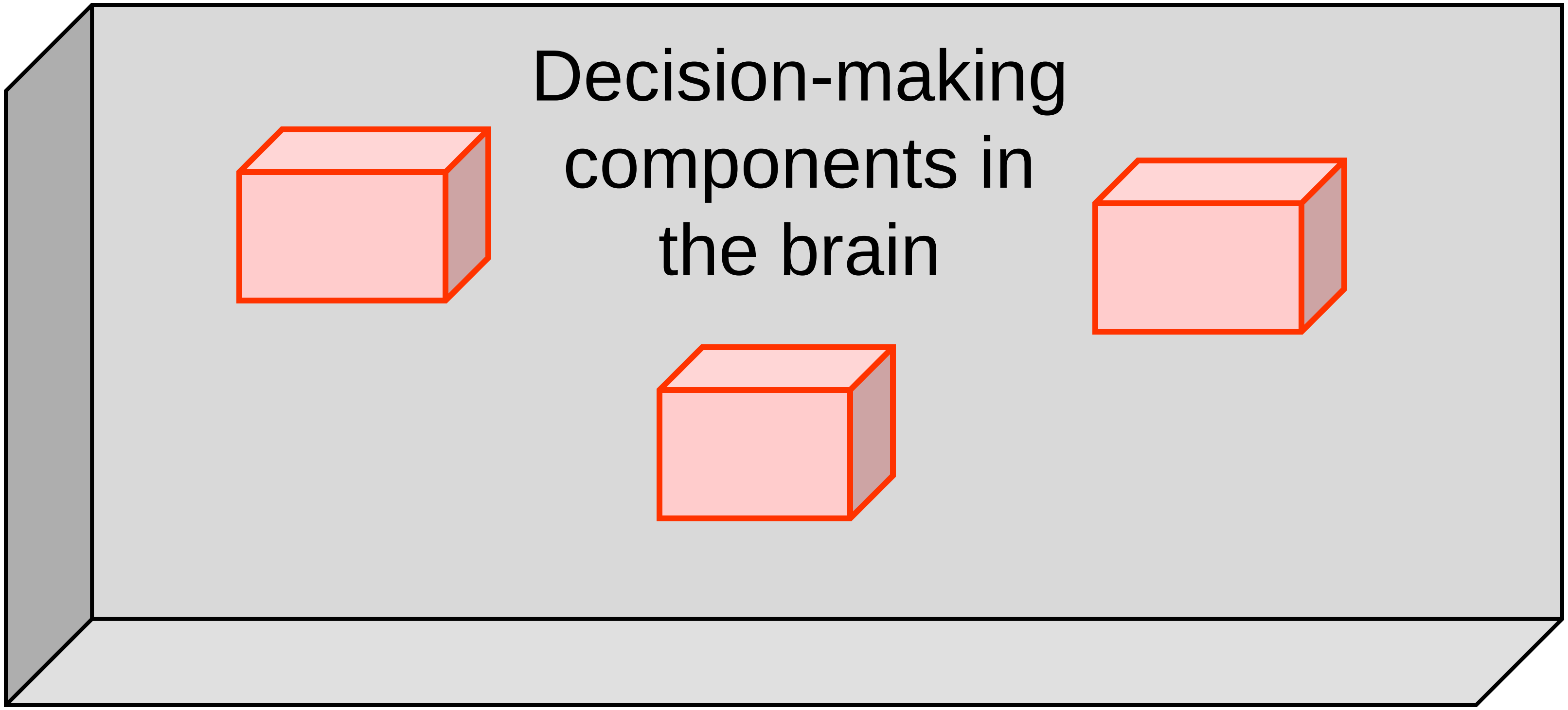
Brain as ~~optimal~~ controller

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

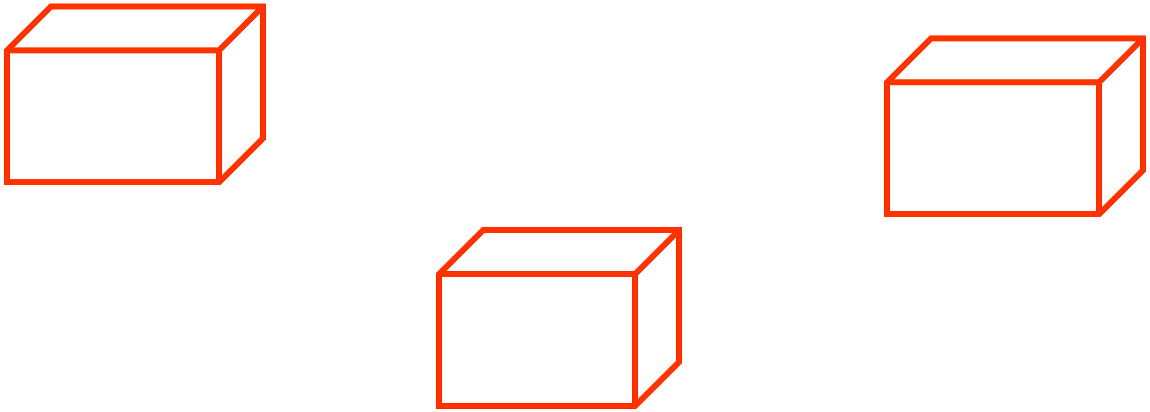


Going beyond black box: control is decentralized with internal delays.

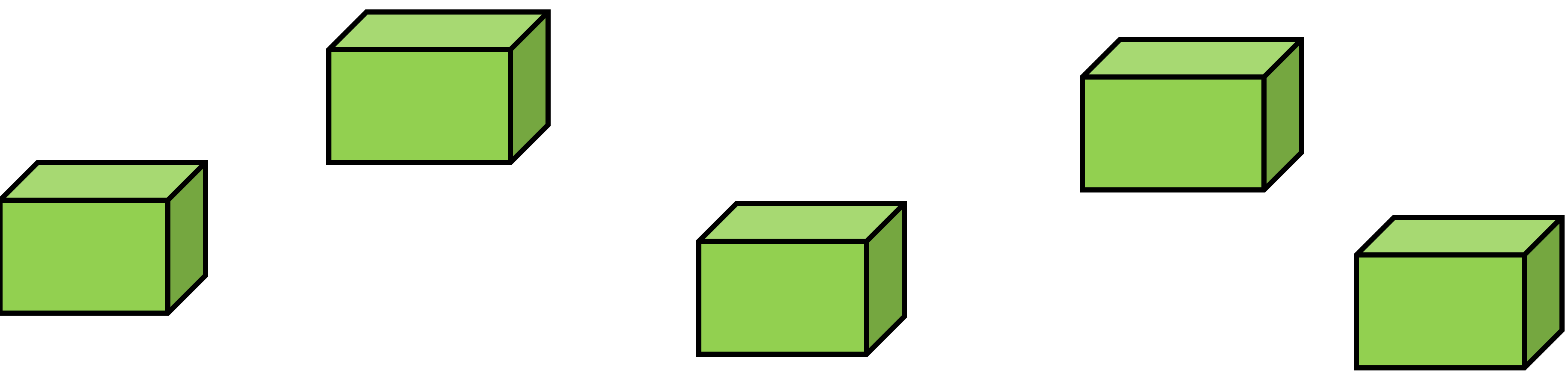




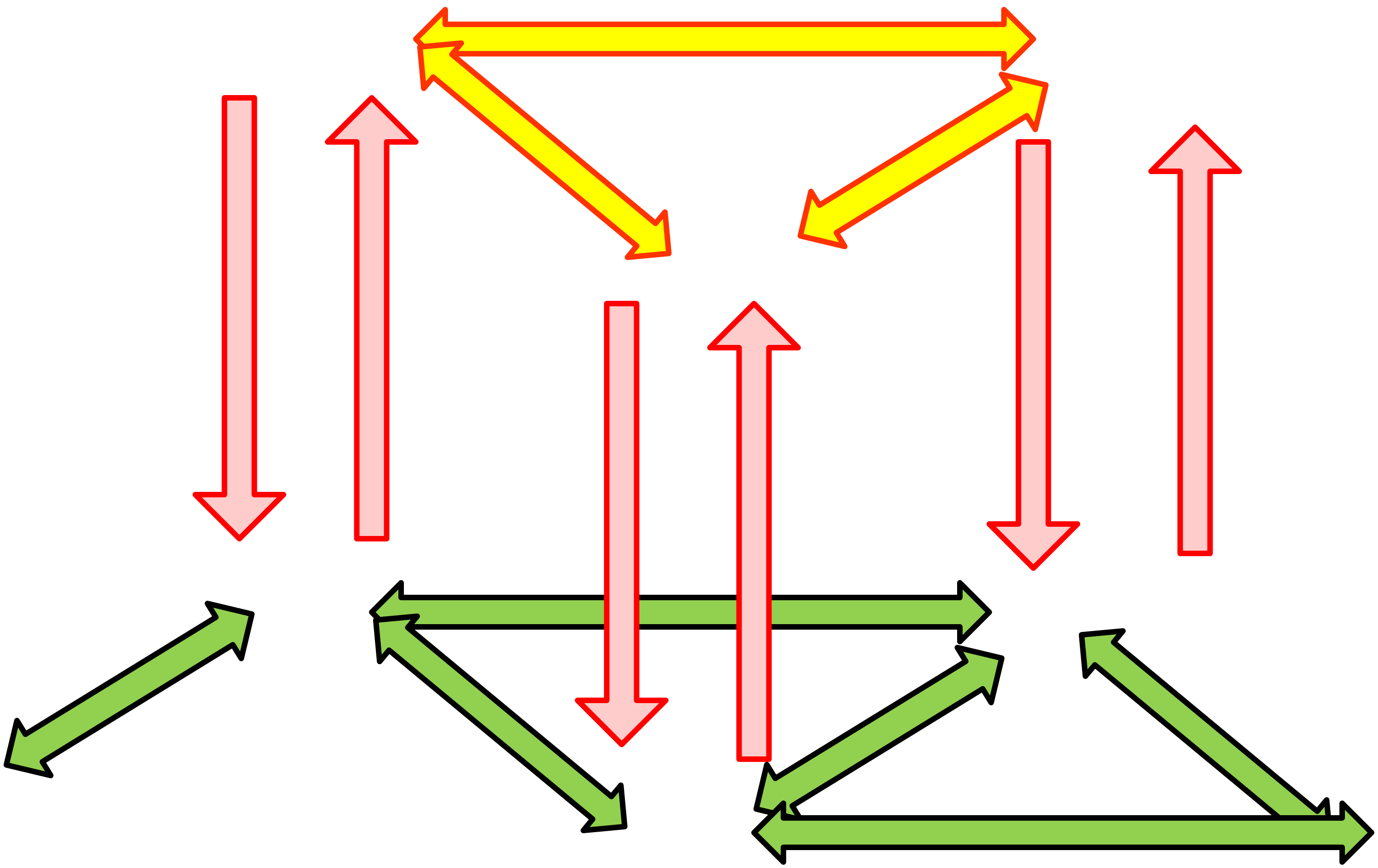
Decentralized, but initially assume
computation is fast and memory is abundant.



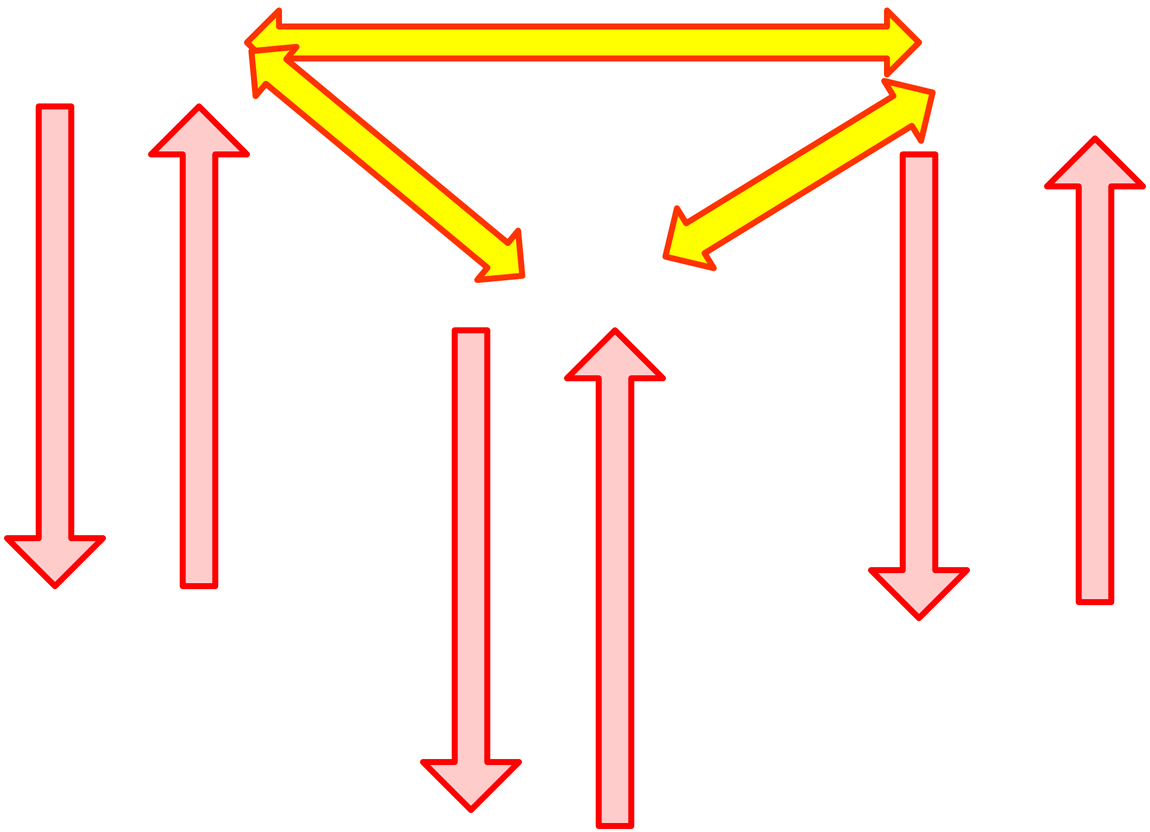
Plant is also distributed with its own component dynamics



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

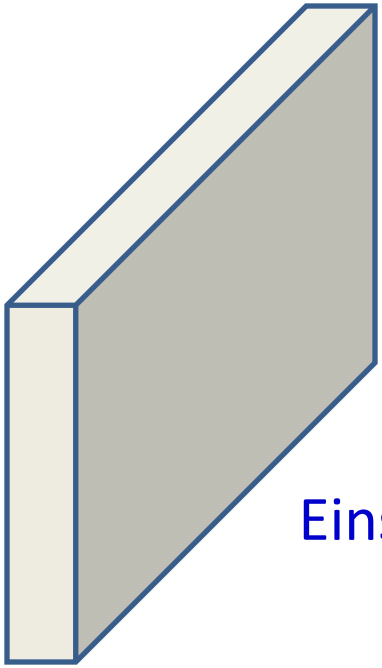
This progress is important.

Shannon

Delay is *most* important

New progress!

Delay is ~~*least*~~ important



Carnot

Boltzmann

Bode

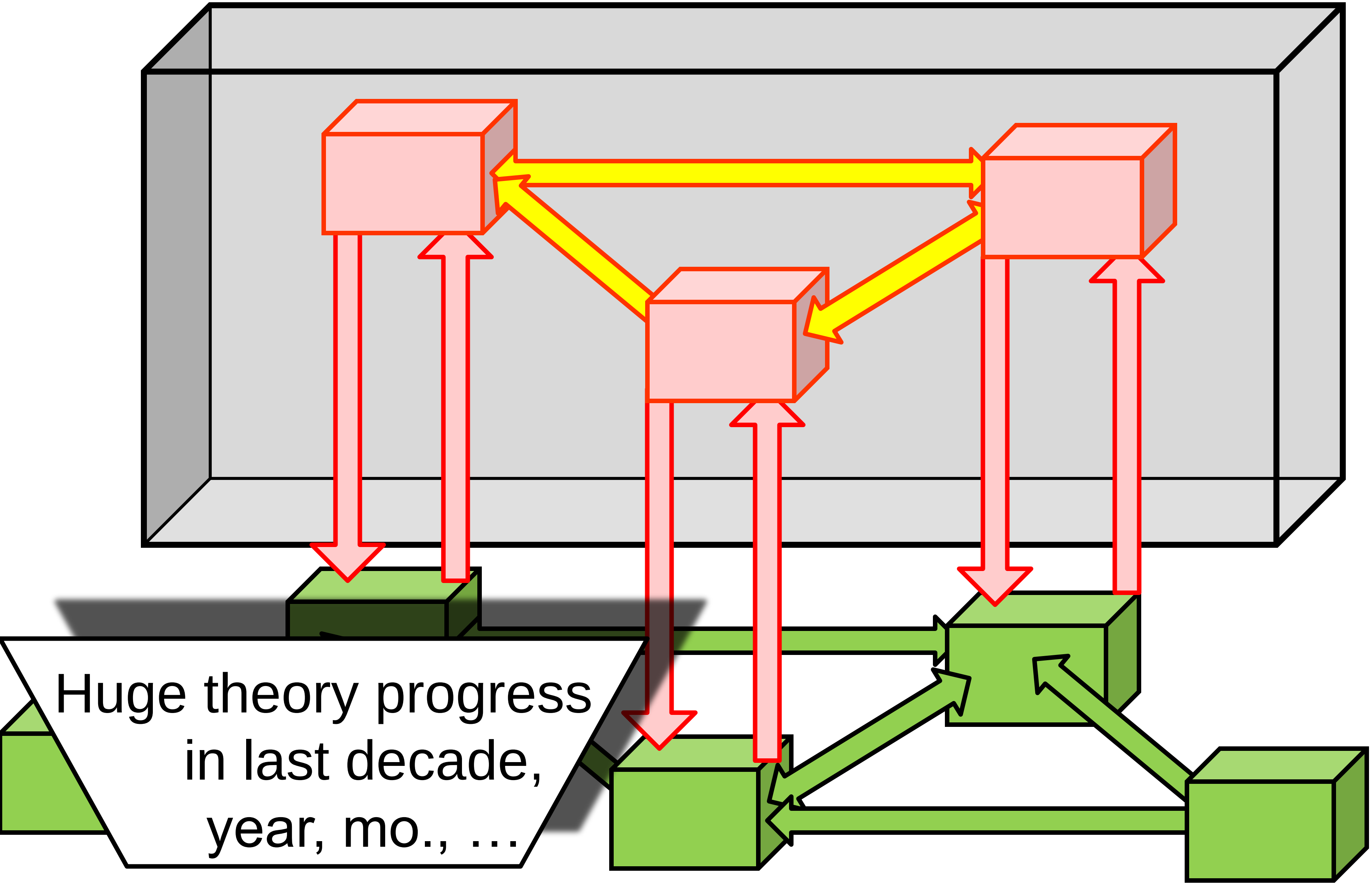
Heisenberg

Control, OR

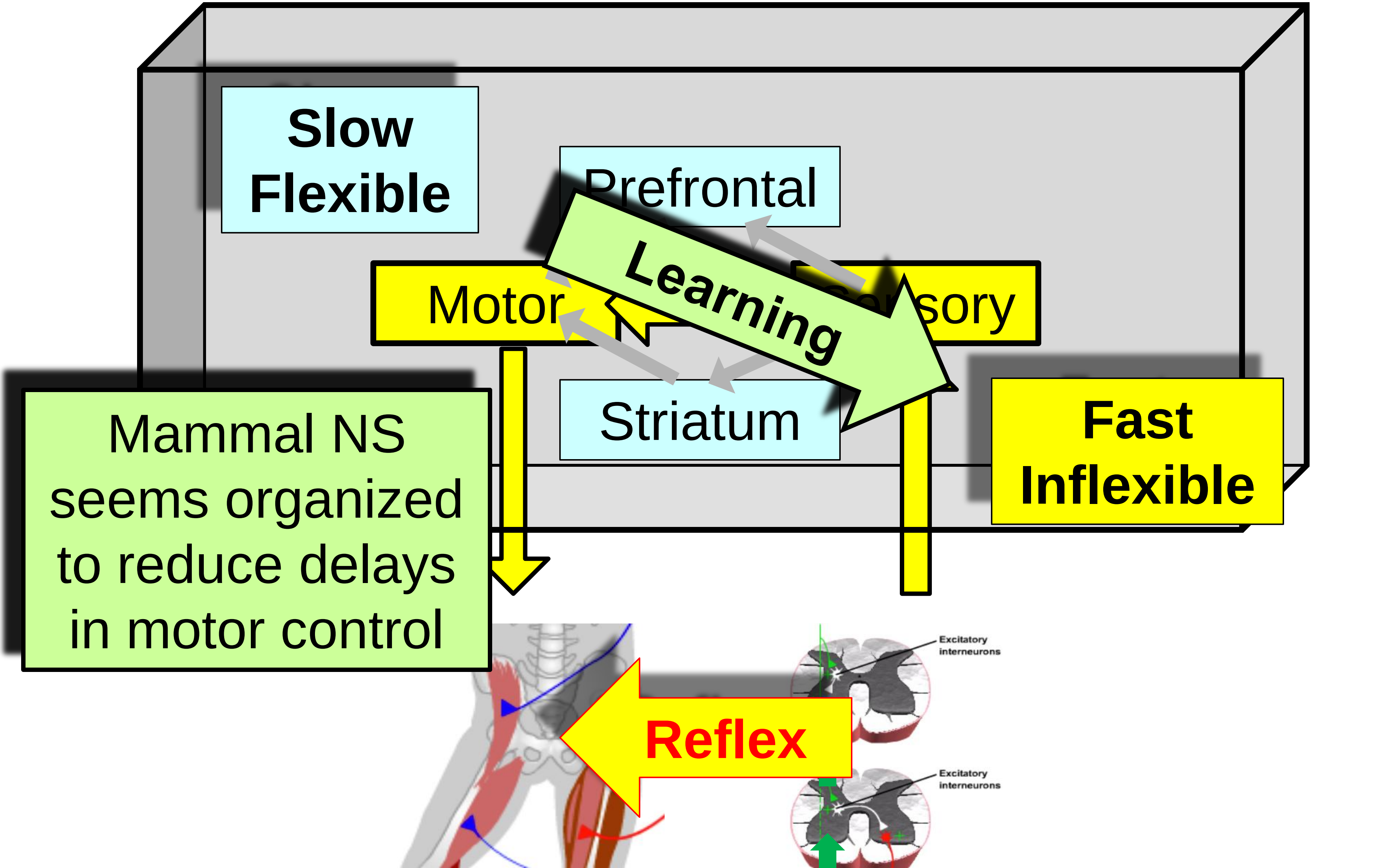
Einstein

Physics

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



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



Universal architectures

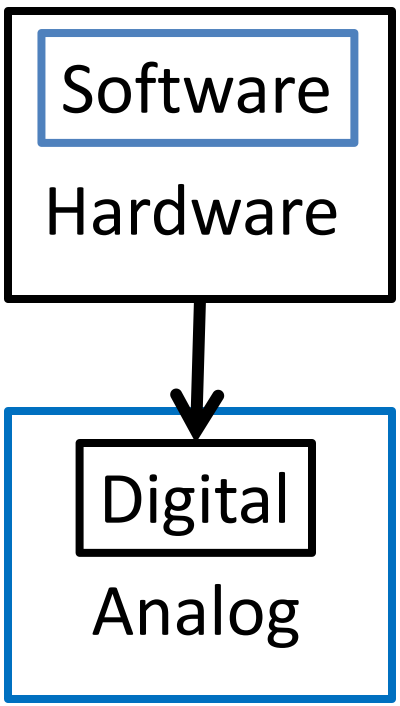
Implications

(Layered architectures discussed elsewhere)

Turing as "new" starting point?

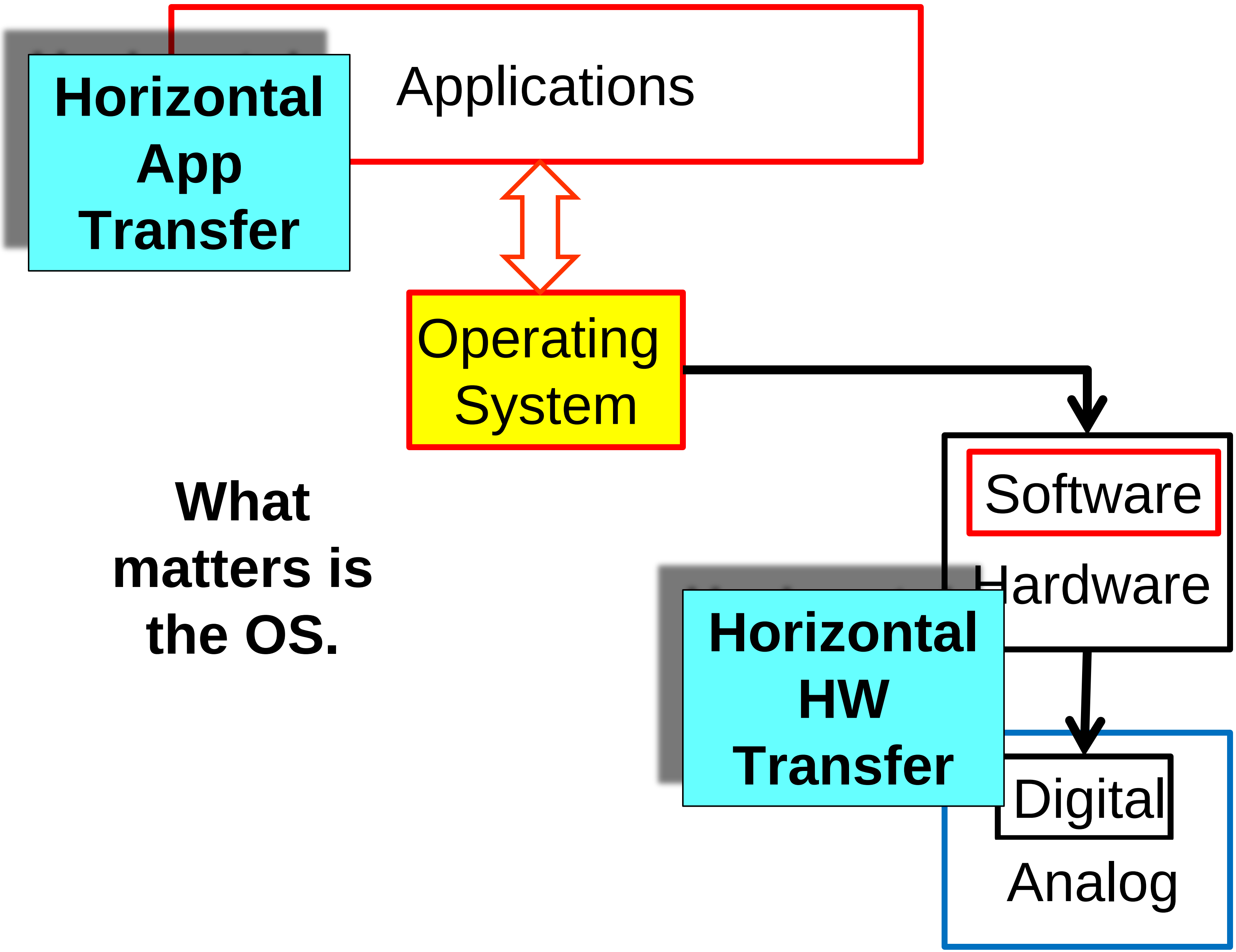
Essentials:

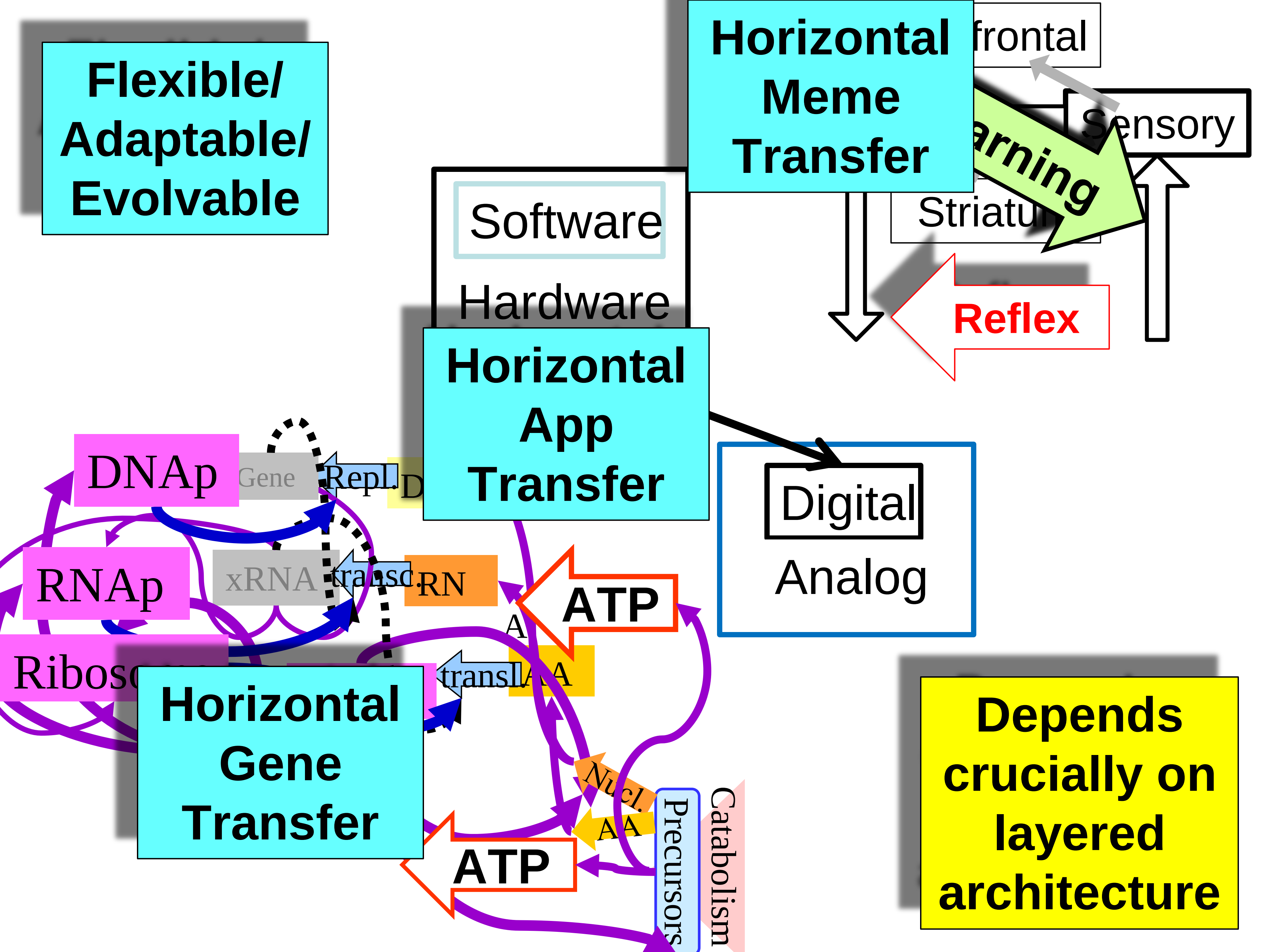
0. Model
1. Universal laws
2. **Universal architecture**
3. Practical implementation



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?)

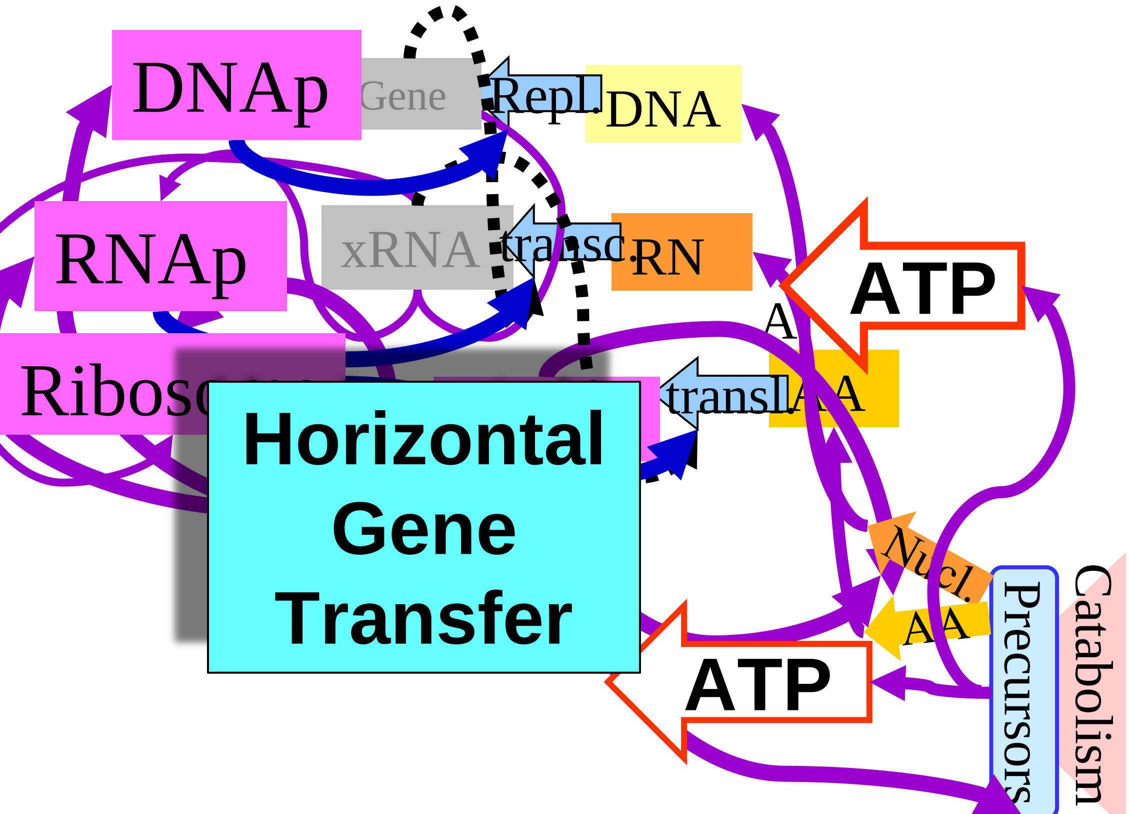

Horizontal App Transfer
Applications
Operating System
What matters is the OS.
Software
Hardware
Horizontal HW Transfer
Digital
Analog



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
transl.
AA
Horizontal
Gene
Transfer
ATP
Nucl.
AA
Precursors
Catabolism
Depends
crucially on
layered
architecture

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

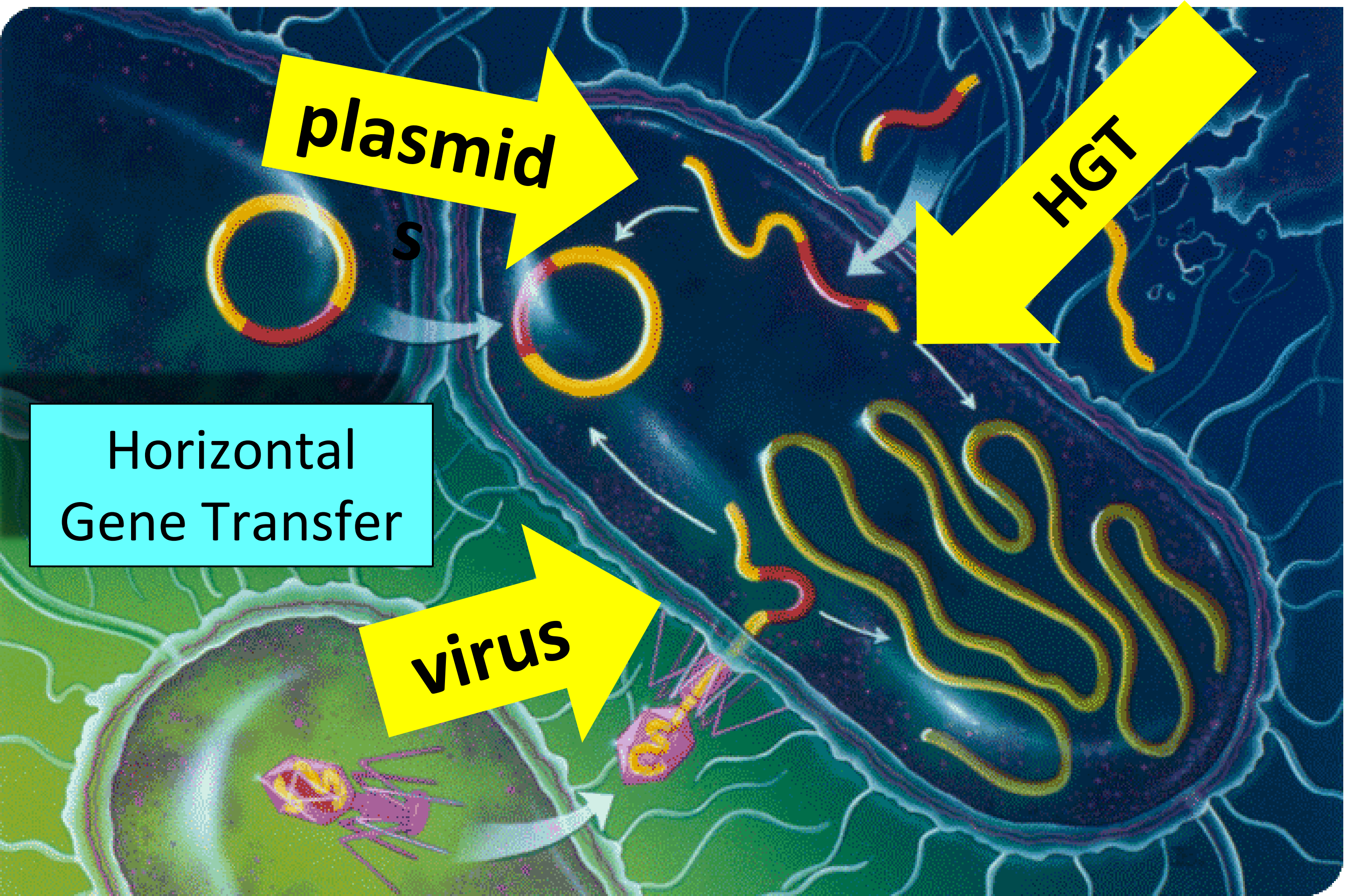
- ~ 4K genes per cell
- ~20K *different* genes in total
- ~ 1K universally shared genes



See slides on microbial biosphere laws and architectures.

selection + drift + mutation + gene flow

+ facilitated *variation*

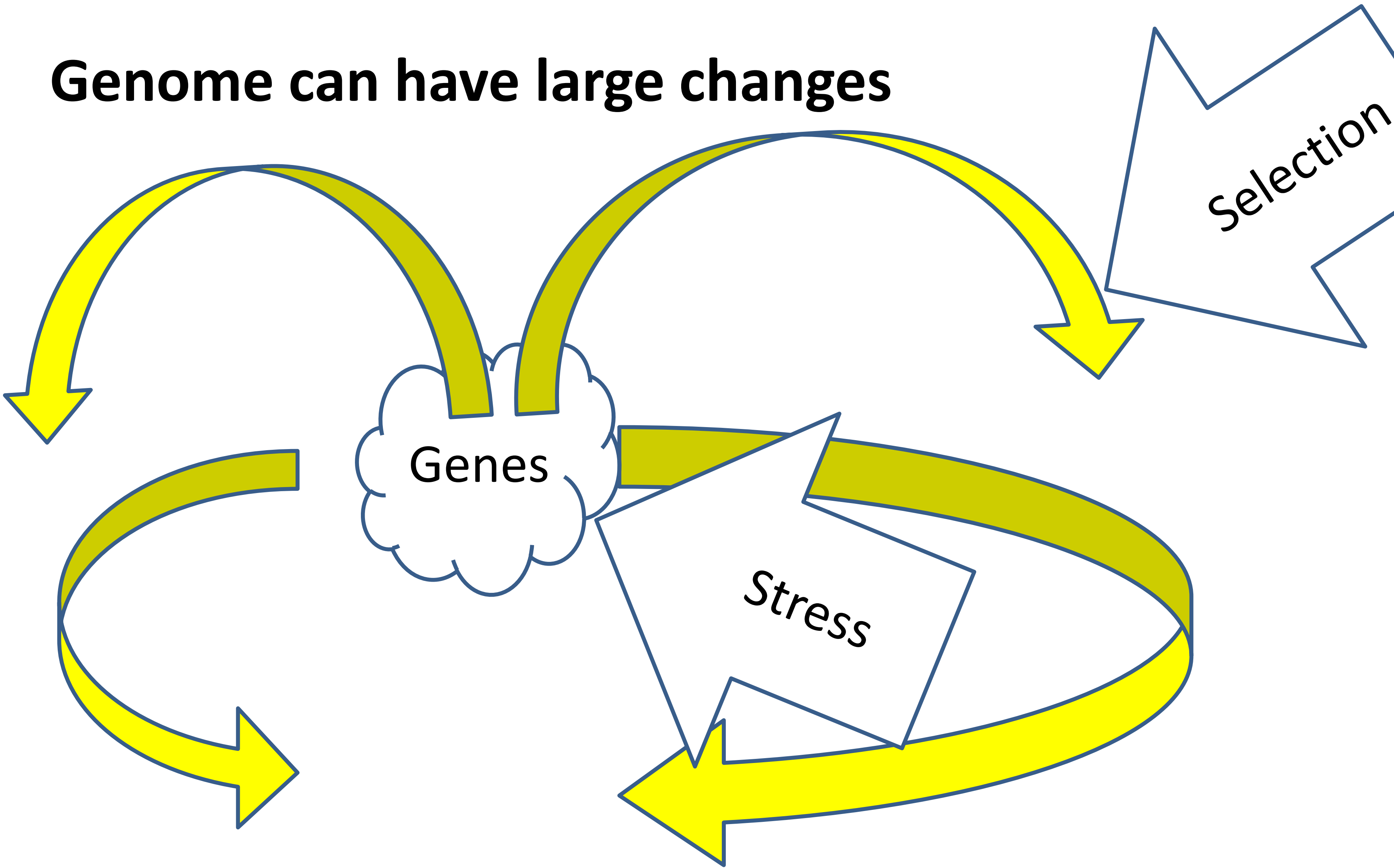


large functional changes in genomes

natural selection + genetic drift + mutation + gene flow

+ facilitated *variation*

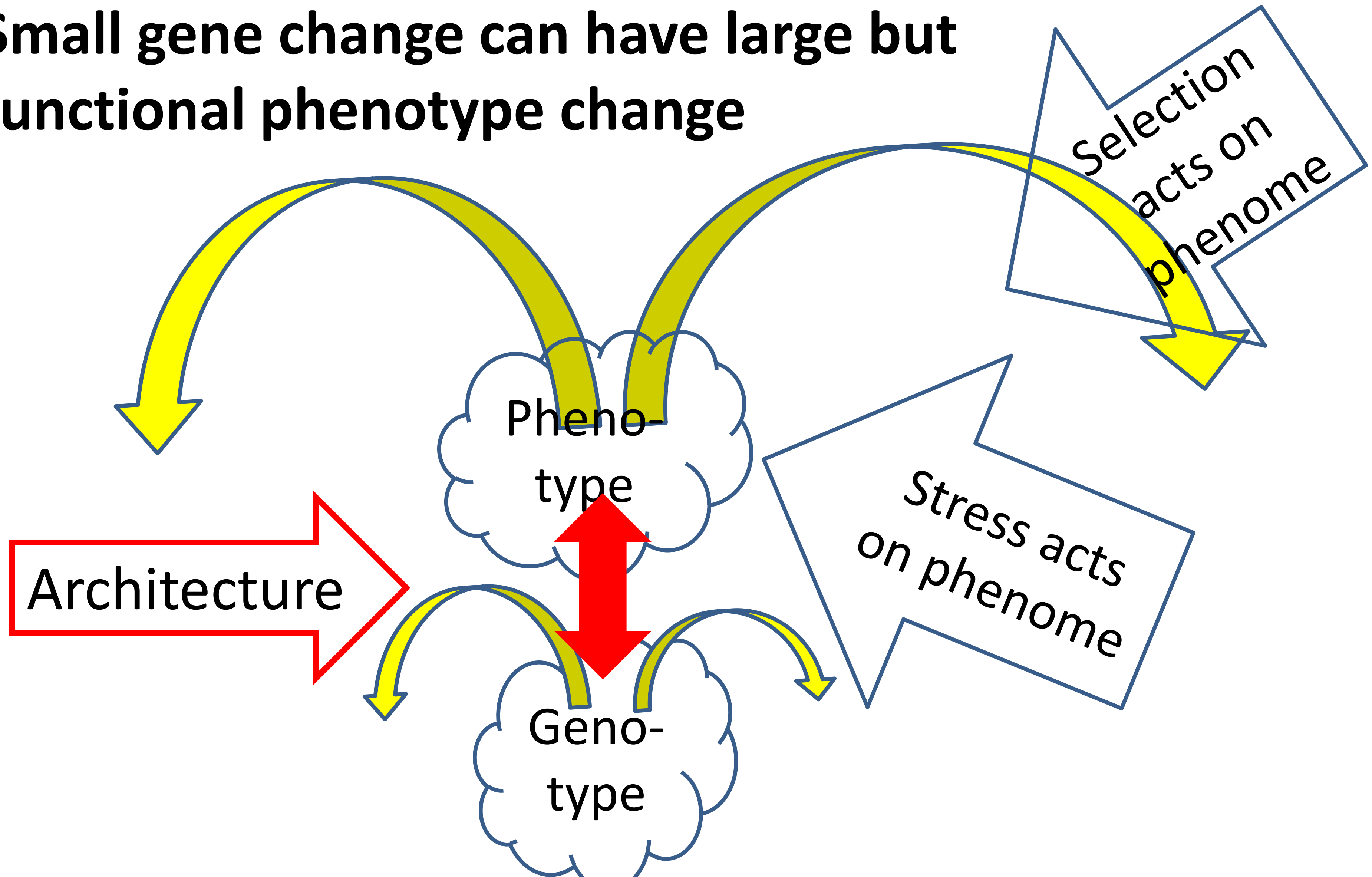
Genome can have large changes



natural selection + genetic drift + mutation + gene flow

+ facilitated *variation*

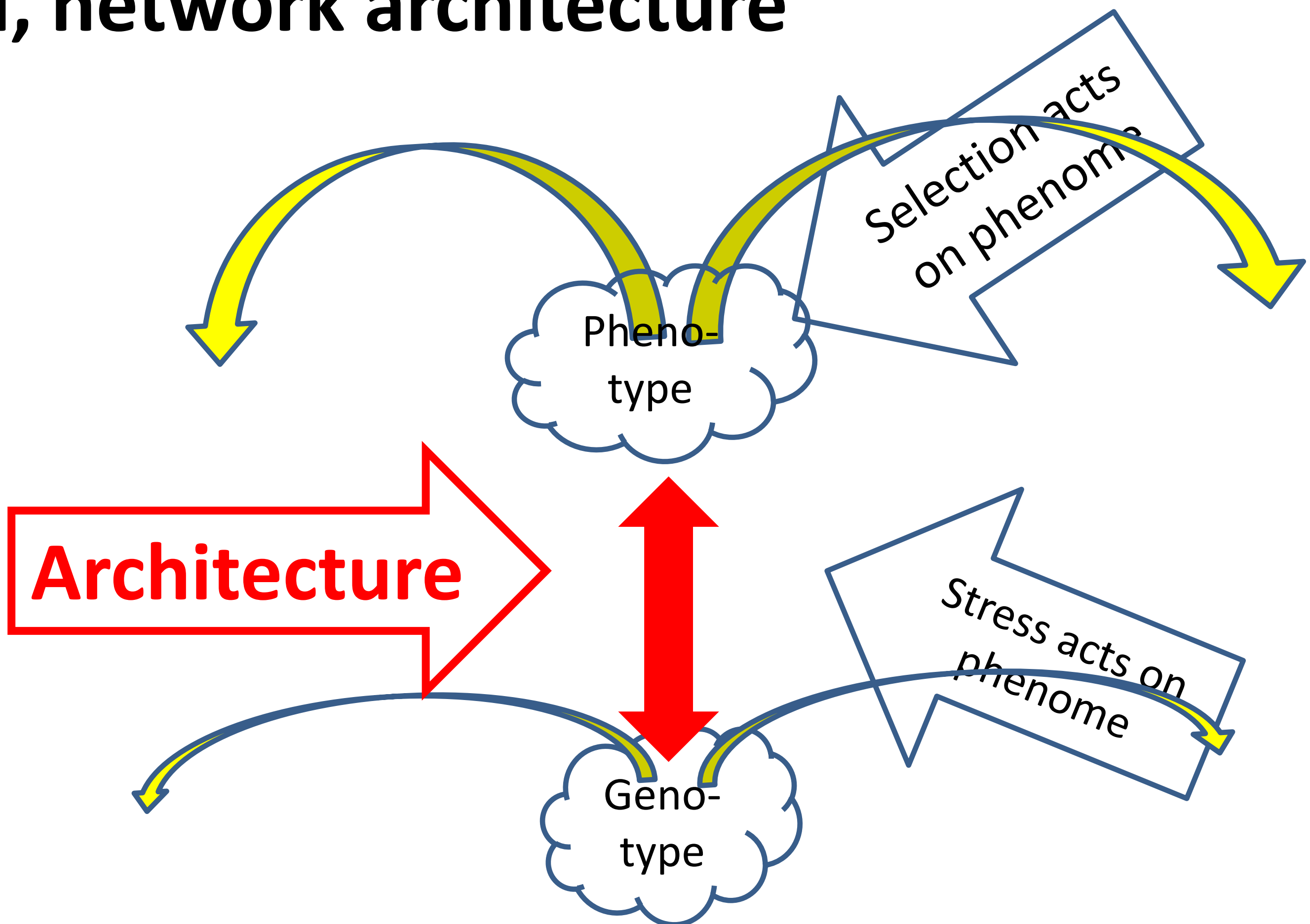
Small gene change can have large but functional phenotype change



natural selection + genetic drift + mutation + gene flow

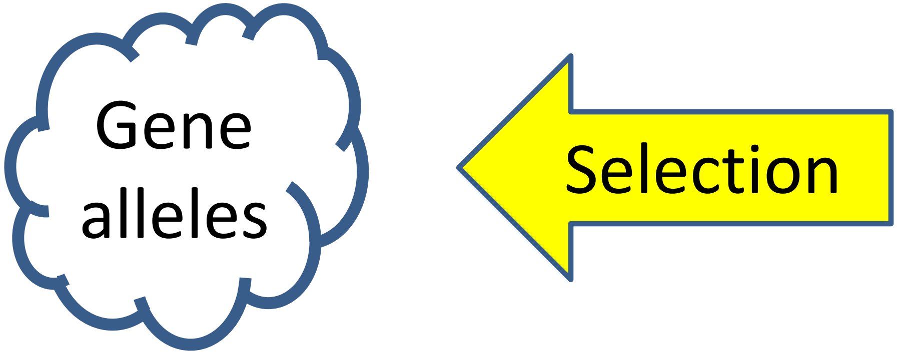
+ facilitated *variation*

Only possible because of shared, layered, network architecture



Standard theory:
natural selection + genetic drift
+ mutation + gene flow

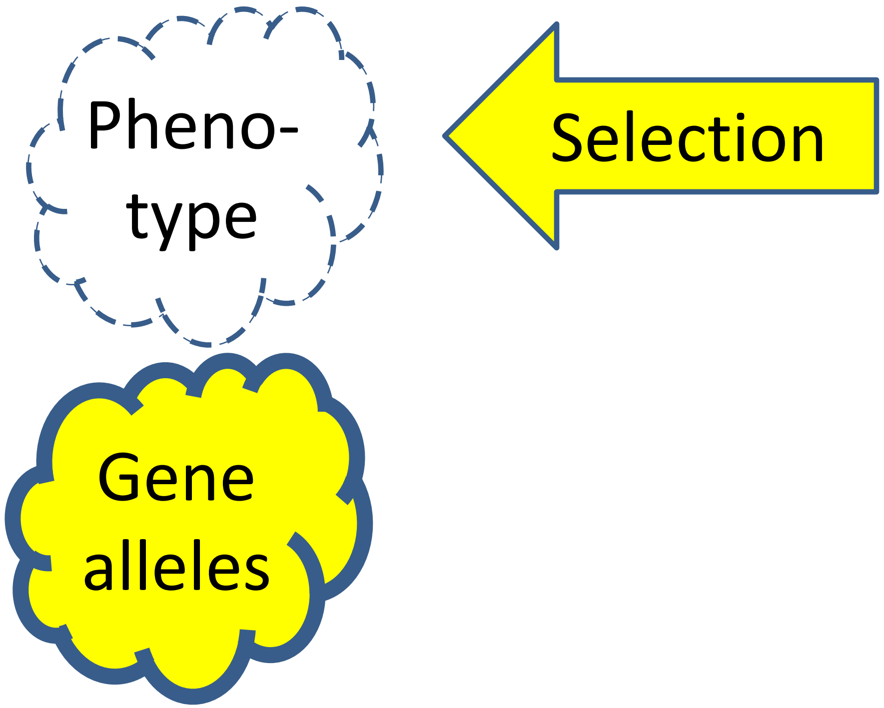
Greatly abridged cartoon here



Shapiro explains well what this is and why it’s incomplete (but Koonin is more mainstream)

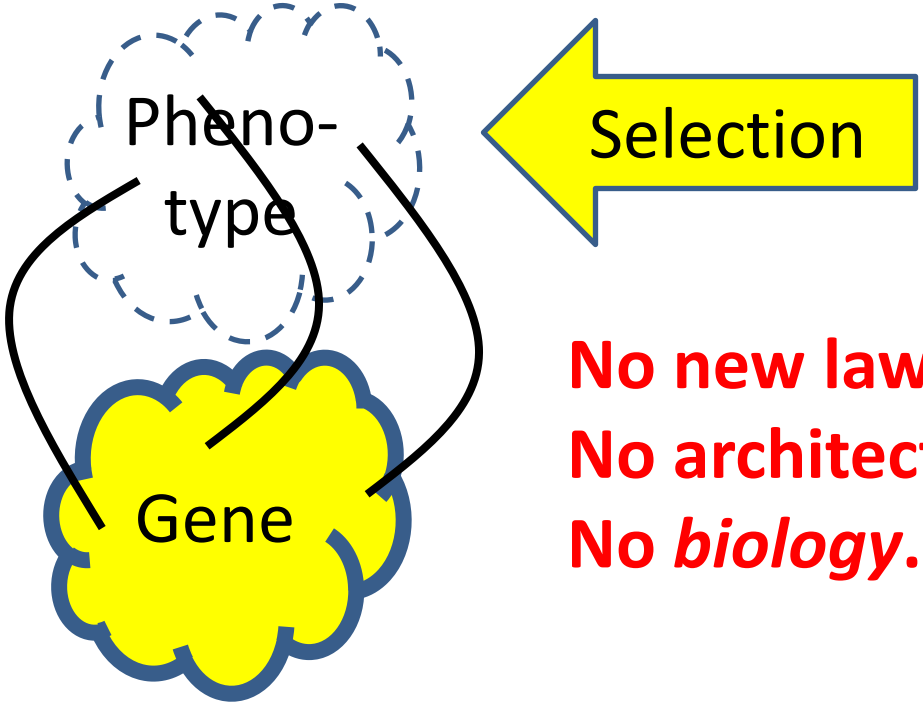
Standard theory:

selection + drift + mutation + gene flow



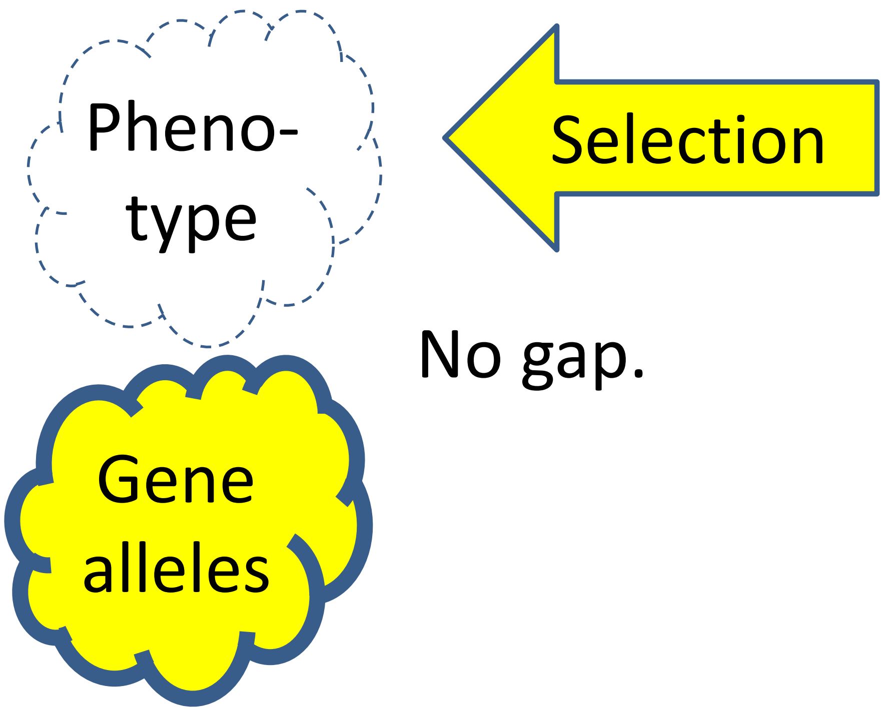
Standard theory:

selection + drift + mutation + gene flow



No new laws.
No architecture.
No *biology*.

selection +
drift +
mutation +
gene flow



***All* complexity is *emergent* from random ensembles with *minimal* tuning .**

No new laws.

No architecture.

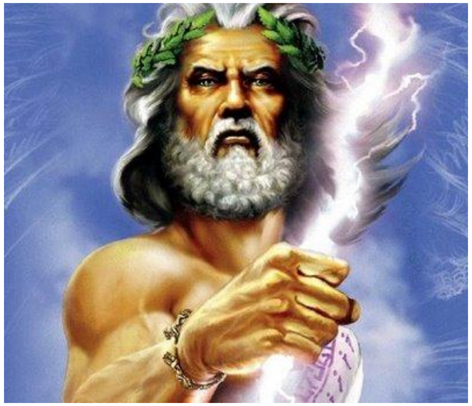
The battleground

Pheno-
type

Pheno-
type

Gene
alleles

No gap.
Just physics.



Huge gap.
Need
supernatural

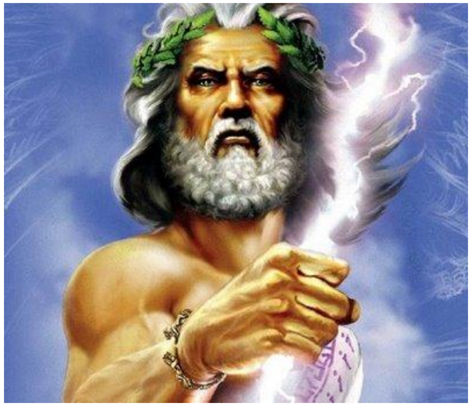
Genes?

What they agree on

Pheno-
type

No new laws.
No architecture.
No biology.

Huge
gap.

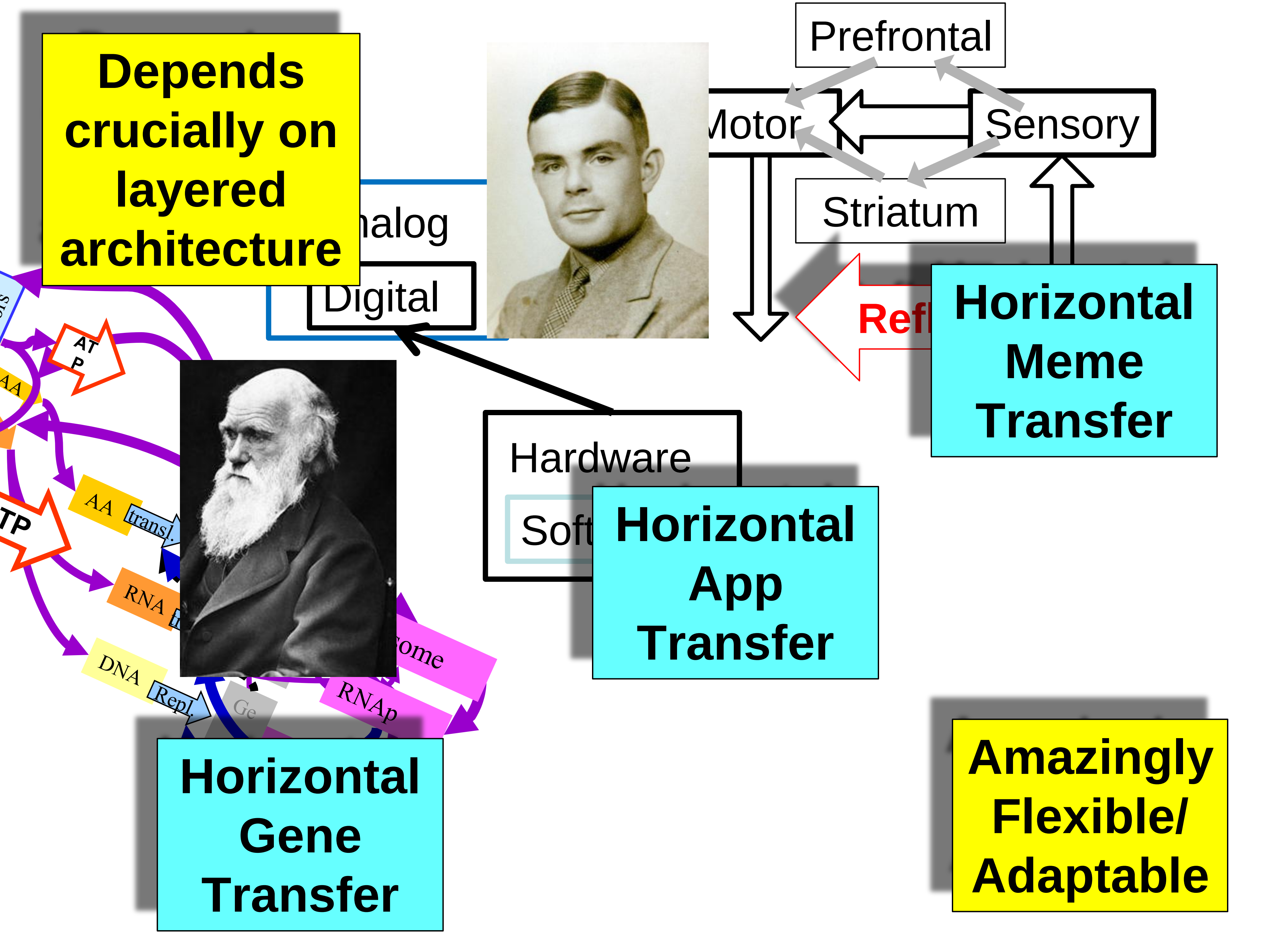


Pheno-
type

No gap.

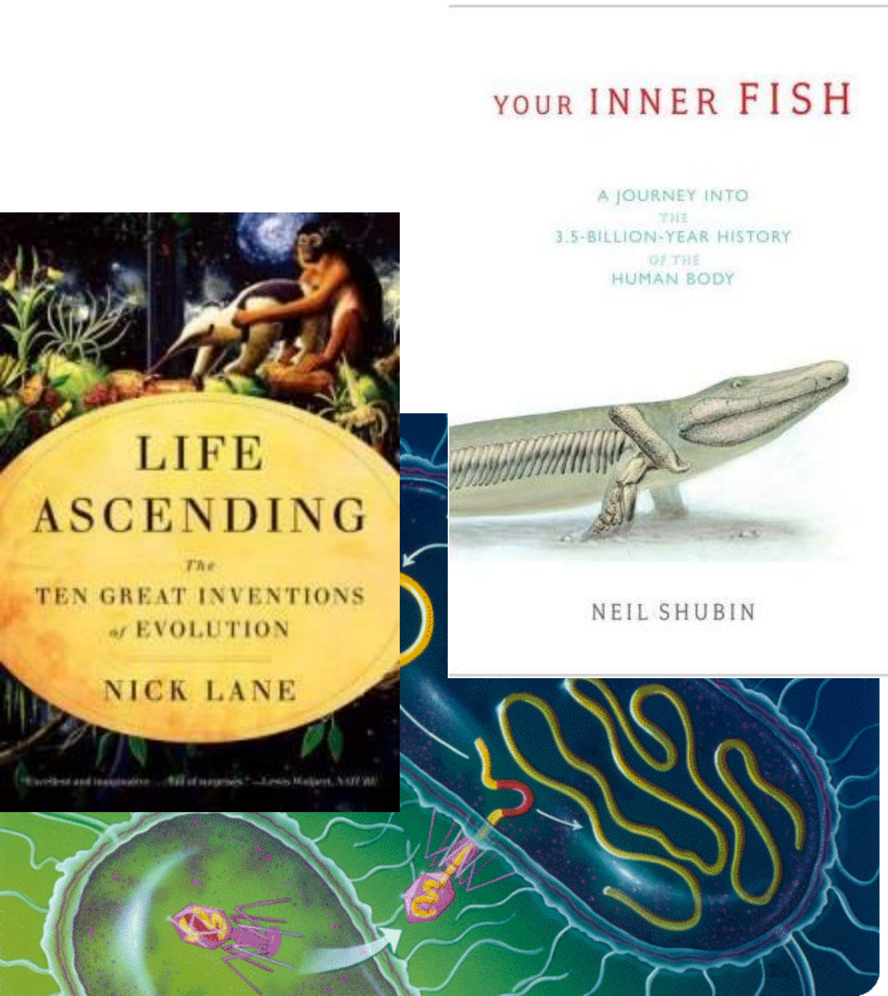
Gene
alleles

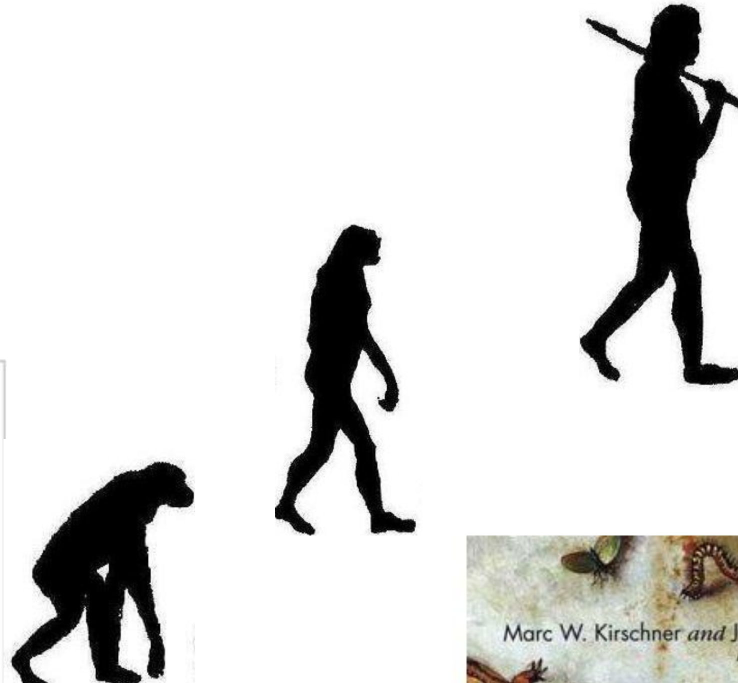
Genes

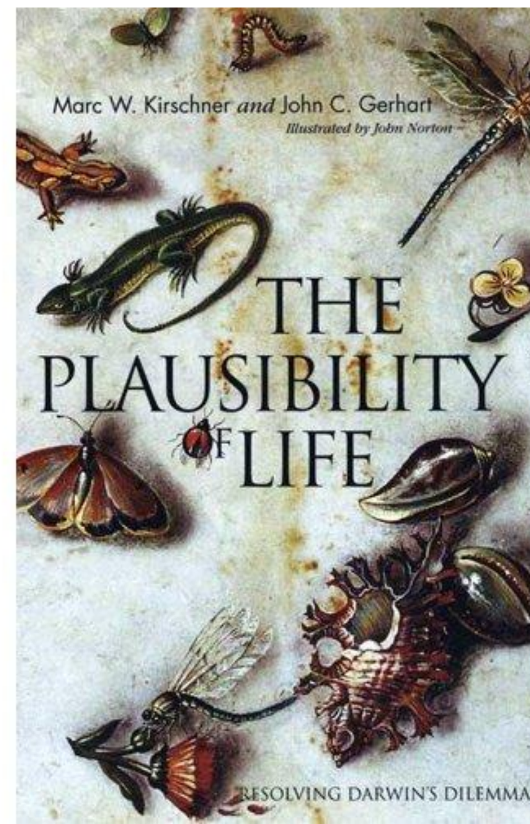


Depends crucially on layered architecture
Prefrontal
Motor
Sensory
Striatum
Digital
Hardware
Soft
Horizontal Meme Transfer
Horizontal App Transfer
Horizontal Gene Transfer
Amazingly Flexible/ Adaptable
AA
trans
RNA
DNA
Repl.
RNAp

Putting biology back into evolution



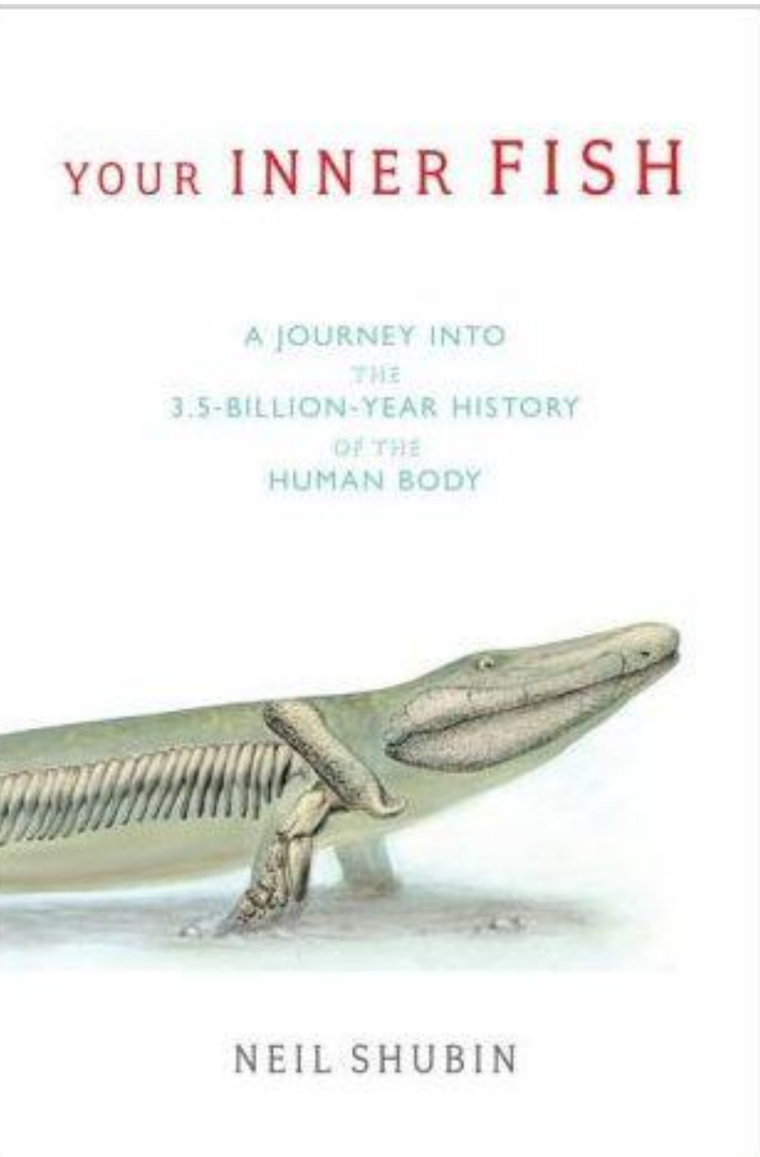


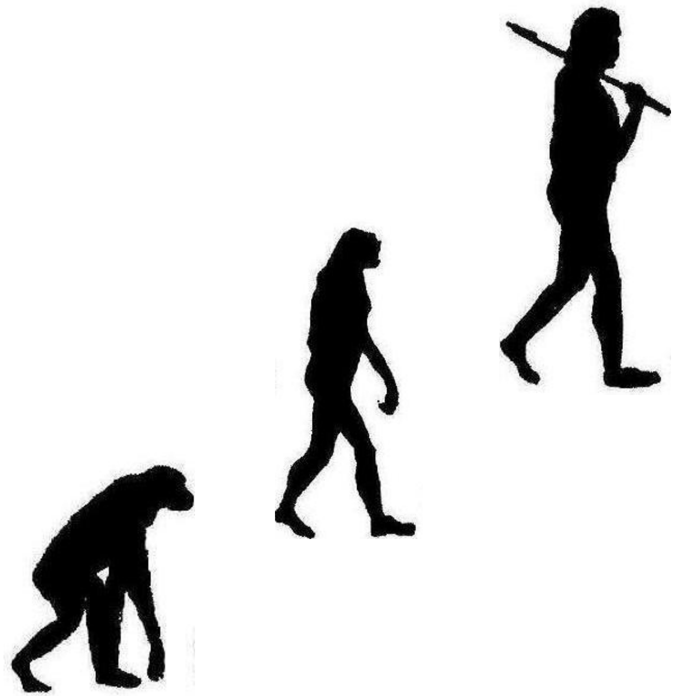


Universal architectures

What can go wrong?

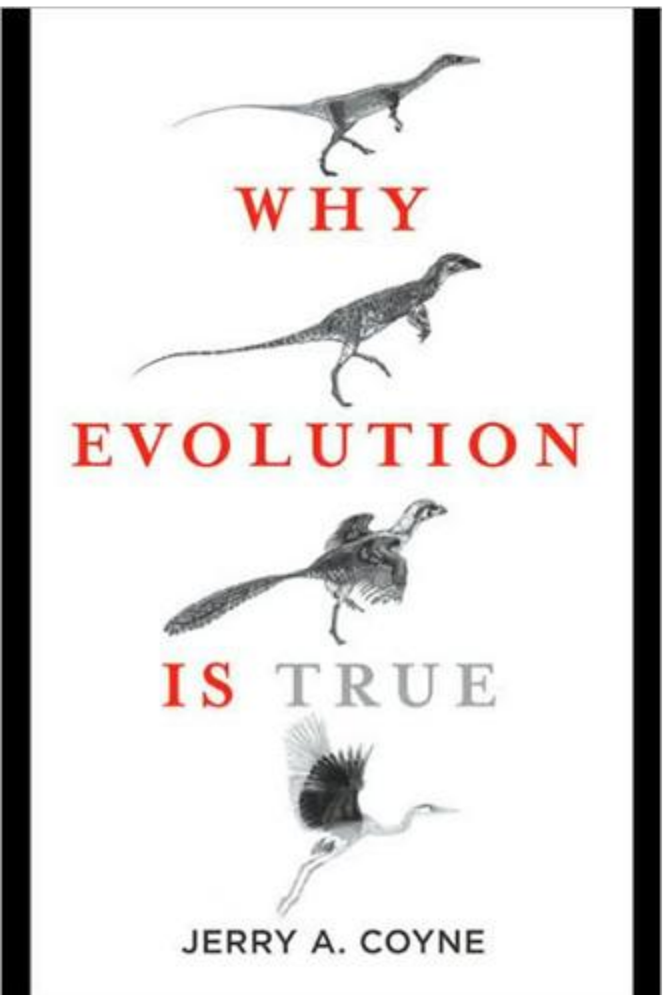
Unfortunately, not intelligent design

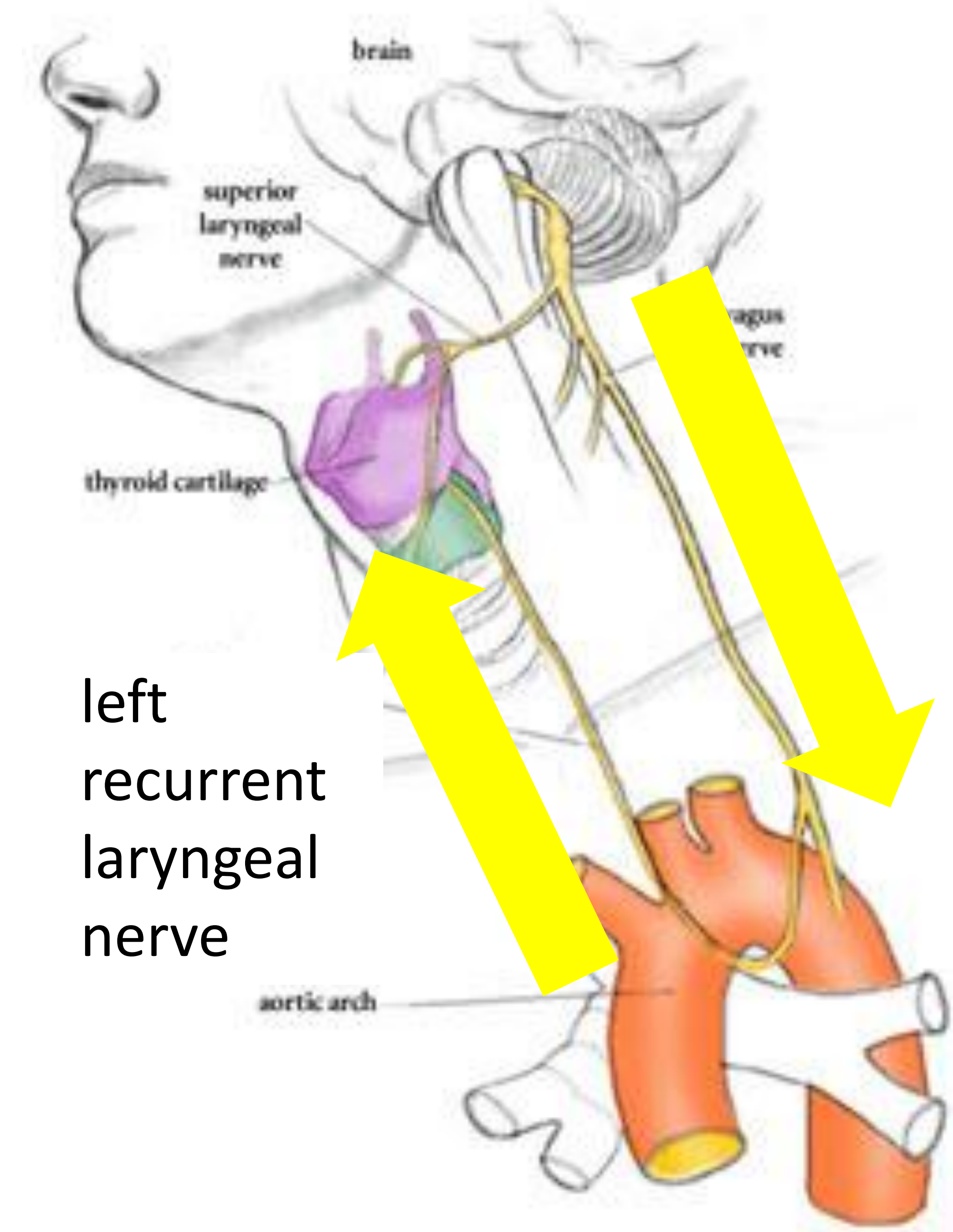




Ouch.

Why?


WHY
EVOLUTION
IS TRUE
JERRY A. COYNE


brain
superior laryngeal nerve
thyroid cartilage
left recurrent laryngeal nerve
aortic arch

Why? Building humans from fish parts.

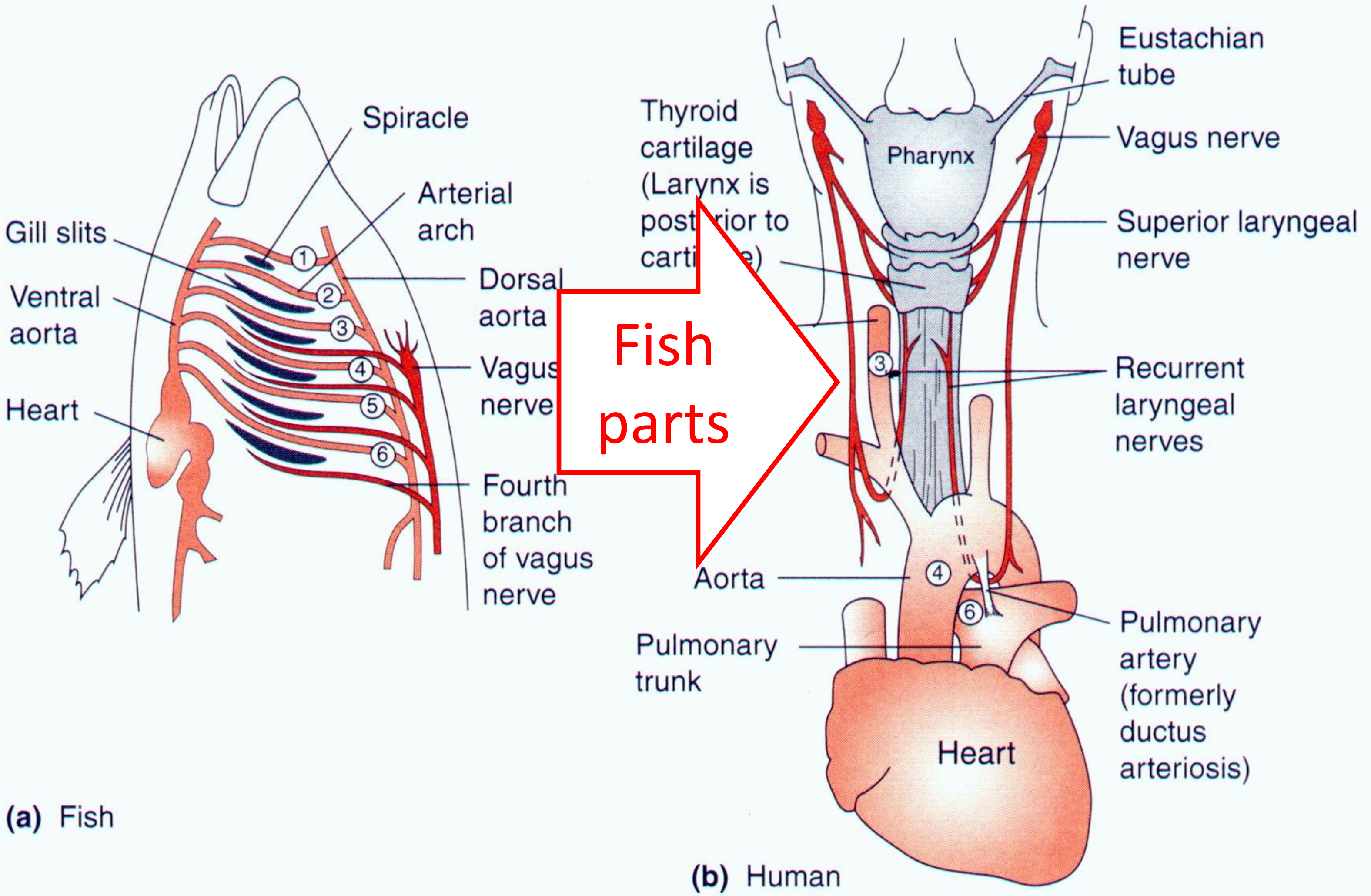
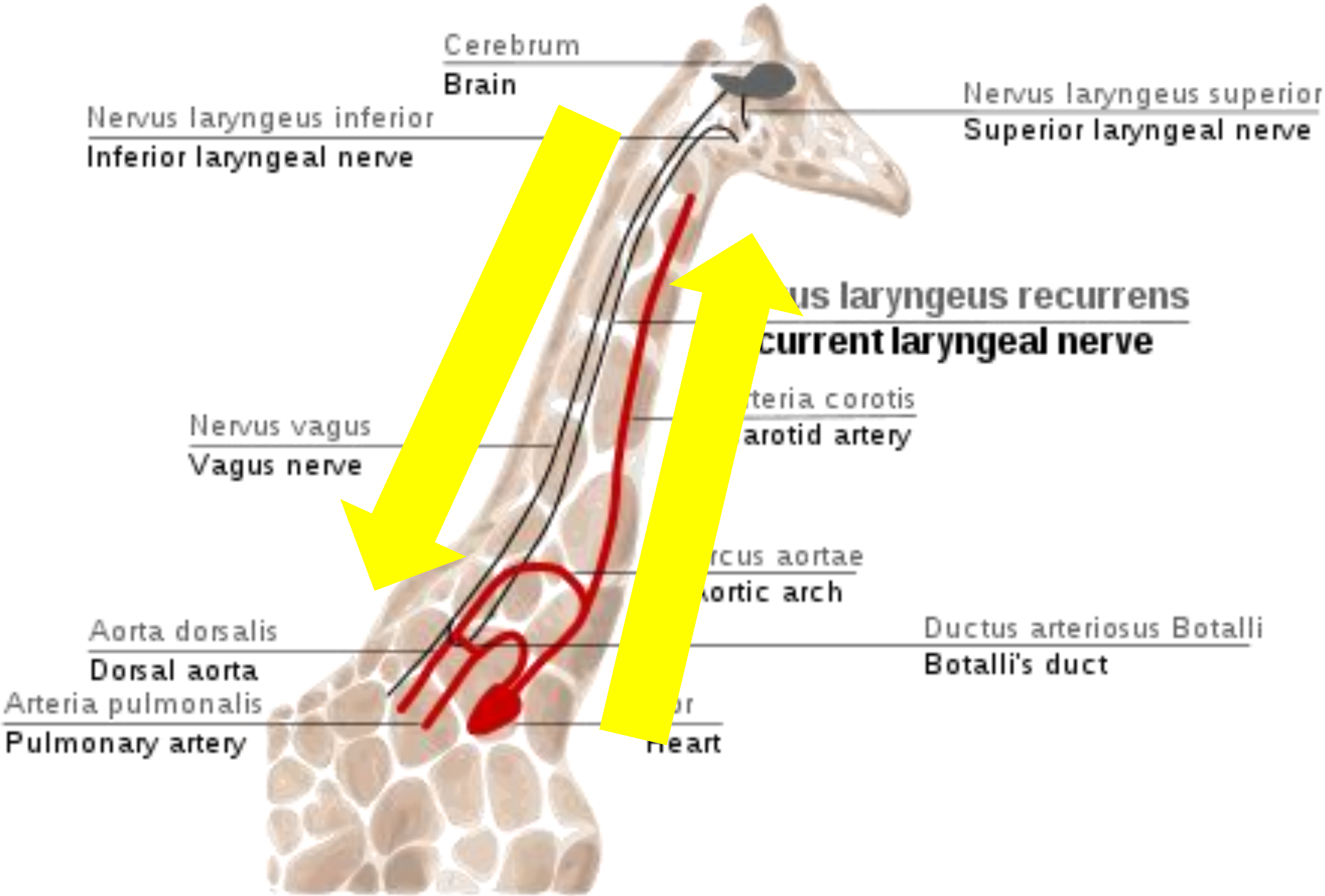
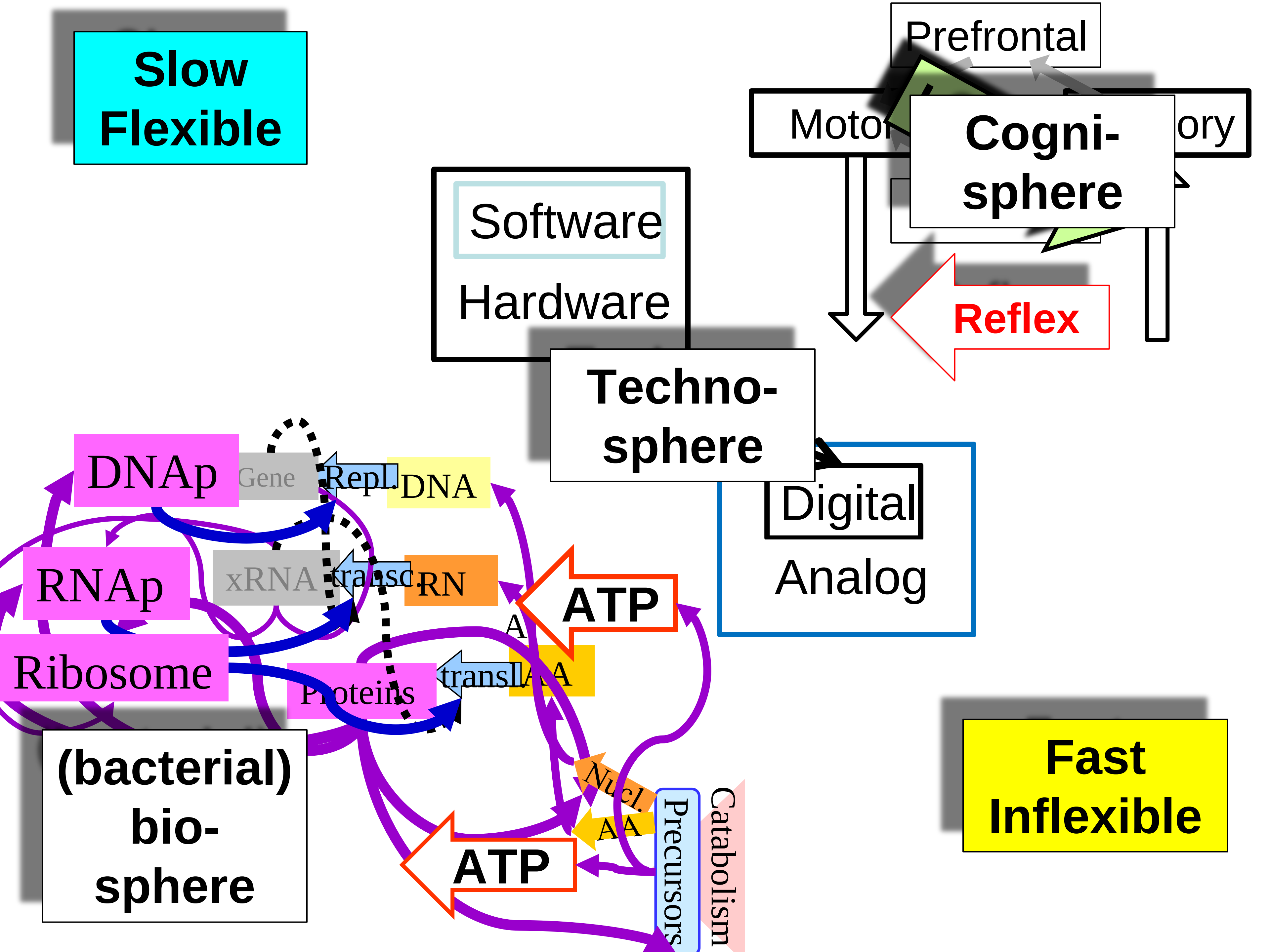


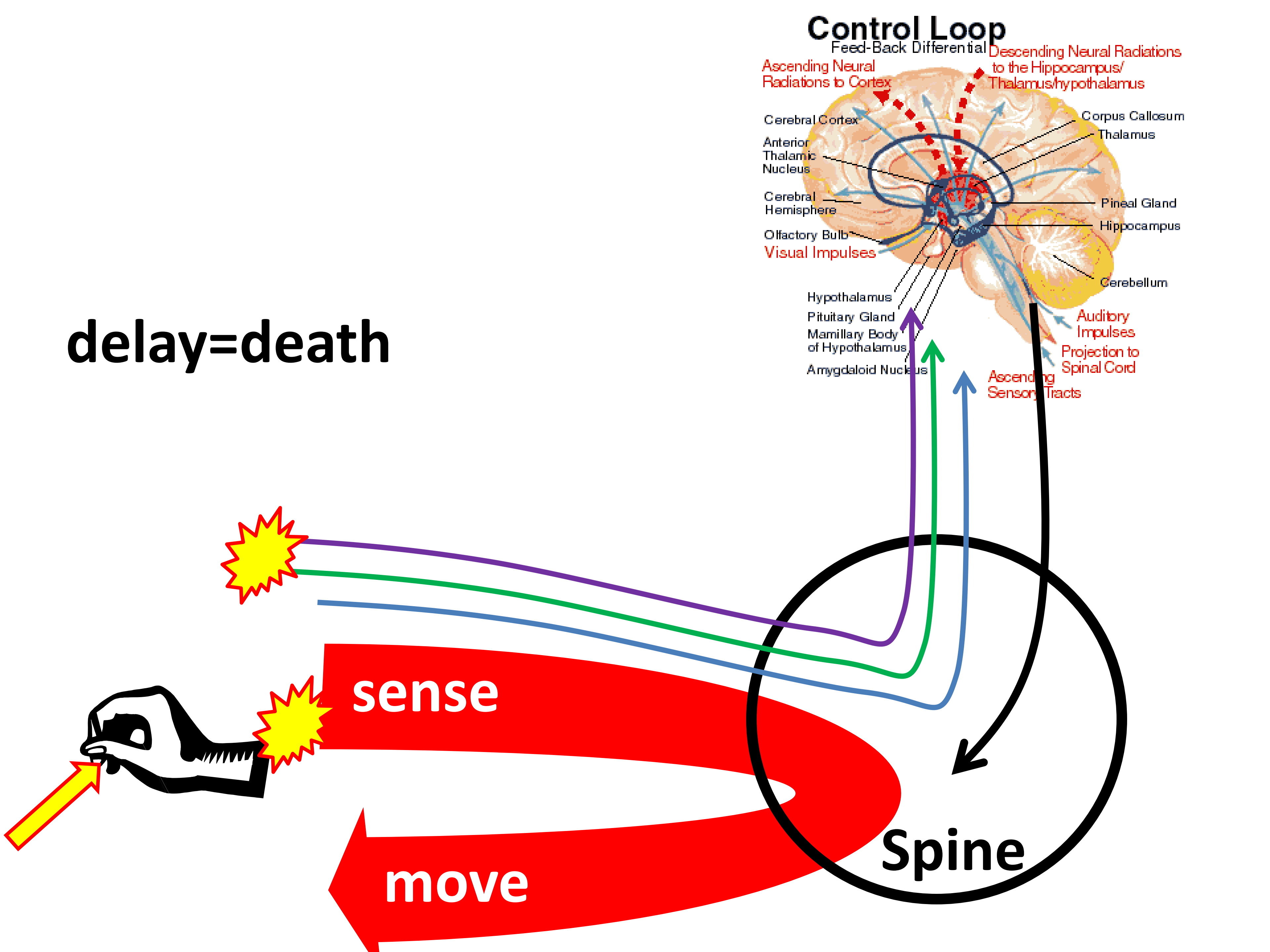
FIGURE 3–11 Schematic diagram showing the relationship between the vagus cranial nerve and the arterial arches in fish (*a*) and human (*b*). Only the third, fourth, and part of the sixth arterial arches remain in placental mammals, the sixth acting only during fetal development to carry blood to the 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.



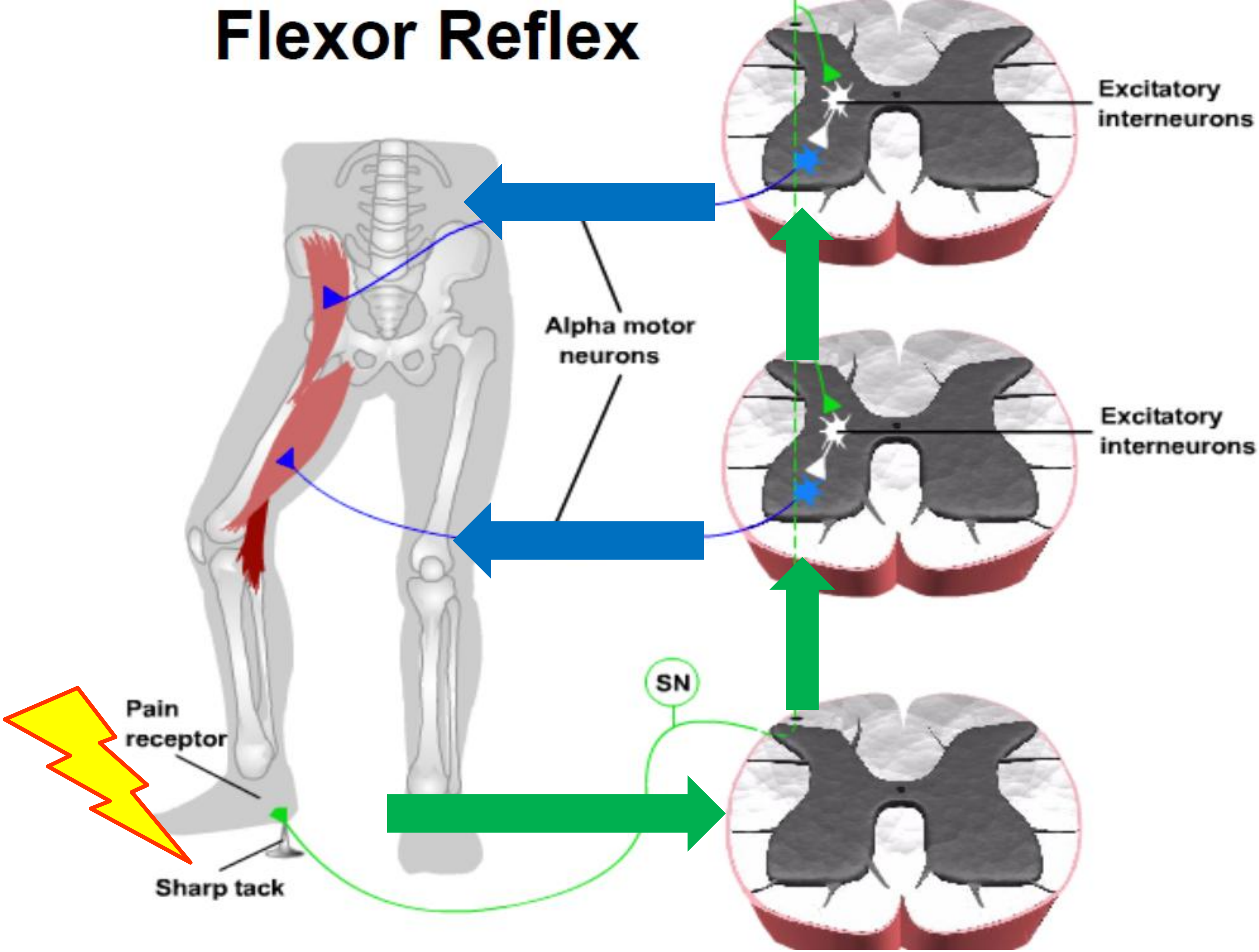


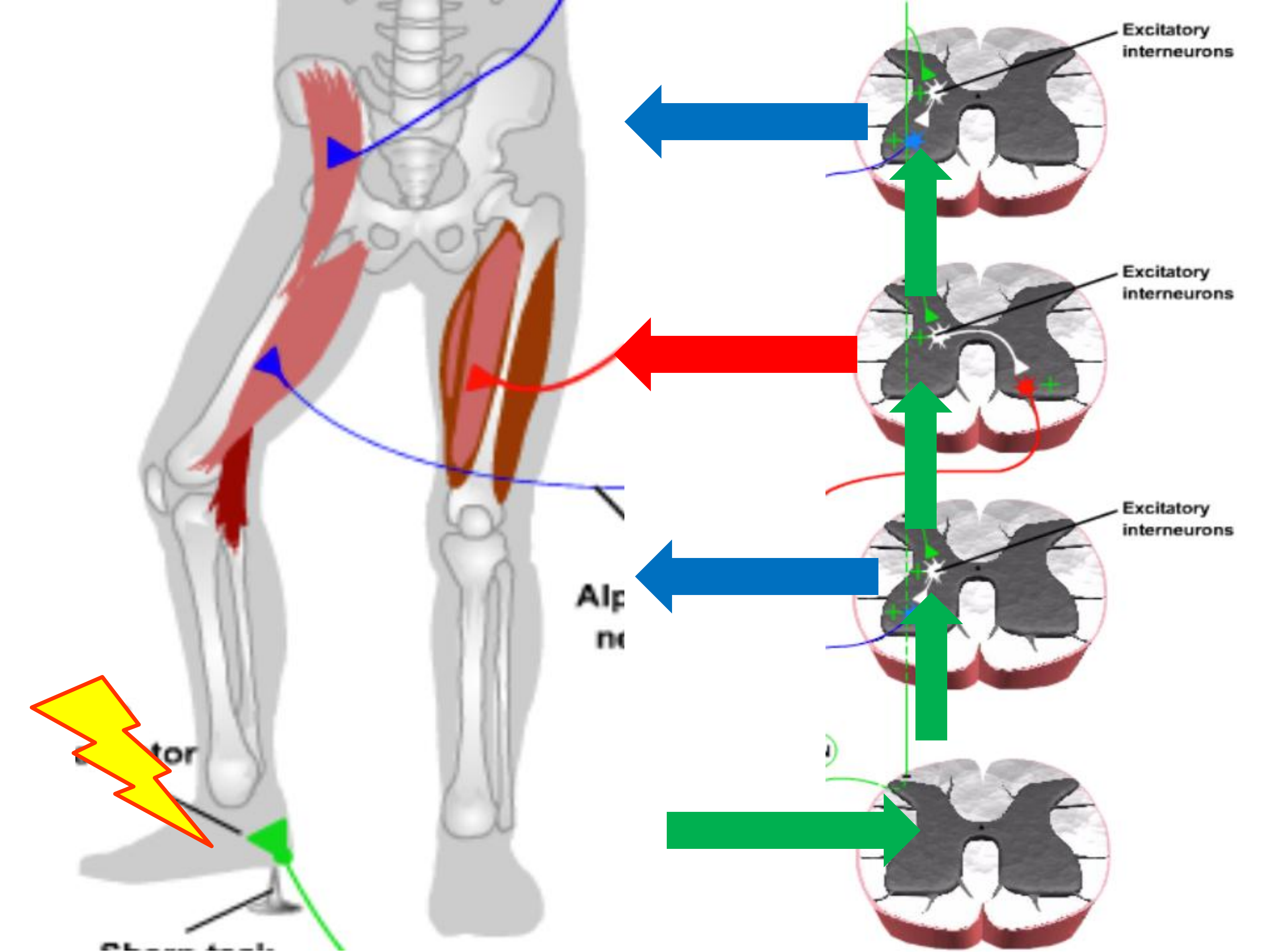
Slow
Flexible
Prefrontal
Motor
ory
Cogni-
sphere
Software
Hardware
Reflex
Techno-
sphere
Digital
Analog
DNAp
Gene
Repl.
DNA
RNAp
xRNA
transc.
RN
ATP
A
Ribosome
Proteins
transl.
AA
Nucl.
AA
Precursors
Catabolism
ATP
(bacterial)
bio-
sphere
Fast
Inflexible



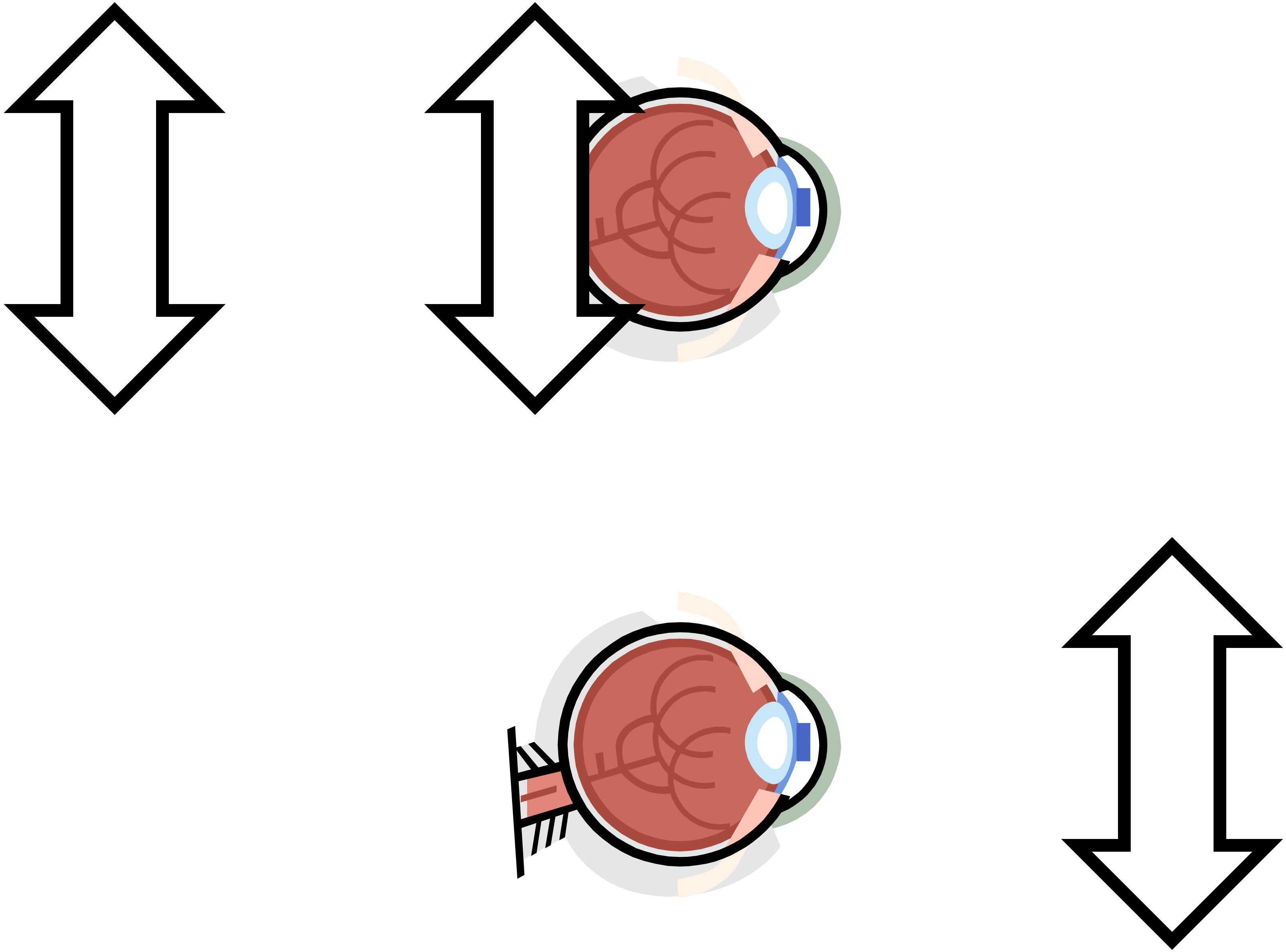
Control Loop
Feed-Back Differential
Ascending Neural Radiations to Cortex
Descending Neural Radiations to the Hippocampus/ Thalamus/hypothalamus
Cerebral Cortex
Corpus Callosum
Thalamus
Anterior Thalamic Nucleus
Cerebral Hemisphere
Pineal Gland
Hippocampus
Olfactory Bulb
Visual Impulses
Cerebellum
Hypothalamus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

Flexor Reflex

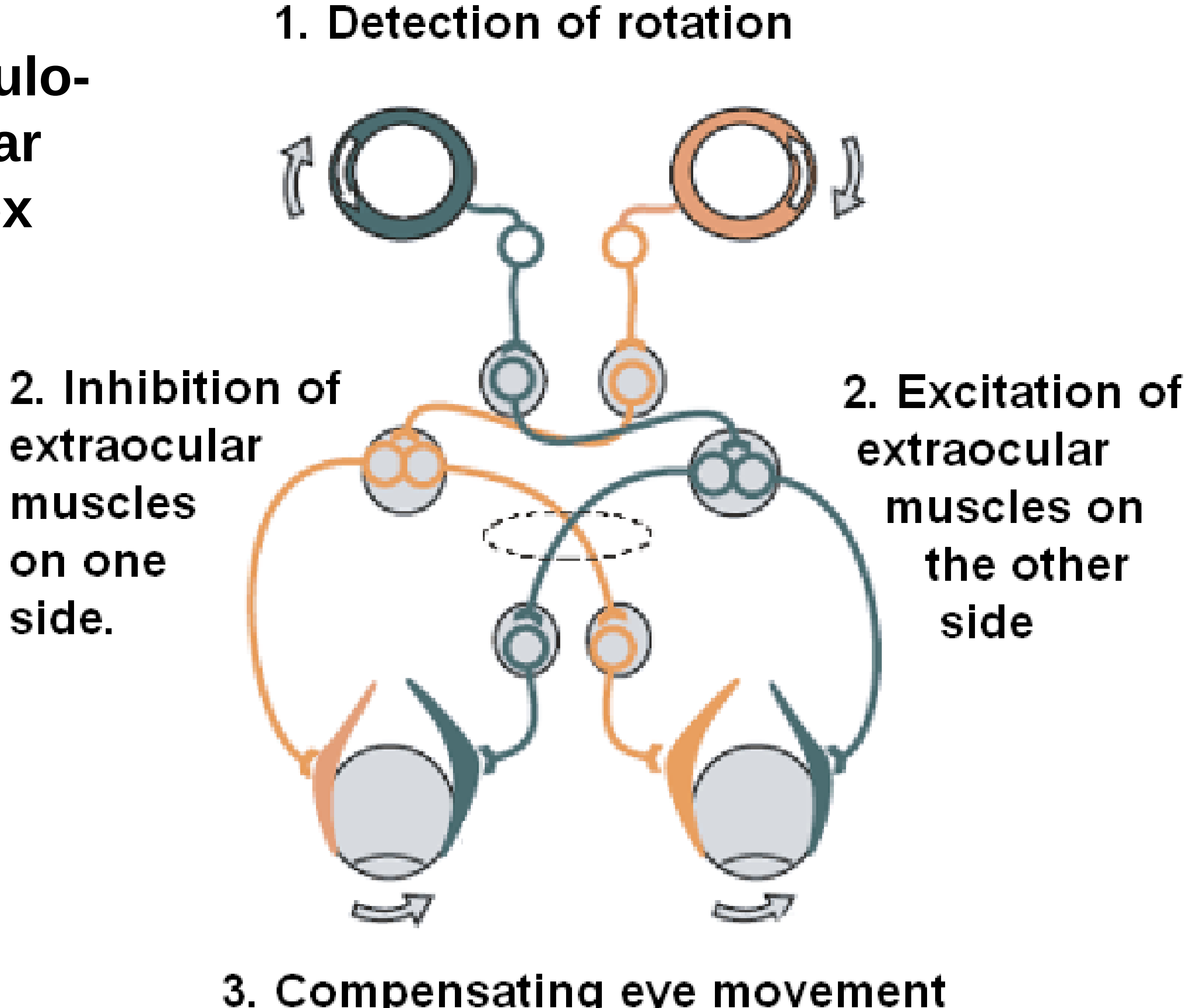


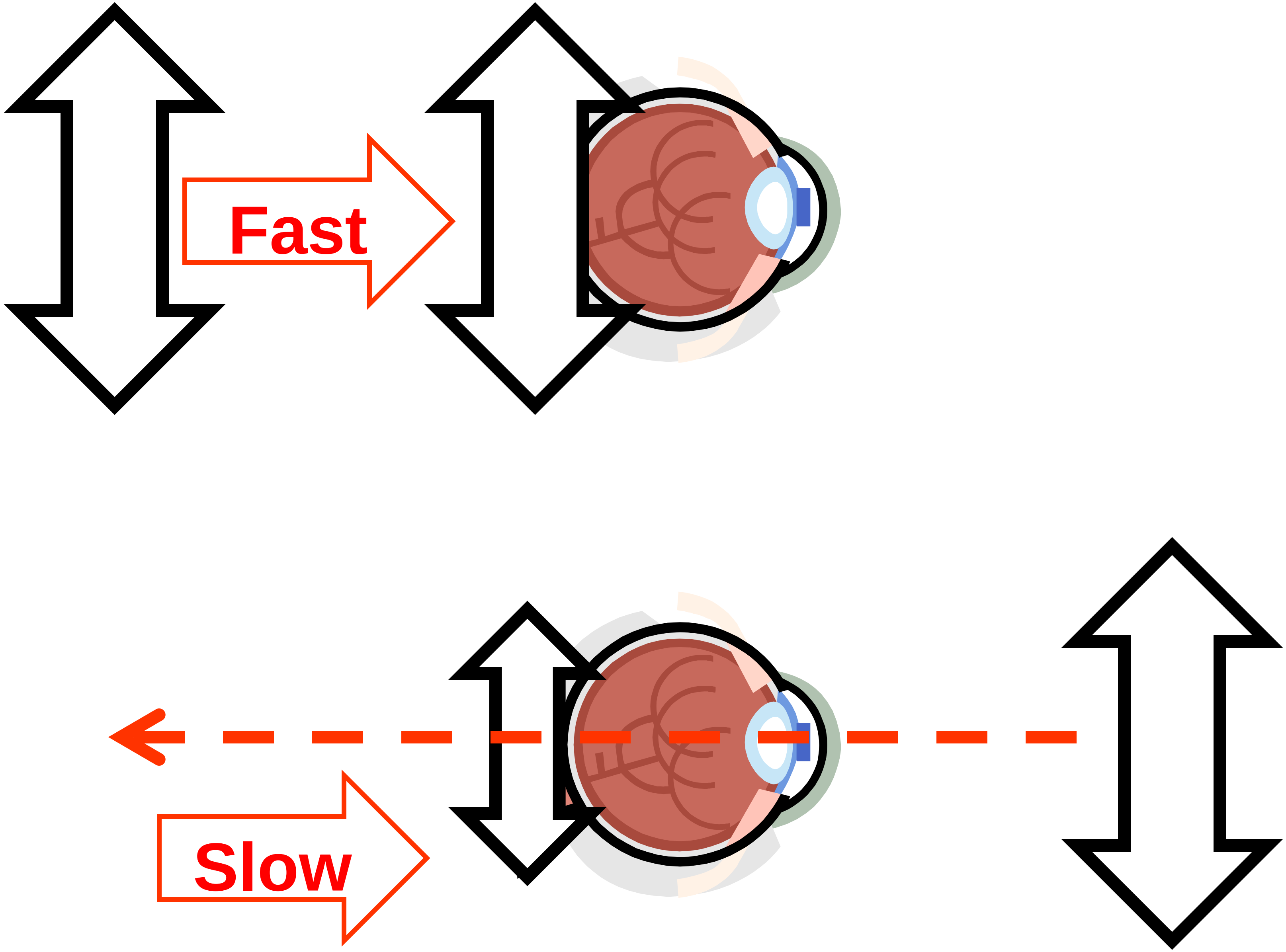


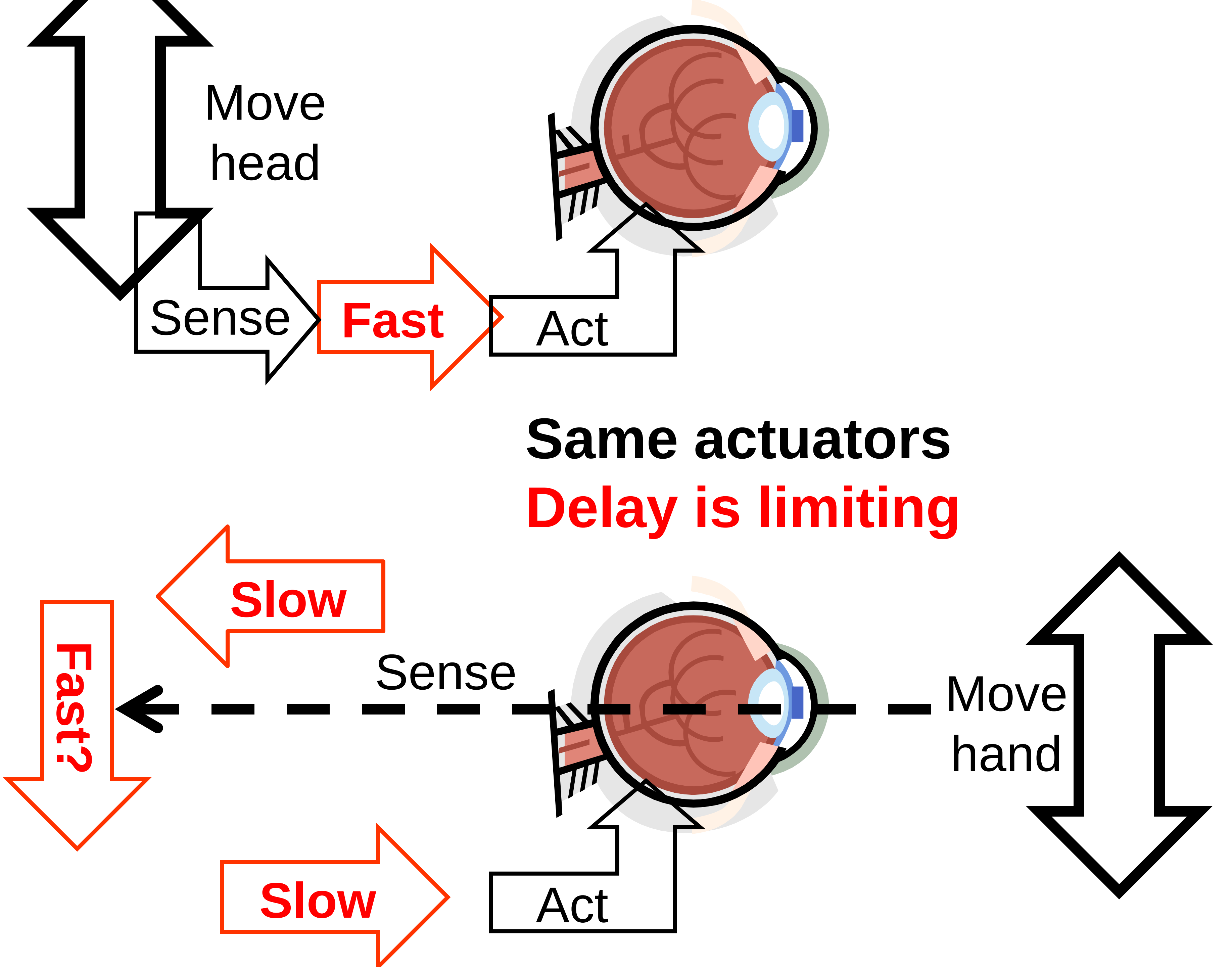
Excitatory interneurons
Excitatory interneurons
Excitatory interneurons



Vestibulo-ocular reflex

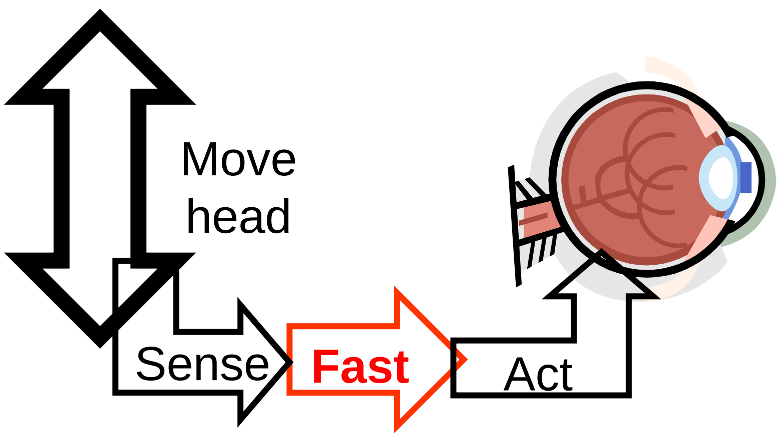



Fast
Slow


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

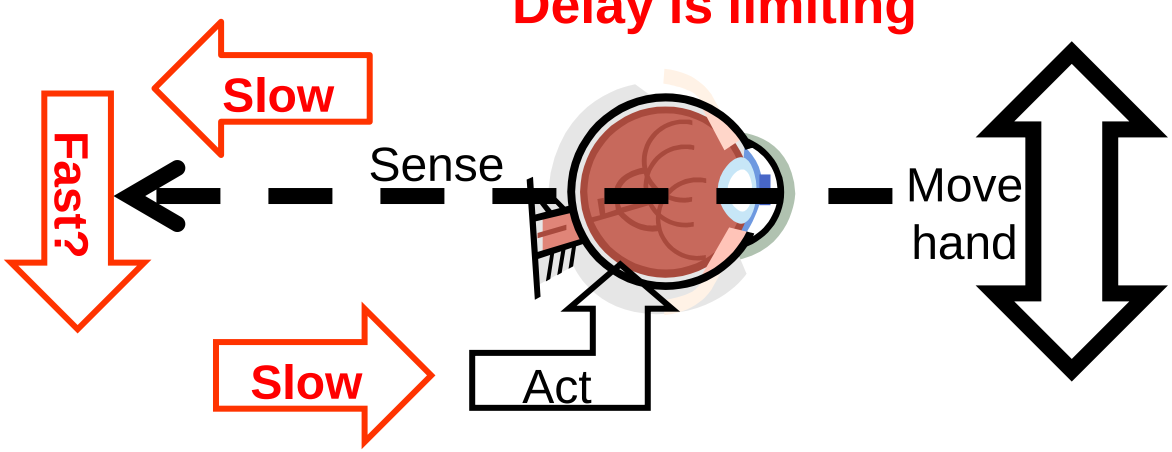
Versus standing on one leg

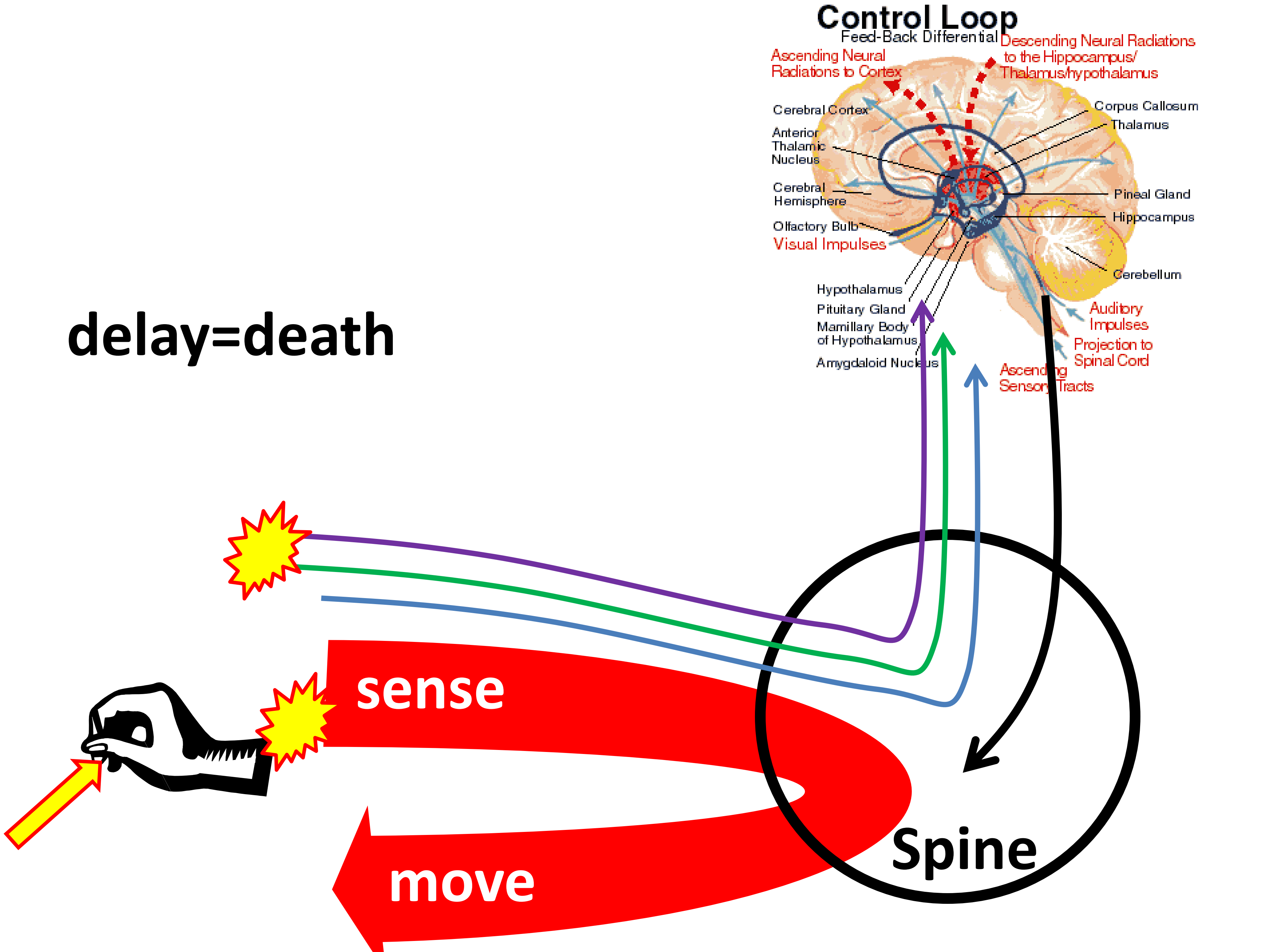
- Eyes open vs closed
- Contrast
  - young surfers
  - old football players

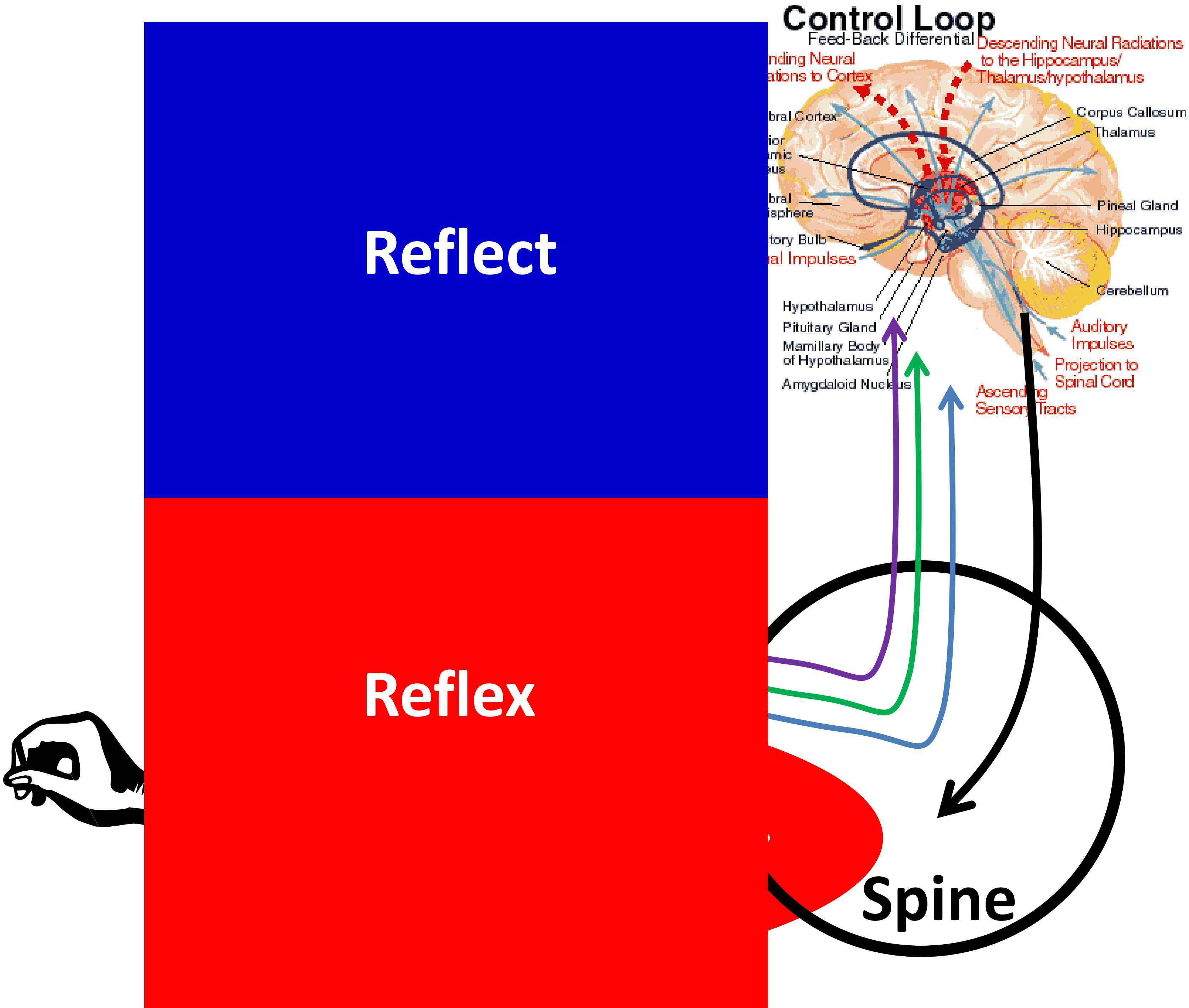


Same actuators

Delay is limiting

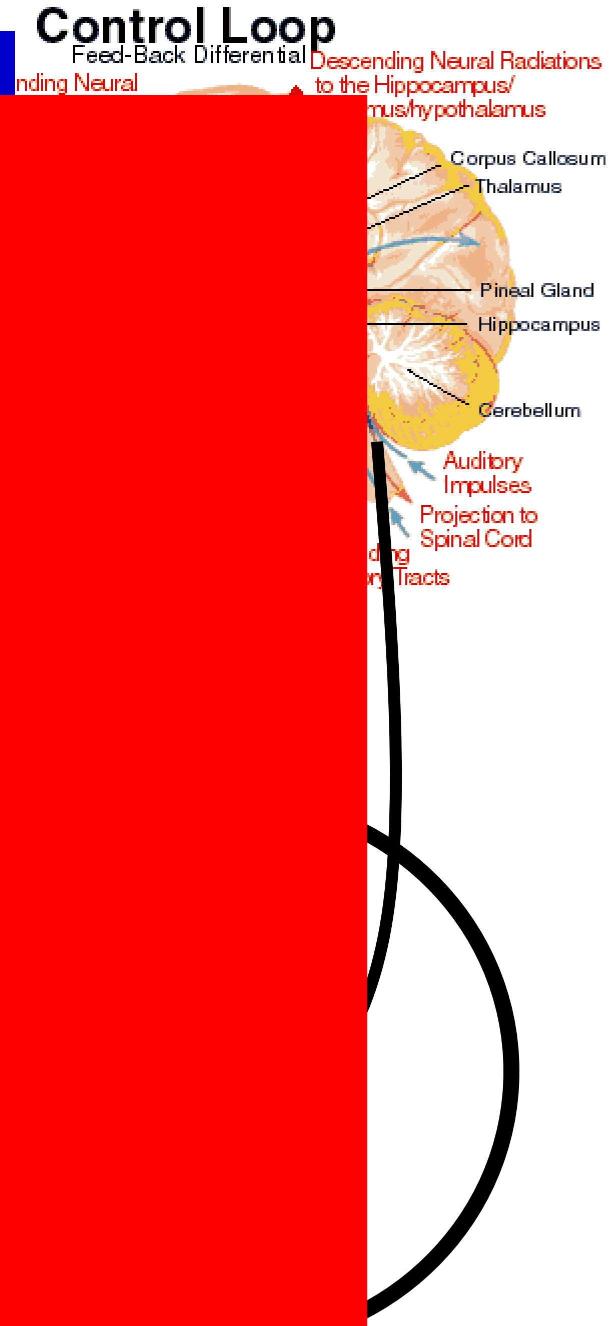



Control Loop
Feed-Back Differential
Ascending Neural Radiations to Cortex
Descending Neural Radiations to the Hippocampus/ Thalamus/hypothalamus
Cerebral Cortex
Anterior Thalamic Nucleus
Cerebral Hemisphere
Olfactory Bulb
Visual Impulses
Corpus Callosum
Thalamus
Pineal Gland
Hippocampus
Cerebellum
Hypothalamus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

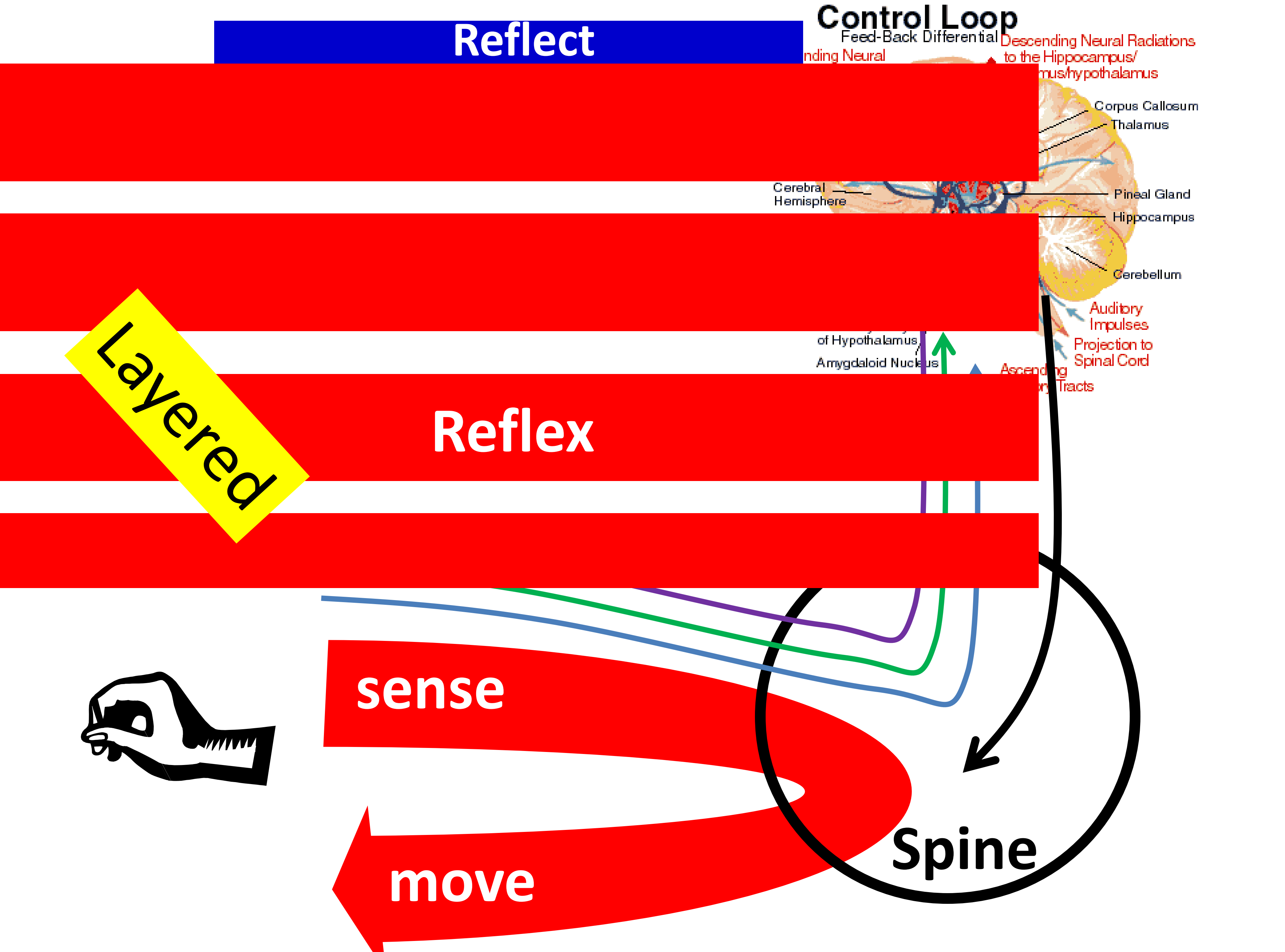


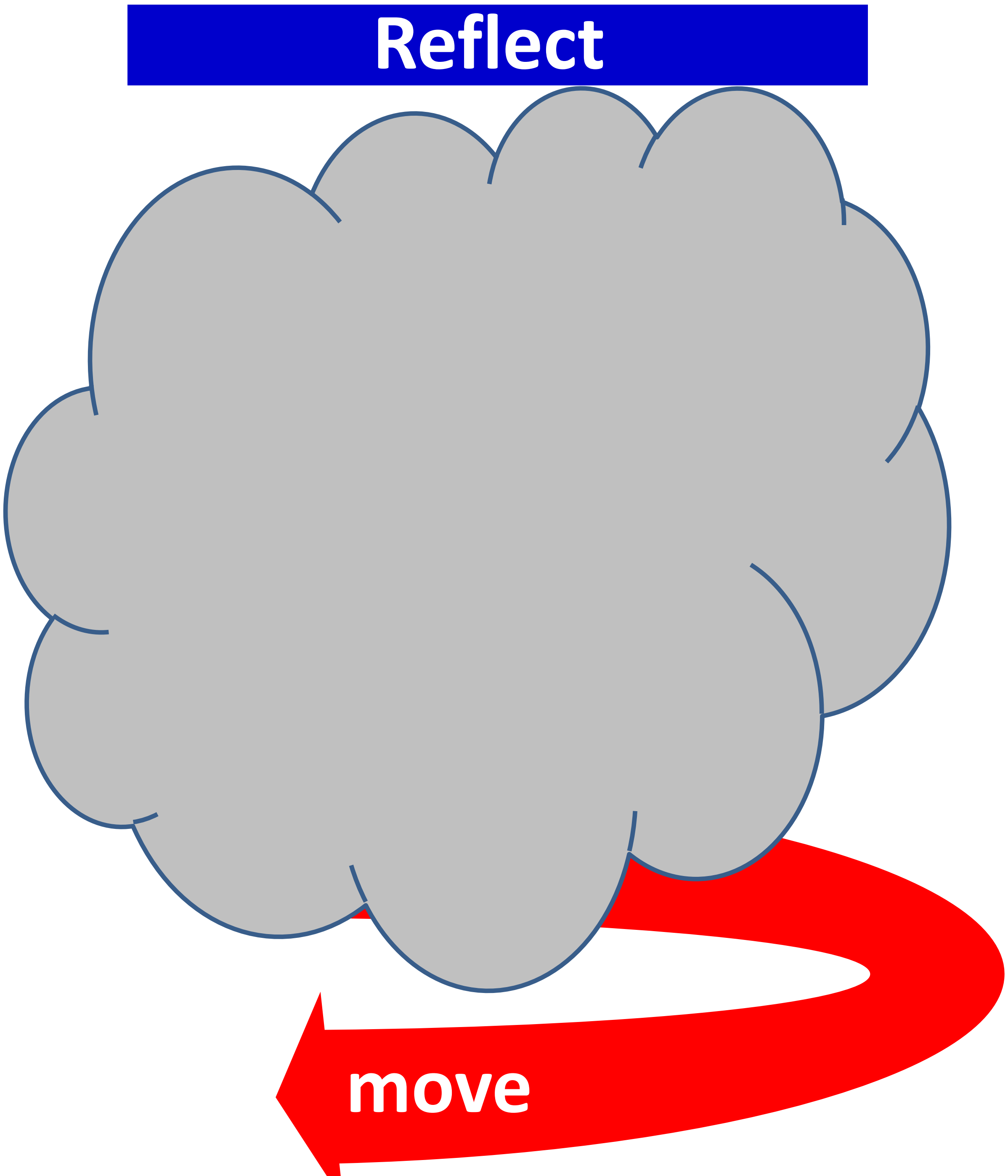
Reflect
Reflex
Control Loop
Feed-Back Differential
Descending Neural Radiations
to the Hippocampus/
Thalamus/hypothalamus
Corpus Callosum
Thalamus
Pineal Gland
Hippocampus
Cerebellum
Hypothalamus
Pituitary Gland
Mamillary Body
of Hypothalamus
Amygdaloid Nucleus
Auditory
Impulses
Projection to
Spinal Cord
Ascending
Sensory Tracts
Spine

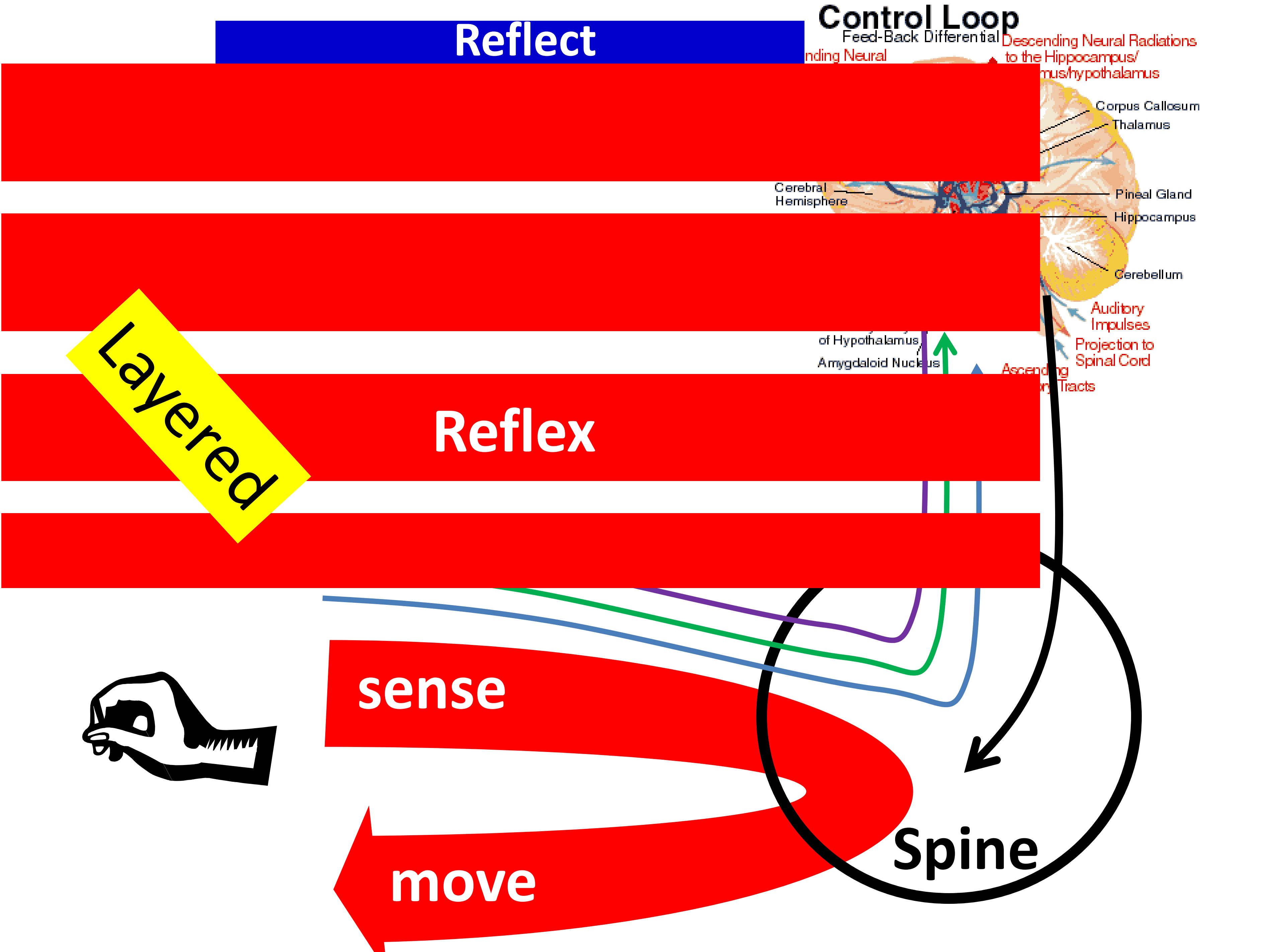
Reflect



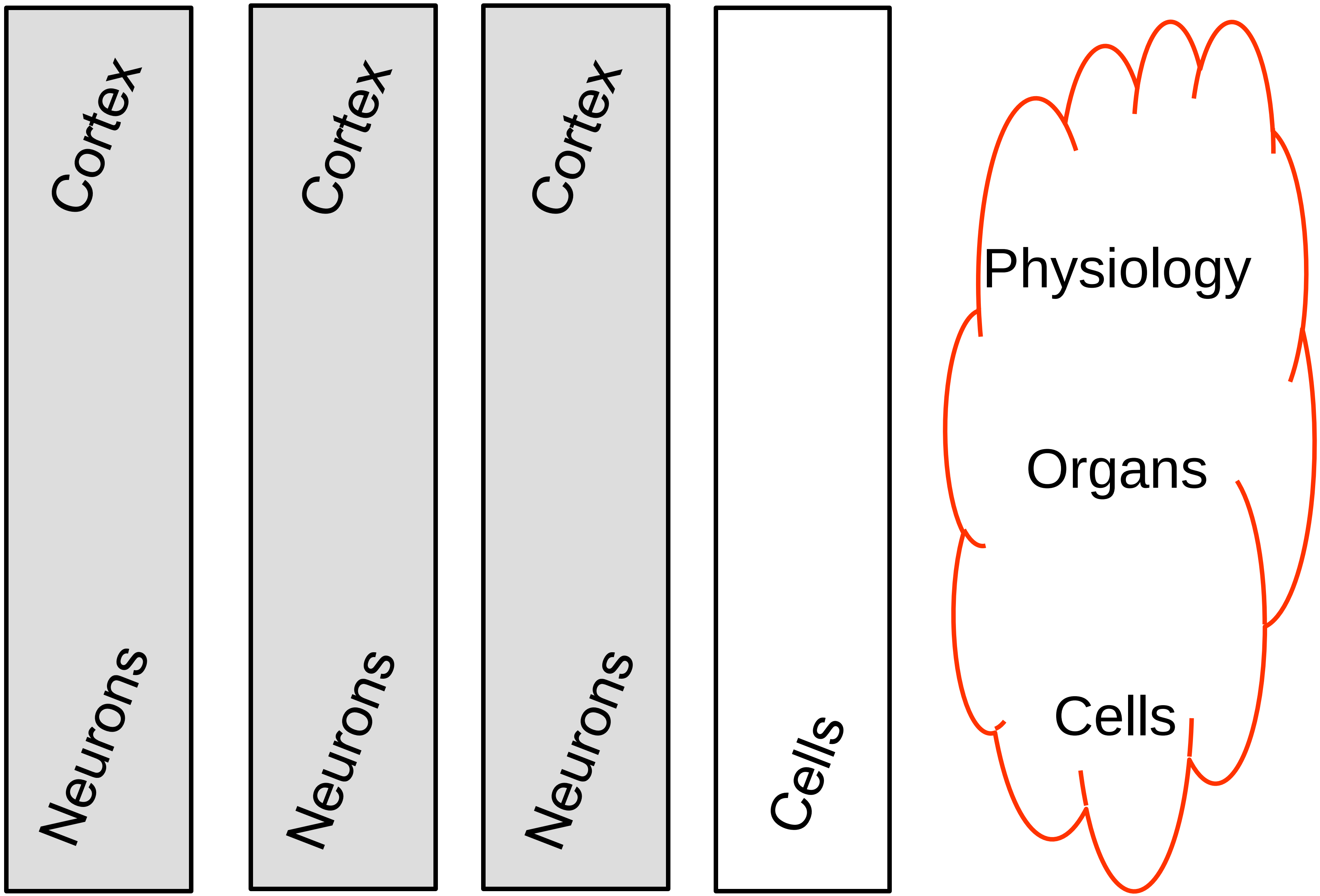
Reflex

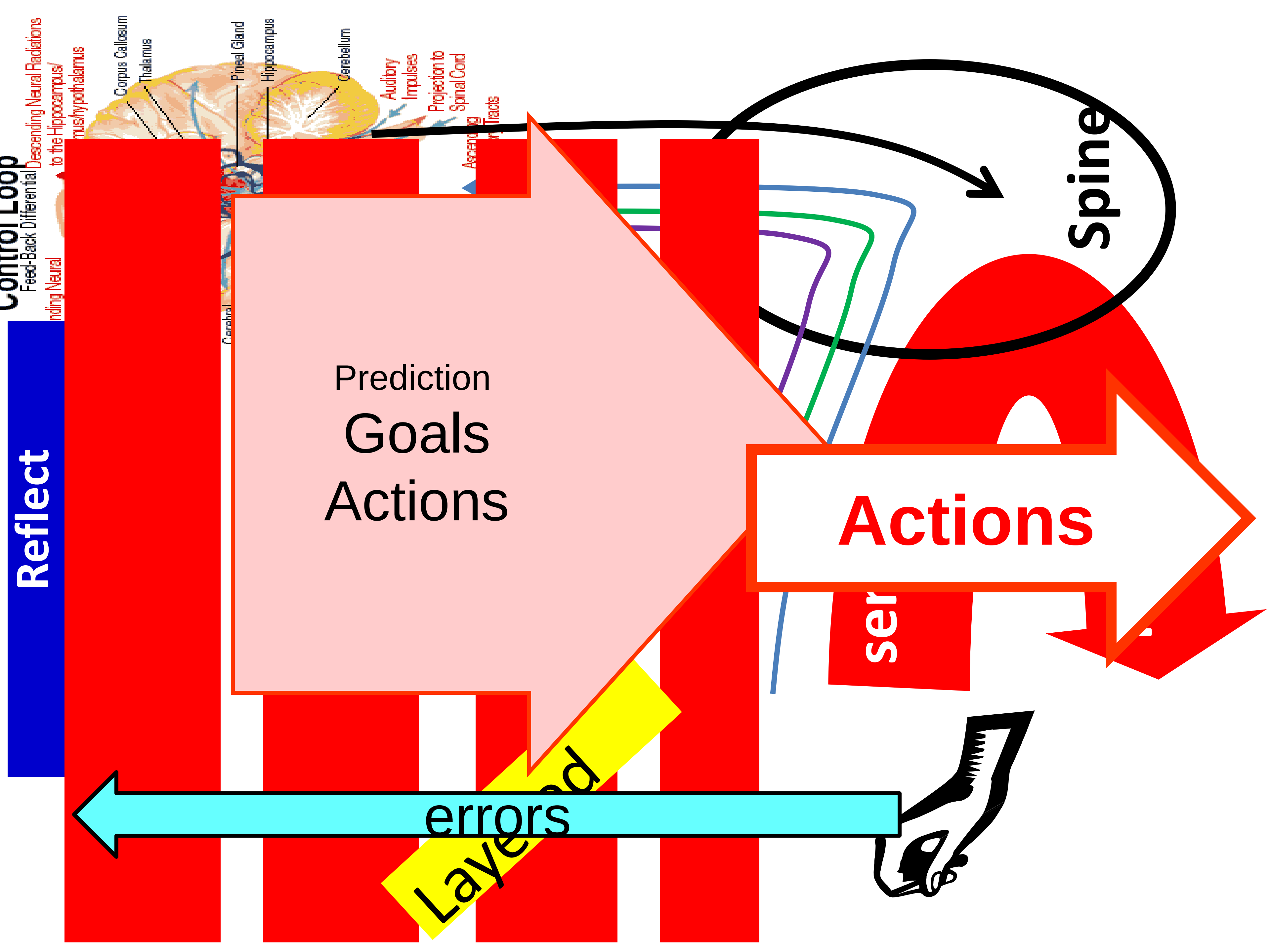

Reflect
Control Loop
Feed-Back Differential
Descending Neural Radiations
to the Hippocampus/
Corpus Callosum
Thalamus
Cerebral
Hemisphere
Pineal Gland
Hippocampus
Cerebellum
Auditory
Impulses
Projection to
Spinal Cord
of Hypothalamus
Amygdaloid Nucleus
Layered
Reflex
sense
move
Spine


Reflect
move


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

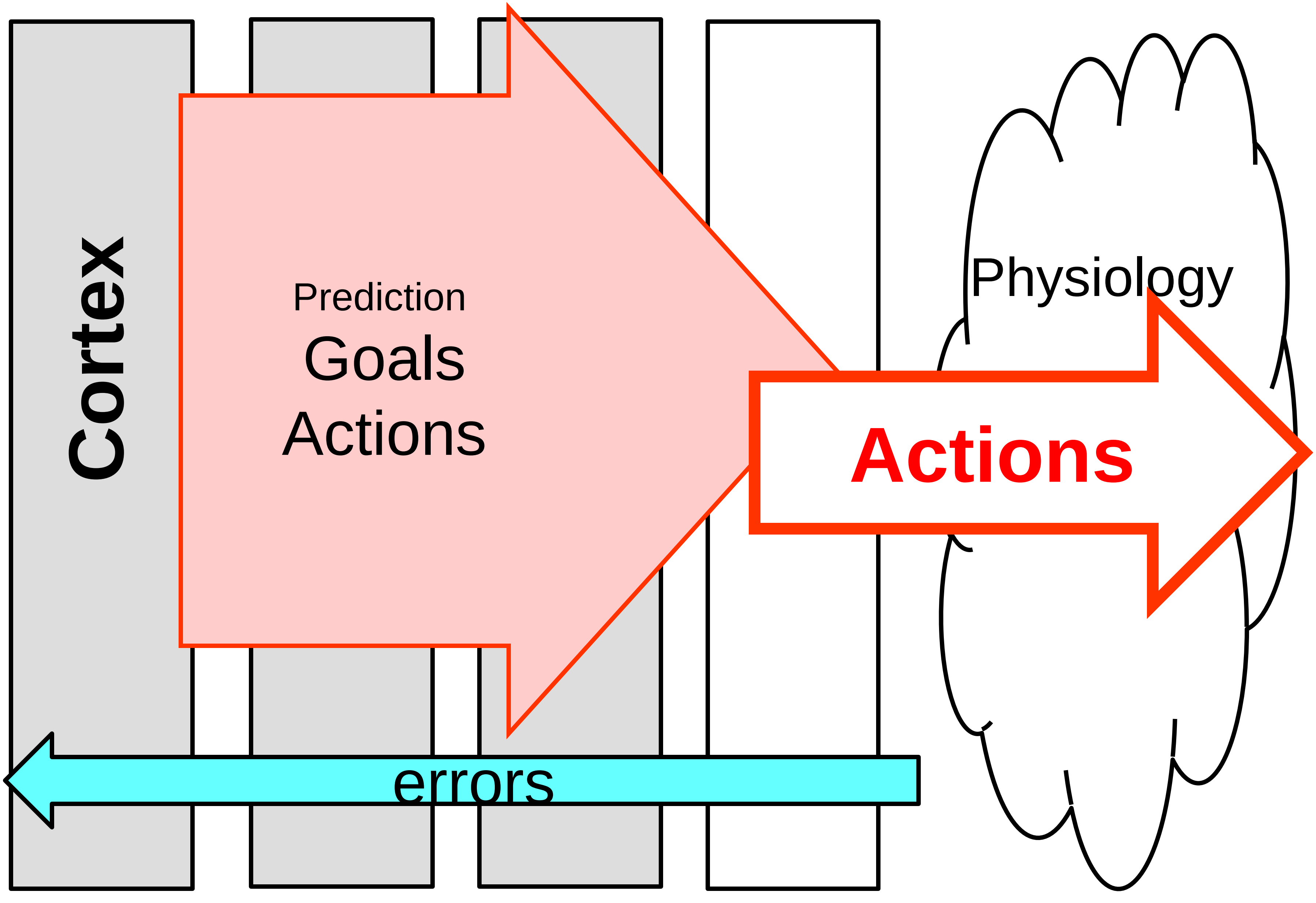
Layered architectures (cartoon)

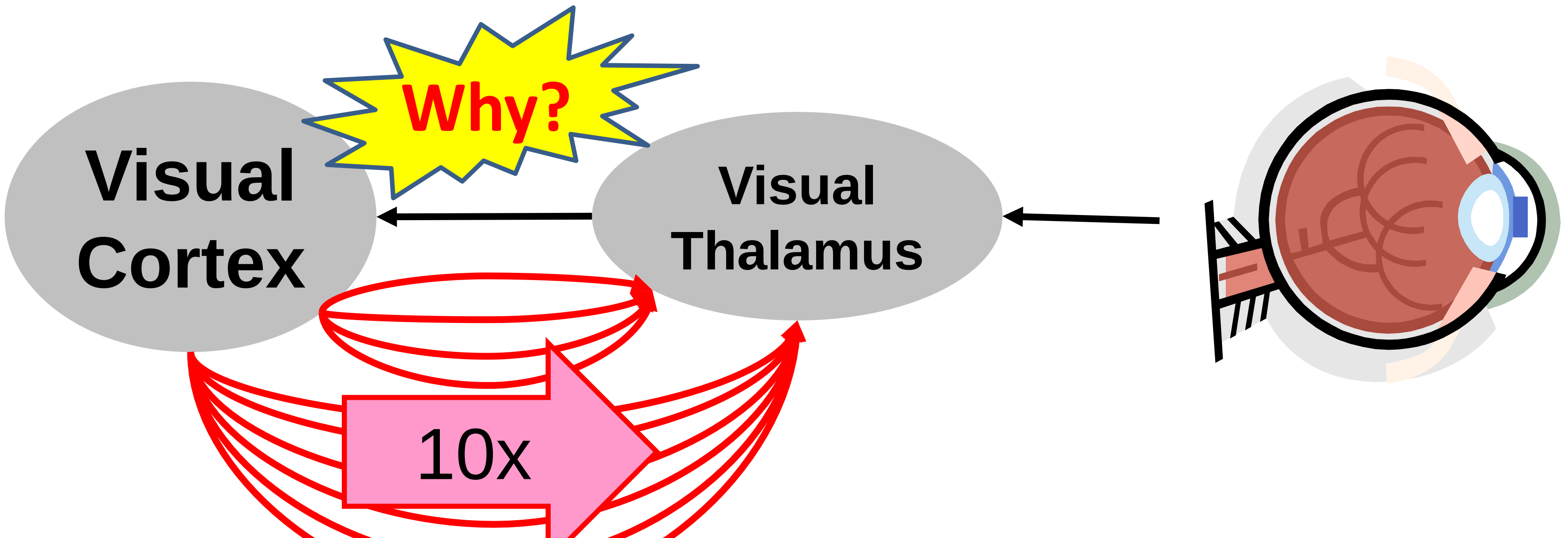


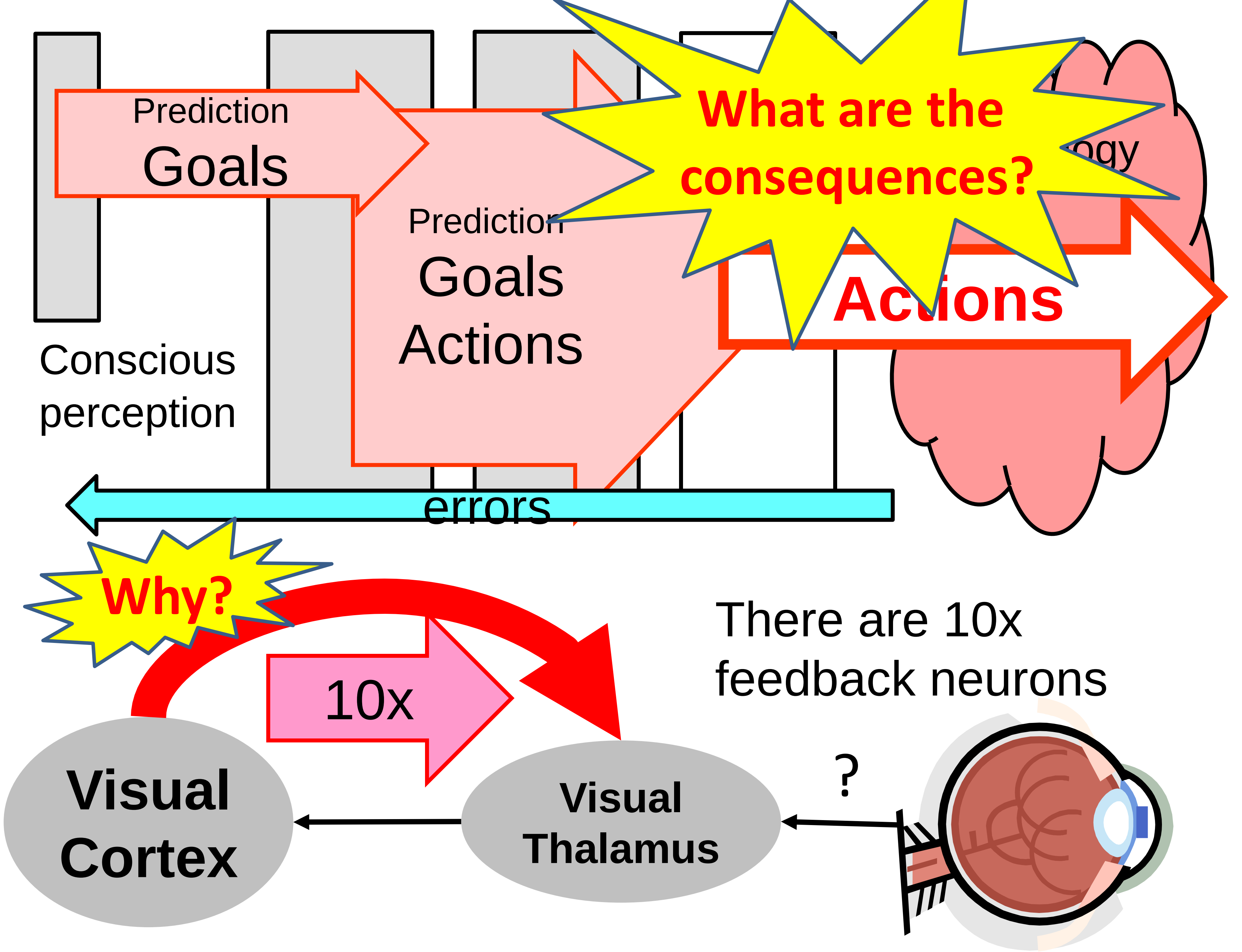


Feed-Back Differential
Corpus Callosum
Thalamus
Pineal Gland
Hippocampus
Cerebellum
Auditory Impulses
Projection to Spinal Cord
Spine
Reflect
Prediction
Goals
Actions
Actions
errors
Layered

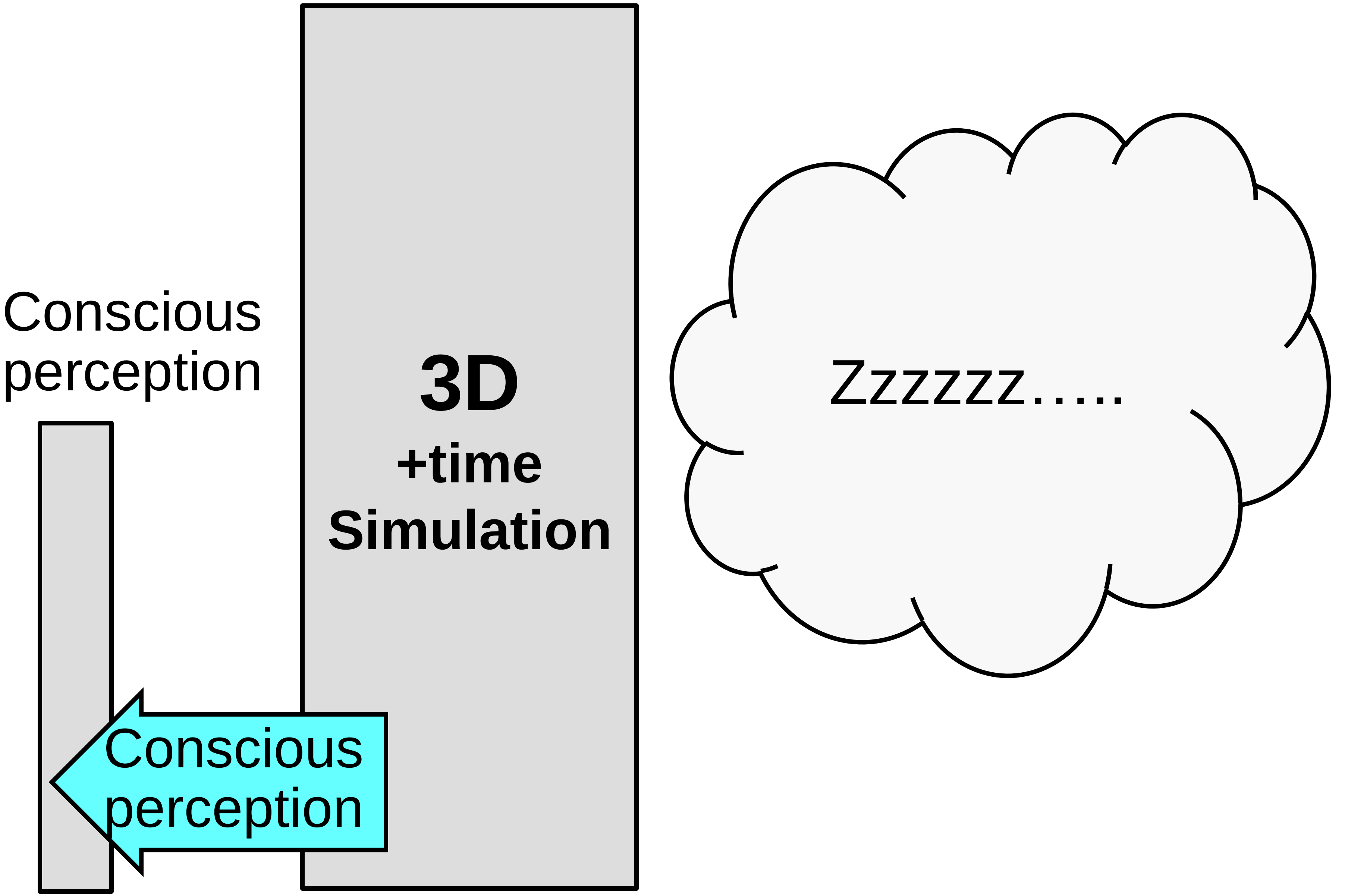
Meta-layers cartoon



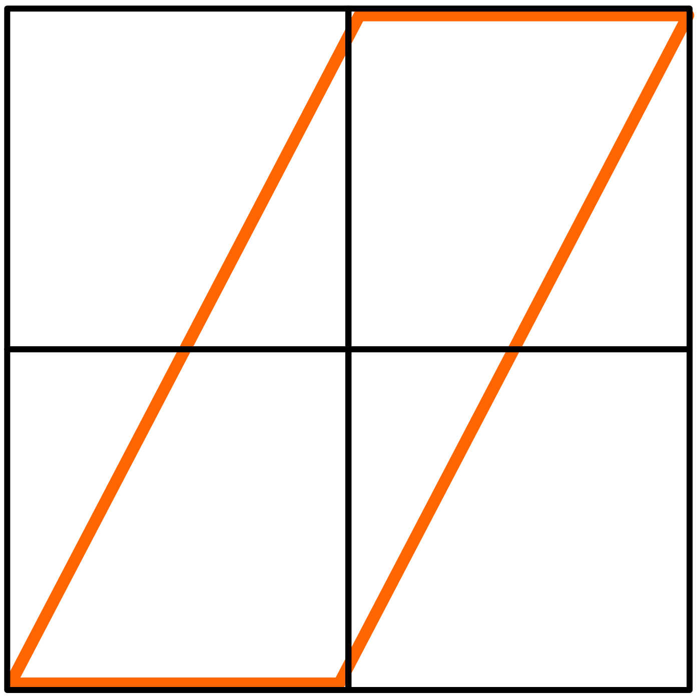
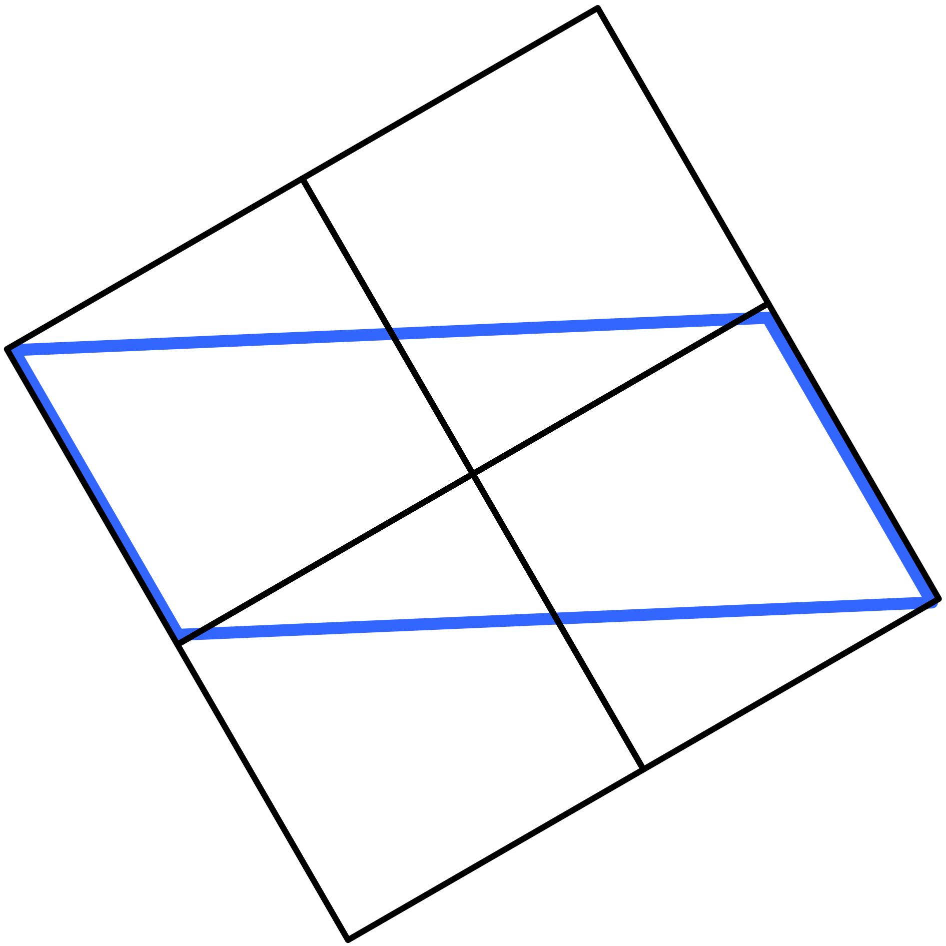

Why?
Visual Cortex
Visual Thalamus
10x

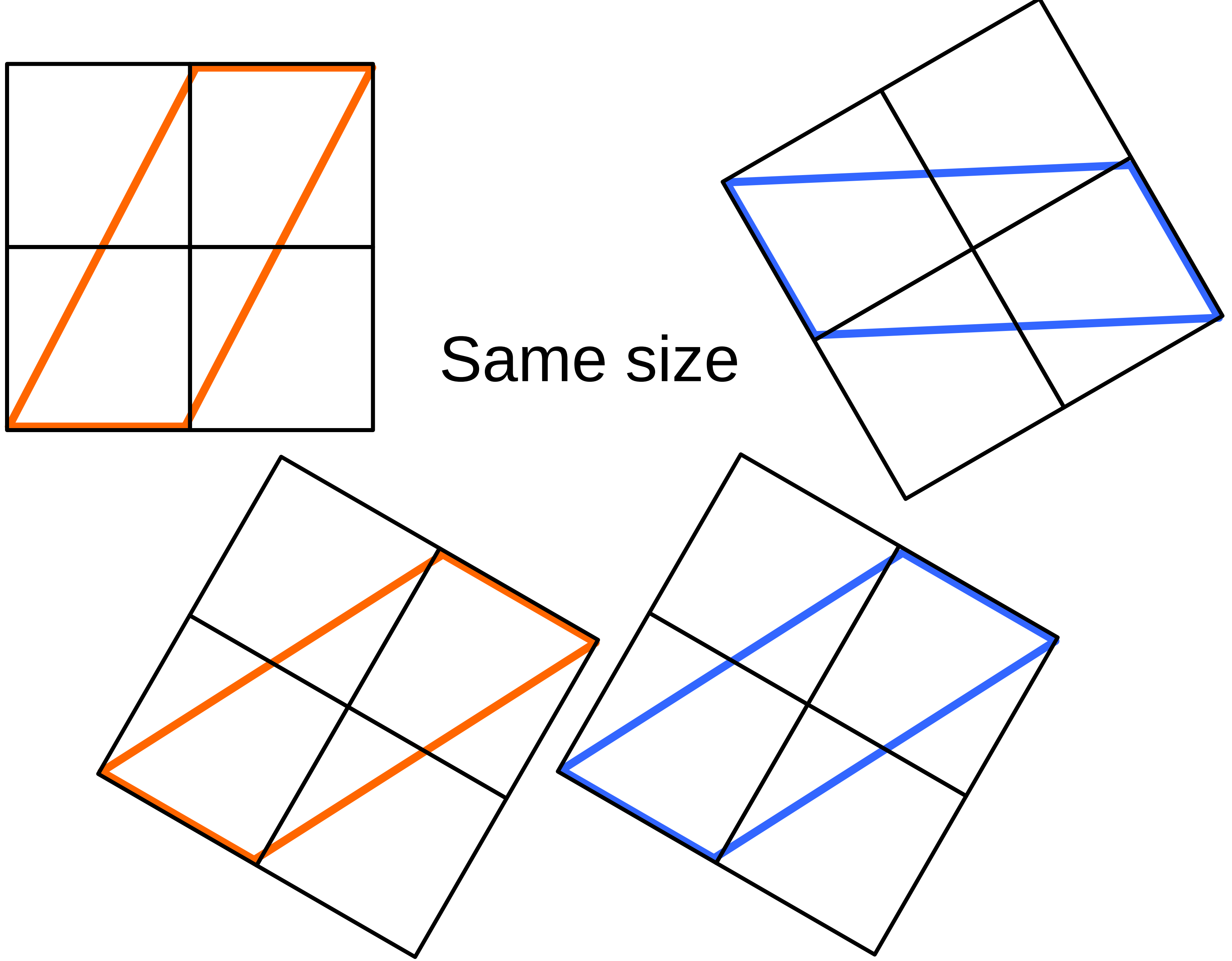

Prediction
Goals
Prediction
Goals
Actions
What are the consequences?
ogy
Actions
Conscious perception
errors
Why?
10x
There are 10x feedback neurons
?
Visual Cortex
Visual Thalamus

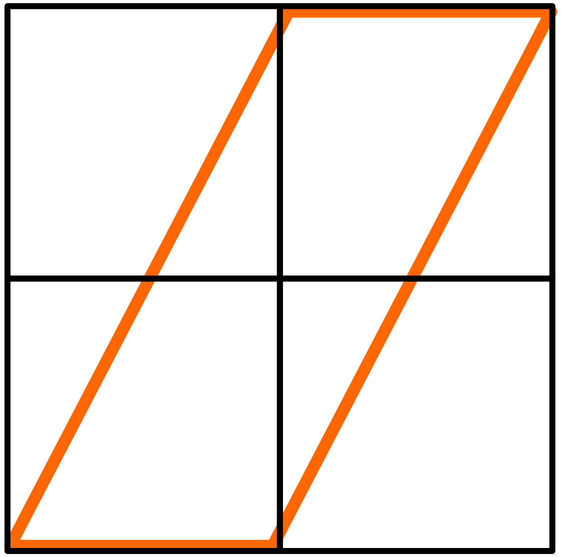
Seeing is ***dreaming***



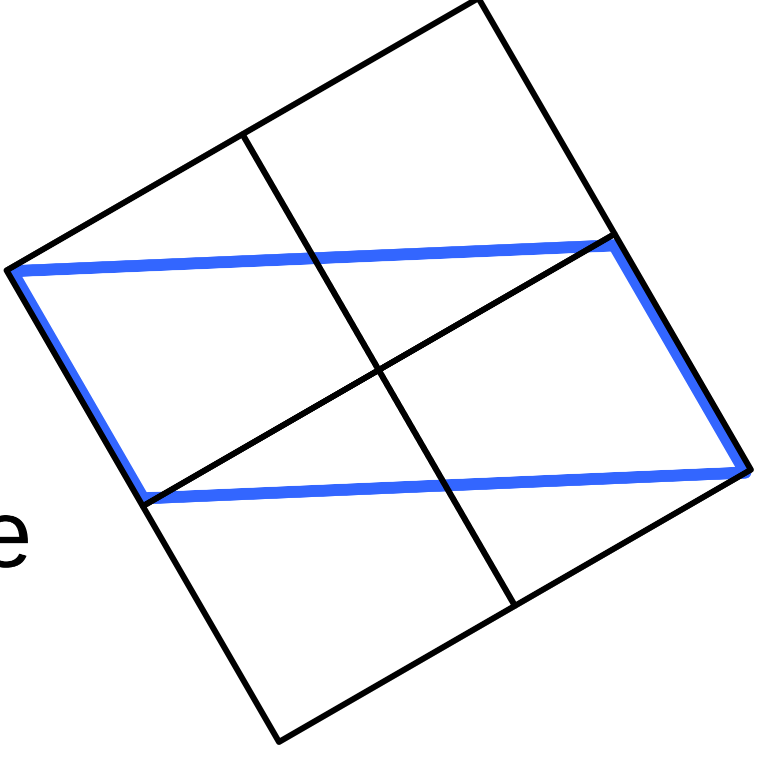
Same size?


Same size



Same size



Same size

Toggle between this slide and
the ones before and after

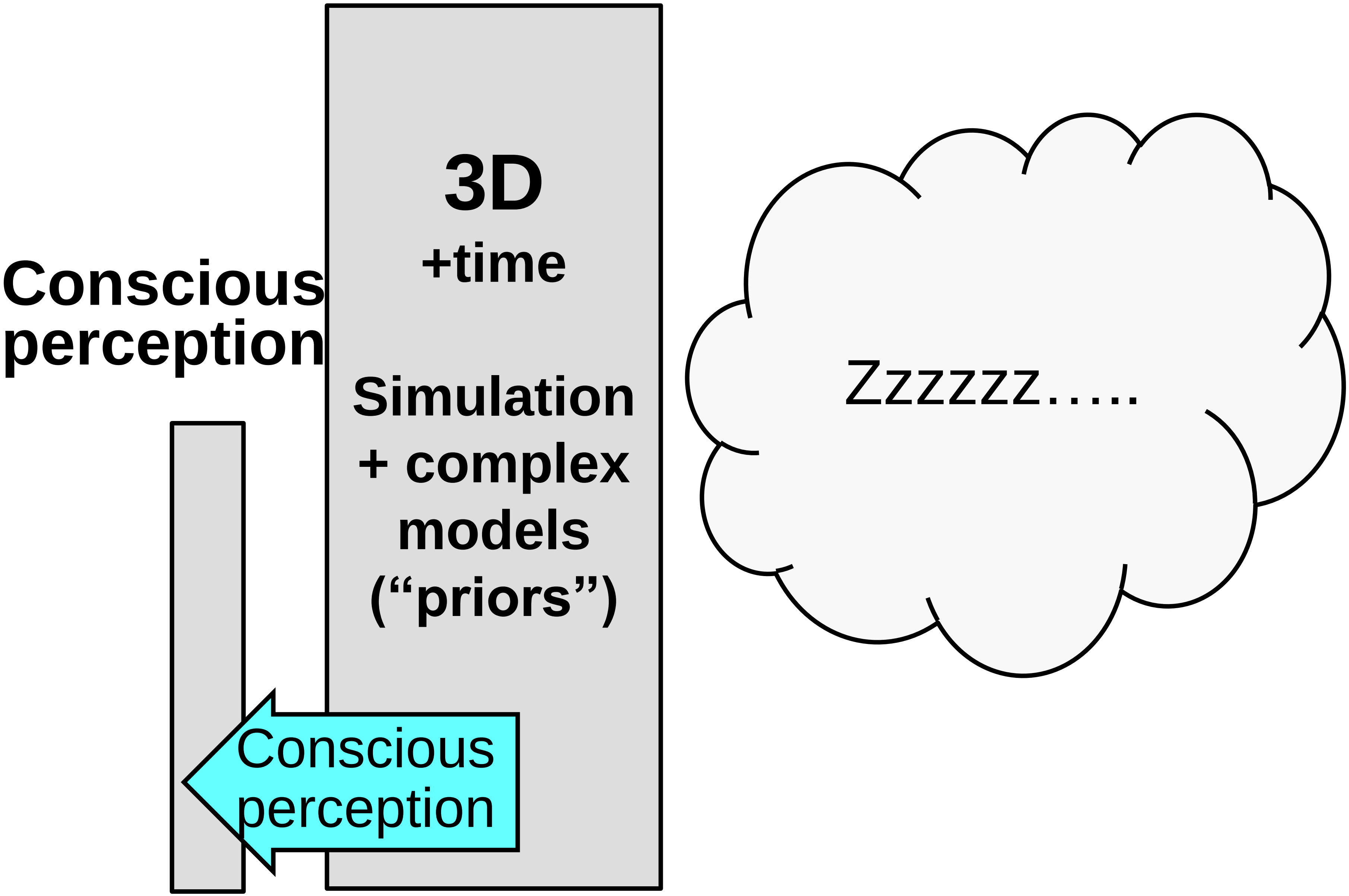
Even when you “know” they are
the same, they appear different

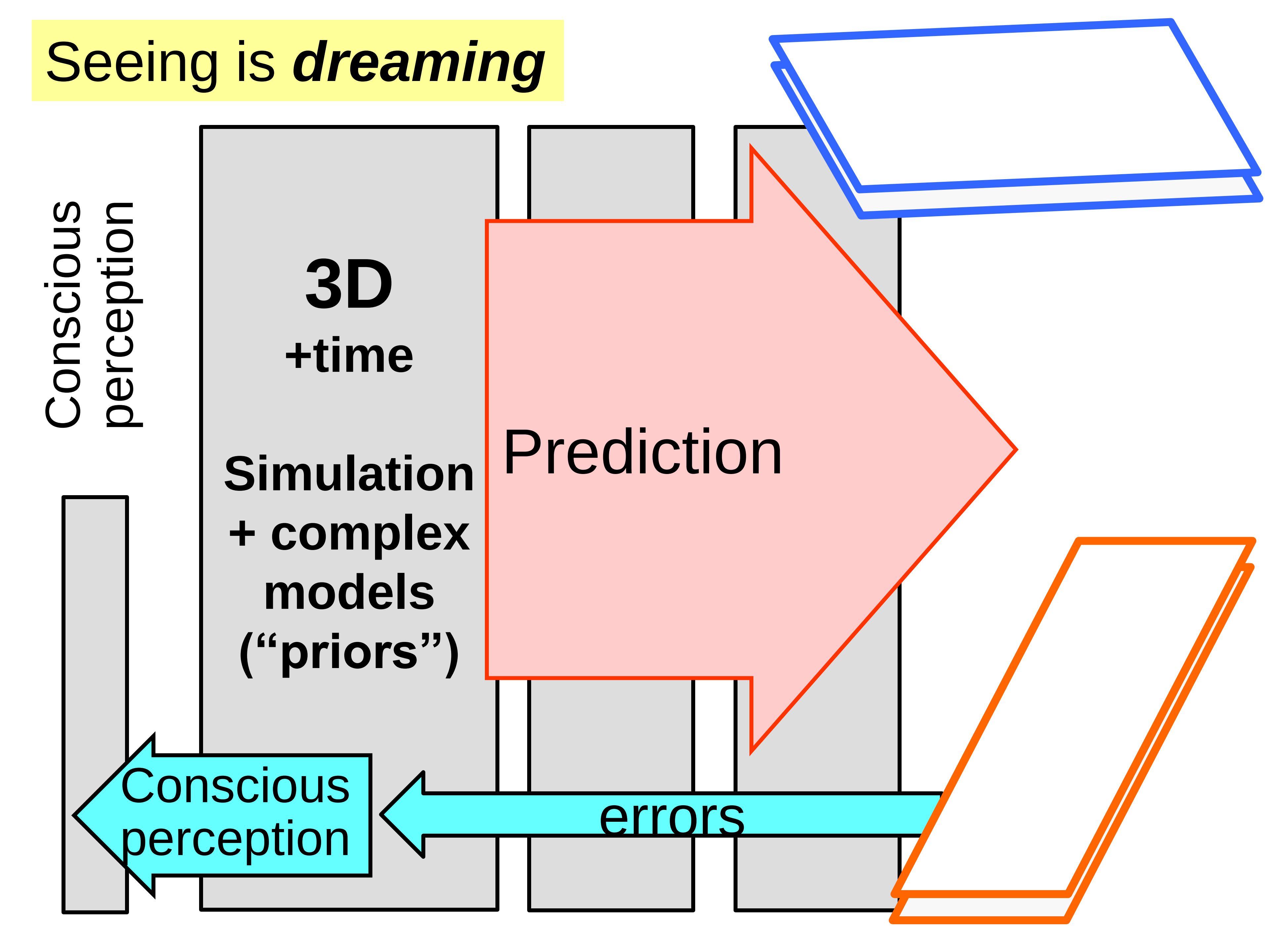
Same size?

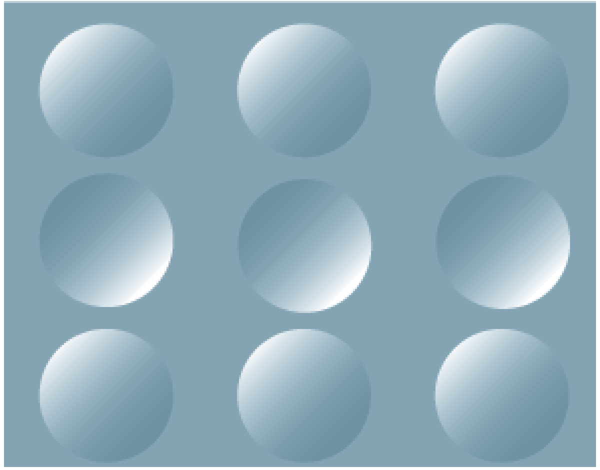
Vision: evolved for complex simulation and control, not 2d static pictures

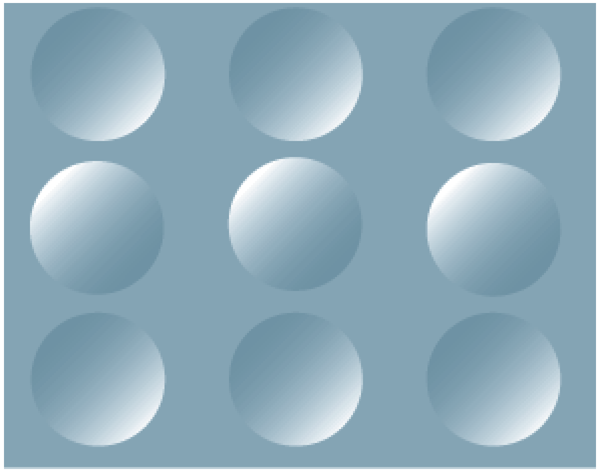
Even when you “know” they are the same, they appear different

Seeing is ***dreaming***

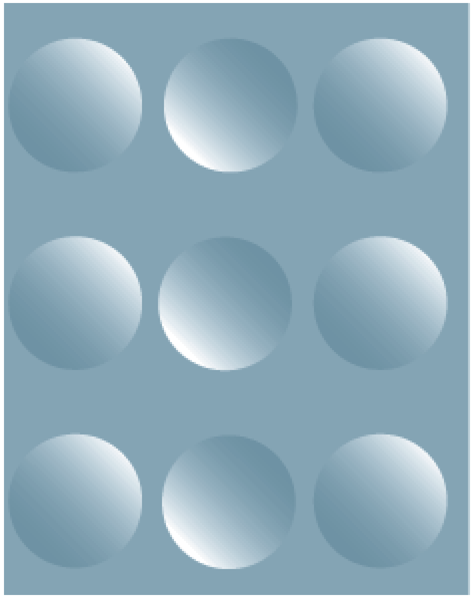


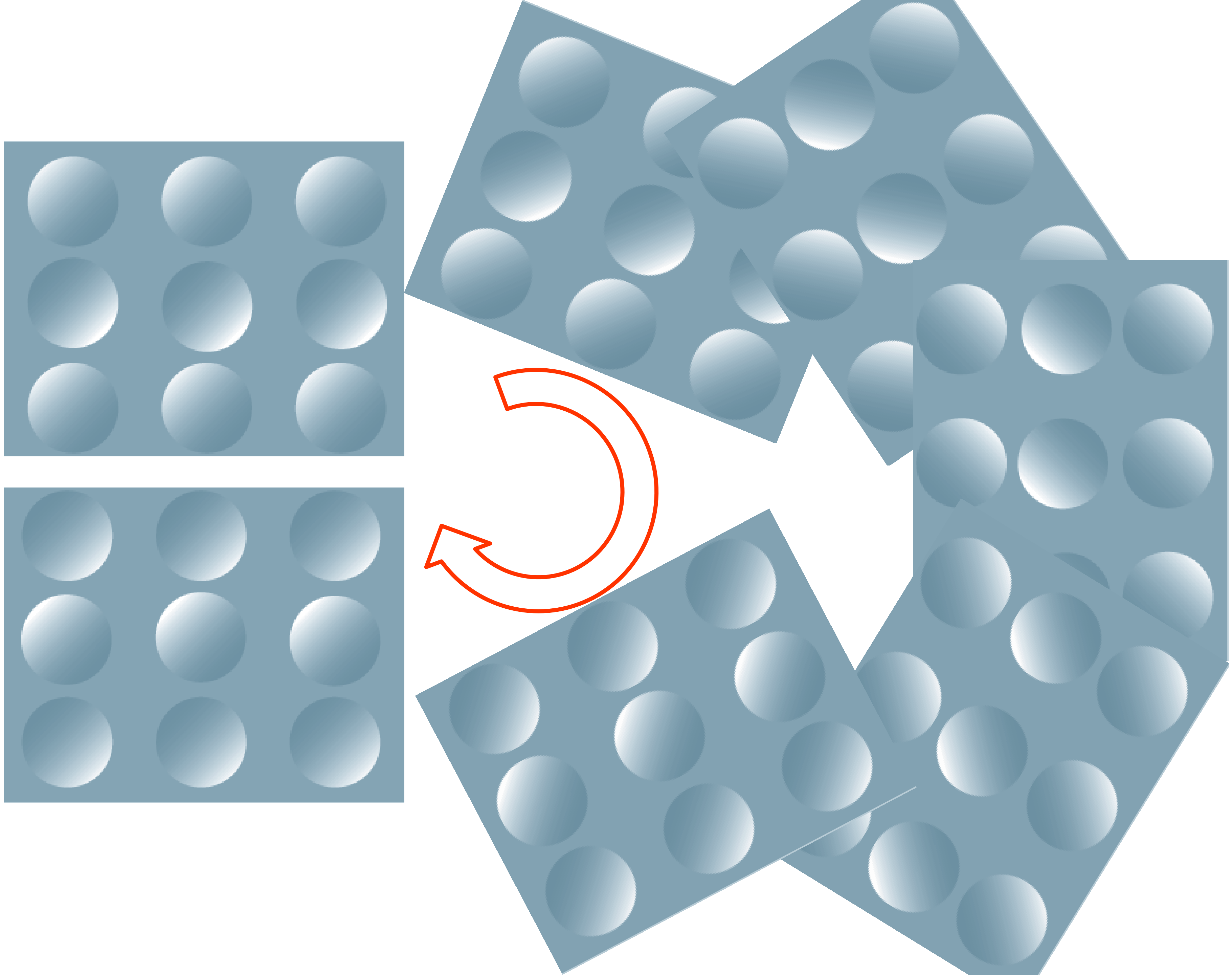

Seeing is ***dreaming***
Conscious perception
3D
+time
Simulation
+ complex
models
("priors")
Prediction
Conscious perception
errors





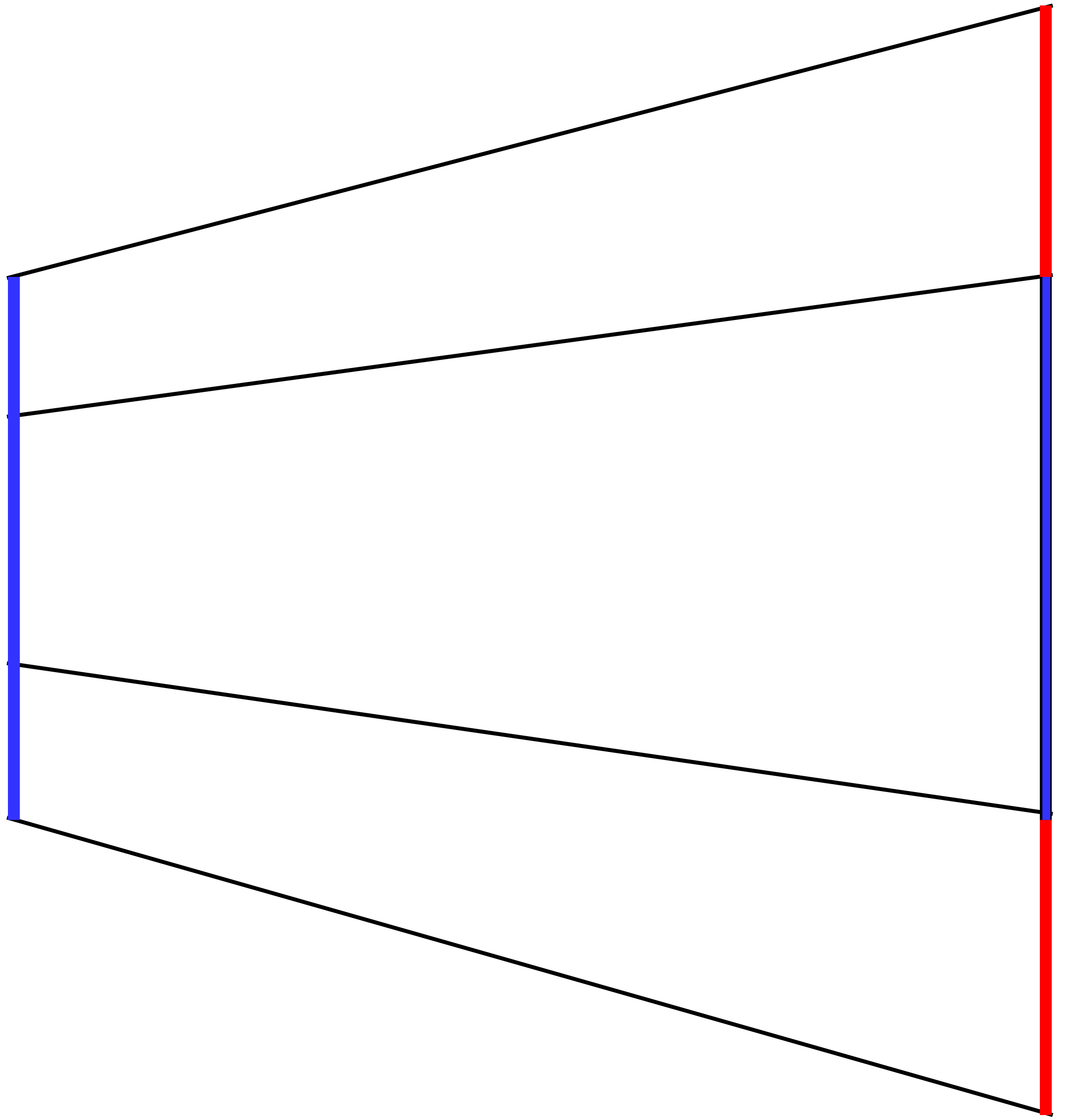
Inferring shape from shading



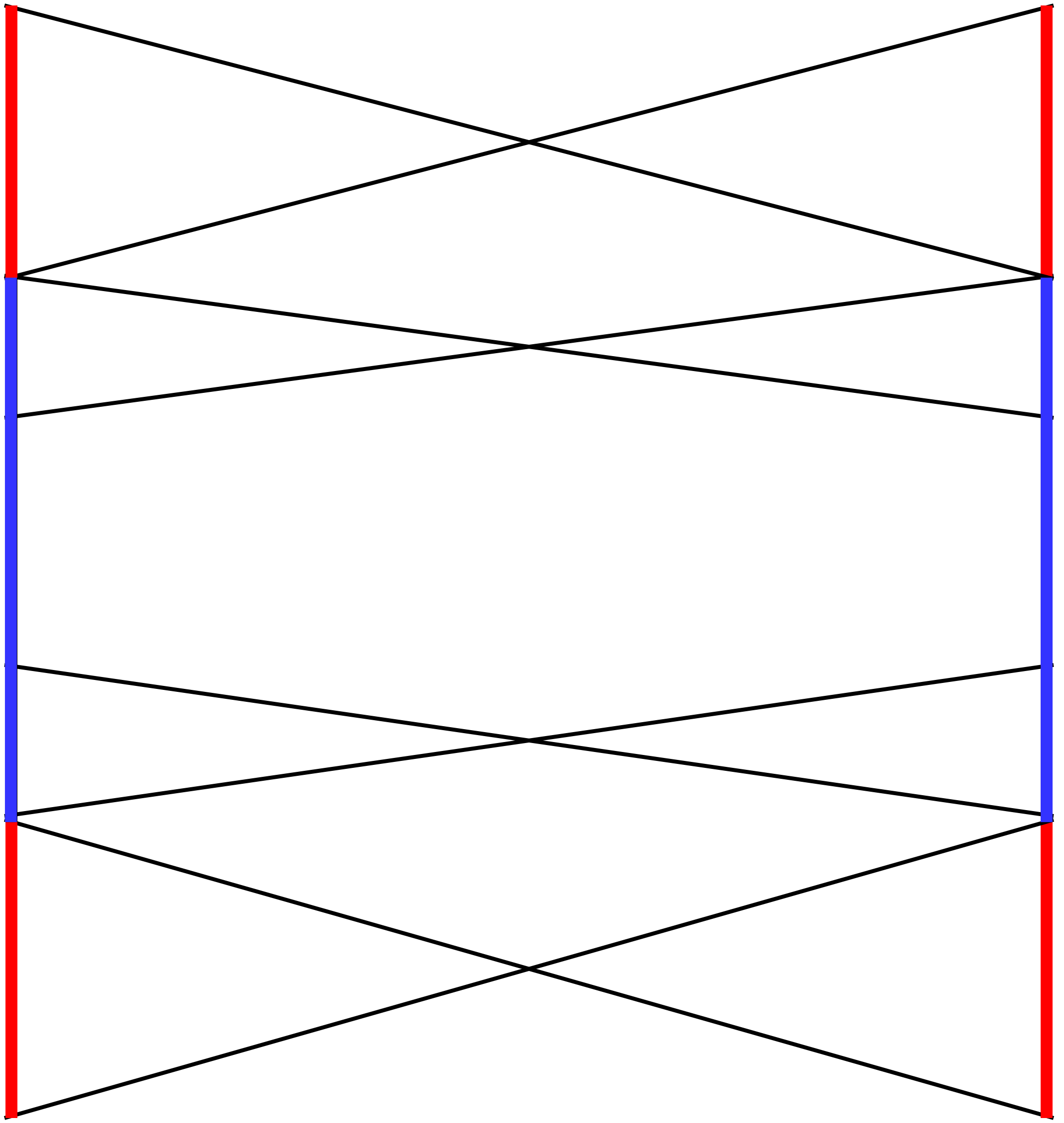


Which blue line is longer?

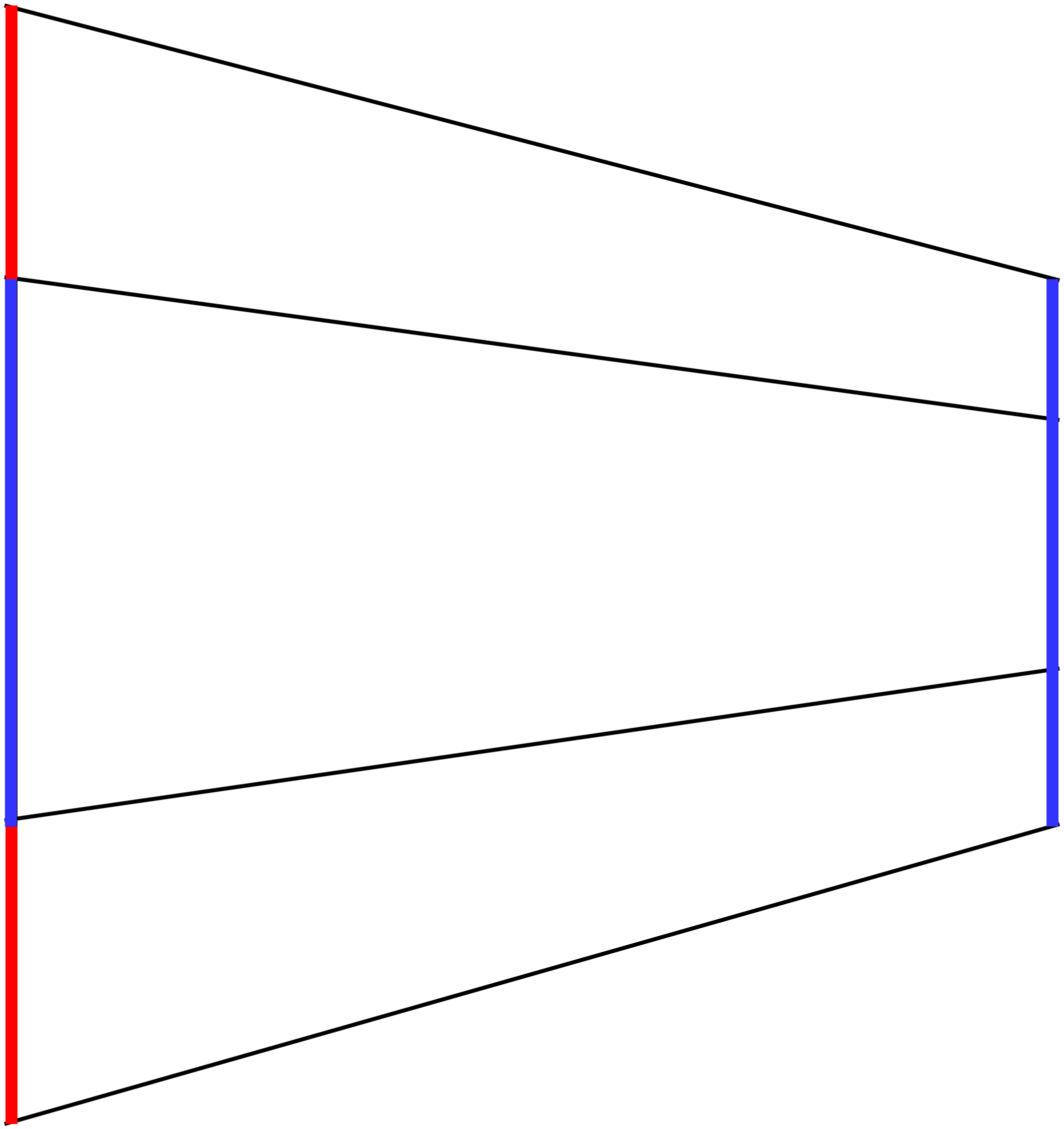
Which blue line is longer?



Which blue line is longer?

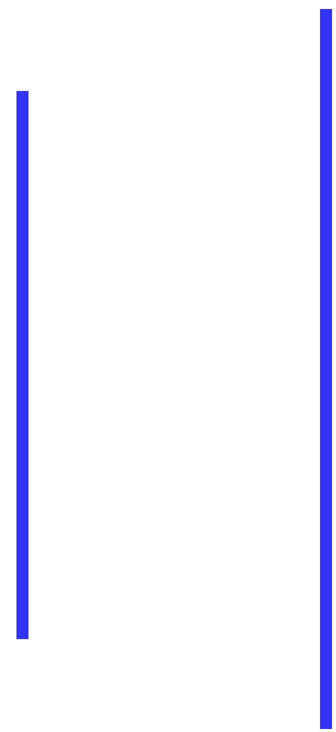


Which blue line is longer?

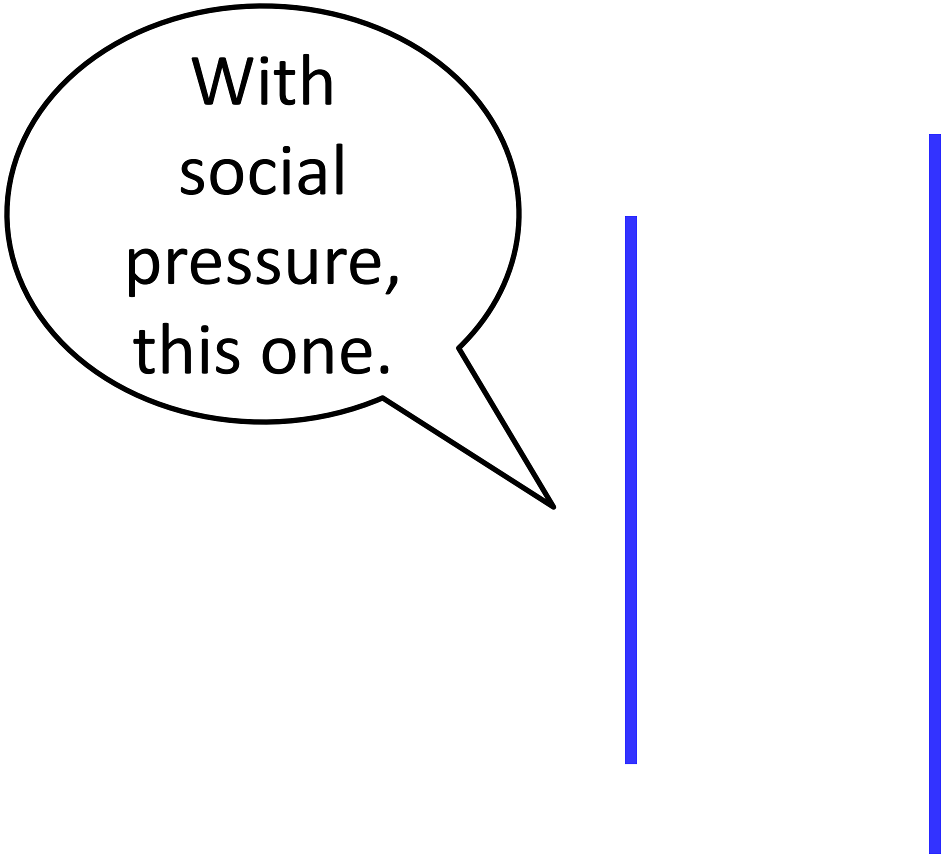


Which blue line is longer?

Which blue line is longer?



Which blue line is longer?

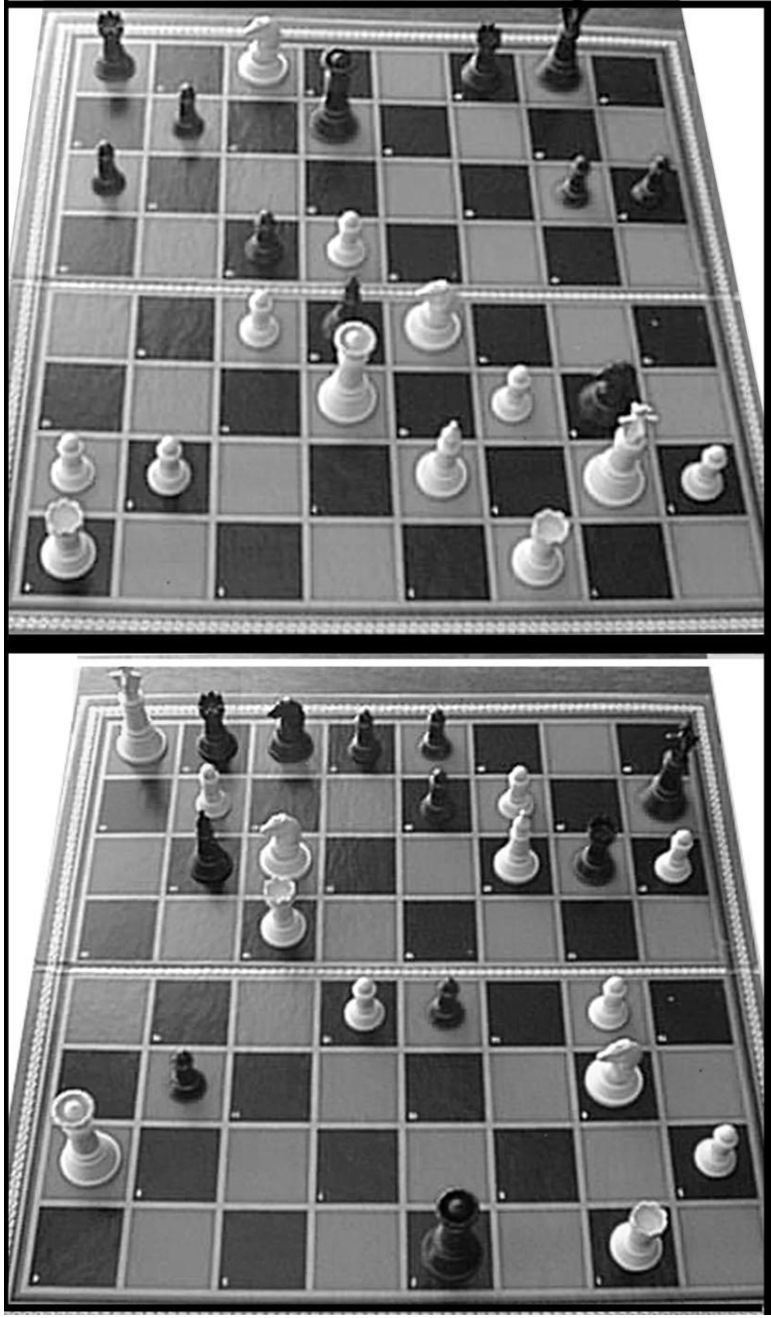


Standard social psychology experiment.


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

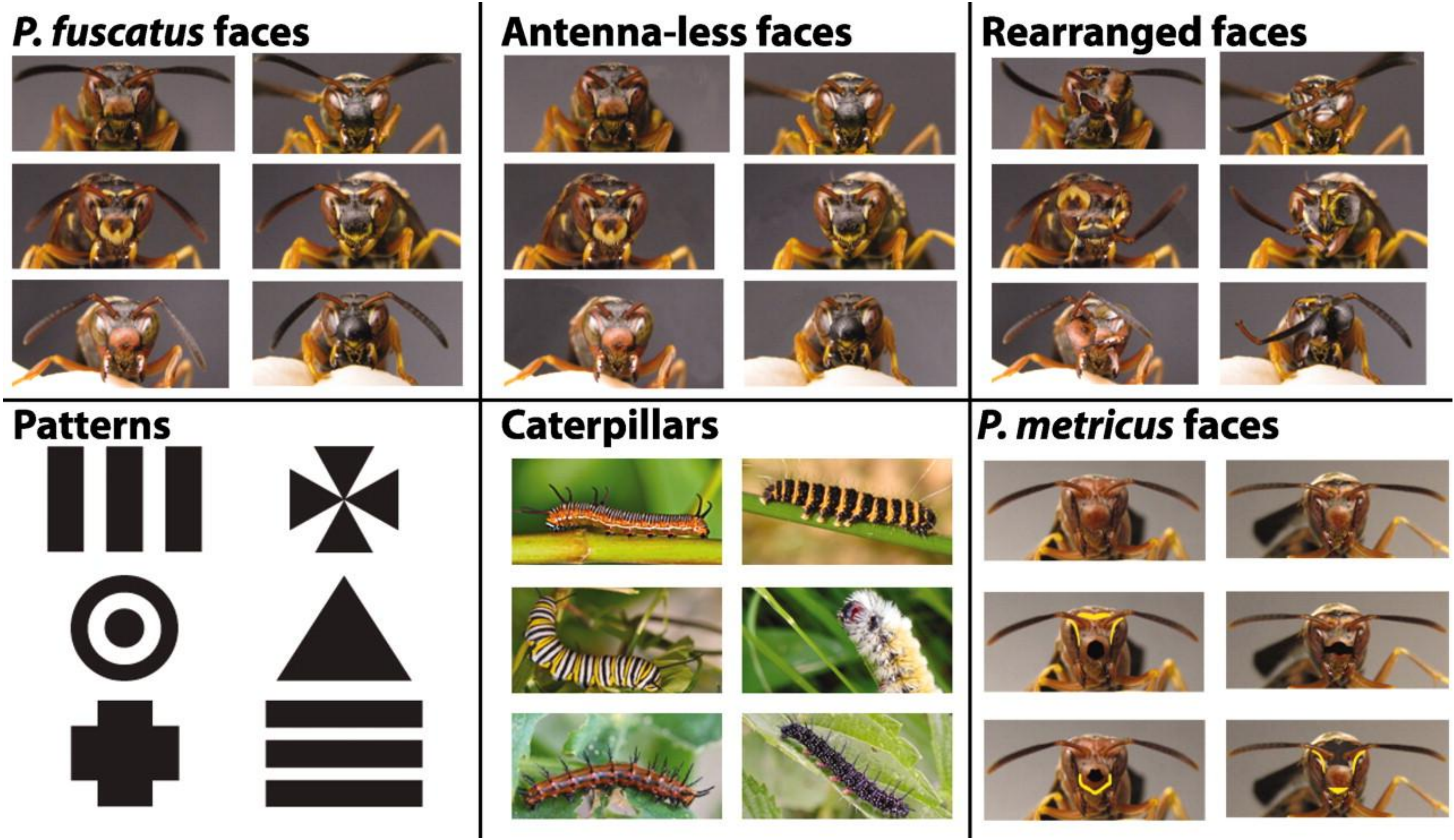
We demonstrate that the evolution of facial recognition in wasps is associated with specialized face-learning abilities. *Polistes fuscatus* can differentiate among normal wasp face images more rapidly and accurately than nonface images or manipulated faces. A close relative lacking facial recognition,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

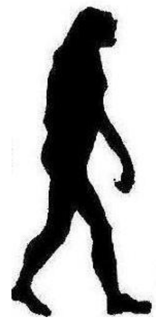


M J Sheehan, E A Tibbetts Science 2011;334:1272-1275

Published by AAAS

Science AAAS

weak
fragile
slow



Human evolution

hands
feet
skeleton
muscle
skin
gut
long helpless childhood

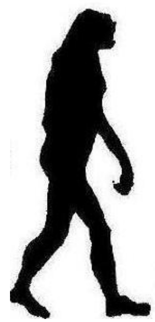
All very different.

Apes

How is this progress?

strong
robust
fast

Homo Erectus?



hands
feet
skeleton
muscle
skin
gut

Roughly modern

Very fragile

weak
fragile

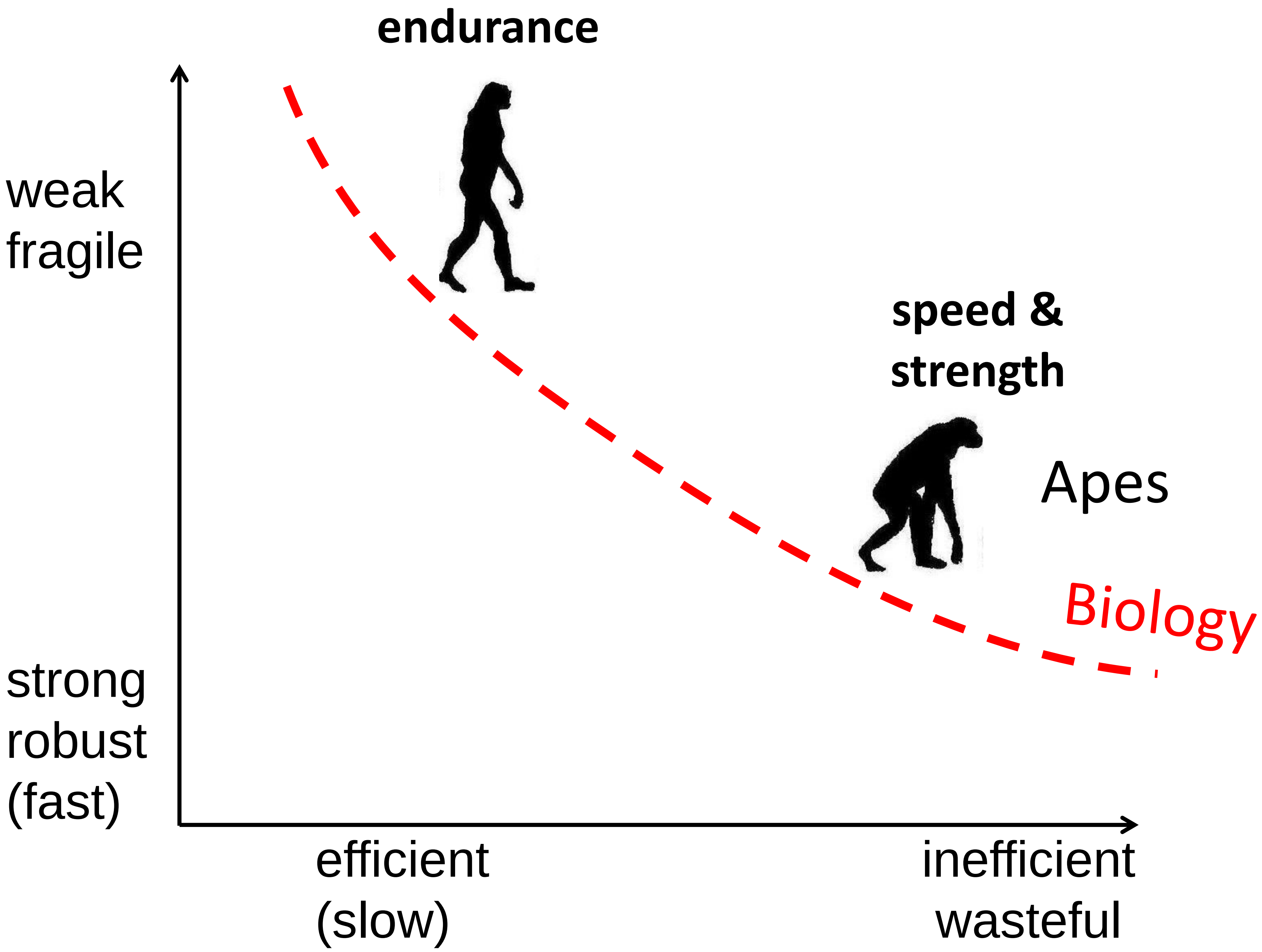
This much seems pretty consistent among experts regarding circa 1.5-2Mya

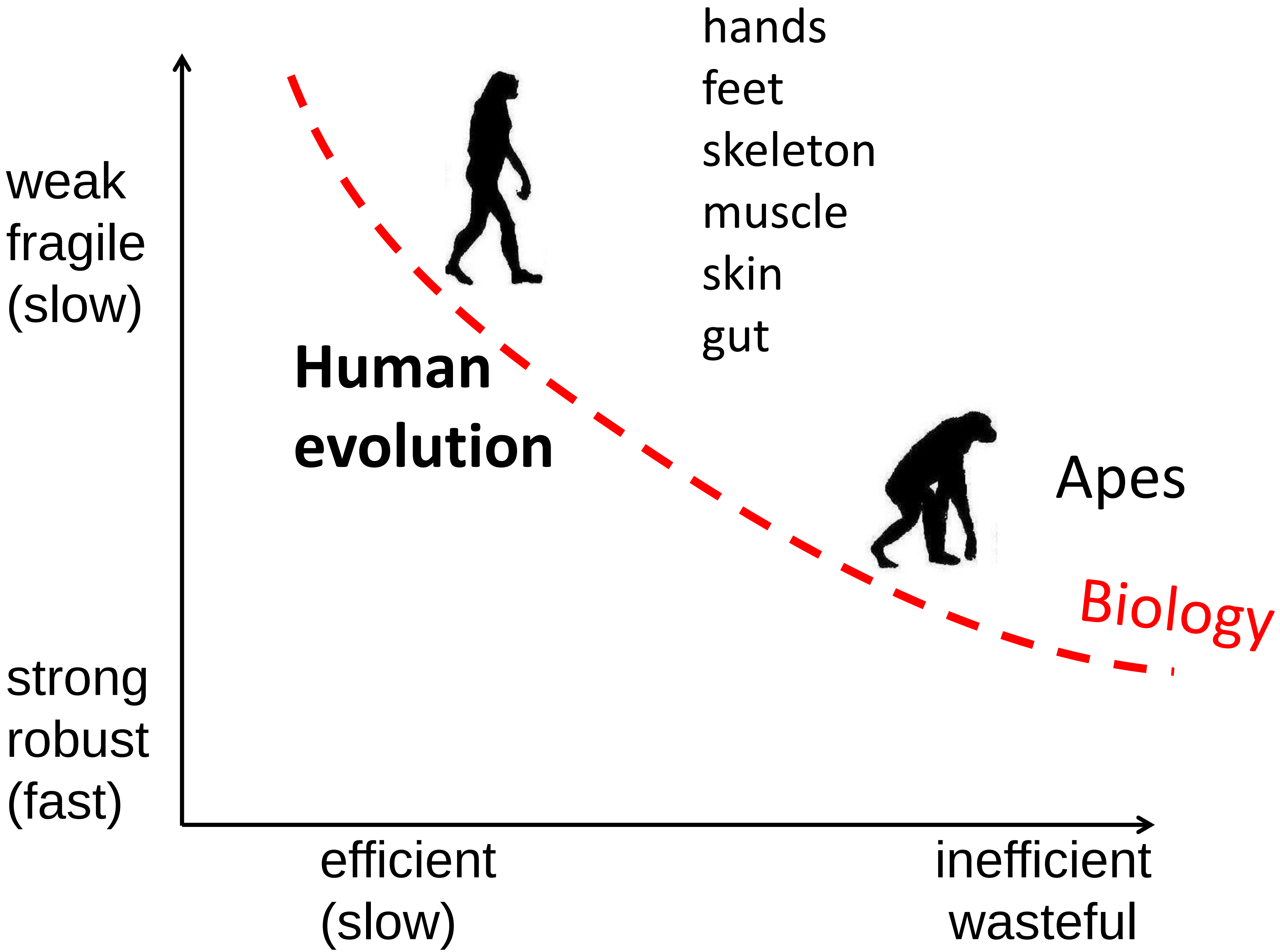
strong
robust

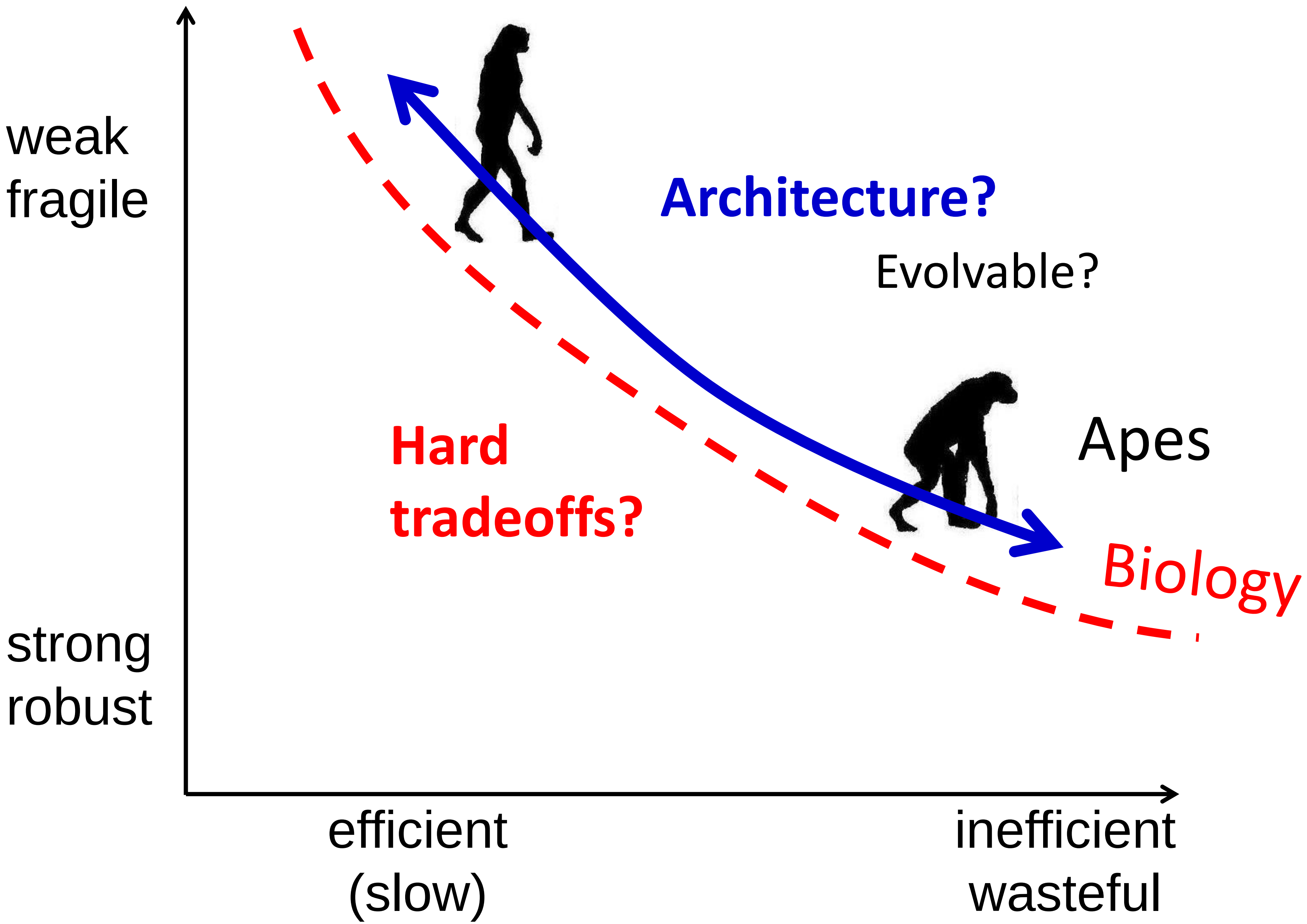
So how did H. Erectus survive and expand globally?

efficient
(slow)

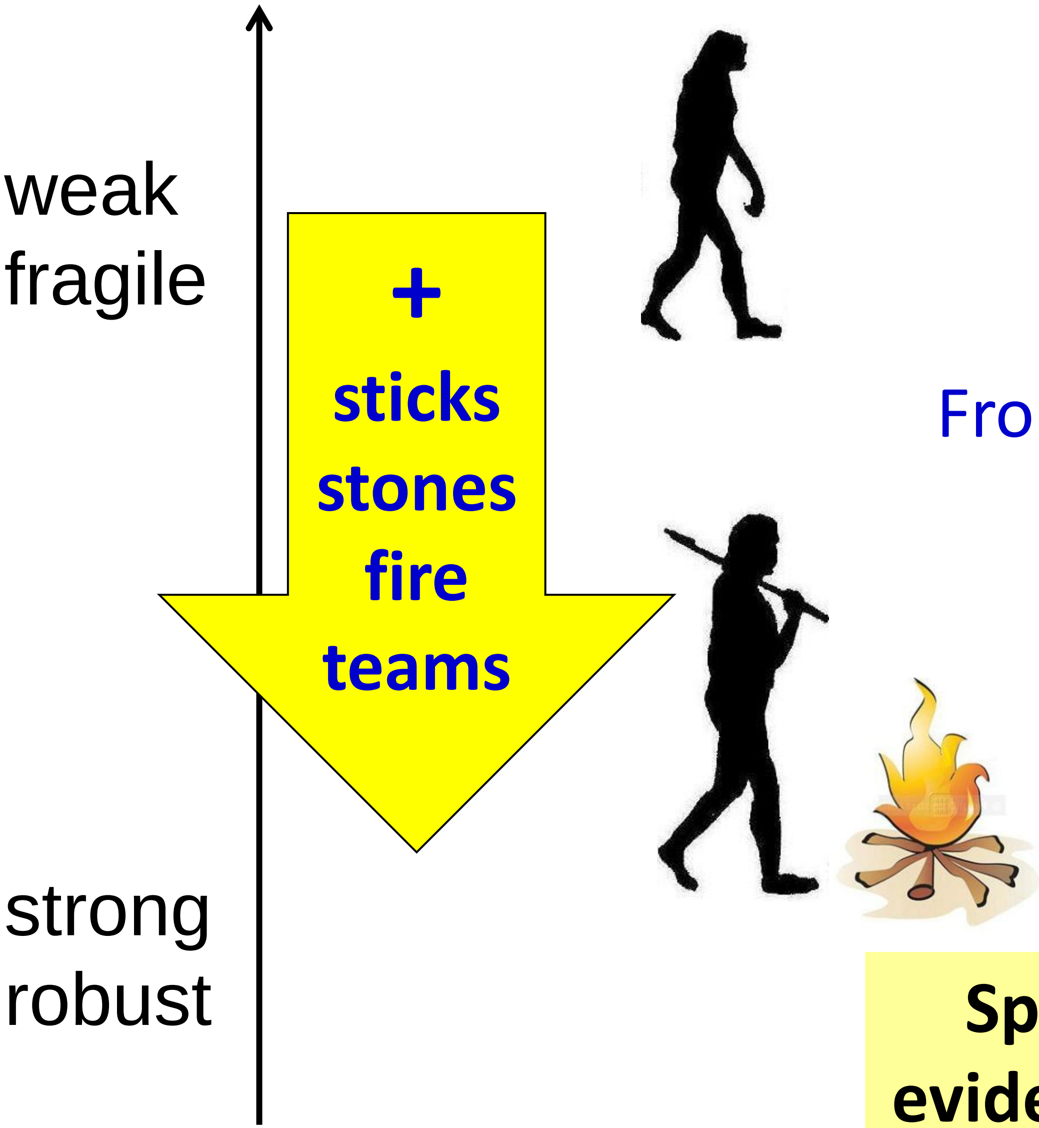
inefficient
wasteful


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

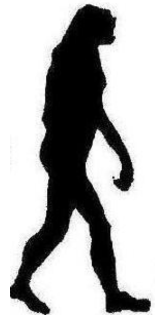


efficient
(slow)

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

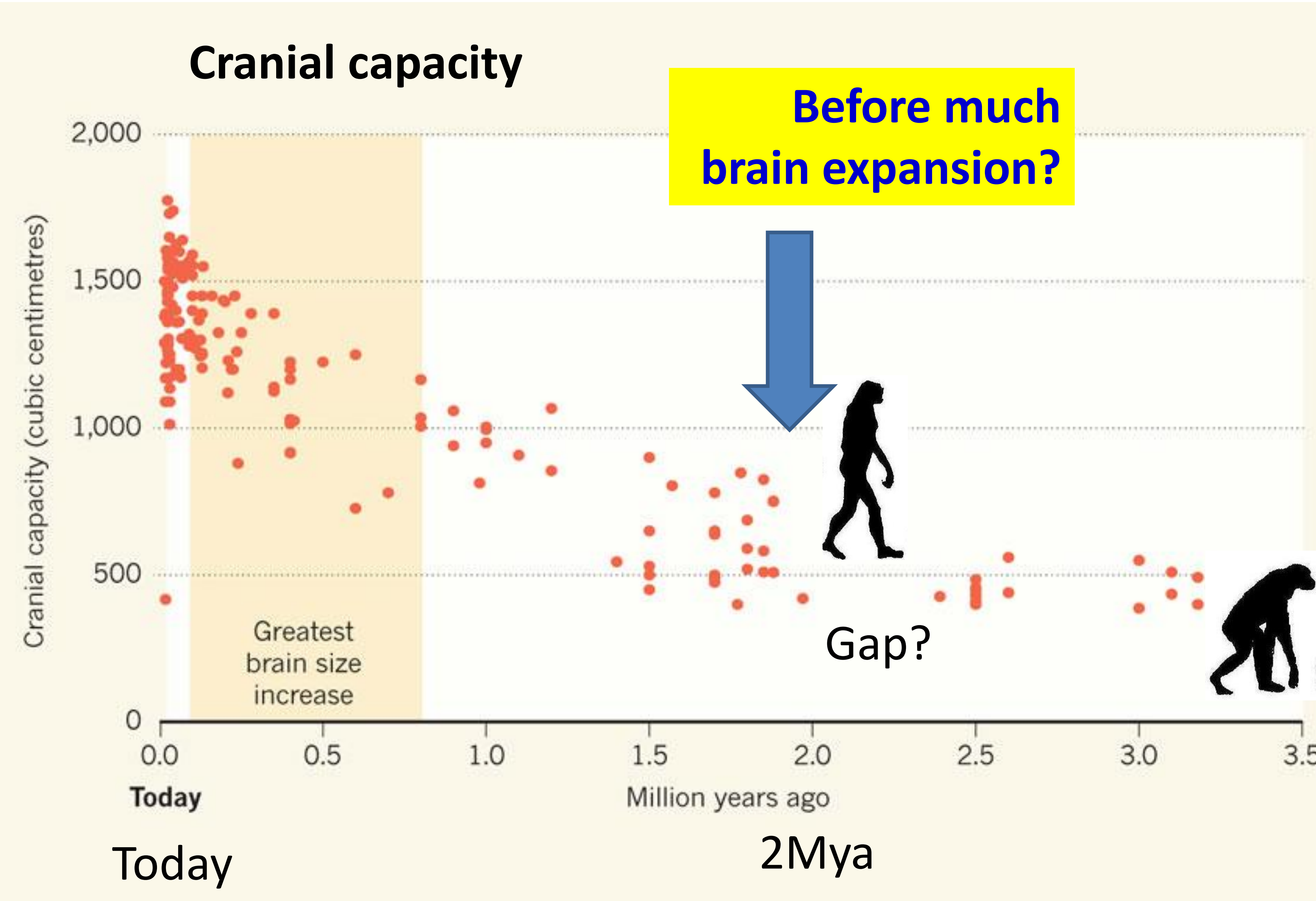
From weak prey to invincible predator

Before much brain expansion?

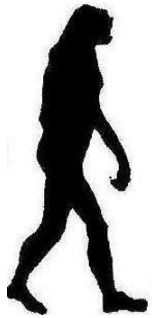
strong
robust

Plausible but speculation?

efficient
(slow)


Cranial capacity
Before much brain expansion?
2,000
1,500
1,000
500
0
Cranial capacity (cubic centimetres)
Greatest brain size increase
Gap?
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:
Our physiology, technology, and brains have co-evolved

From weak prey to invincible predator

\+
sticks
stones
fire

Probably true no matter what

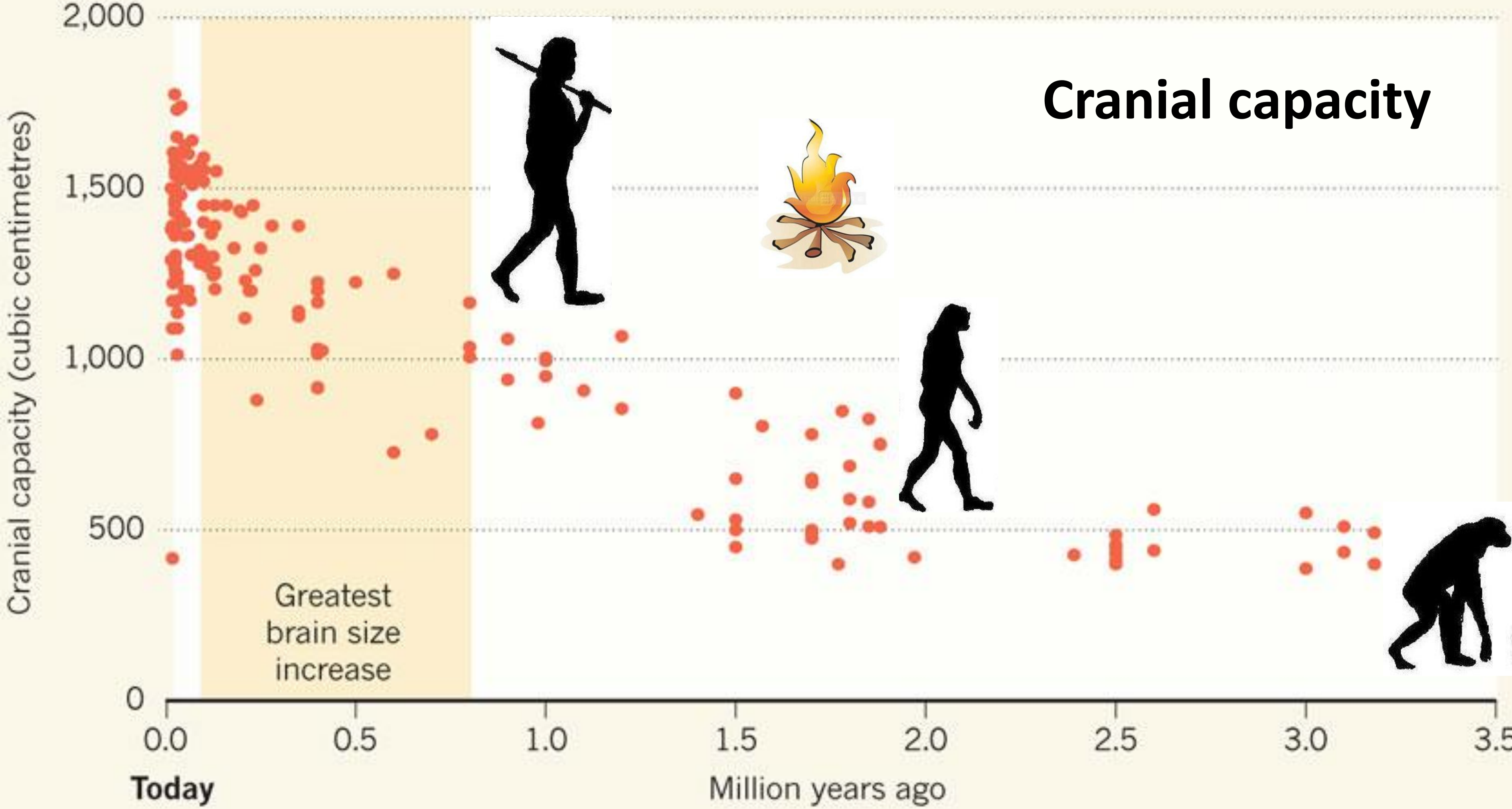
strong
robust

Before much brain expansion?

efficient
(slow)

Huge implications.

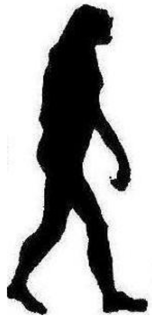
Cranial capacity



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.

+
sticks
stones
fire

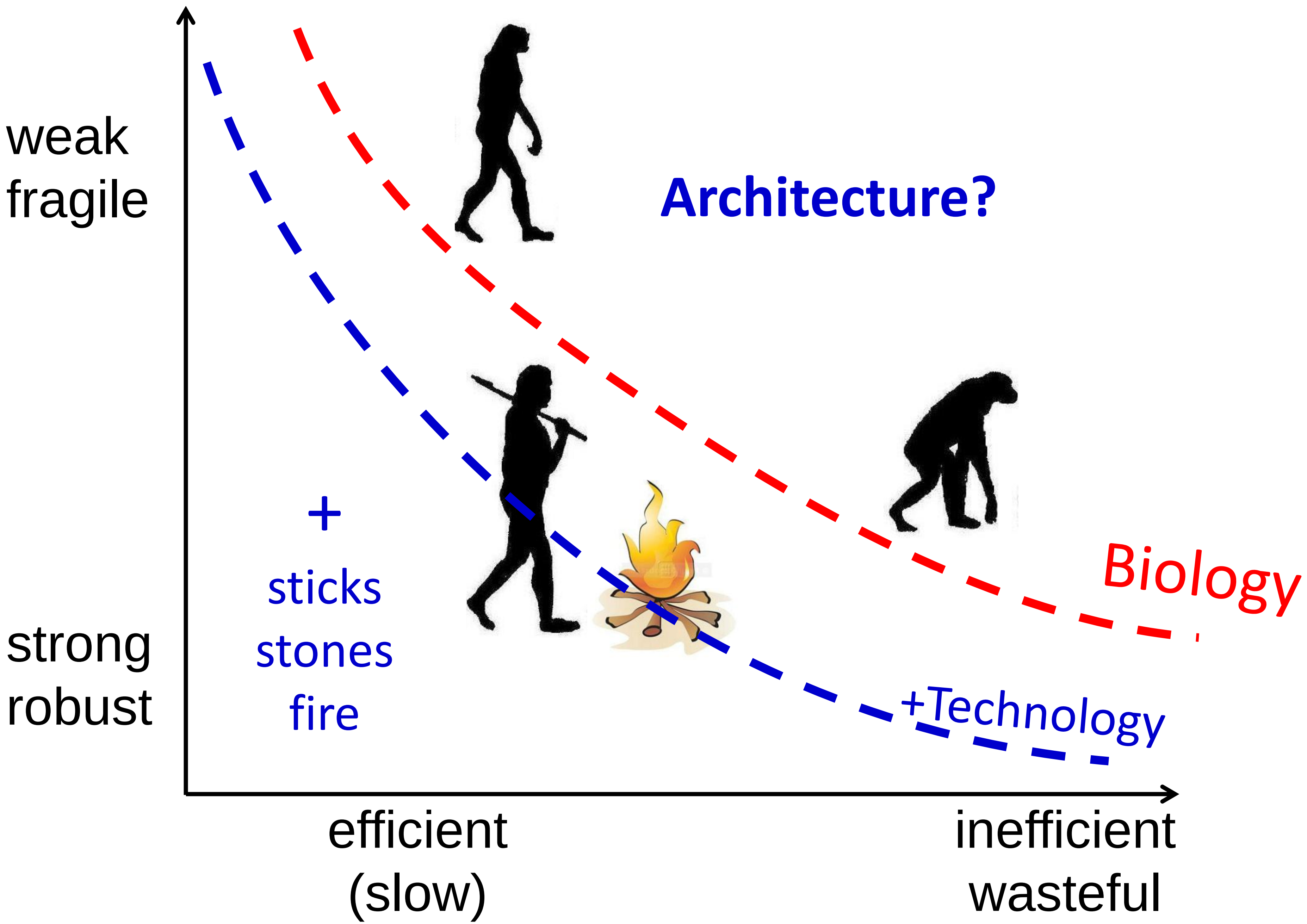
From weak prey
to invincible
predator

strong
robust

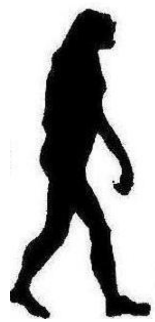
Before much
brain expansion?

efficient
(slow)

Huge
implications.


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

weak
fragile



hands
feet
skeleton
muscle
skin
gut

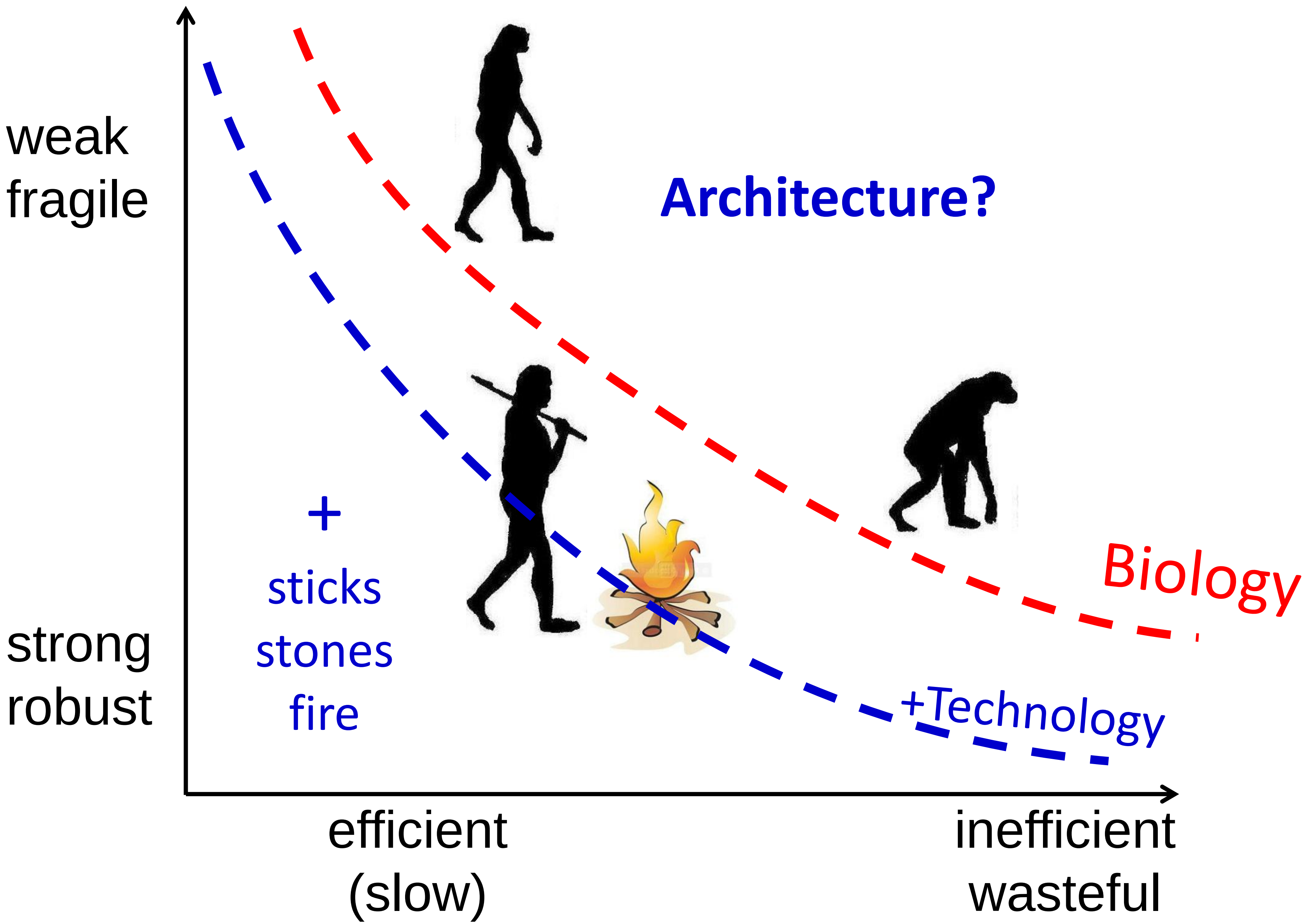
strong
robust

+
sticks
stones
fire

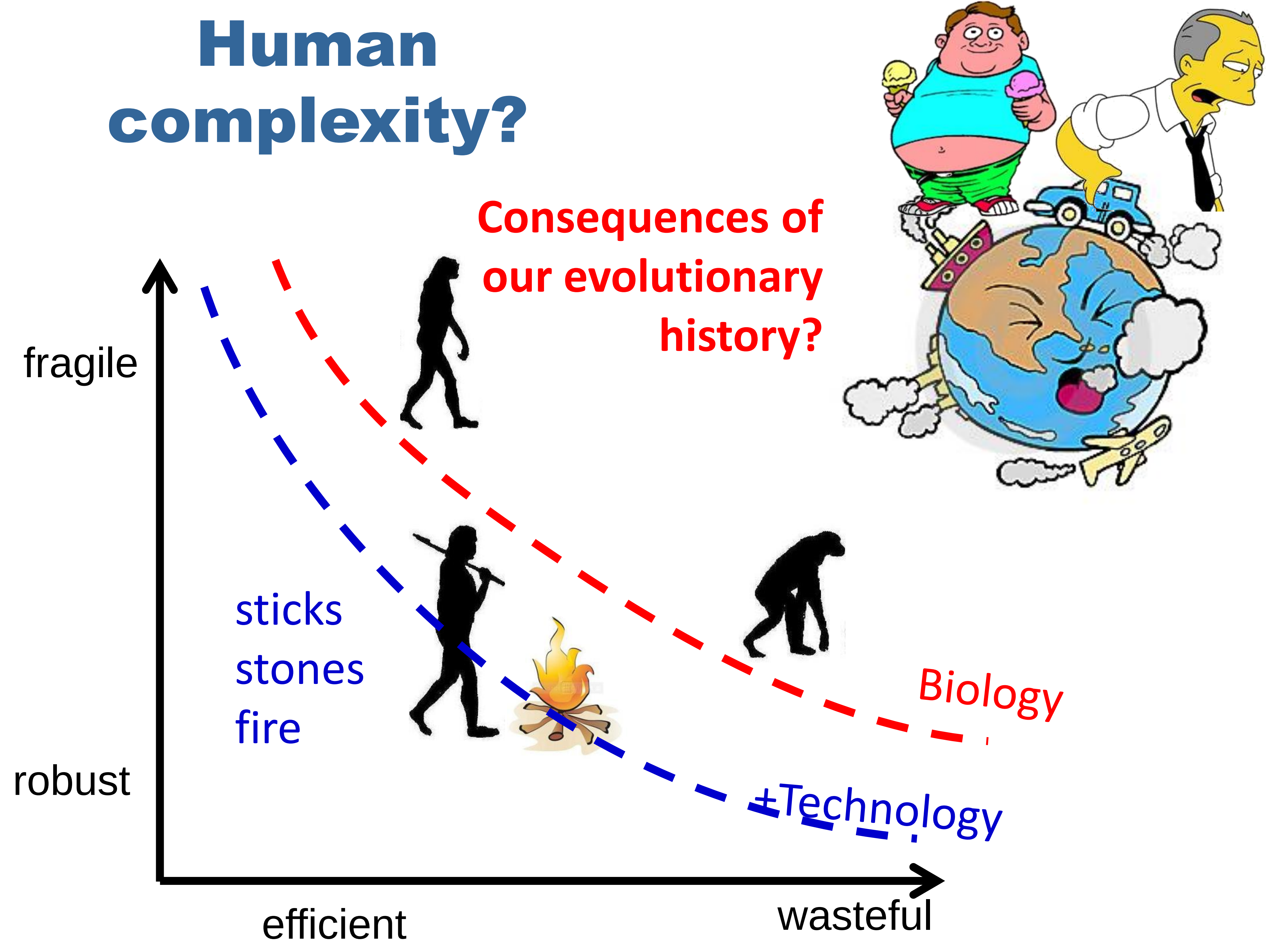
From weak prey
to invincible
predator

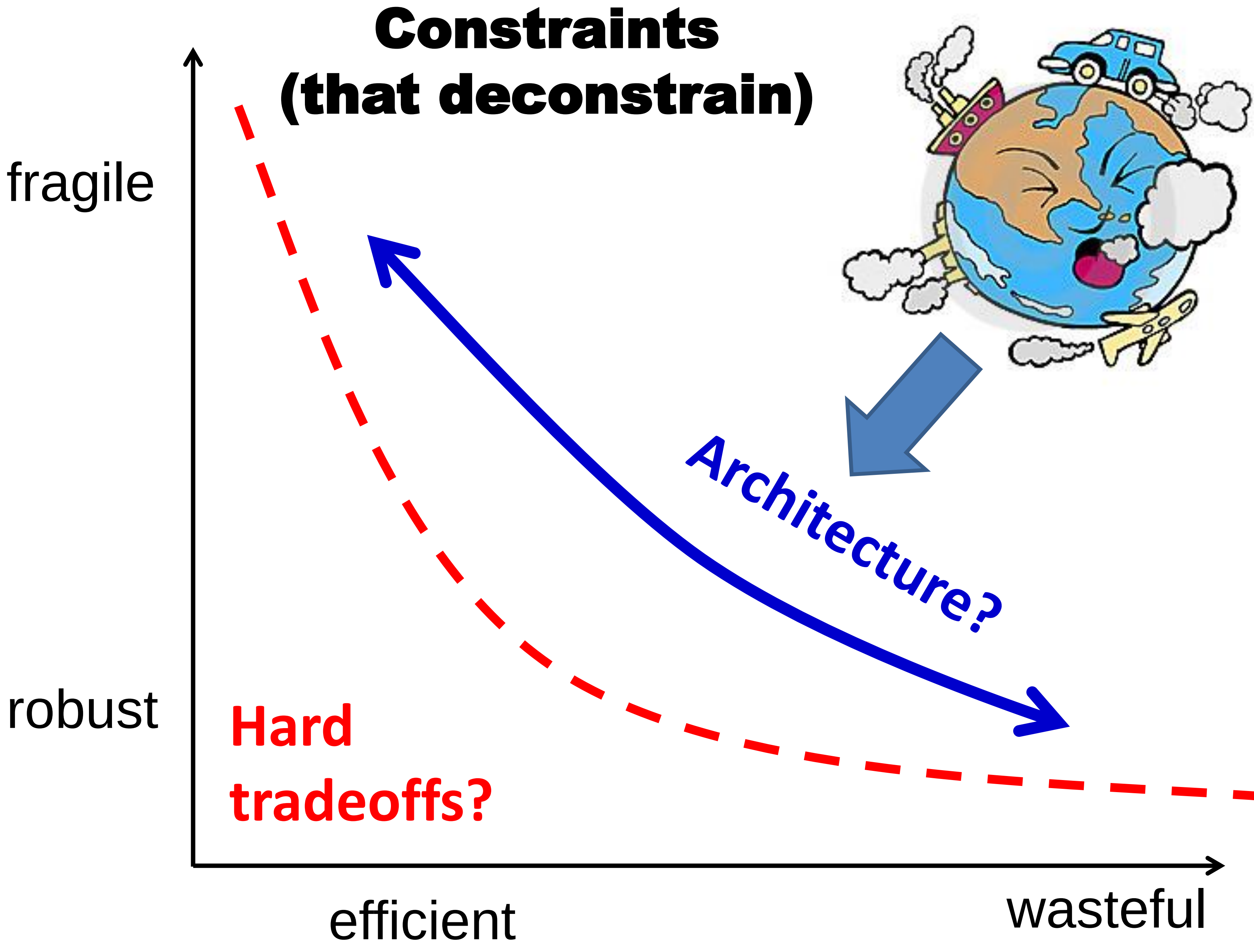
efficient
(slow)

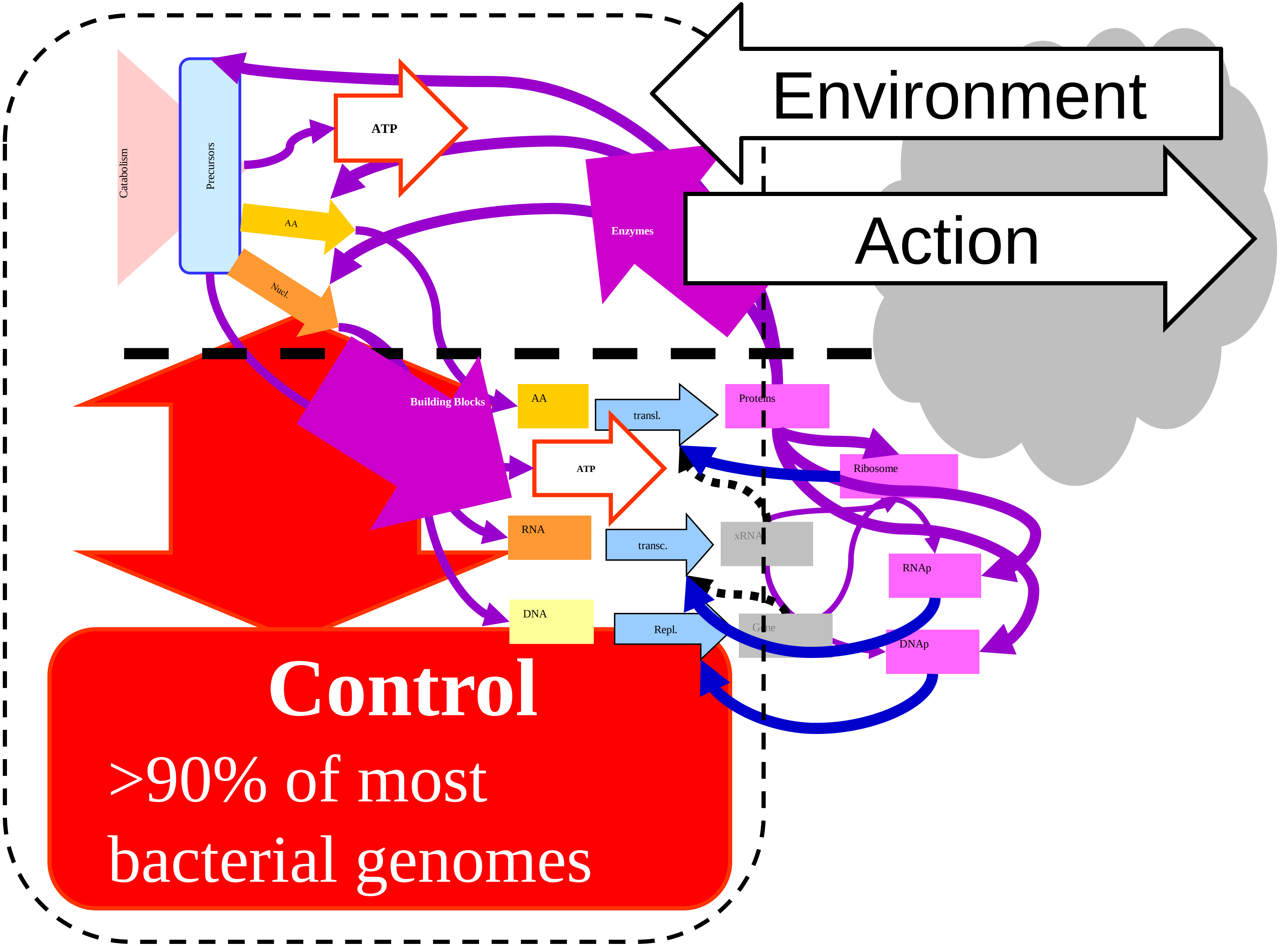
Before much
brain expansion?

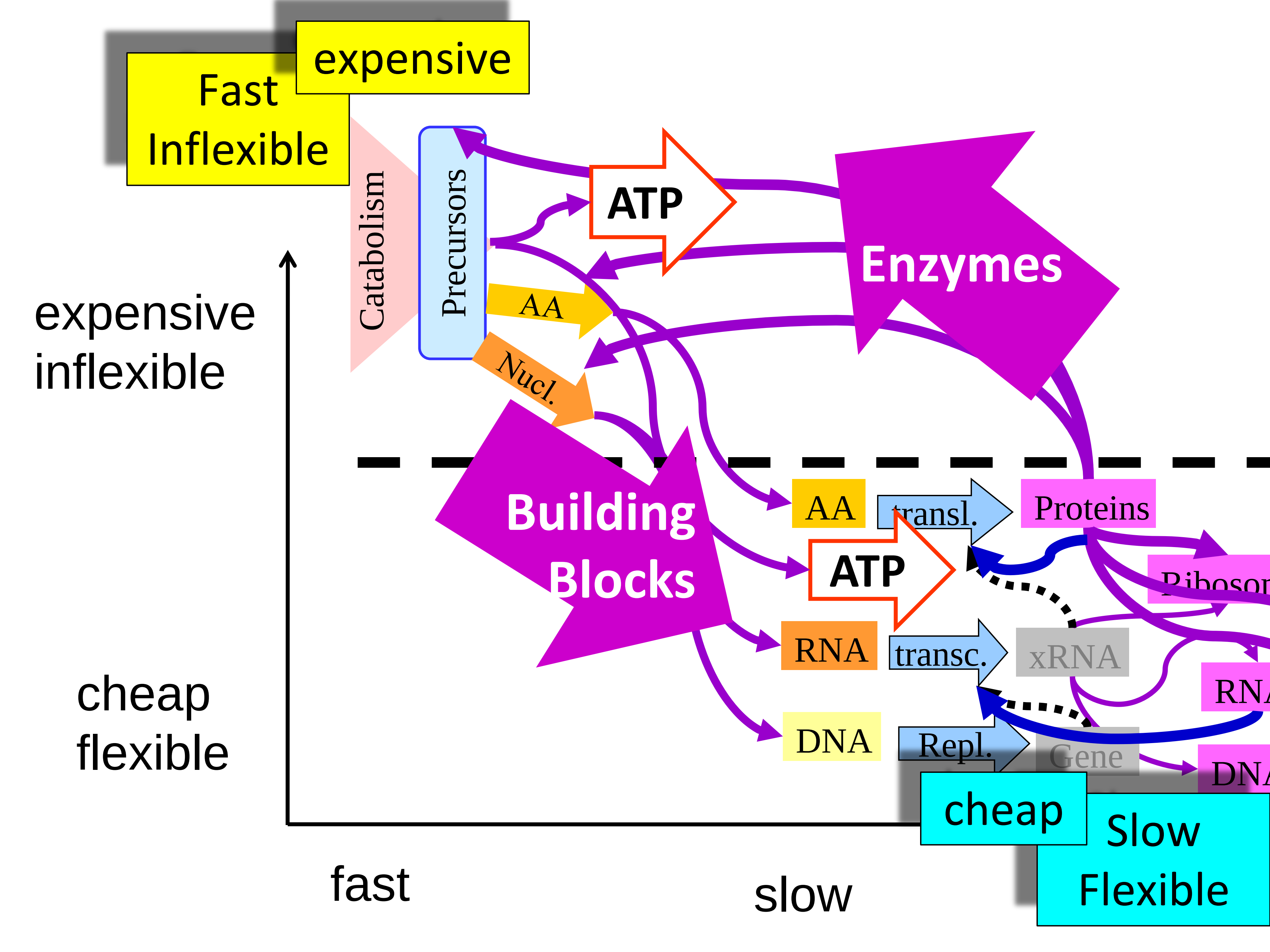

weak
fragile
Architecture?
+
sticks
stones
fire
strong
robust
Biology
+Technology
efficient
(slow)
inefficient
wasteful

Human complexity?

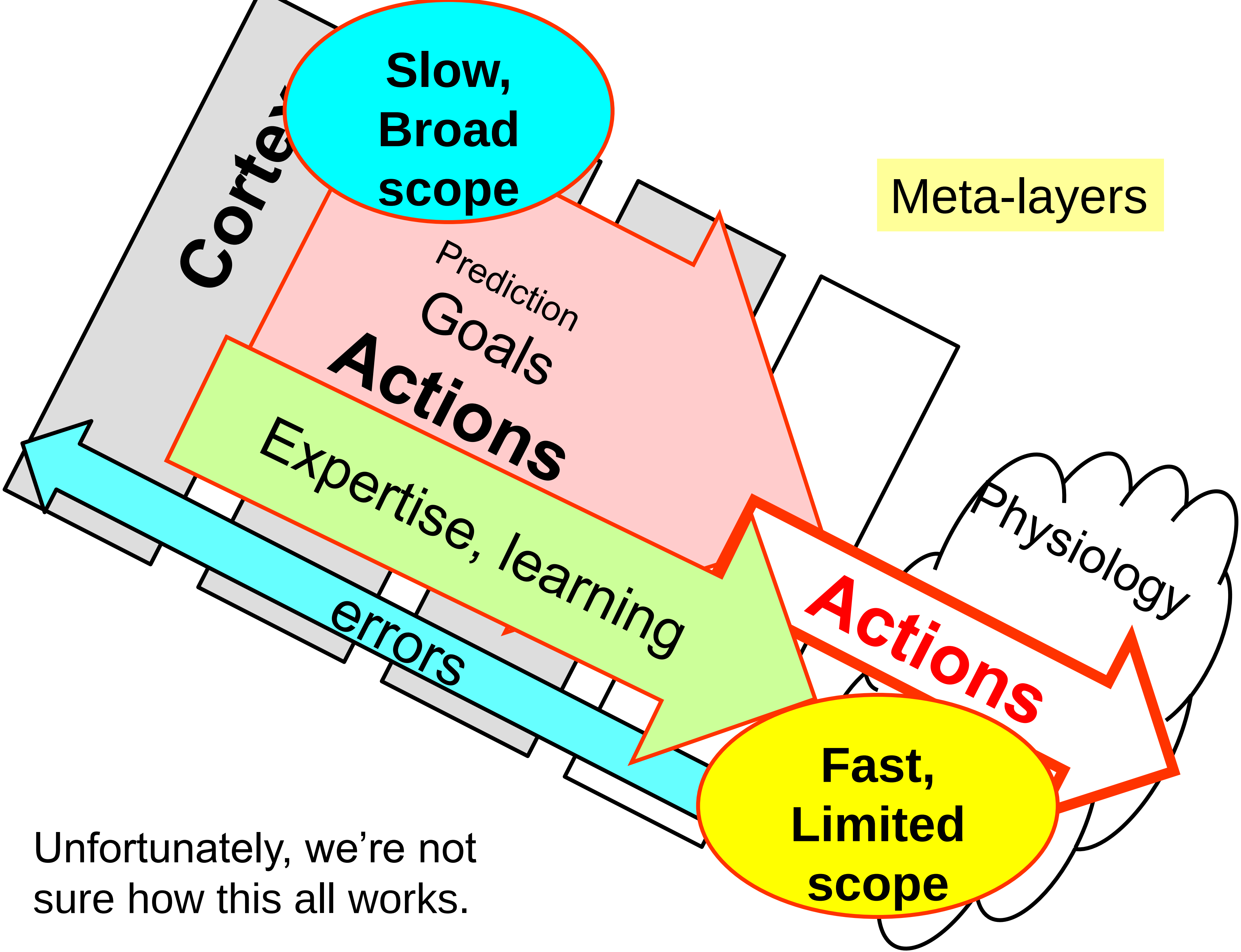



Constraints
(that deconstrain)
fragile
robust
Architecture?
Hard
tradeoffs?
efficient
wasteful

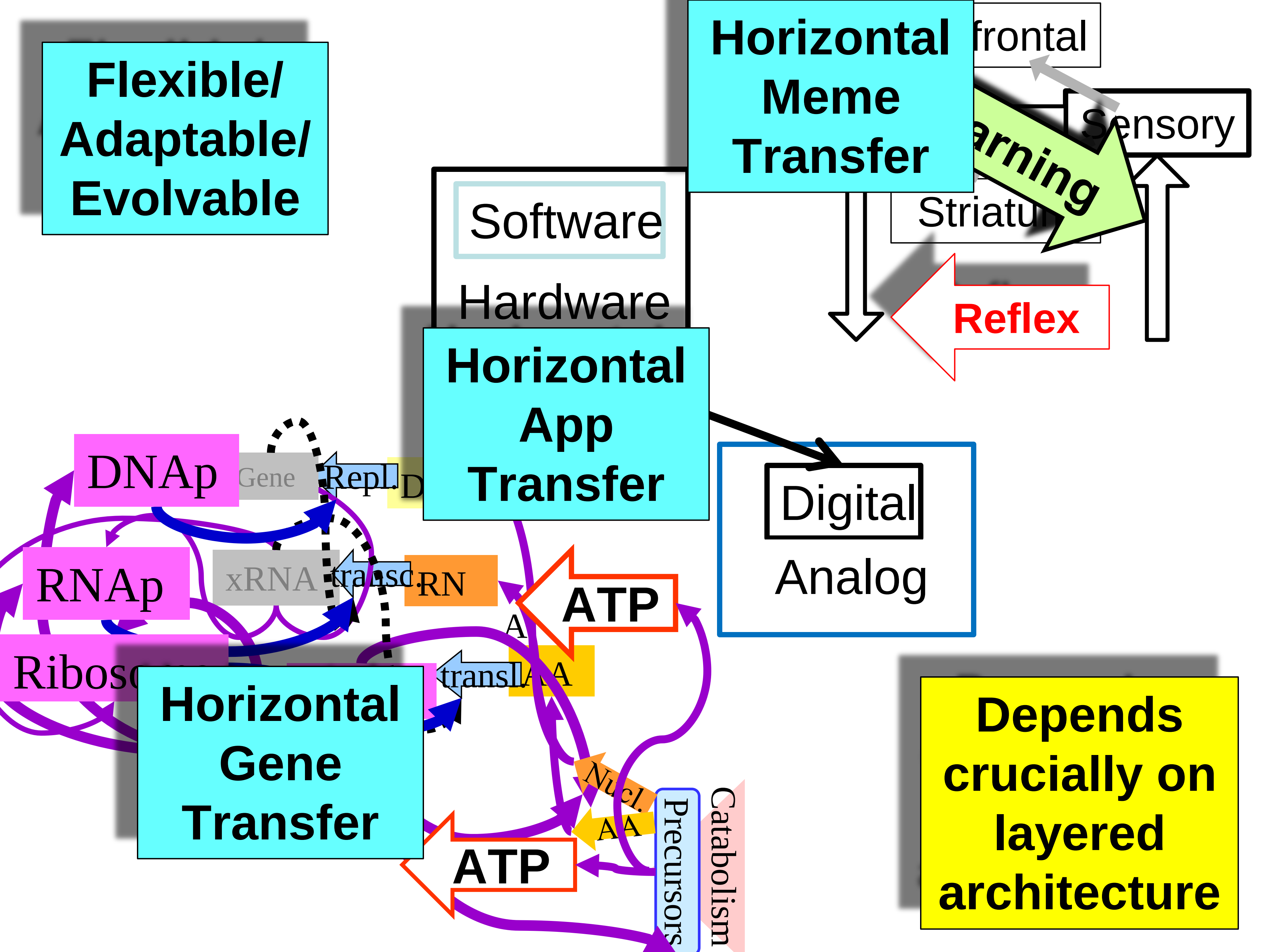

Environment
Action
Catabolism
Precursors
ATP
AA
Nucl.
Enzymes
Building Blocks
AA
transl.
Proteins
ATP
Ribosome
RNA
transc.
xRNA
RNAp
DNA
Repl.
Gene
DNAp
Control
>90% of most
bacterial genomes



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



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



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
Riboso
transl.
AA
Horizontal Gene Transfer
Nucl.
AA
Precursors
Catabolism
ATP
Depends crucially on layered architecture

“New sciences” of “complexity” and “networks”?

Science as
- Pure fashion
- Ideology
- Political
- Evangelical
- Nontech trumps tech

- Edge of chaos
- Self-organized criticality
- Scale-free “networks”
- Creation “science”
- Intelligent design
- Financial engineering
- Risk management
- “Merchants of doubt”
- …

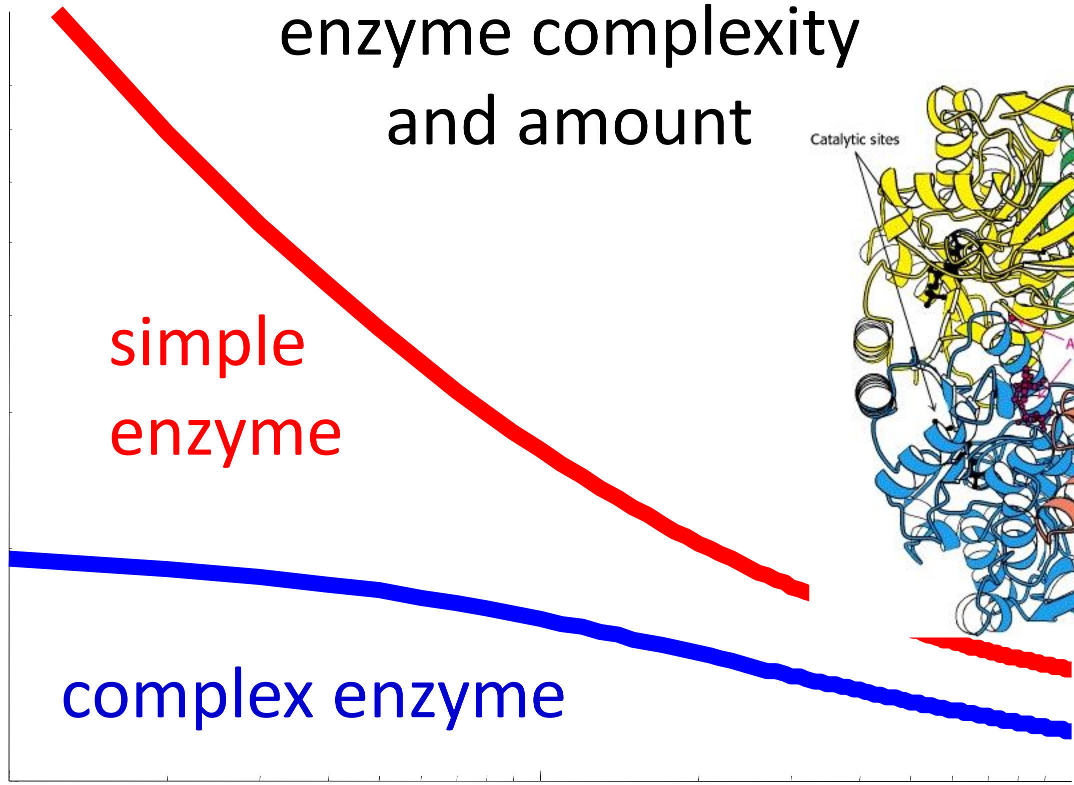
Theorem!

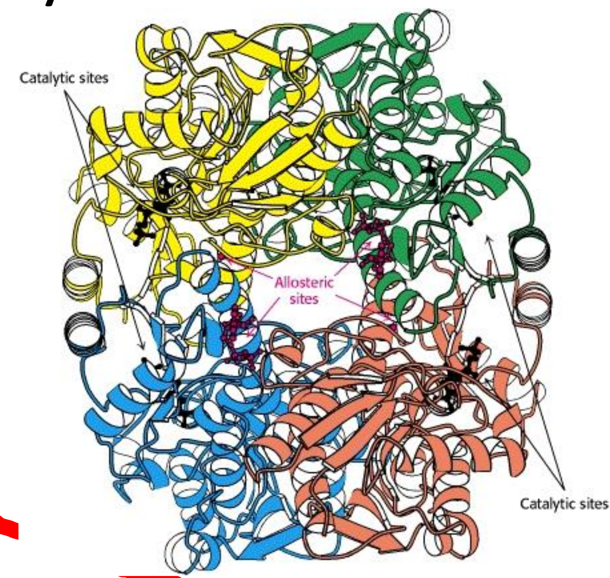
$$\frac{1}{\pi}\int_0^{\infty} \ln\left|S(j\omega)\right|\left(\frac{z}{z^2+\omega^2}\right)d\omega \geq \ln\left|\frac{z+p}{z-p}\right|$$

z and p functions of enzyme complexity and amount

Fragility

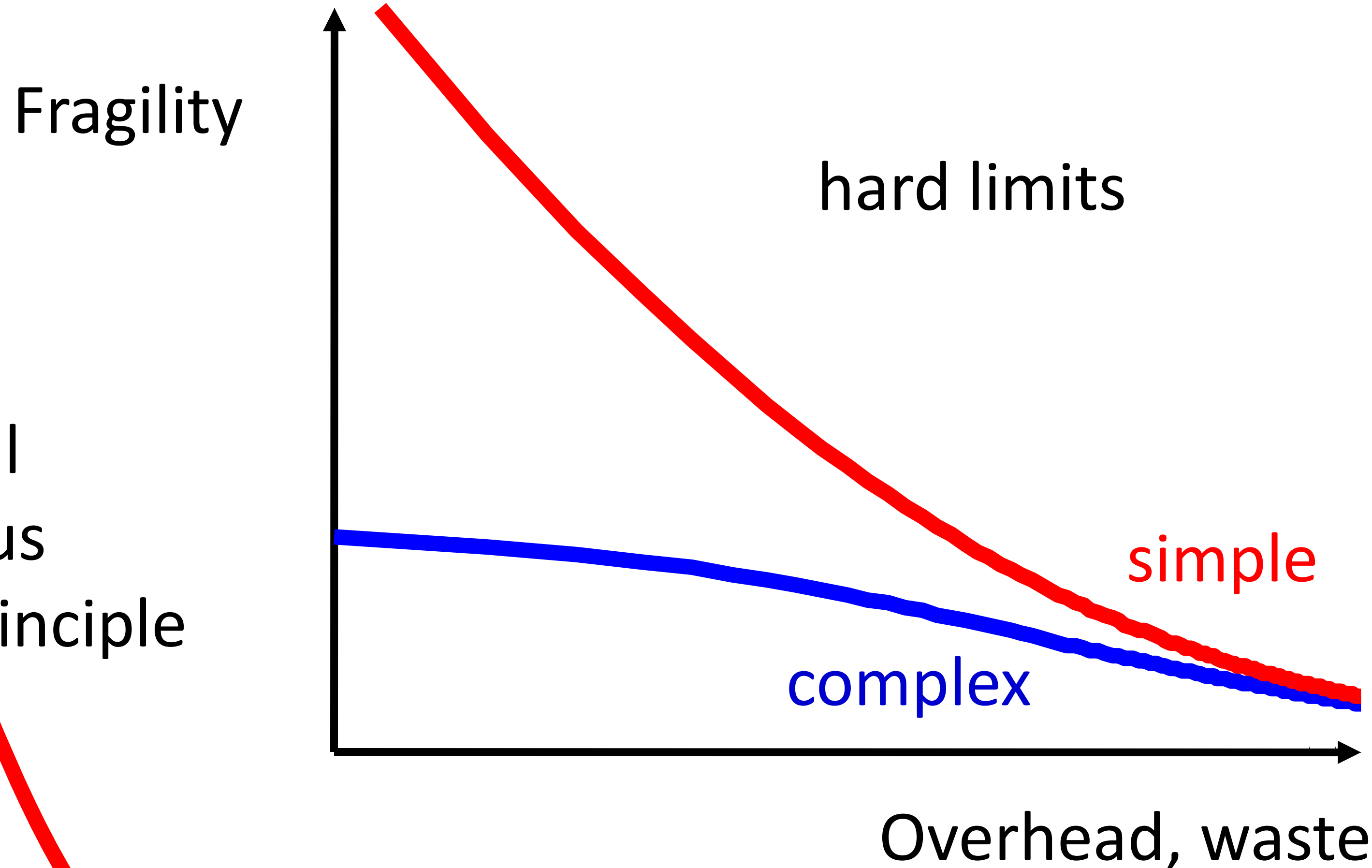
$$\ln\left|\frac{z+p}{z-p}\right|$$



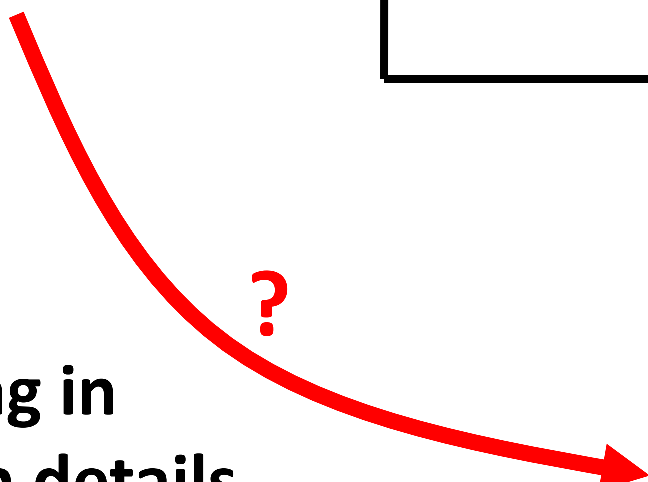


Enzyme amount

Savageaumics



- General
- Rigorous
- First principle



Plugging in domain details

- Domain specific
- Ad hoc
- Phenomenological

Control Wiener **Comms**

Bode

robust control

Shannon

Kalman

- General
- Rigorous
- First principle

- Fundamental multiscale physics
- Foundations, origins of
  - noise
  - dissipation
  - amplification
  - catalysis

?

Carnot

Boltzmann

Heisenberg

Physics

What I'm not going to talk much about

- It's true that most "really smart scientists" think almost everything in these talks is nonsense
- Why they think this
- Why they are wrong

- Time (not space) is our problem, as usual
- Don't have enough time for what is true, so have to limit discussion of what isn't
- No one ever changes a made up mind (almost)
- But here's the overall landscape

Control **Comms**

Complex networks

Wildly "successful"

Compute

"New sciences" of complexity and networks

edge of chaos, self-organized criticality, scale-free,...

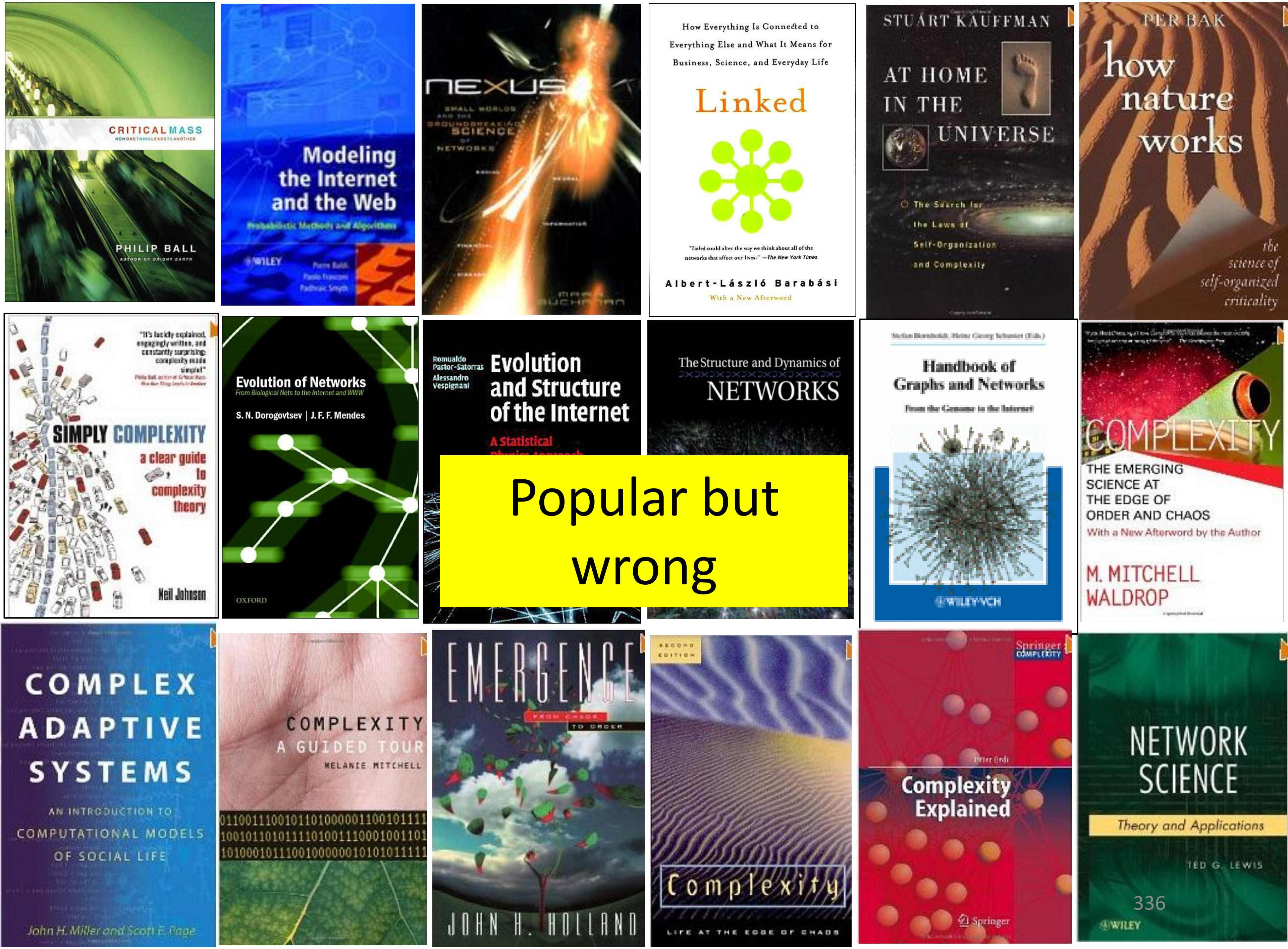
Stat physics

Carnot

Boltzmann

Heisenberg

Physics



Popular but wrong

Complex systems?

Even small amounts can create bewildering complexity

Fragile

- Scale
- Dynamics
- Nonlinearity
- Nonequlibrium
- Open
- Feedback
- Adaptation
- Intractability
- Emergence
- …

Complex systems?

Robust

- Scale
- Dynamics
- Nonlinearity
- Nonequlibrium
- Open
- Feedback
- Adaptation
- Intractability
- Emergence
- …

Fragile

- Scale
- Dynamics
- Nonlinearity
- Nonequlibrium
- Open
- Feedback
- Adaptation
- Intractability
- Emergence
- …

Complex systems?

Robust complexity

- Scale
- Dynamics
- Nonlinearity
- Nonequlibrium
- Open
- Feedback
- Adaptation
- Intractability
- Emergence
- …

- Resources
- Controlled
- Organized
- Structured
- Extreme
- ***Architected***
- …

- These words have lost much of their original meaning, and have become essentially meaningless synonyms
- e.g. nonlinear ≠ not linear

- Can we recover these words?

- Idea: make up a new word to mean "I'm confused but don't want to say that"
- Then hopefully we can take these words back (e.g. nonlinear = not linear)

Fragile complexity

- Scale
- Dynamics
- Nonlinearity
- Nonequlibrium
- Open
- Feedback
- Adaptation
- Intractability
- Emergence
- …

New words

Emergulent

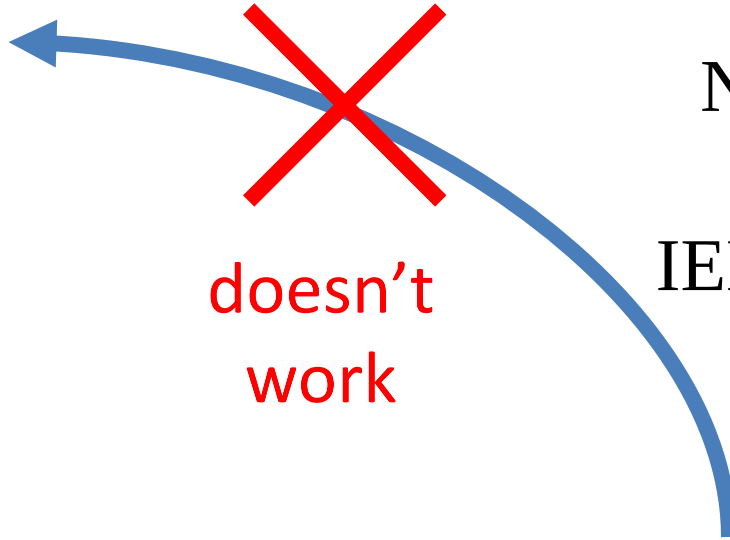
Emergulence at the edge of chaocritiplexity

Fragile complexity

- Scale
- Dynamics
- Nonlinearity
- Nonequlibrium
- Open
- Feedback
- Adaptation
- Intractability
- Emergence
- …

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

Complex networks



Stat physics

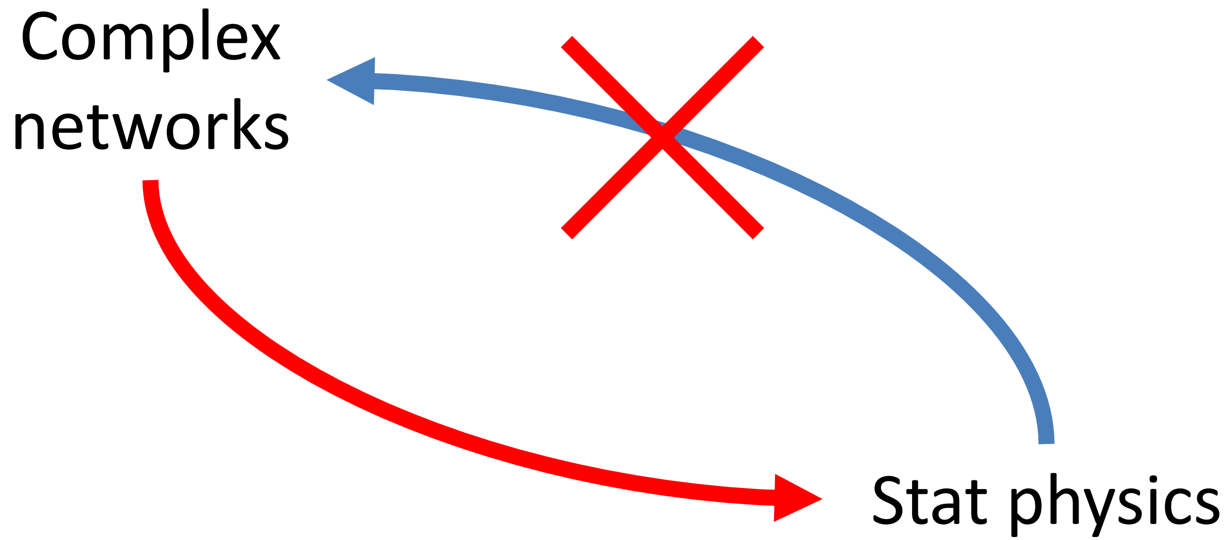
"New sciences" of complexity and networks

edge of chaos, self-organized criticality, scale-free,…

Complex systems?

Control **Comms**

Compute



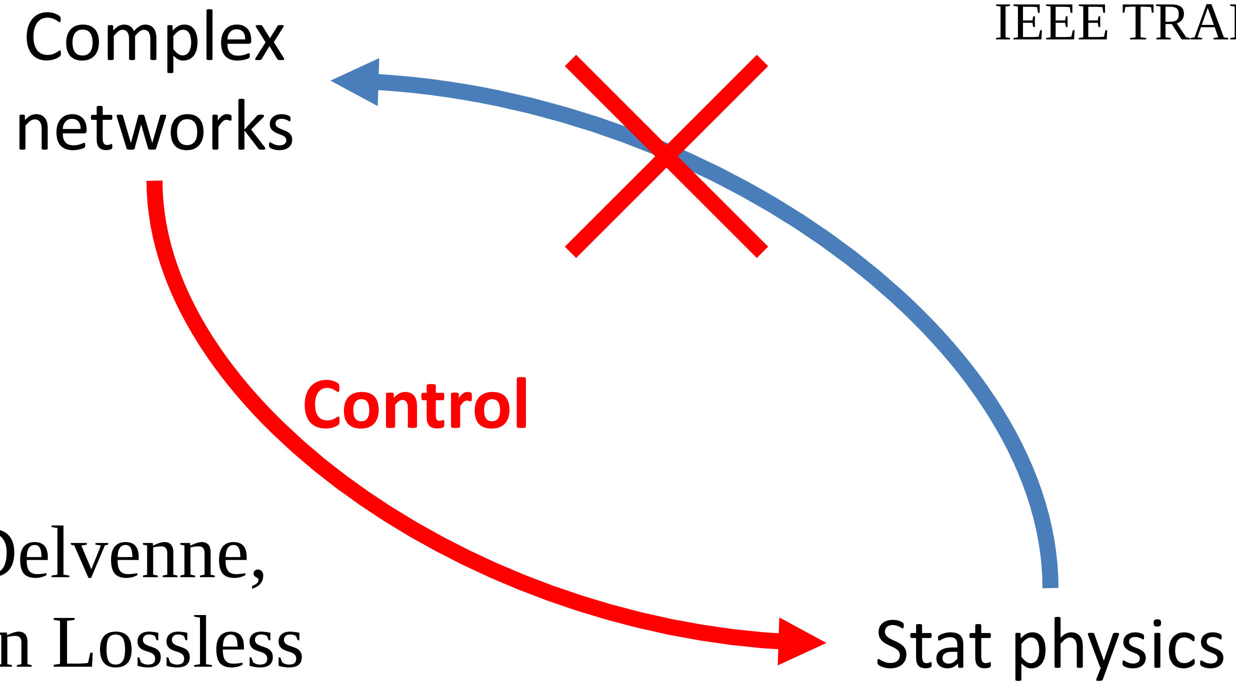
Carnot

Boltzmann

Heisenberg

Jean Carlson, UCSB Physics **Physics**

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

"The last 70 years of the 20th century will be viewed as the dark ages of theoretical physics." (Carver Mead)

Complex networks

"orthophysics"

From prediction
to mechanism
to control

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

Stat physics, fluids, QM

Carnot

Boltzmann

Heisenberg

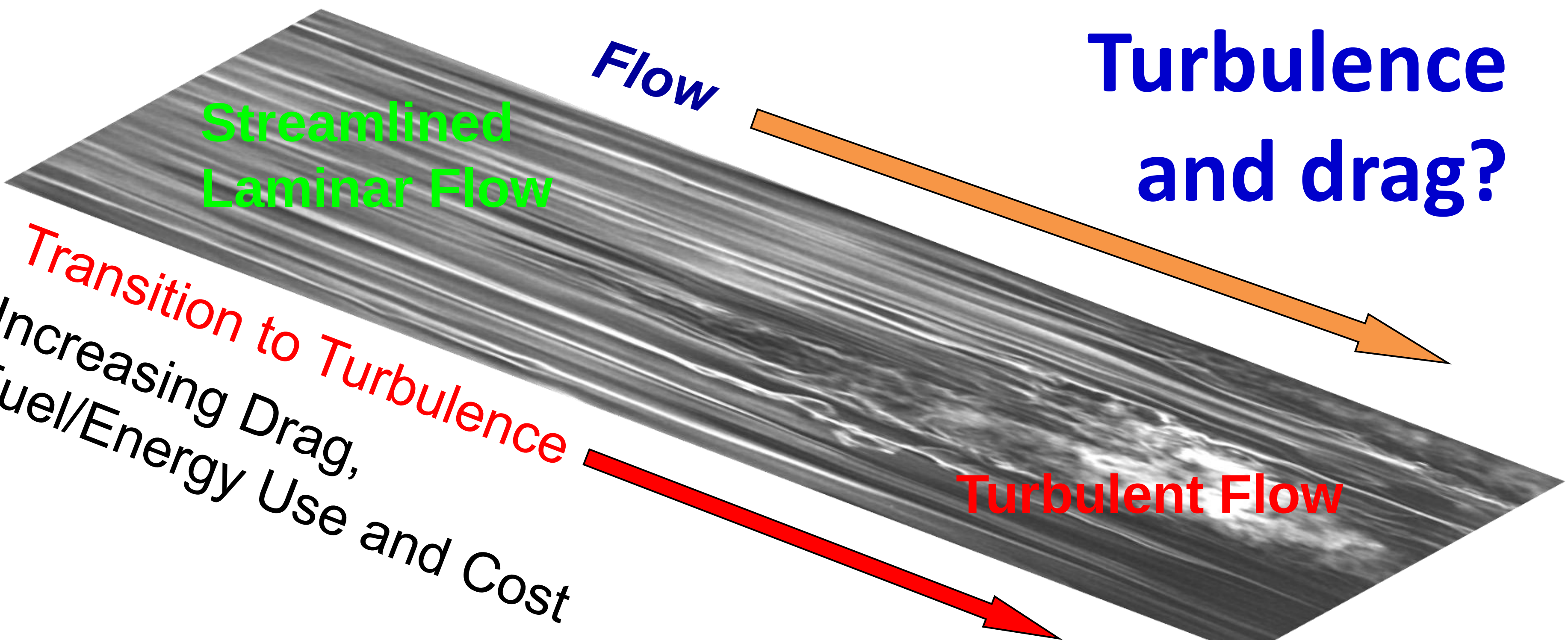
Physics

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]



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 Papachristodoul
and John C. Doyle[3]

Dennice Gayme,
Beverley McKeon,
Bassam Bamieh (UCSB ME),
Antonis Papachristodoulou,
John Doyle

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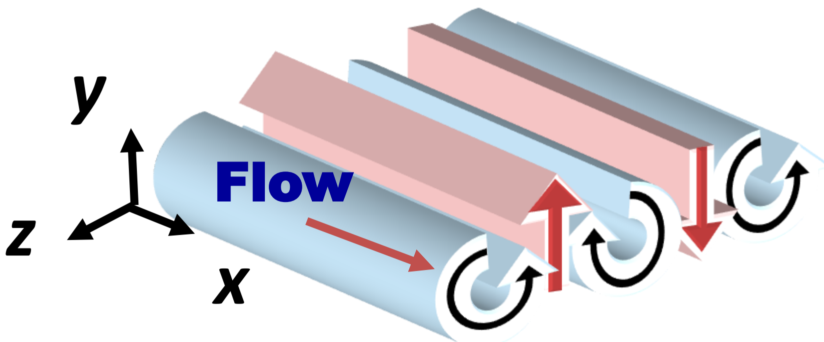
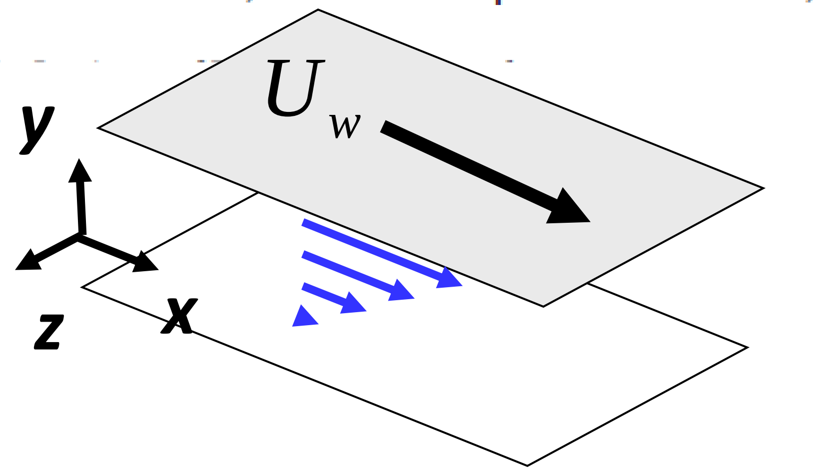
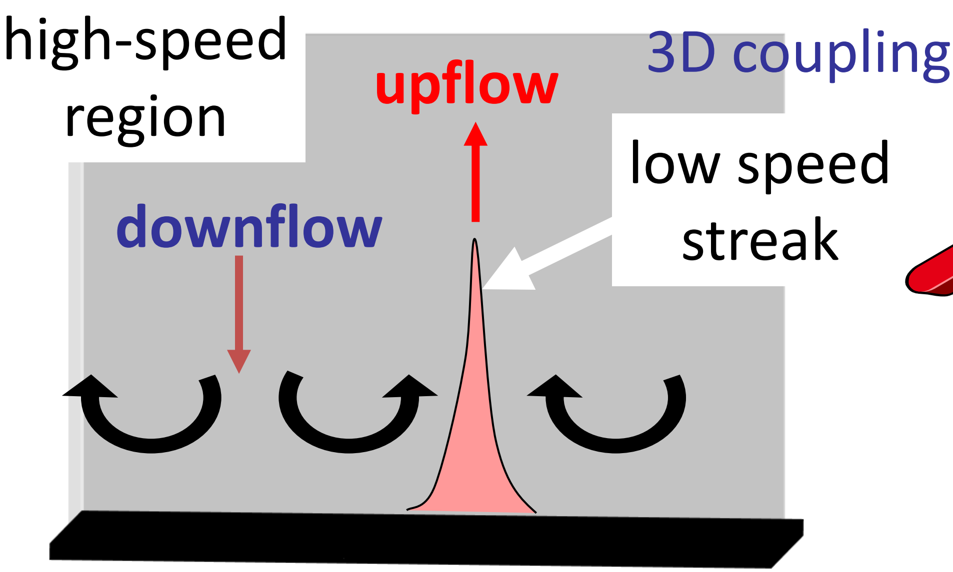
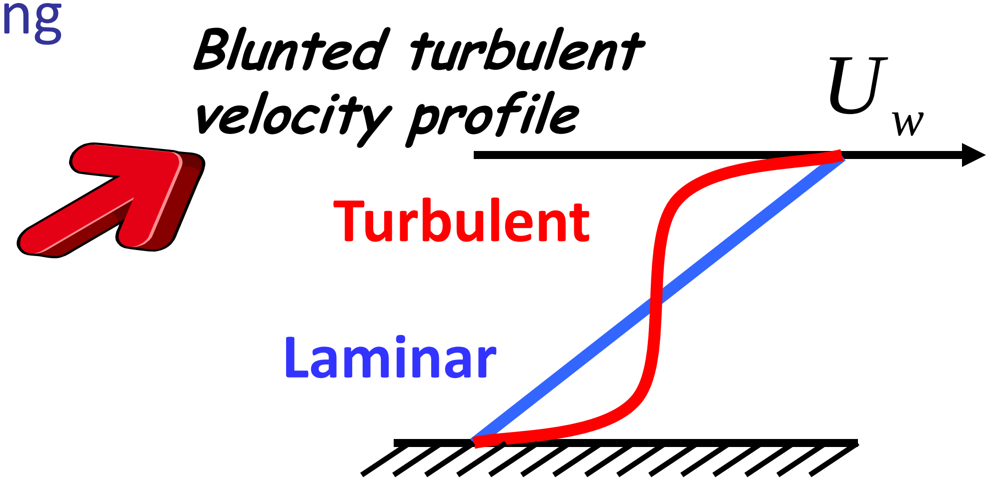


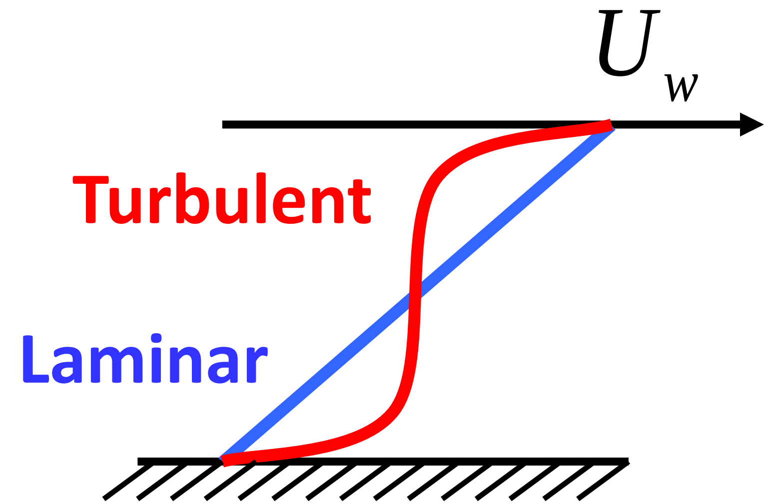


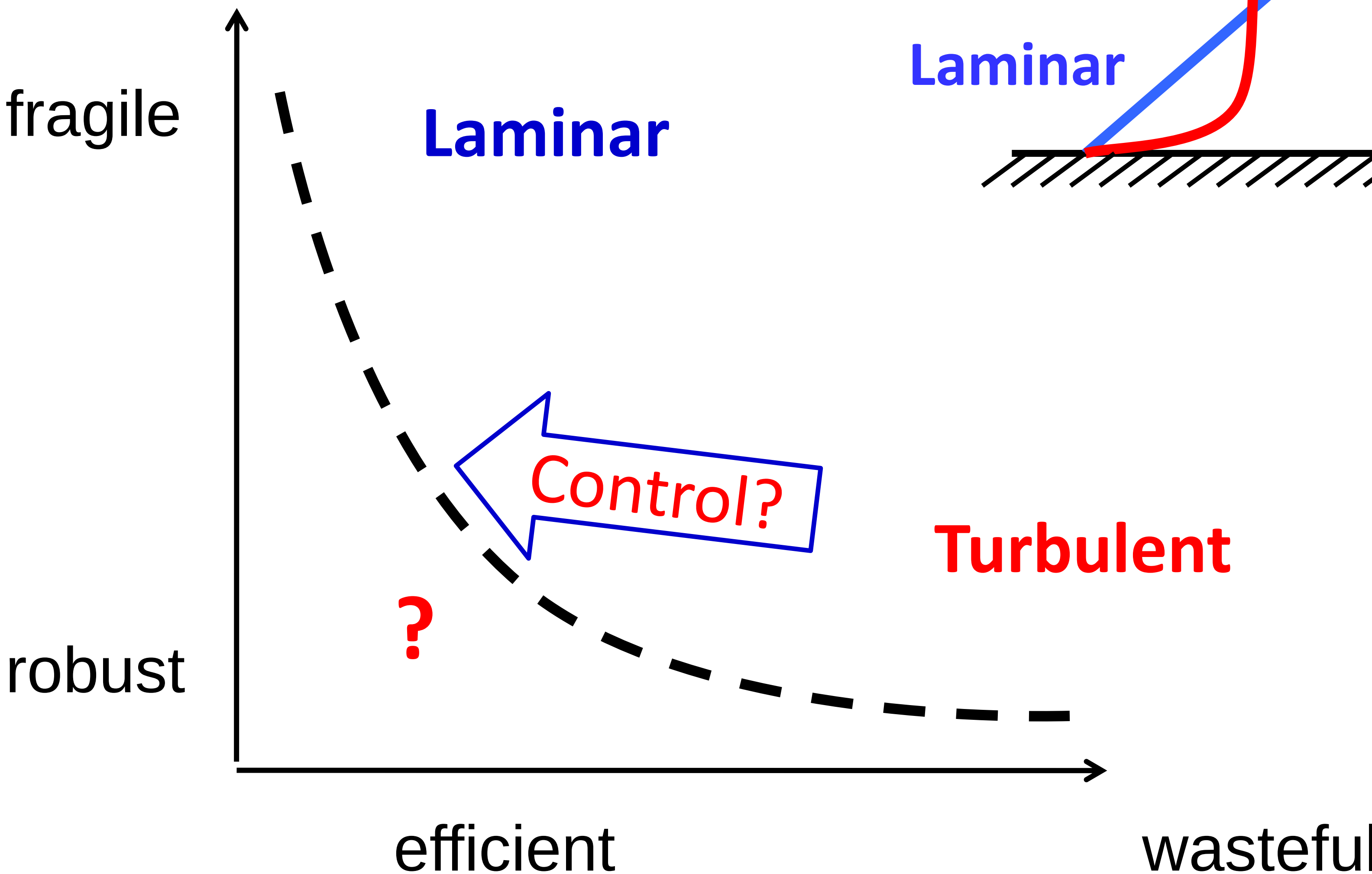
Coherent structures and turbulent drag






entals!


U_w
Turbulent
Laminar


fragile
robust
Laminar
Control?
?
Turbulent
efficient
wasteful

Existing design frameworks

- Sophisticated components
- Poor integration
- Limited theoretical framework

Fix?