Universal laws and architecture 3:
Foundations for Sustainable Infrastructure

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

Turing on layering

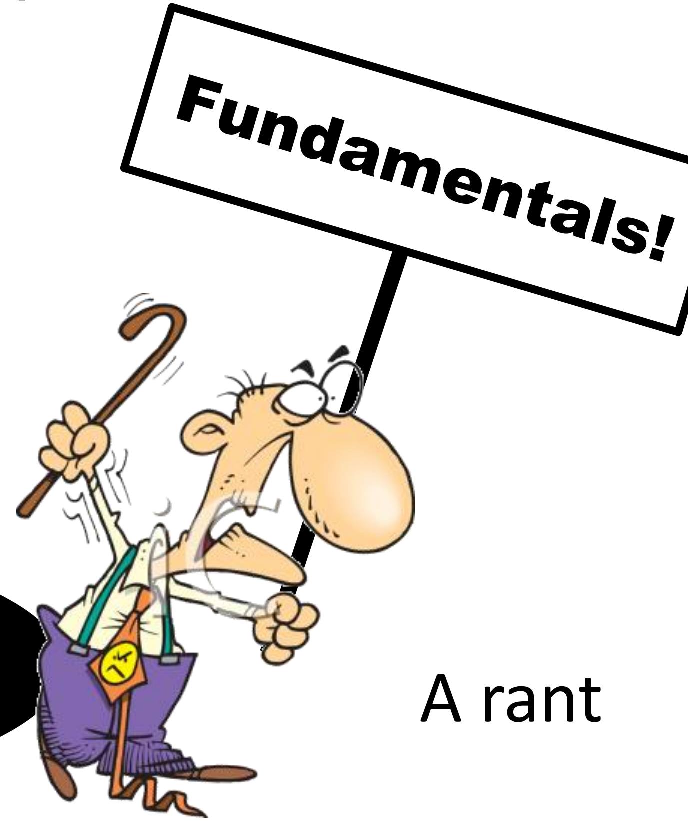
The 'skin of an onion' analogy is also helpful. In considering the functions of the mind or the brain we find certain operations which we can explain in purely mechanical terms. This we say does not correspond to the real mind: it is a sort of skin which we must strip off if we are to find the real mind. 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?



Systems

A rant

- 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

Turing (1912-1954)

Compute

*Also world-class runner.

Key papers/results

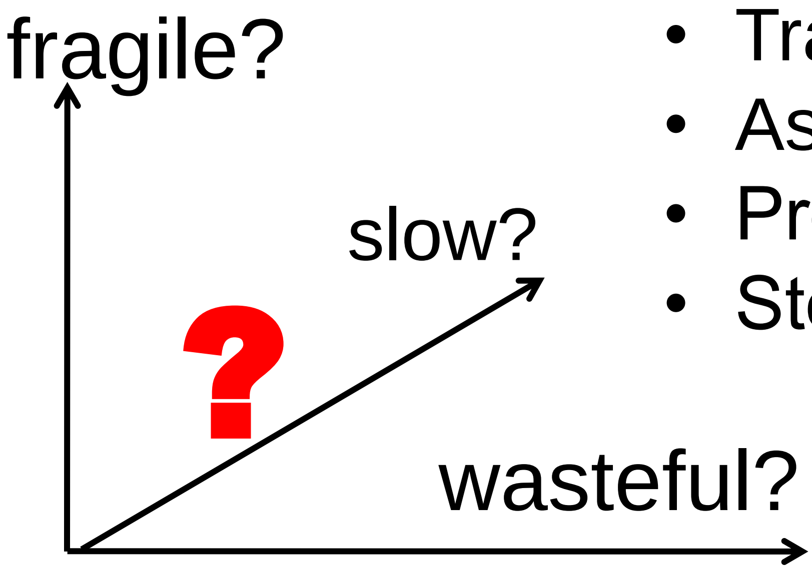
- Theory (1936): Turing machine (TM), computability, (un)decidability, universal machine (UTM)
- Practical design (early 1940s): code-breaking, including the design of code-breaking machines
- Practical design (late 1940s): general purpose digital computers and software, layered architecture
- Theory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

Control

Bode

Comms

Shannon



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

Carnot

Boltzmann

Turing

Godel

Heisenberg

Compute

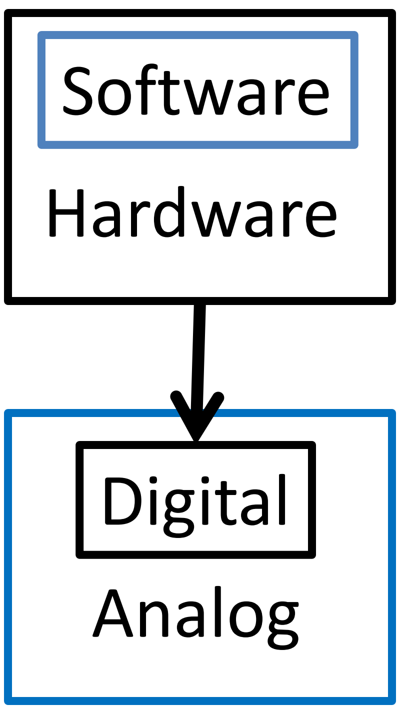
Physics

Einstein

Turing as "new" starting point?

Essentials:

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



Turing's 3 step research:

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

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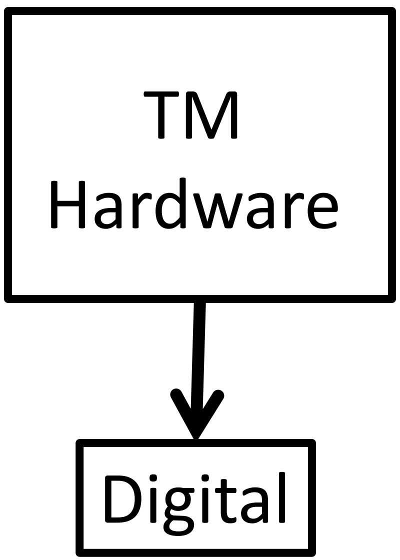

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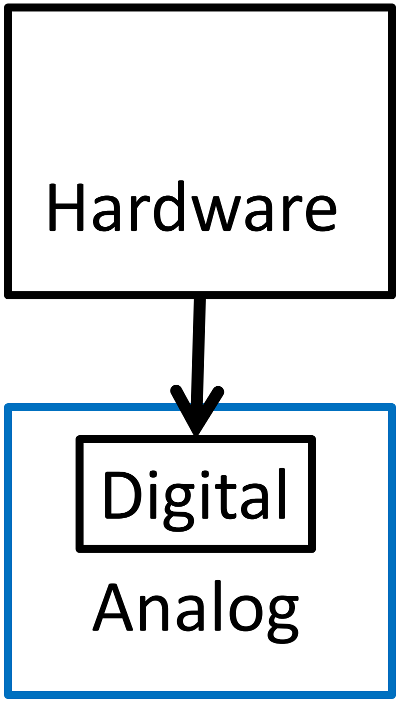
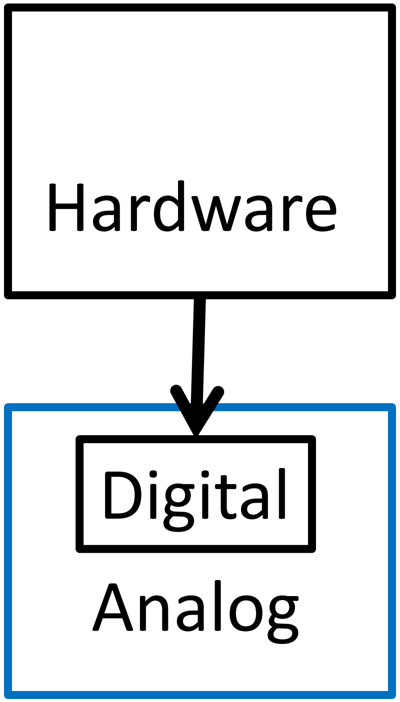


- …being digital should be of greater interest than that of being electronic. That it is electronic is certainly important because these machines owe their high speed to this… But this is virtually all that there is to be said on that subject.
- That the machine is digital however has more subtle significance.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

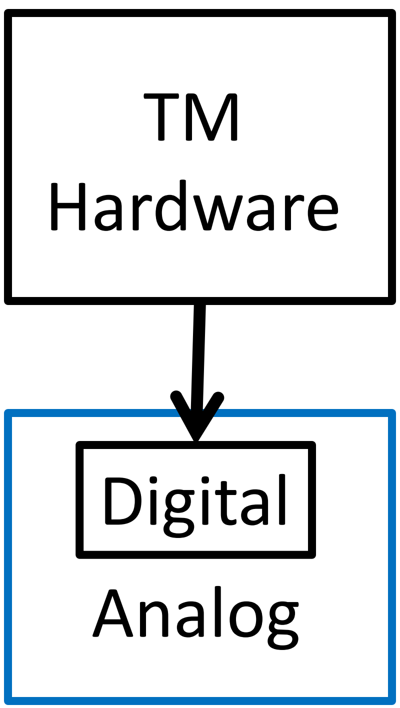
1947 Lecture to LMS



- … 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

- 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

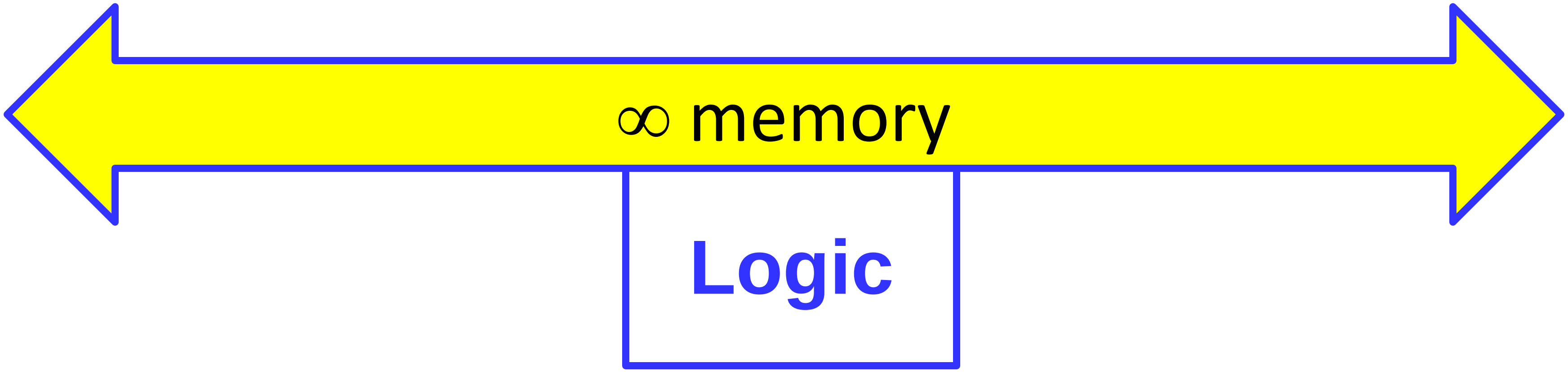
- … quite small errors in the initial conditions can have an overwhelming effect at a later time. The displacement of a single electron by a billionth of a centimetre at one moment might make the difference between a man being killed by an avalanche a year later, or escaping.

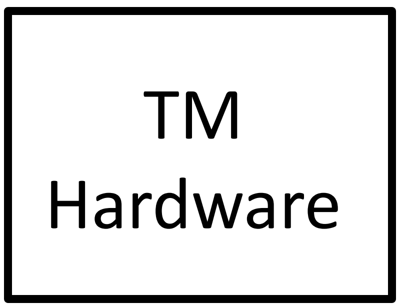
1950, Computing Machinery and Intelligence, *Mind*

- … 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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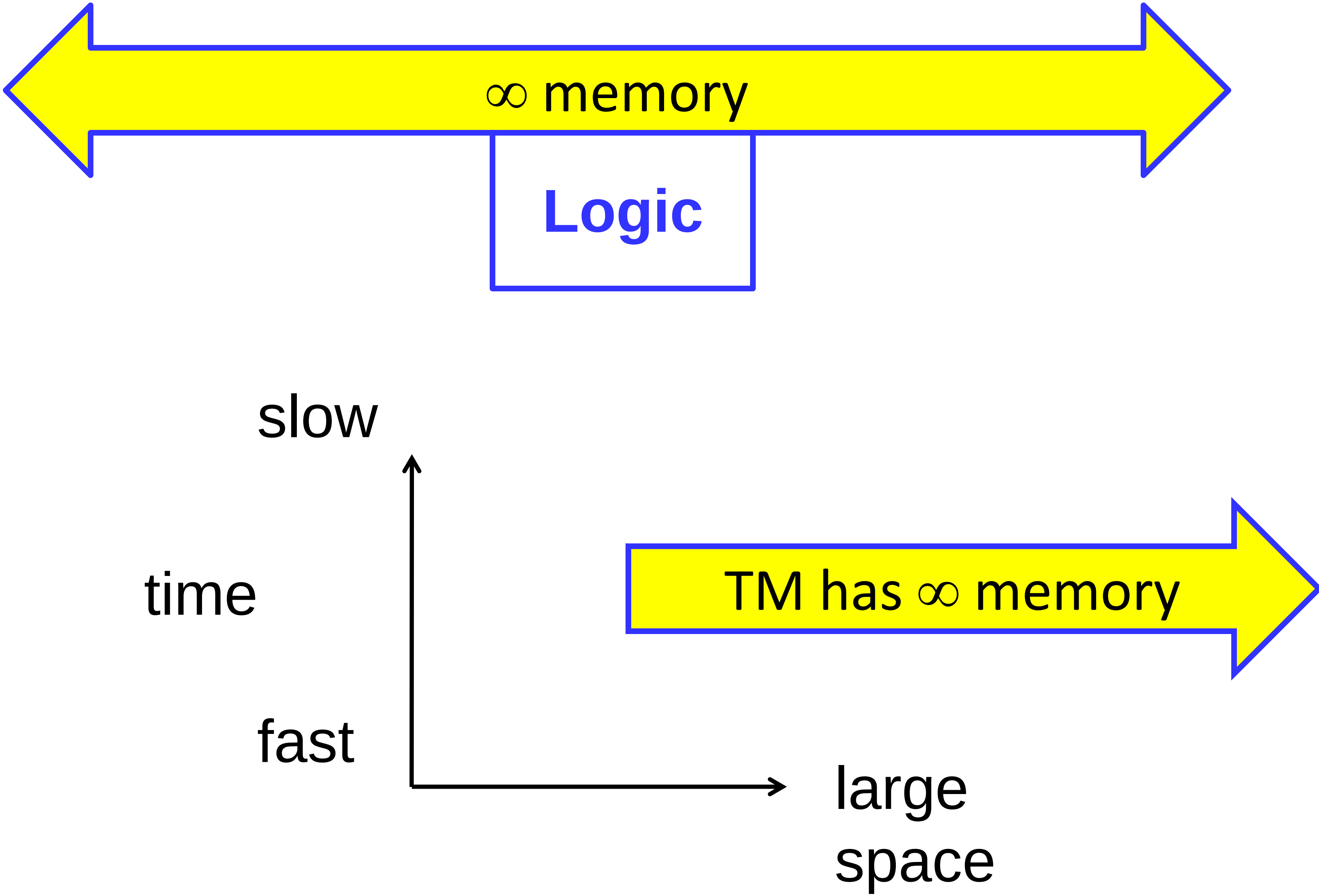
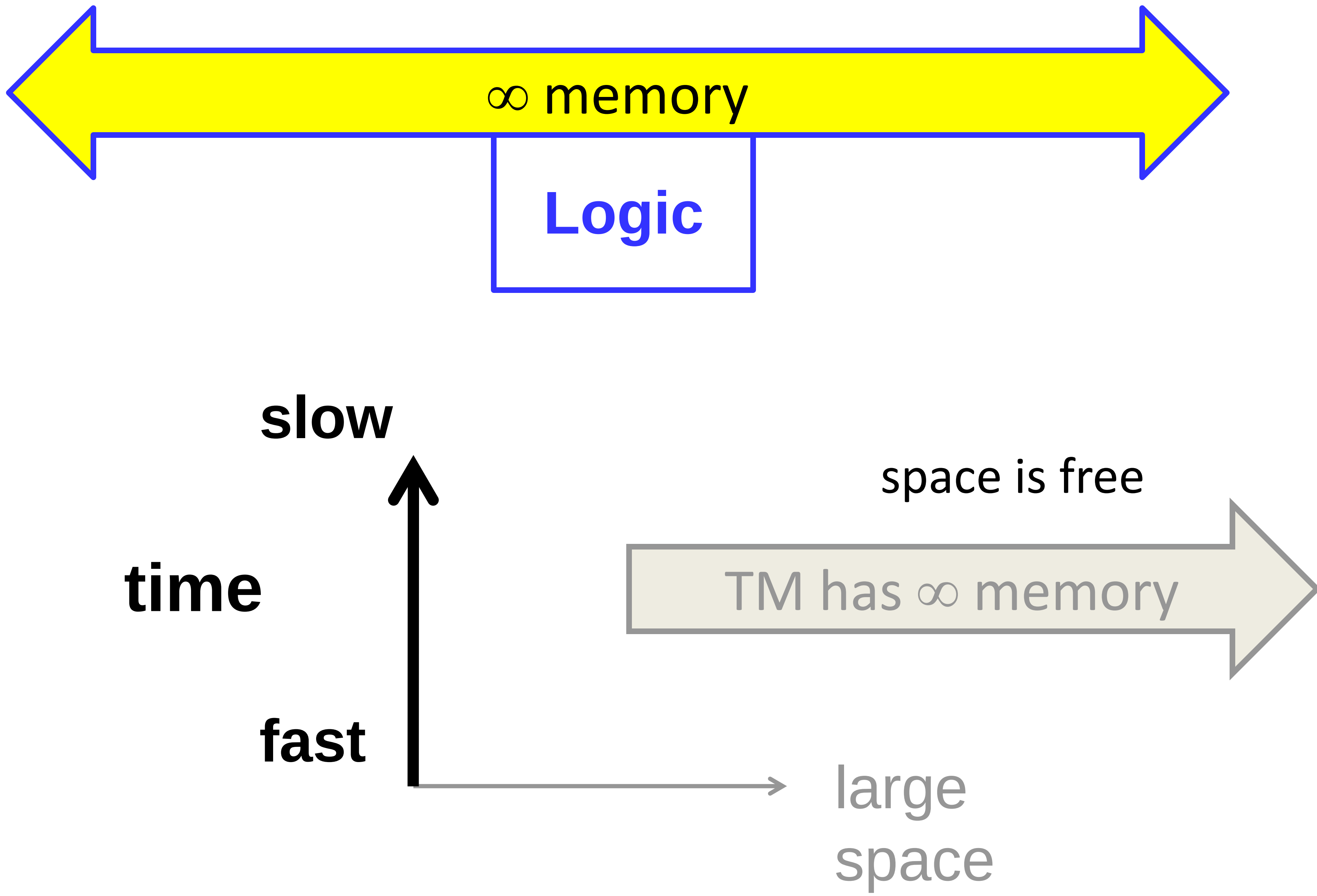
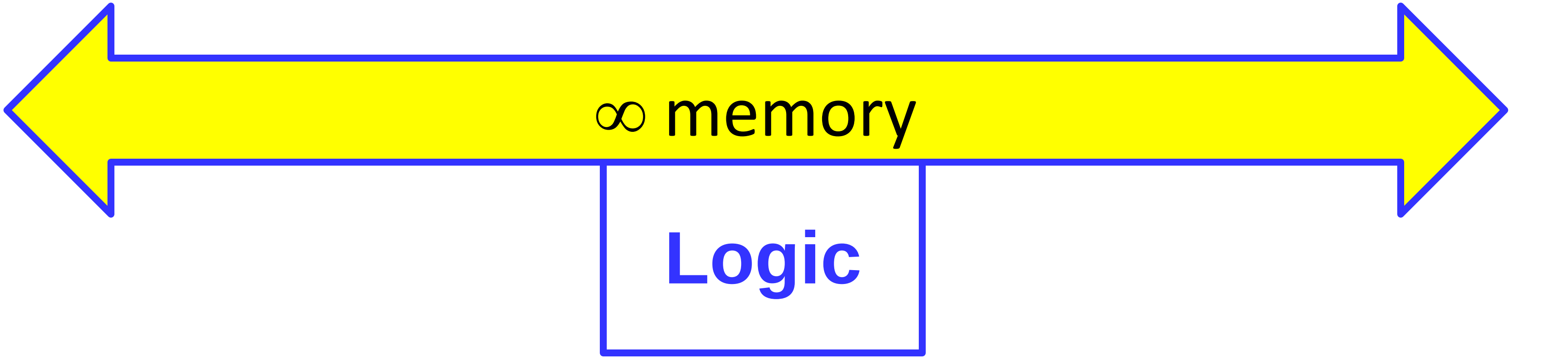

∞ memory
Logic
slow
time
fast
TM has ∞ memory
large
space

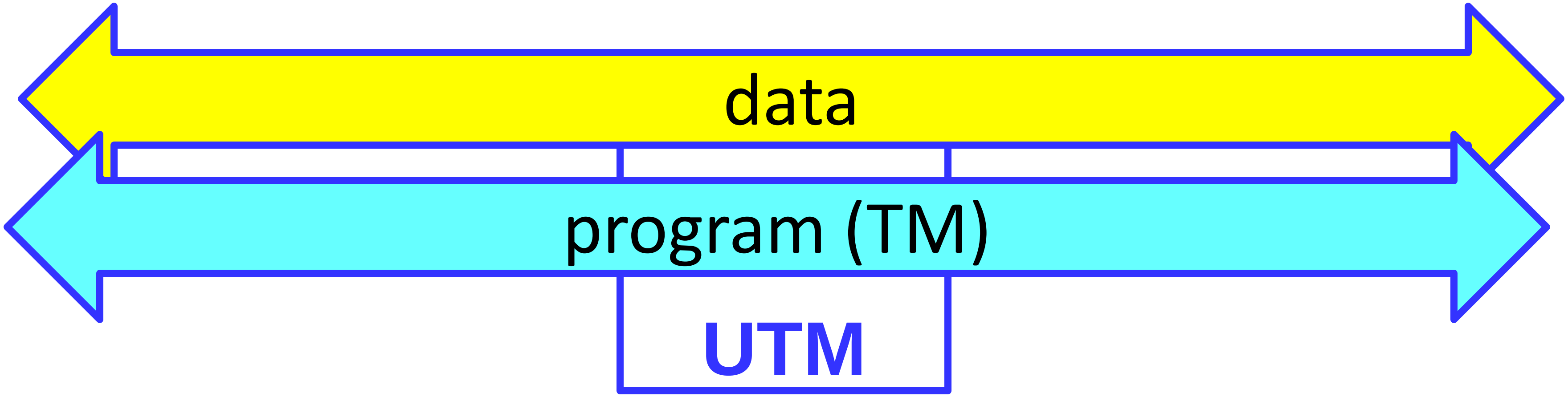

∞ memory
Logic
slow
time
fast
space is free
TM has ∞ memory
large
space



time?

Decidable problem = ∃ algorithm that solves it

Most naively posed problems are undecidable.



Turing’s 3 step research:

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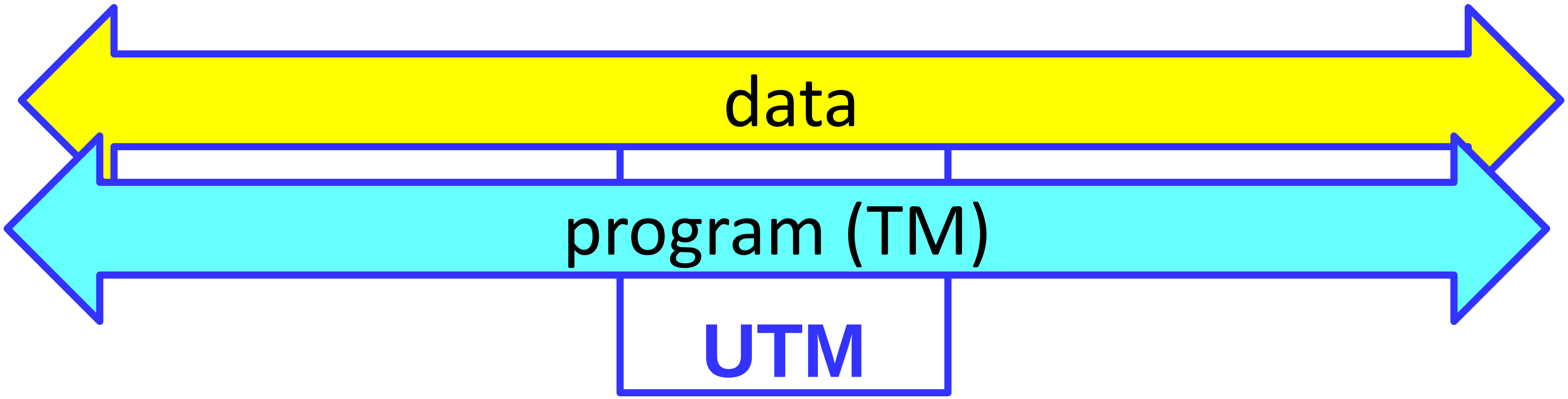
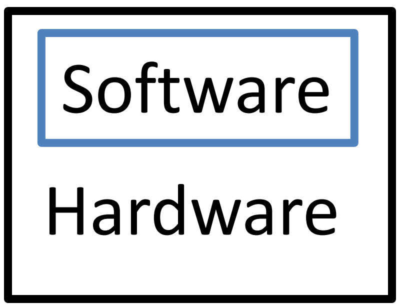
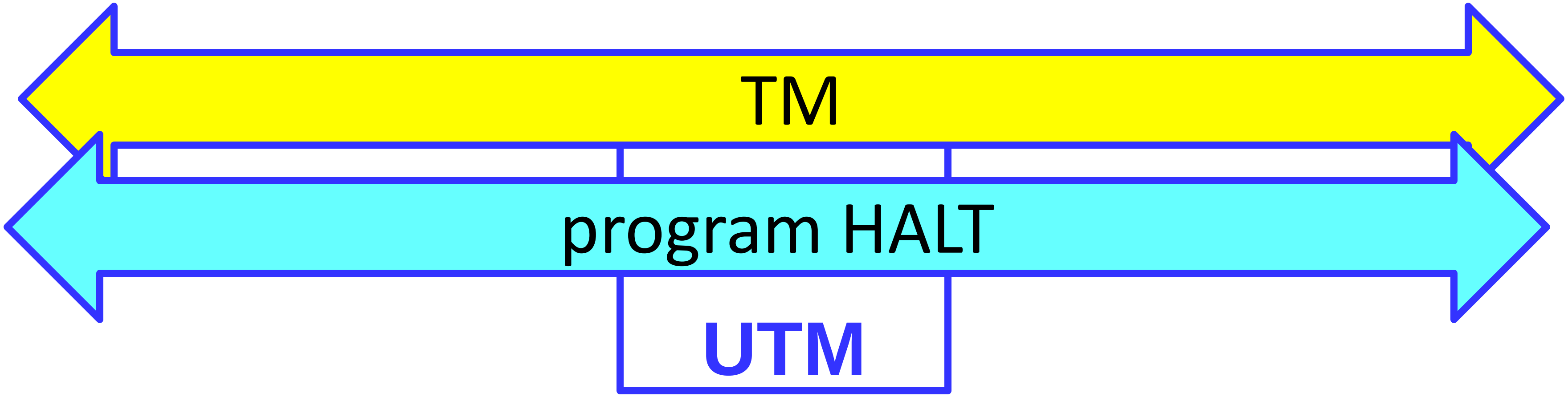




2. Universal architecture achieving hard limits (UTM)

- 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.



The halting problem

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

Thm: TM H=HALT does not exist.

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

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

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

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

Thm: No such H exists.

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

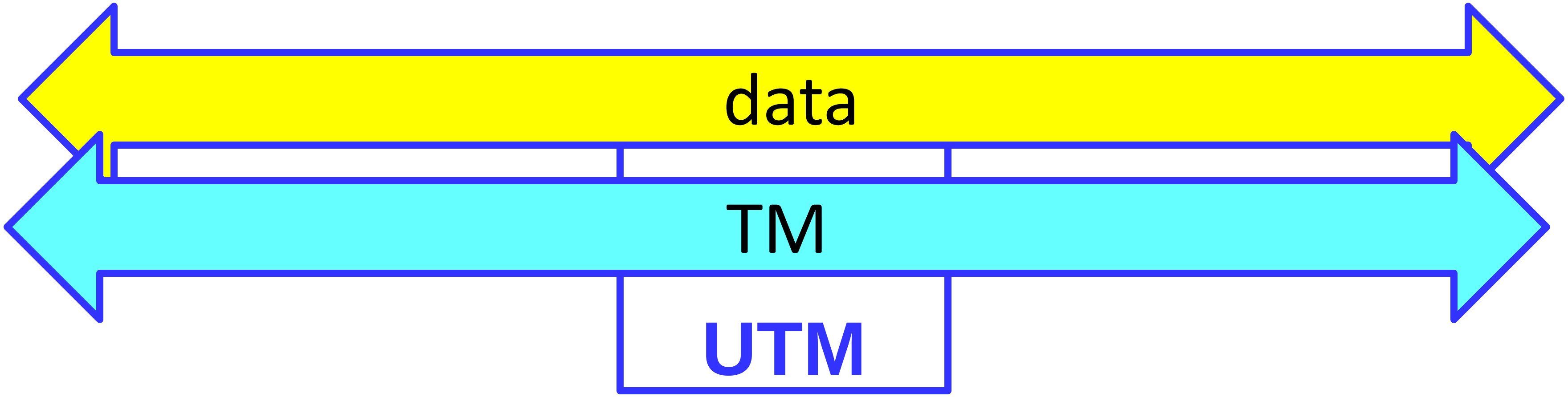
$$H'(TM, input) \triangleq \begin{cases} 1 \text{ if } H(TM, input) = 0 \\ \text{loop forever otherwise} \end{cases}$$

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

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

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

Contradiction!



Implications

- 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, many questions NOT about TMs.
- Large, thin, nonconvex everywhere…

Issues for engineering

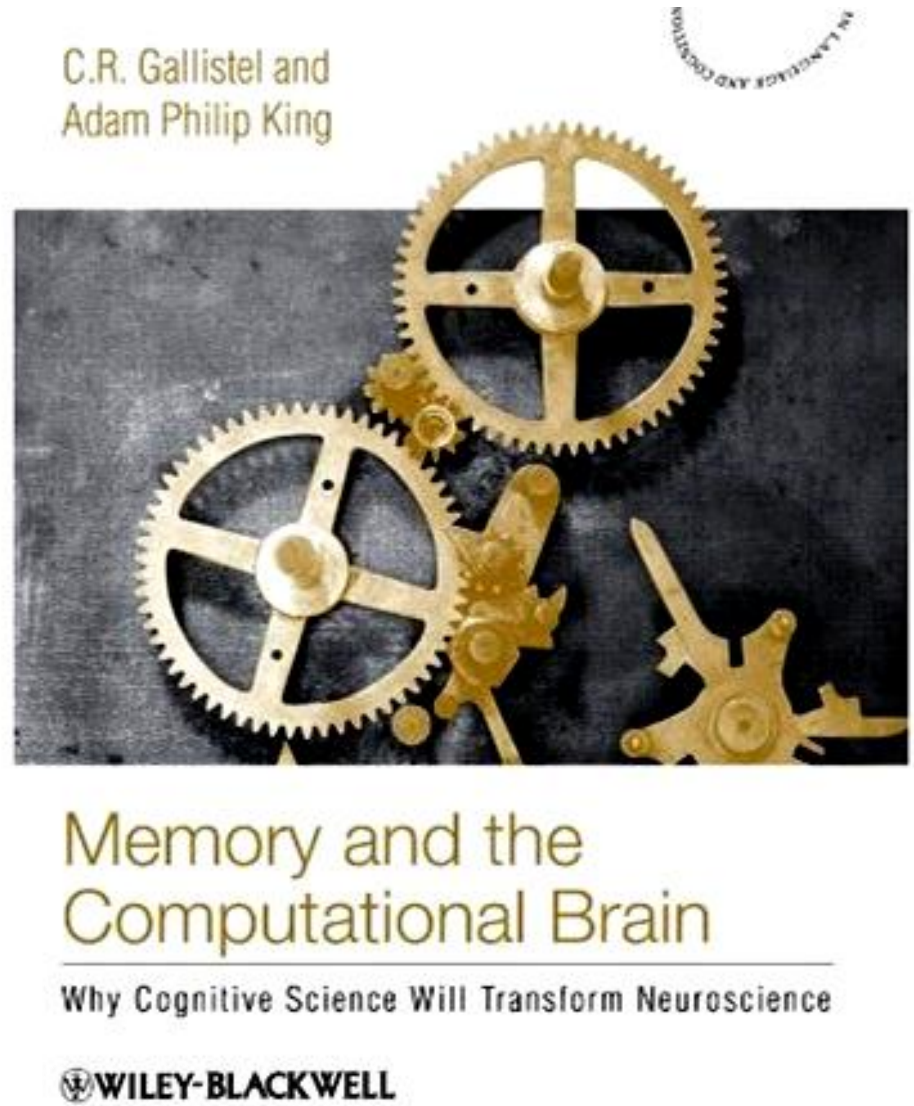
- Turing remarkably relevant for 76 years
- UTMs are ≈ implementable
  - Time is most critical resource
  - Space (memory) almost free
- Read/write random access memory hierarchies
- Further gradations of decidable (P/NP/coNP)

- Must crucial: You can fix bugs but it is hard to automate finding/avoiding them

Issues for neuroscience

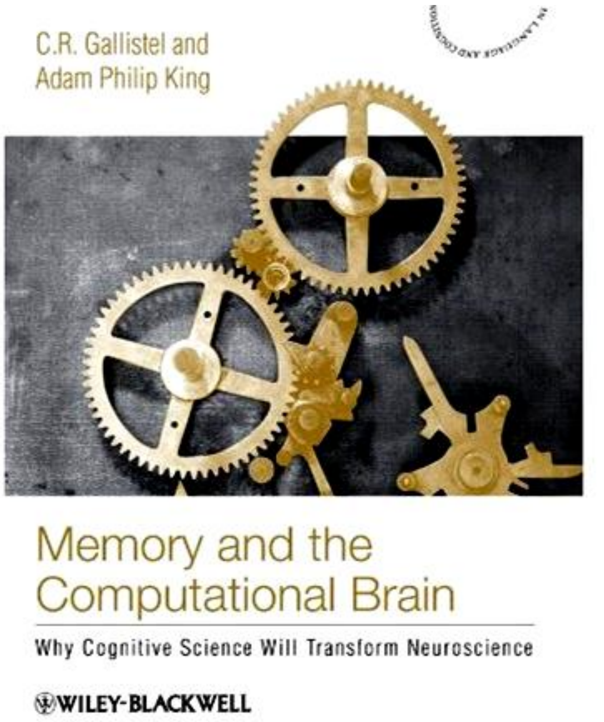
- Brains and UTMs?
  - Time is most critical resource?
  - Space (memory) almost free?
- Read/write random access memory hierarchies?
- Brain >> UTM?

Gallistel and King



Conjecture

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***?

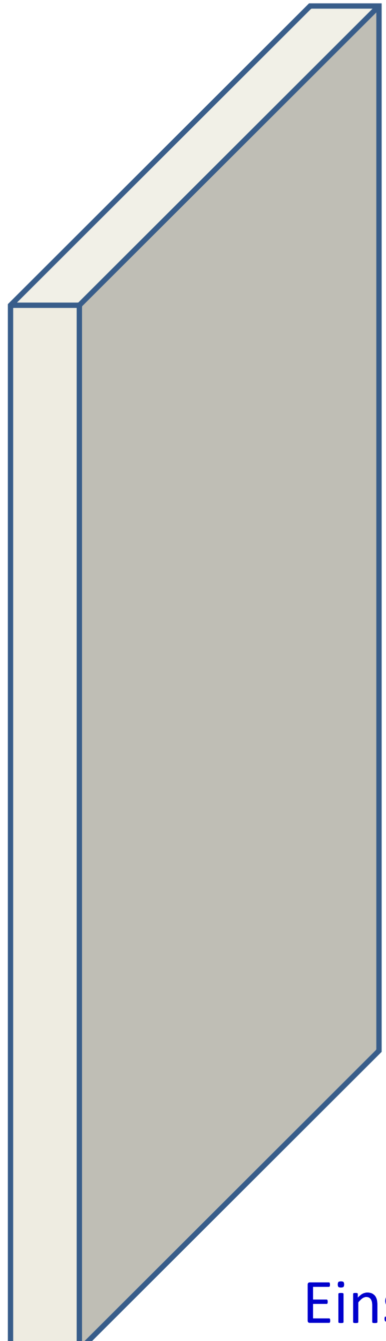
Compute

Turing

Delay is *most* important

Bode

Control, OR



Communicate

Shannon

Delay is *least* important

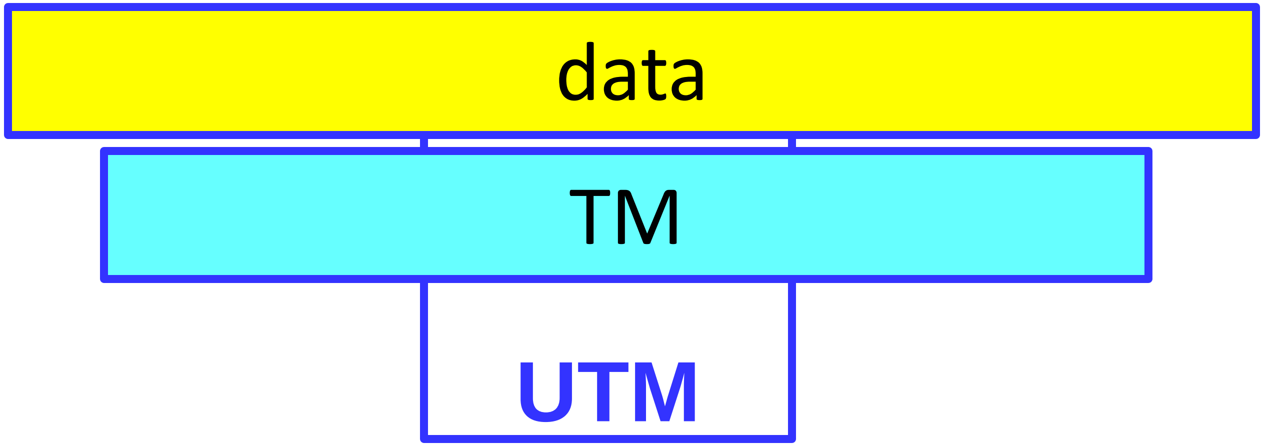
Carnot

Boltzmann

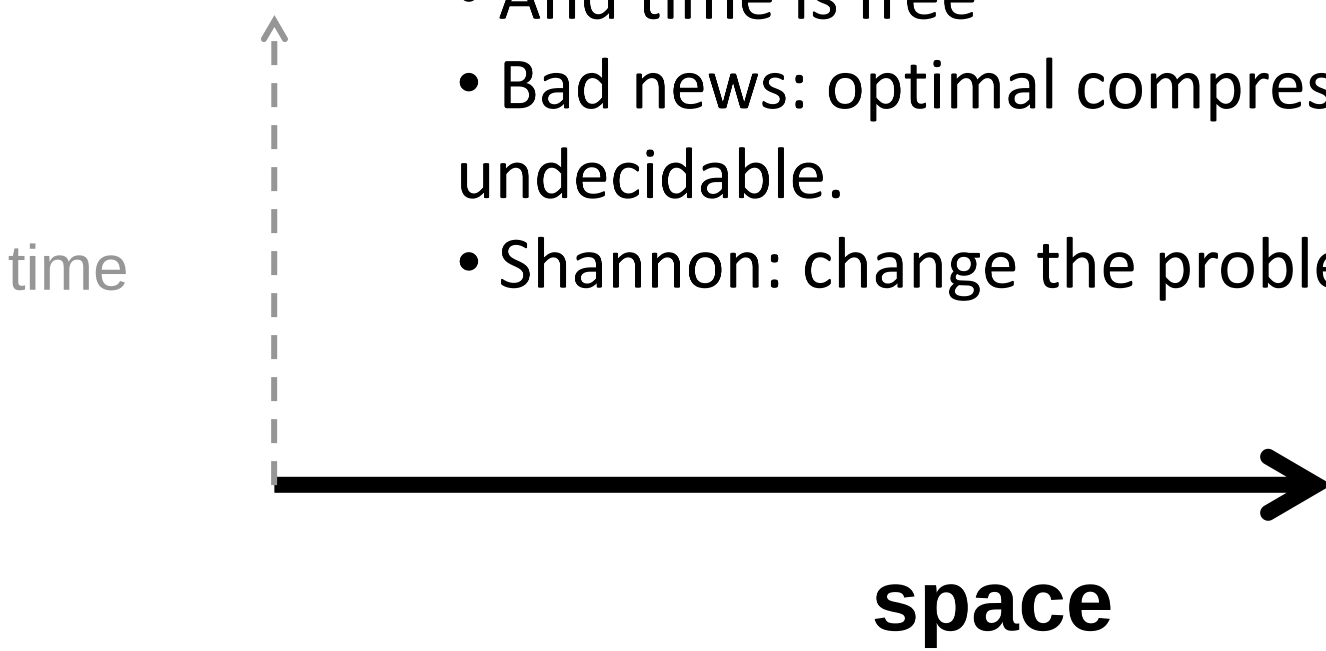
Heisenberg

Physics

Einstein



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



Communications

Shannon

Shannon’s brilliant insight

- Don’t worry about time or delay!
- Don’t compress and code files, worry only about ***infinite random ensembles***
- Information theory is most popular and accessible topic in systems engineering
- ***Fantastic*** for engineering, almost useless for biology (But see Lestas, Vinnicombe, Paulsson)
- (And largely irrelevant to Internet architecture)
- Misled and distracted generations of biologists and neuroscientists
- New generation of information theorists are putting delay back in. (Cheer!)

Compute

Turing

Communicate

Shannon

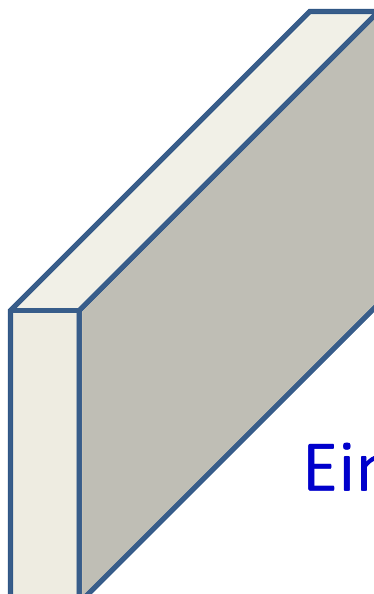
Delay is *most* important

Delay is ~~*least*~~ important

Carnot

Boltzmann

Bode



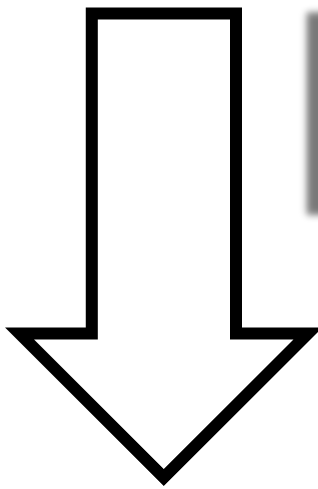
Heisenberg

Einstein

Control, OR

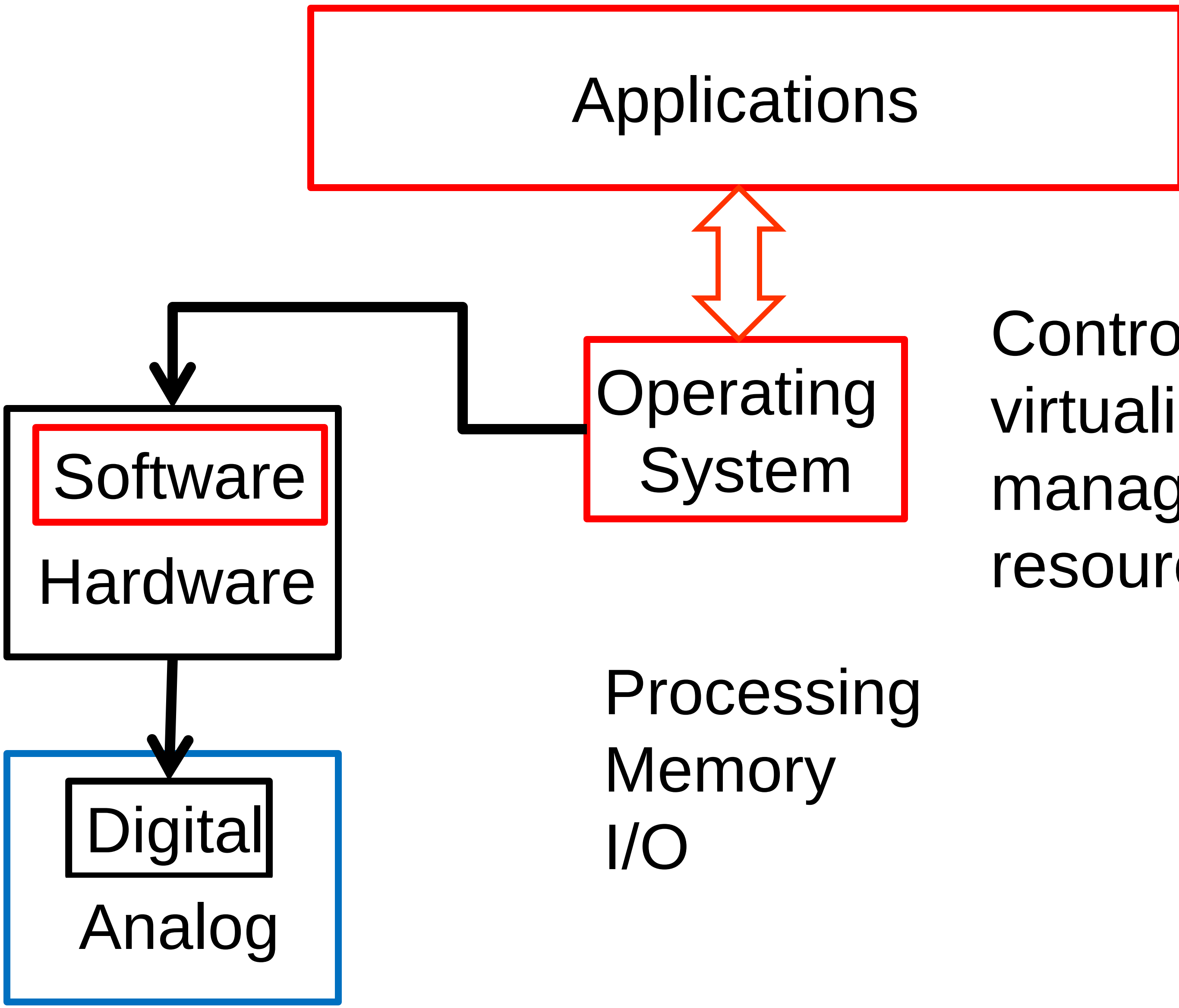
Physics

Slow execution
Flexible reprogramming



Faster execution
Less flexible

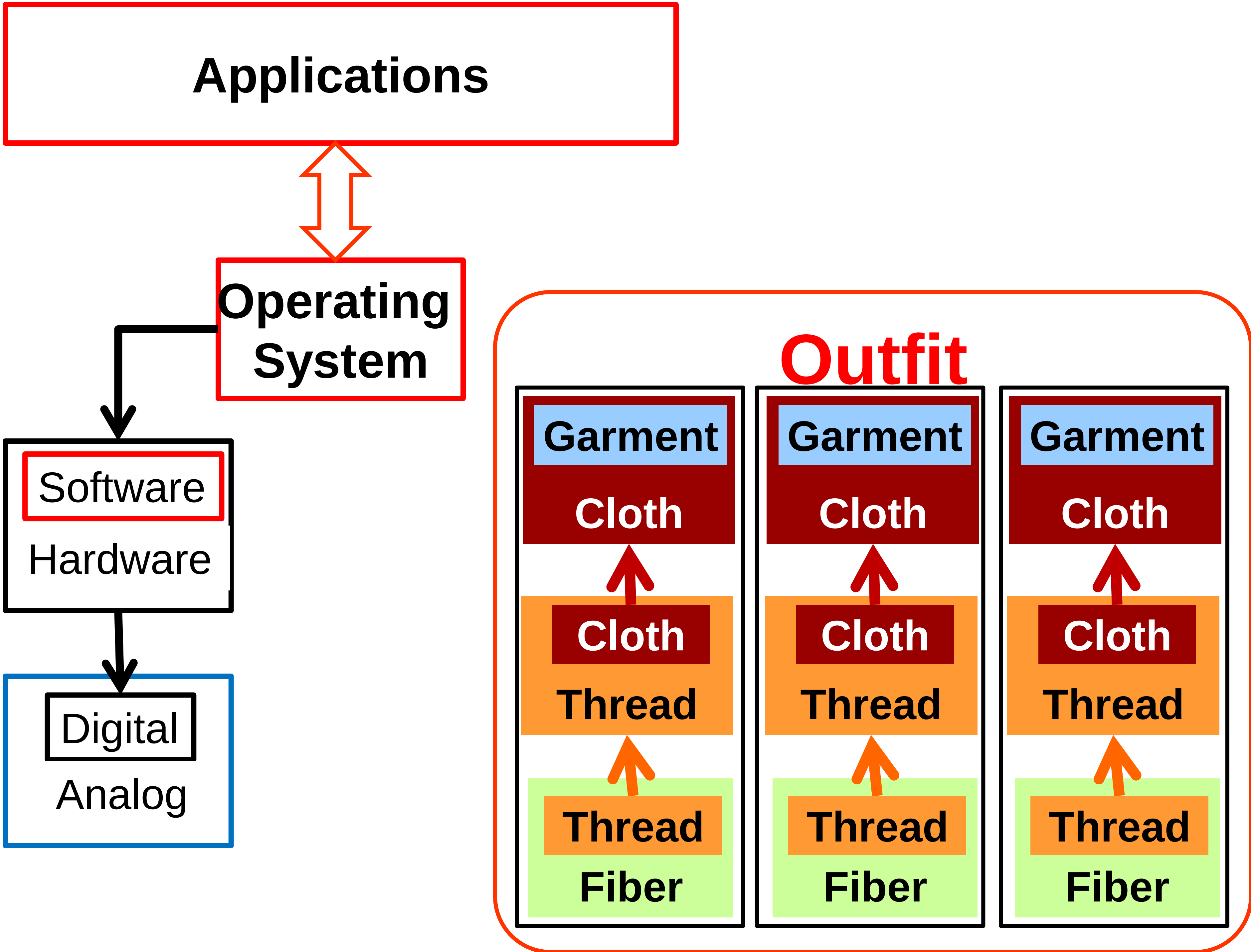
Modern technology gives lots of intermediate alternatives.



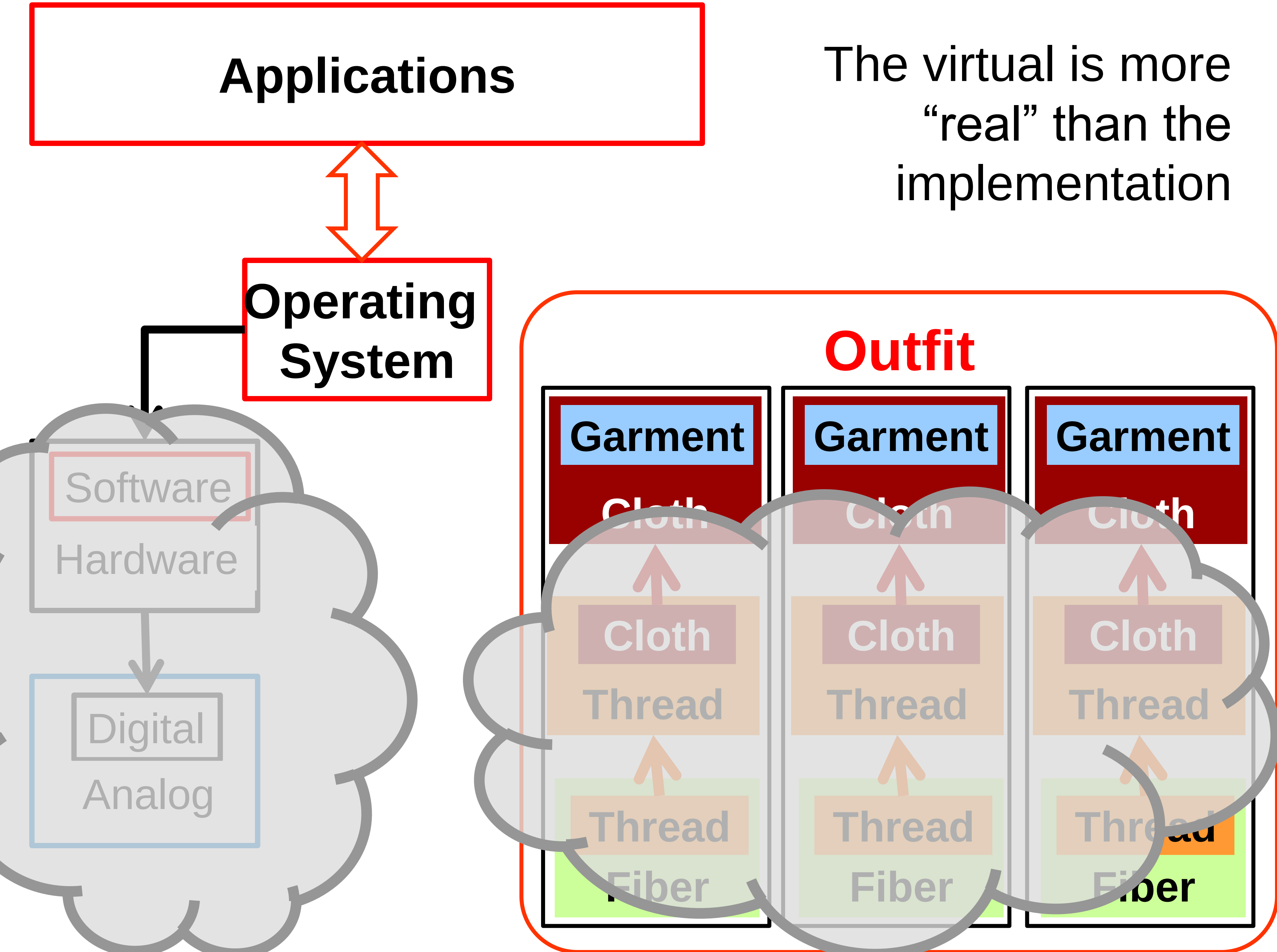
Control, share, virtualize, and manage resources

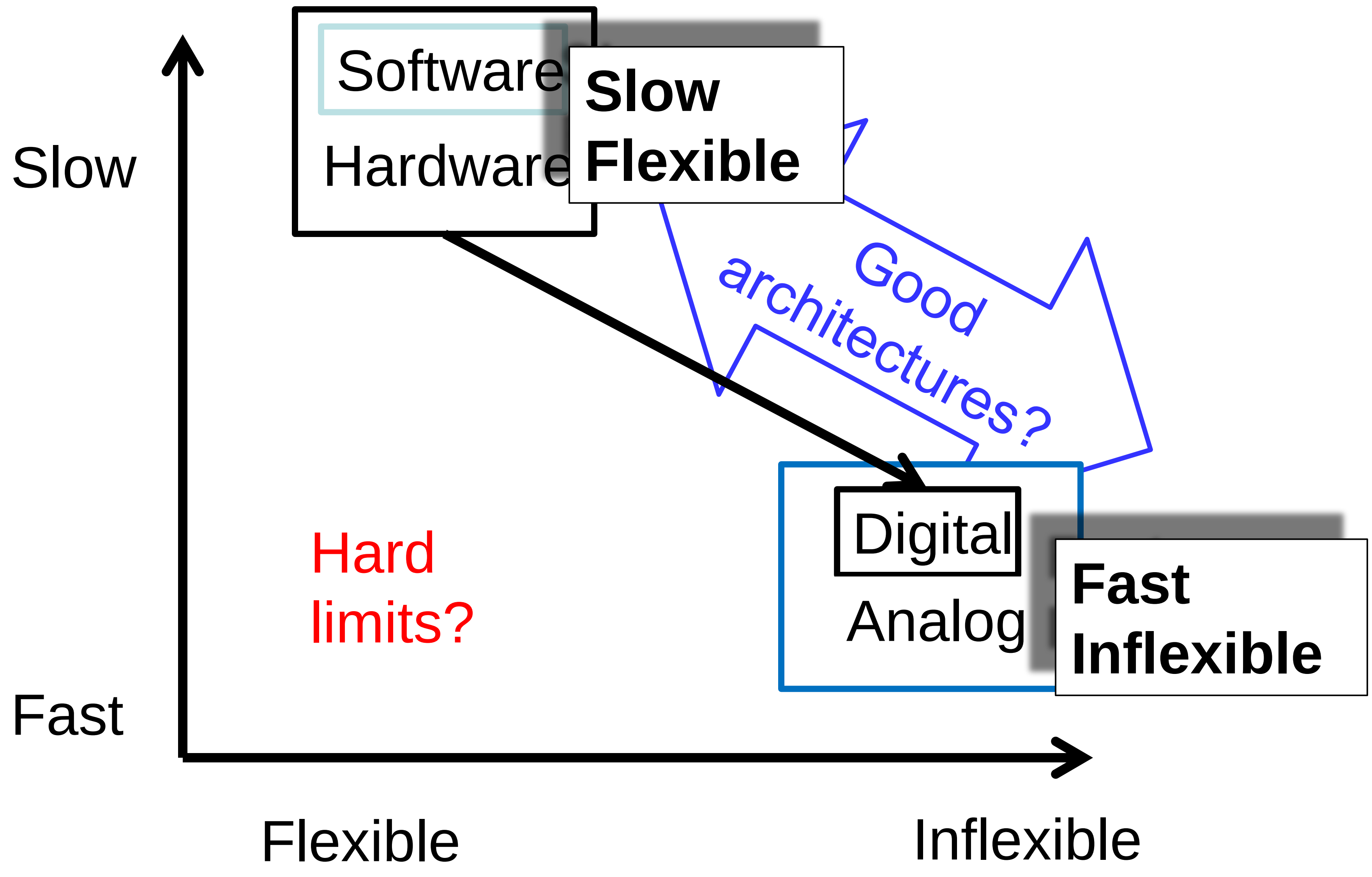
Processing
Memory
I/O

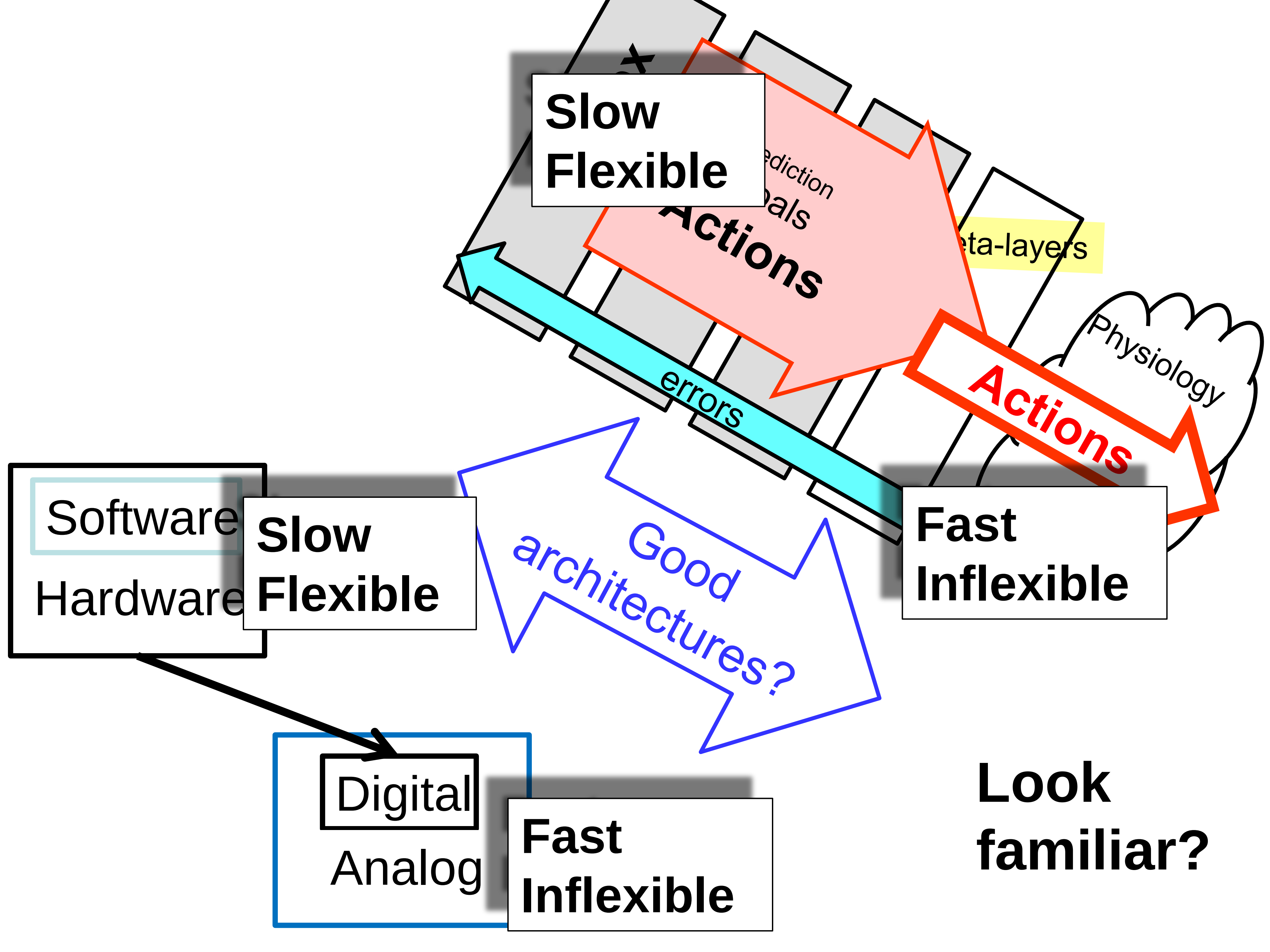
Want to emphasize the differences between these two types of layering.

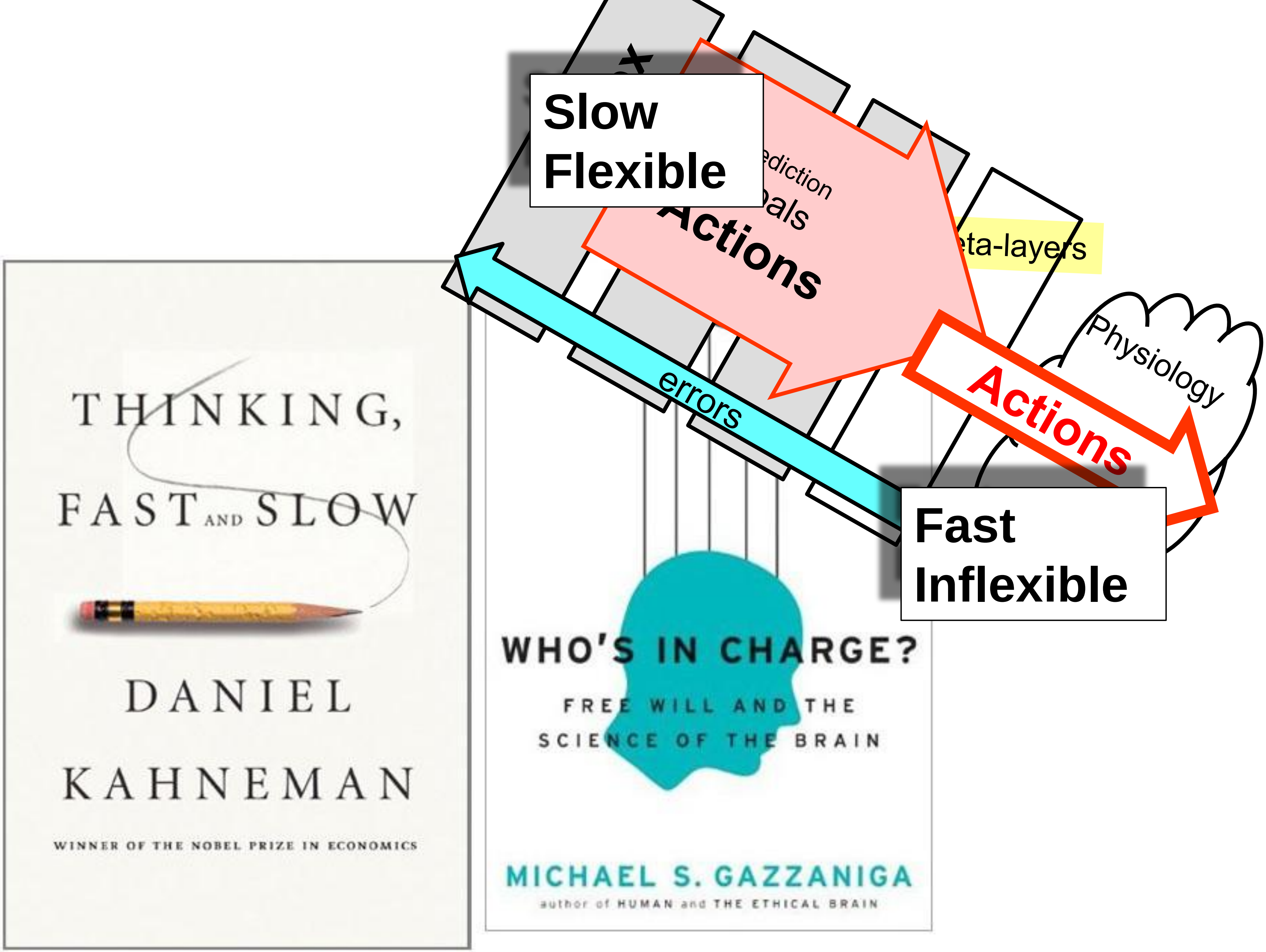

Applications
Operating System
Software
Hardware
Digital
Analog
Outfit
Garment
Cloth
Cloth
Thread
Thread
Fiber
Garment
Cloth
Cloth
Thread
Thread
Fiber
Garment
Cloth
Cloth
Thread
Thread
Fiber

The virtual is more "real" than the implementation

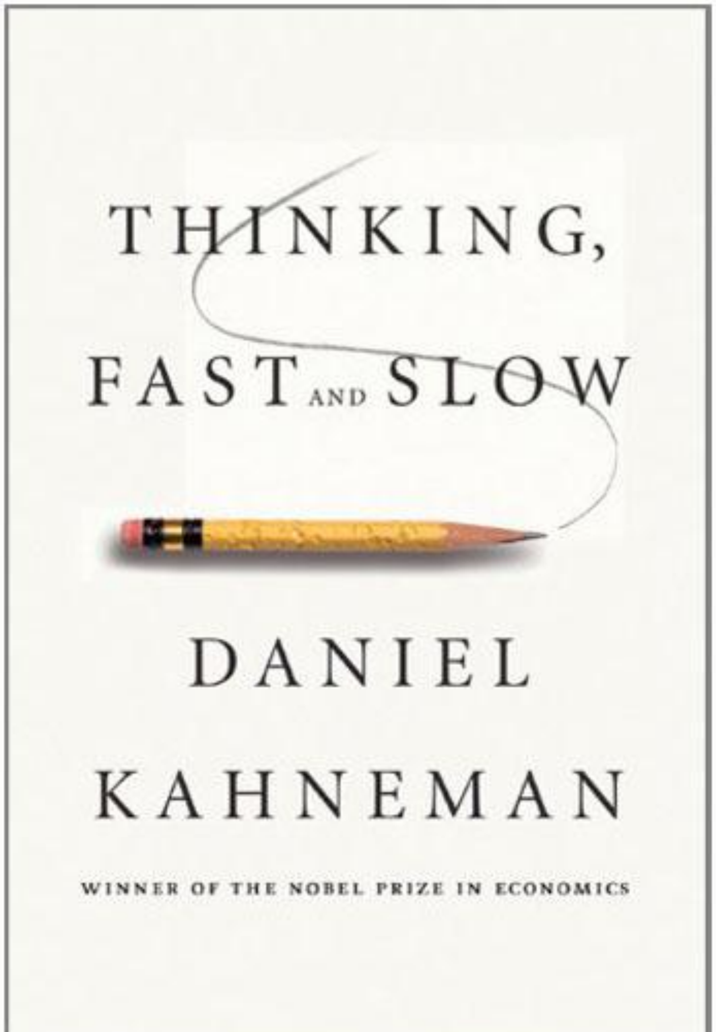



Software
Hardware
Slow
Flexible
Slow
Good
architectures?
Hard
limits?
Digital
Analog
Fast
Inflexible
Fast
Flexible
Inflexible

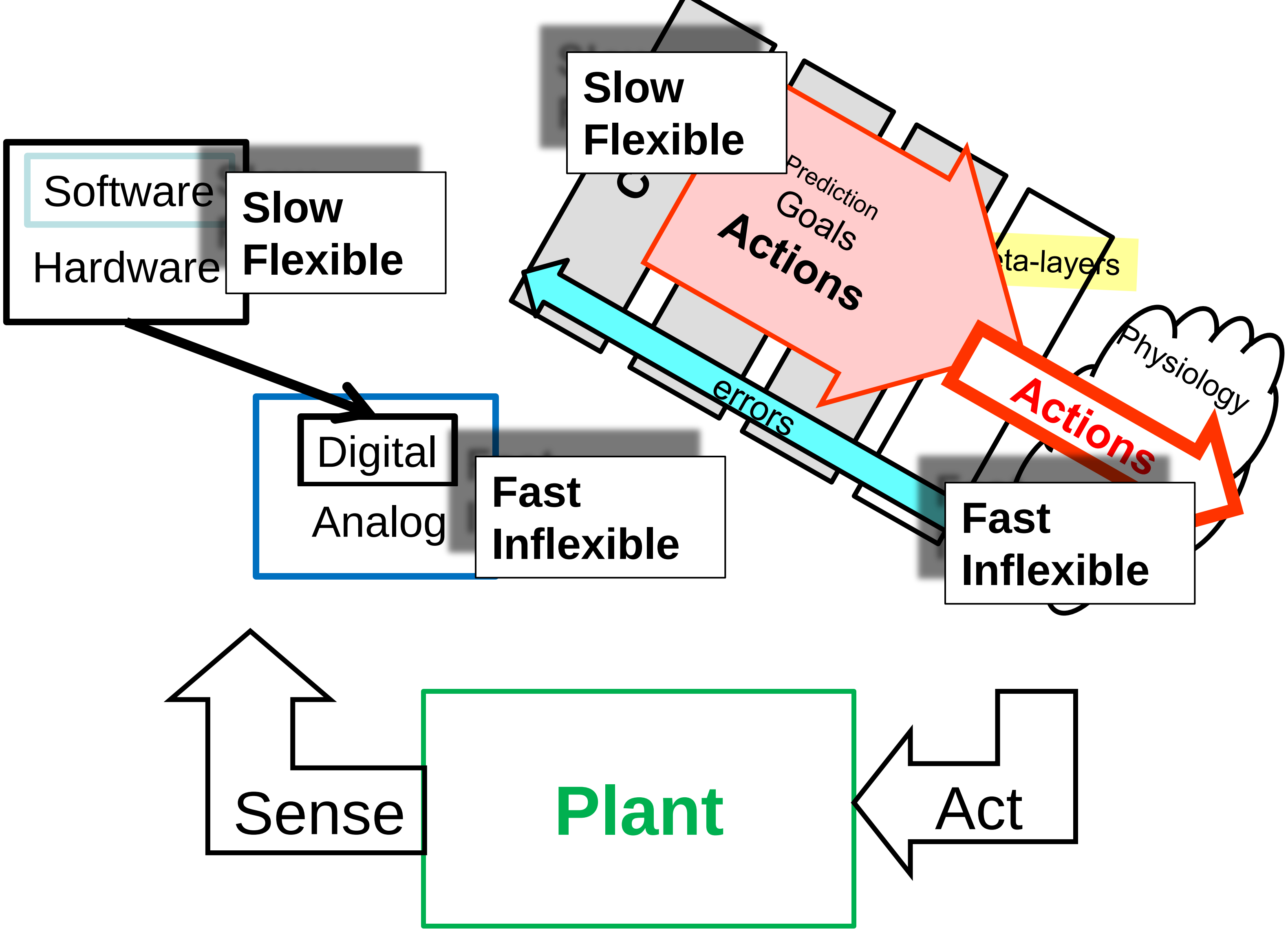

Slow
Flexible
Actions
errors
Actions
Physiology
Fast
Inflexible
Software
Hardware
Slow
Flexible
Good
architectures?
Digital
Analog
Fast
Inflexible
Look
familiar?


Slow
Flexible
Actions
Physiology
errors
Actions
Fast
Inflexible
THINKING, FAST AND SLOW
DANIEL KAHNEMAN
WINNER OF THE NOBEL PRIZE IN ECONOMICS
WHO'S IN CHARGE?
FREE WILL AND THE SCIENCE OF THE BRAIN
MICHAEL S. GAZZANIGA
author of HUMAN and THE ETHICAL BRAIN

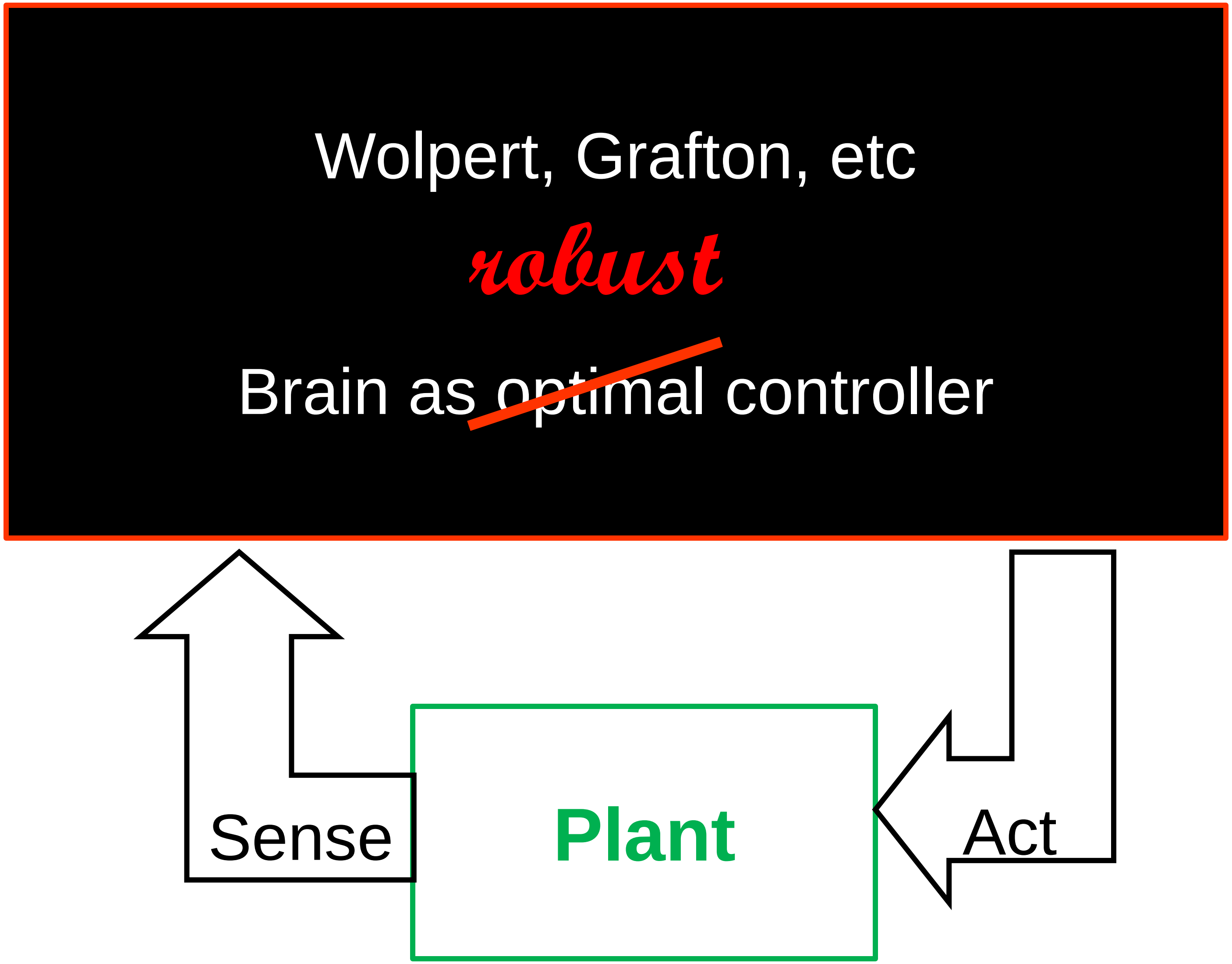
Essentials To Do



- Reyna/Brainerd: Gist, false memory
- Ashby: Automaticity, multiple memory systems,…
- Cosmides/Tooby: Risk, uncertainty, cooperation, evolution,…



Speed and flexibility are crucial to implementing robust controllers.



Speed and flexibility are crucial to implementing robust controllers.

Beyond black boxes:
Putting brain physiology back in the picture

Essentials (following Turing)

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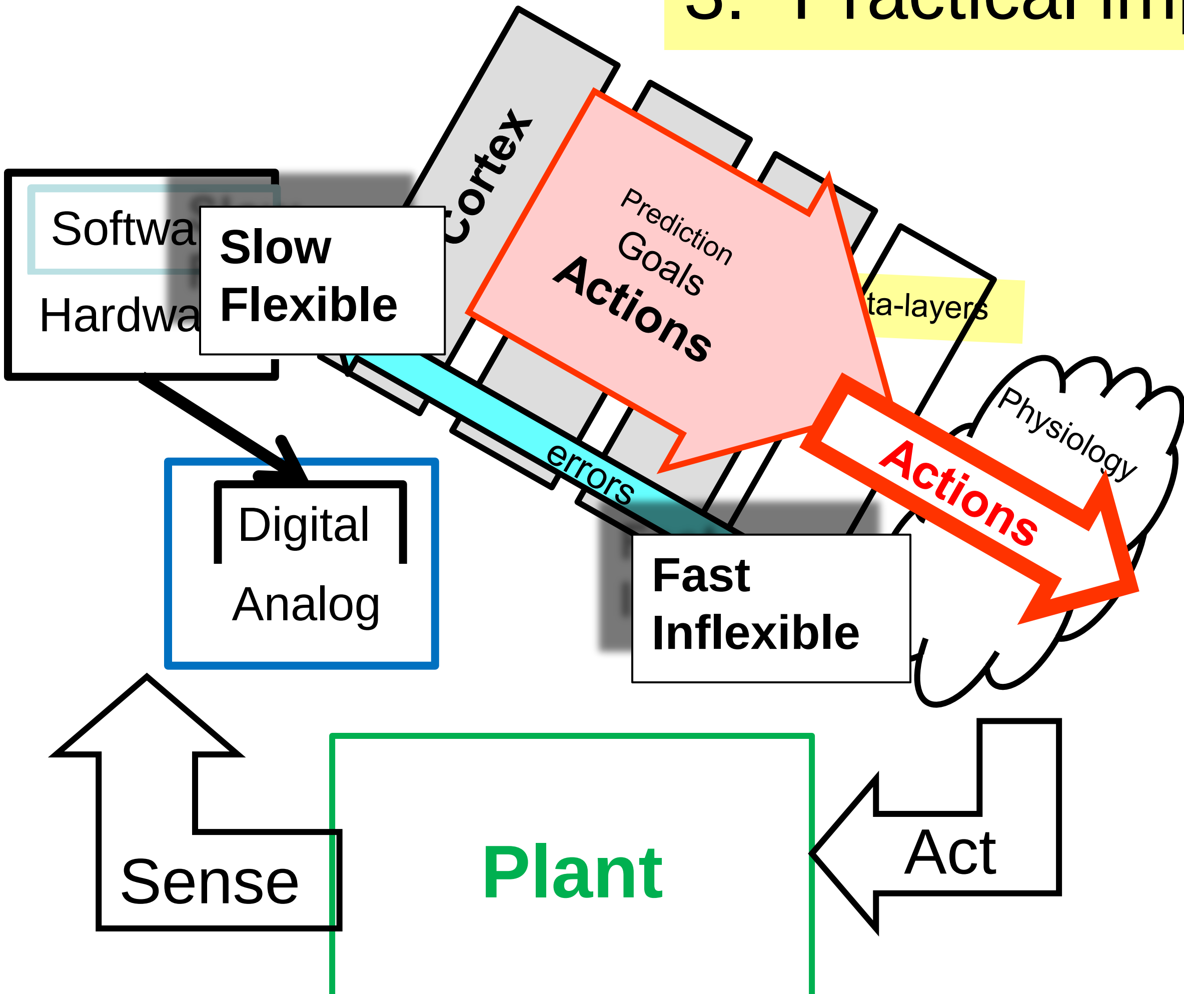
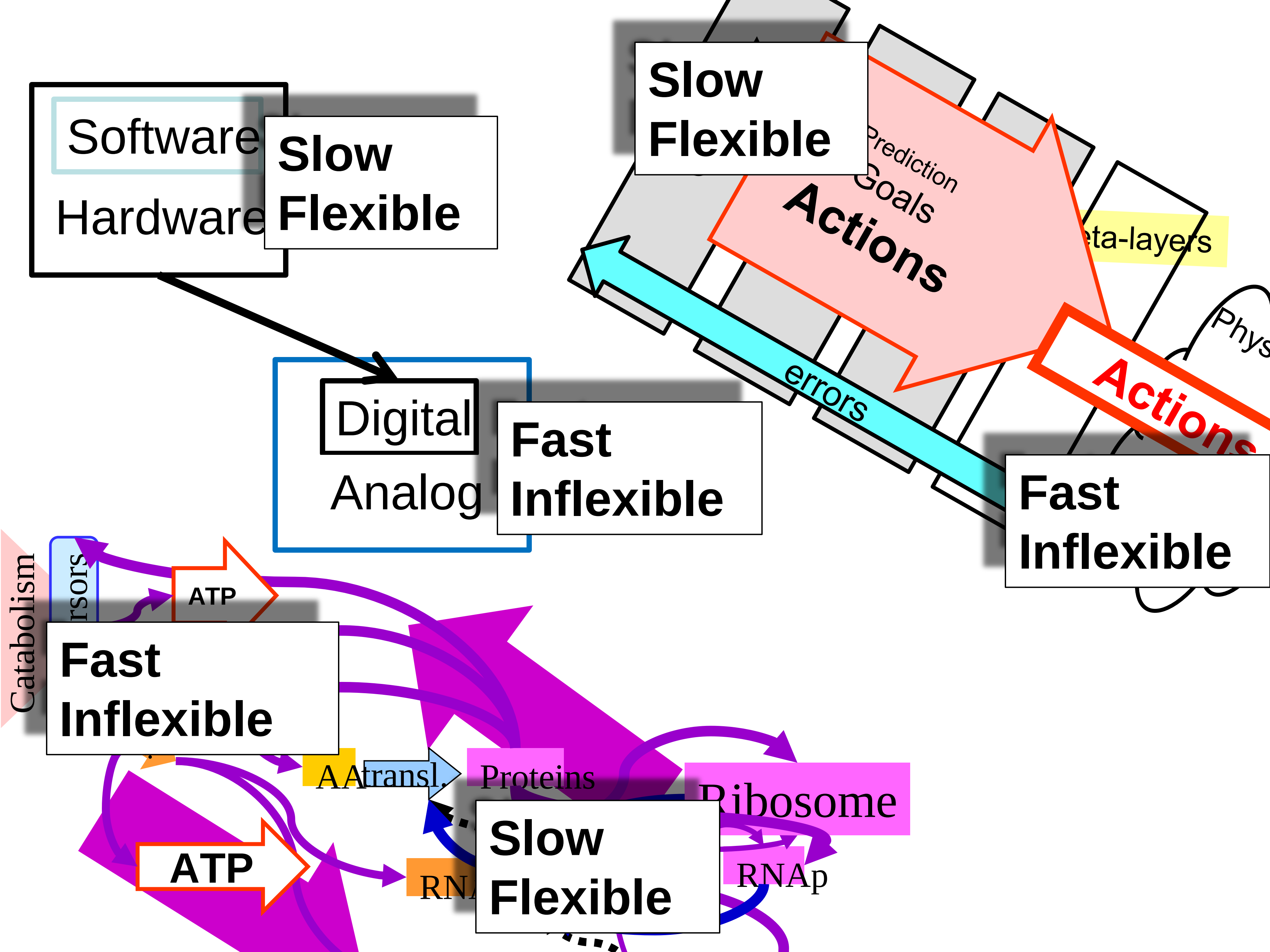
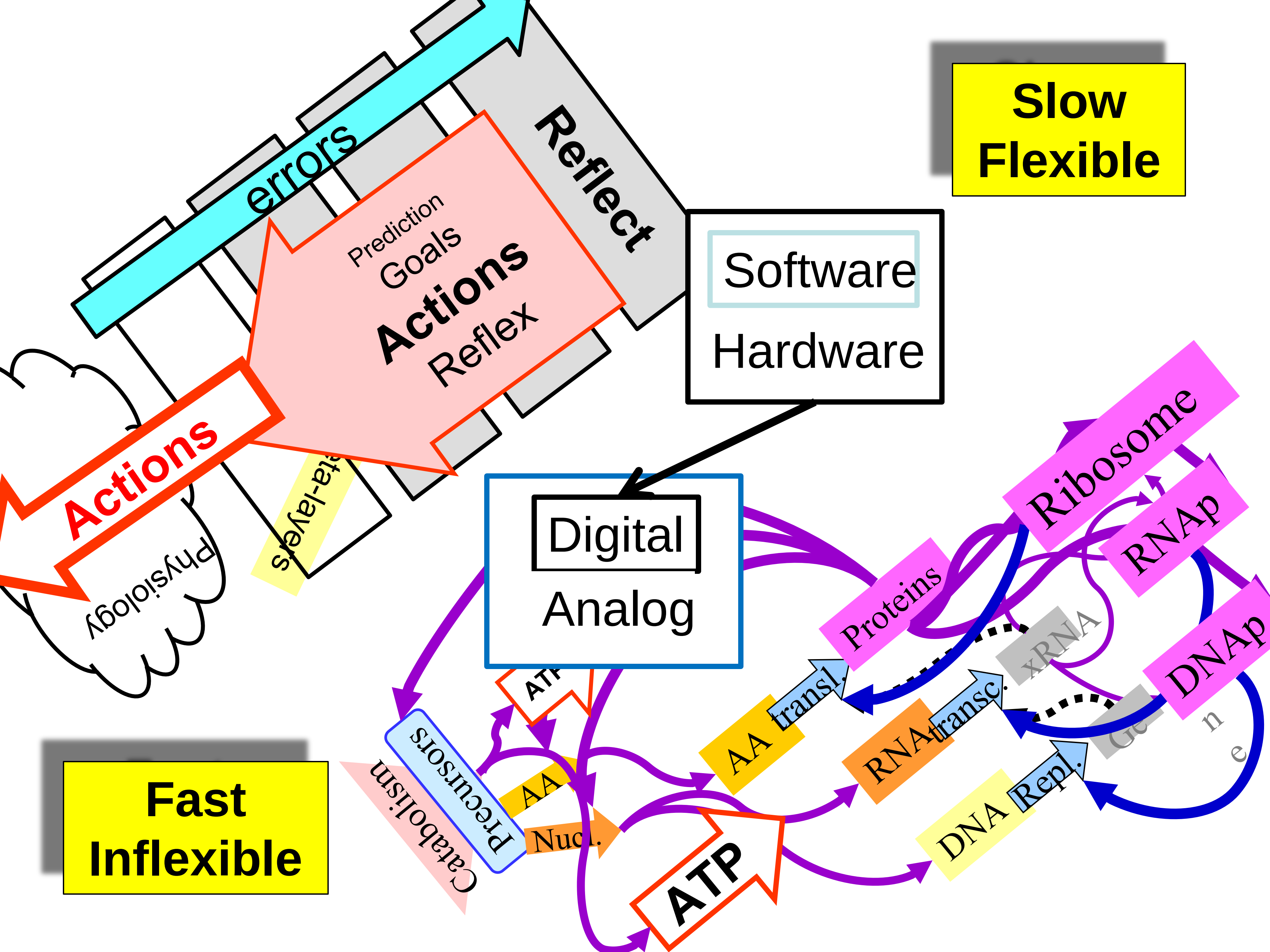
1. Universal laws
2. Universal architecture
3. Practical implementation




Software
Hardware
Slow
Flexible
Digital
Analog
Fast
Inflexible
Slow
Flexible
Prediction
Goals
Actions
errors
Actions
Fast
Inflexible
Catabolism
ATP
Fast
Inflexible
AA
transl.
Proteins
Ribosome
Slow
Flexible
ATP
RNAp

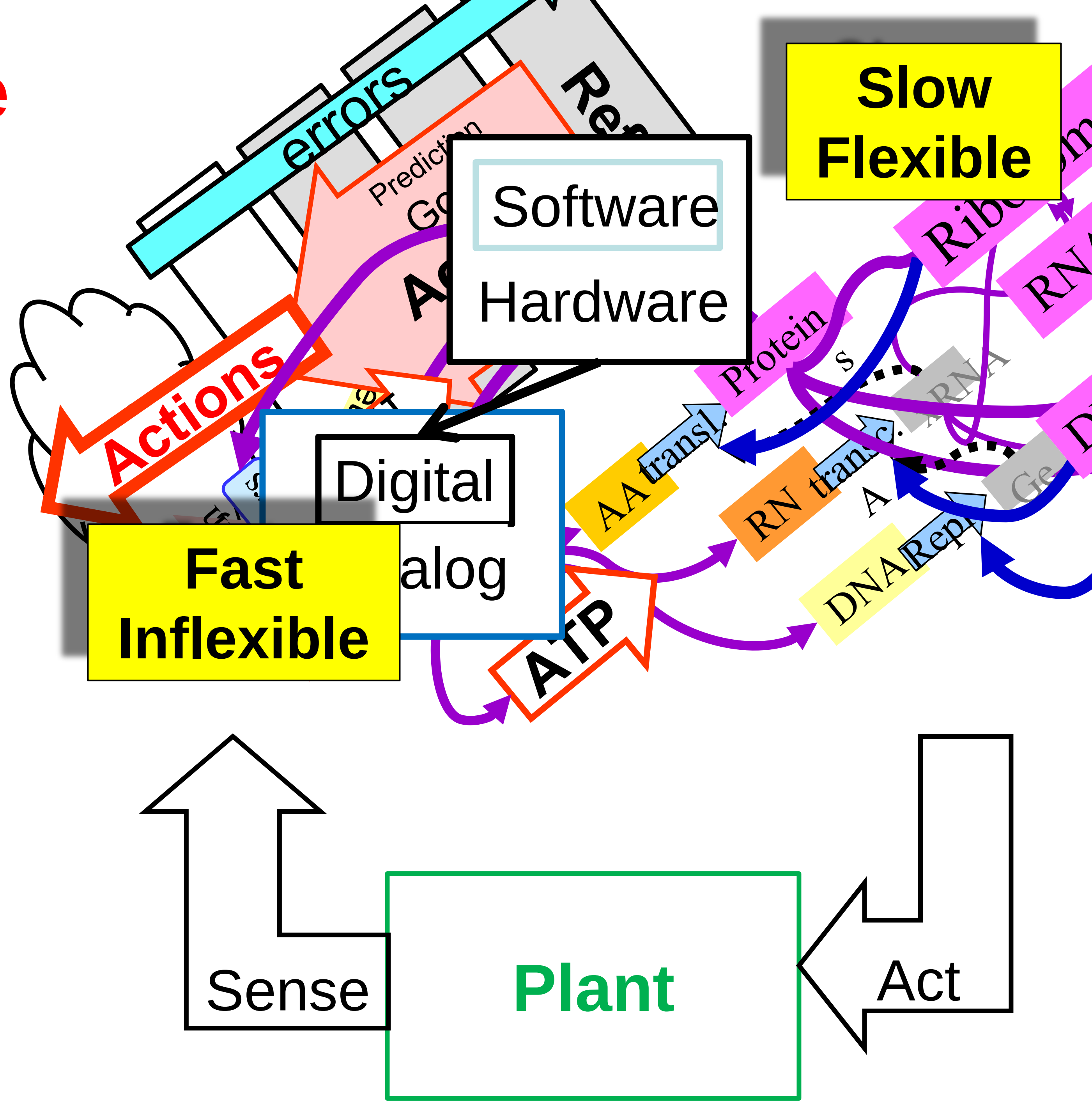


Slow
Flexible
Fast
Inflexible
errors
Reflect
Prediction
Goals
Actions
Reflex
Actions
Physiology
Software
Hardware
Digital
Analog
Ribosome
RNAp
DNAp
Proteins
xRNA
AA
transl.
RNA
transc.
DNA
Repl.
Precursors
Catabolism
AA
Nucl.
ATP

Compute

Turing

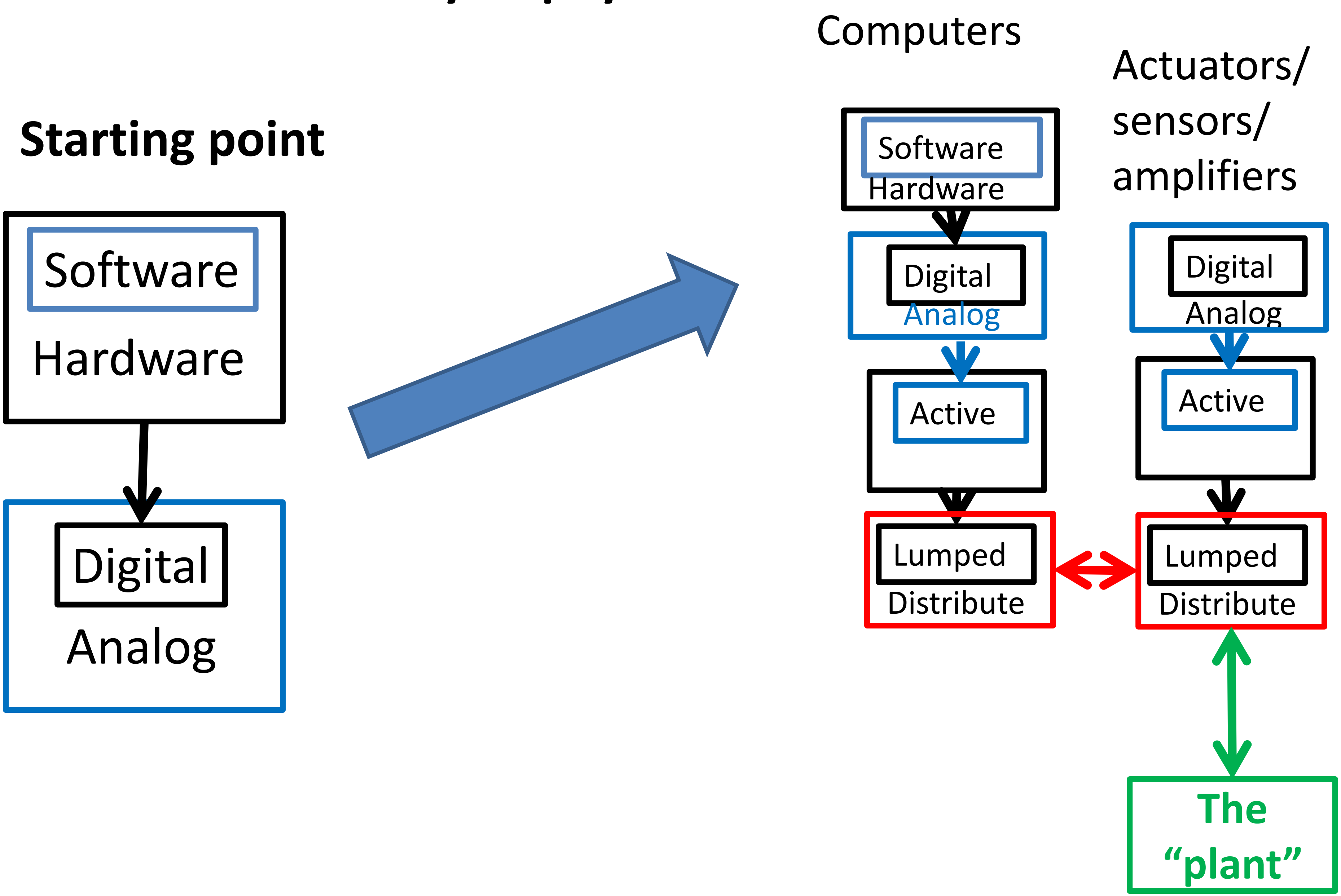
Delay is *most* important



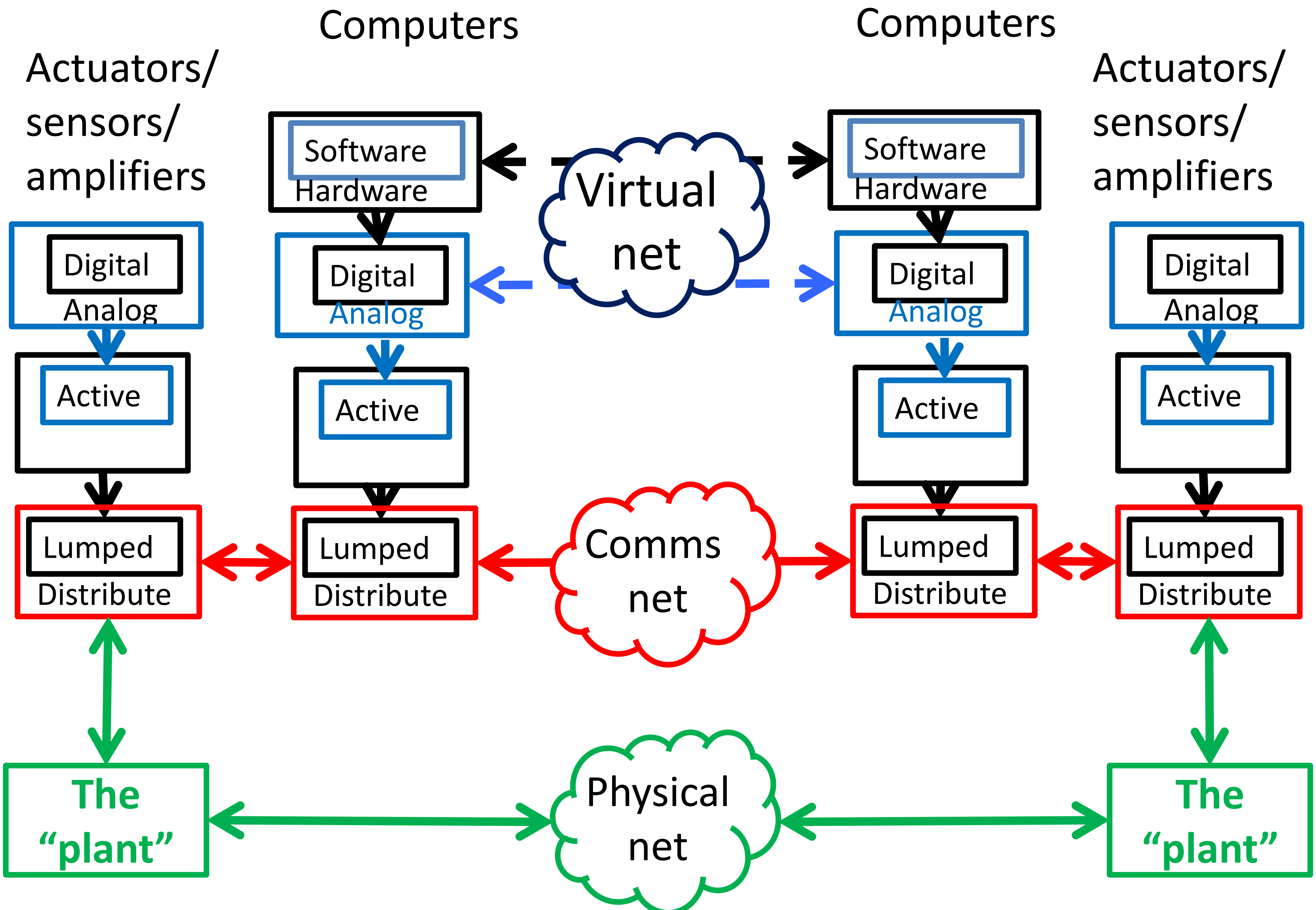
Bode

Control

Cyberphysical



Cyberphysical



Turing as "new" starting point?

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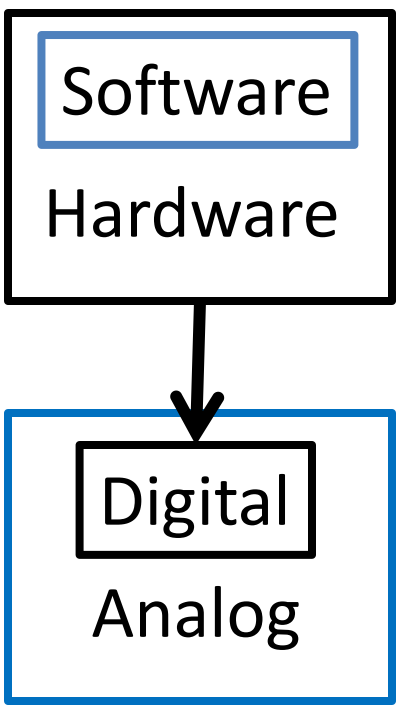


Maybe start from here with Turing's 3 step research:

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

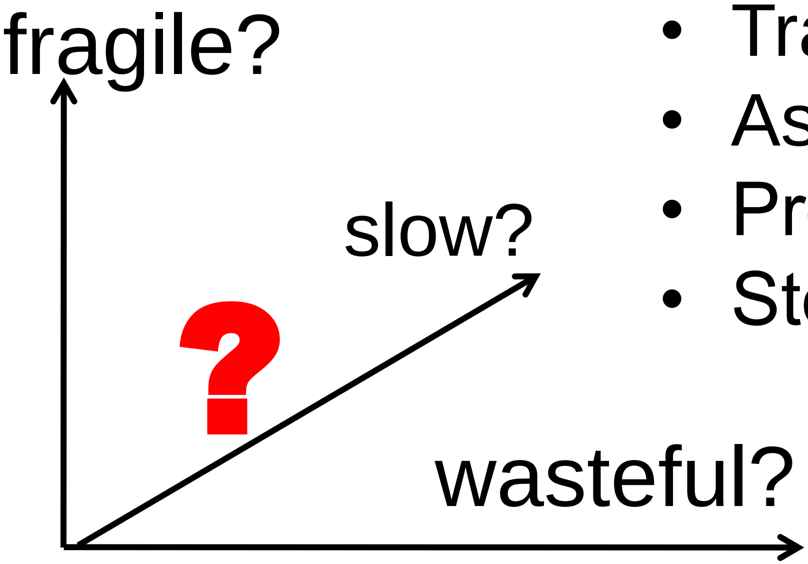
Control

Bode

Comms

Shannon

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



Carnot

Boltzmann

Turing

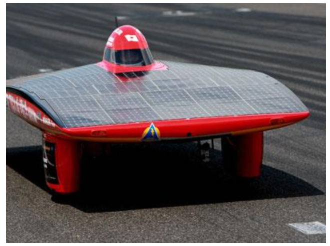
Godel

Heisenberg

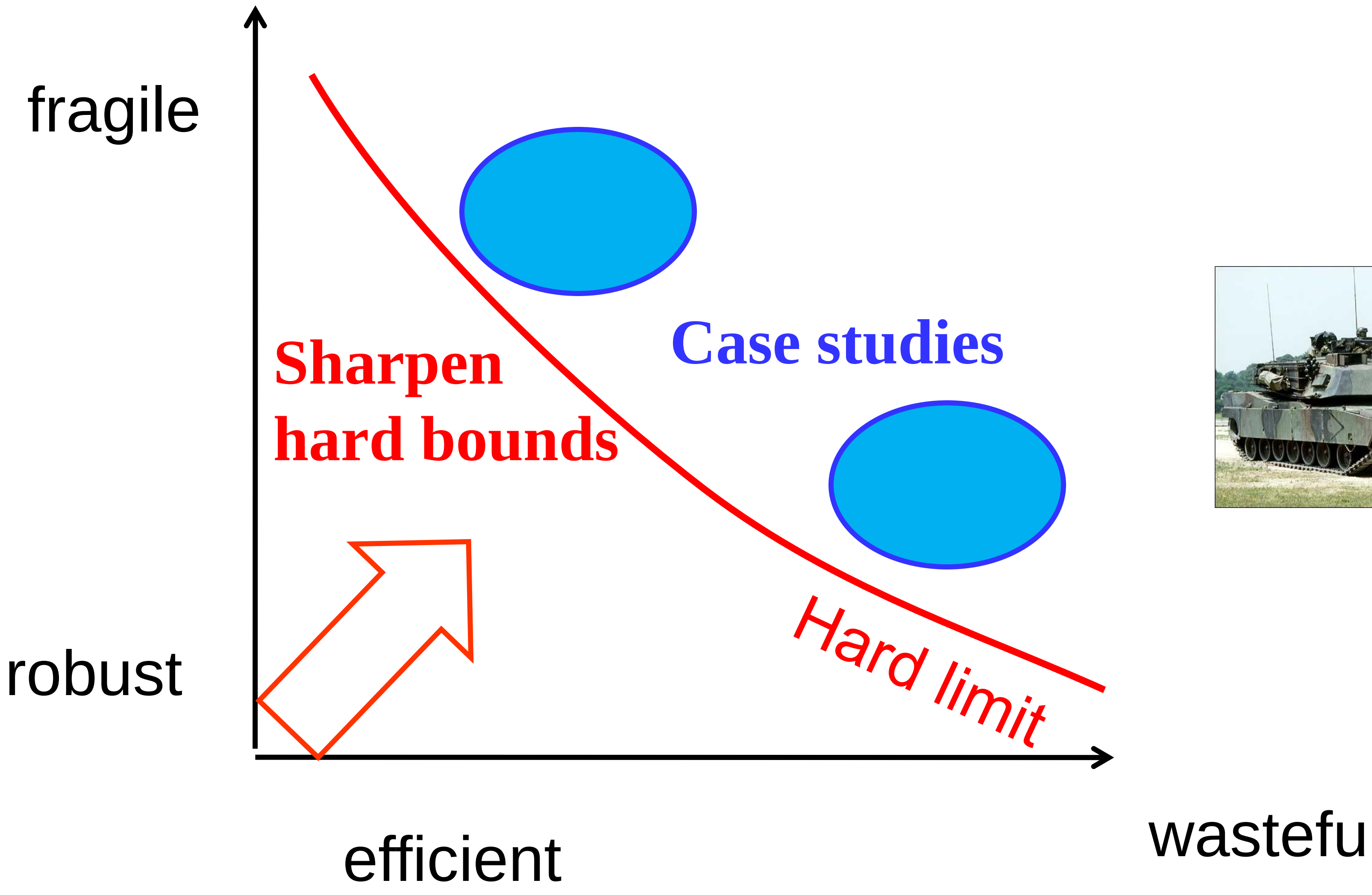
Compute

Physics

Einstein



laws and architectures?



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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

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