What a mathematical foundation for unconventional computing should deliver and how it might look like

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Moving science forward.

My (non-)field: neuromorphic computing

A. Digital computing: energy footprint and bandwidth crisis ahead

B. Biological brains: better by orders of magnitude

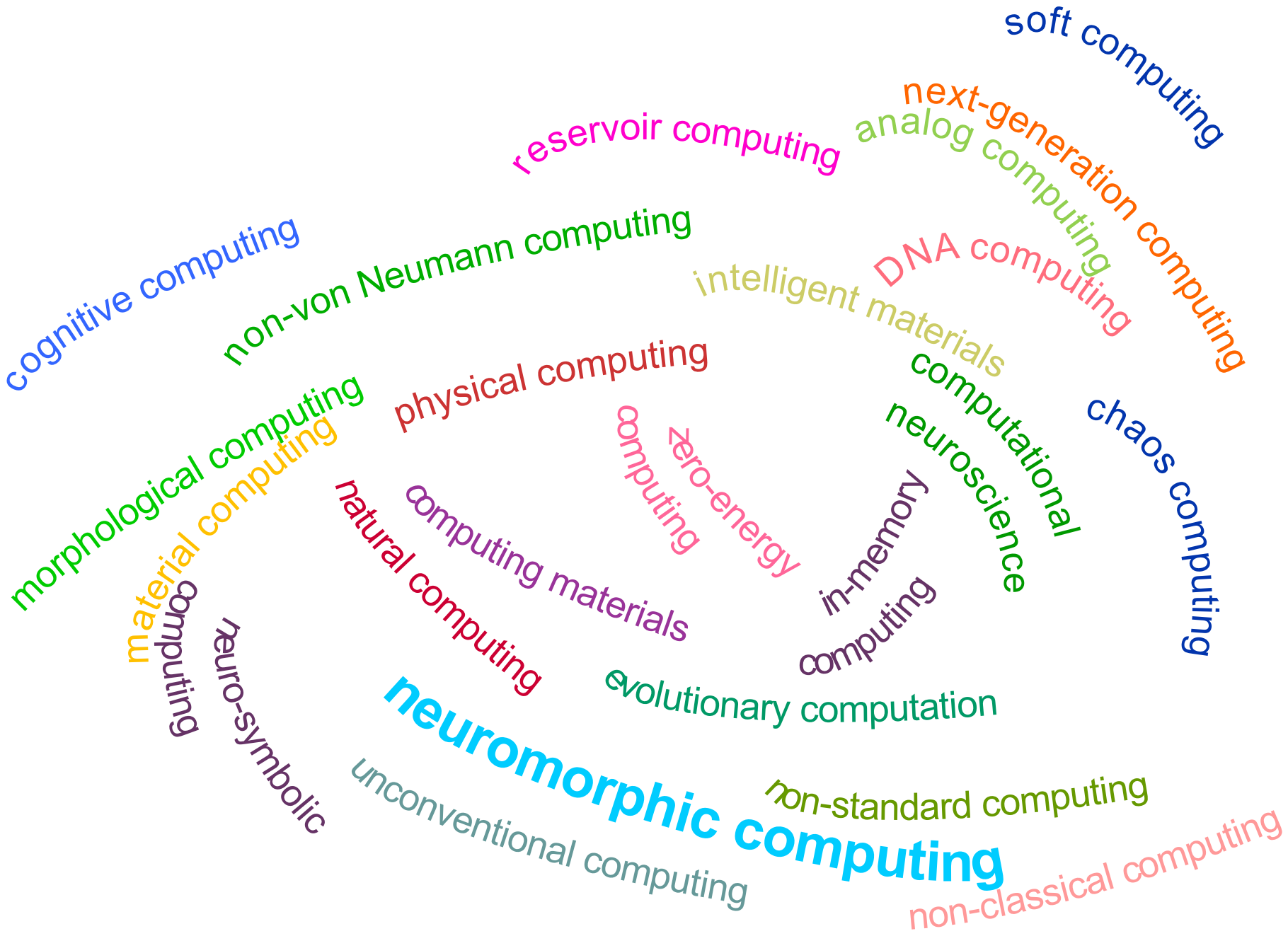
C. Neuromorphic materials, devices and methods: brain-like!

https://faithit.com/wp-content/uploads/2015/10/crw_4370.jpg

A & B & C ⇒ Neuromorphic computing will save us from crisis

- I’m not thinking here of *simulating* neural systems / artificial neural networks on classical digital machines
- It’s about *physical incarnations* of brain-inspired ”computing”
- Catchphrase: “exploit the physics directly”
  - for instance, spikes in neuromorphic microchips are electrical pulses

It’s not “a” field, but a whirlpool of eddies



It's not only "brain inspired" but reaches out to general physics

- catchphrase: compute with whatever physics offers
- brandings: in-materio computing, physical computing, unconventional computing, natural computing
- exploit phenomena in any mode: electrical, electromagnetic, chemical, biological, mechanical
- thousands of novel materials are being explored
- disciplines involved:
  - materials science, theoretical physics
  - microelectronics, microchip fabrication tech
  - computational neuroscience
  - signal processing & control
  - theoretical computer science
  - dynamical systems theory, complex systems research
  - machine learning
  - cognitive science
  - philosophy of computation and of mind

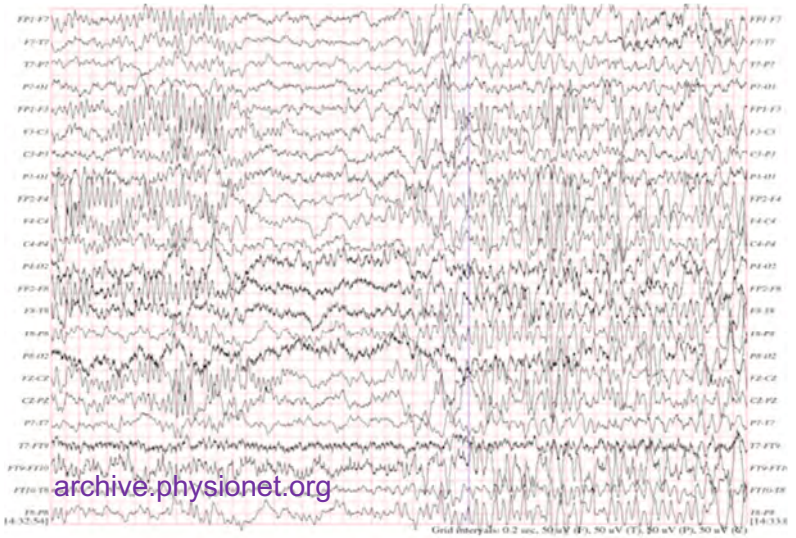
A collection of bummers

- Analog-physical „numerics“
  - „fluid“ quantities
  - no high-precision math models (no ODEs)
  - not even $\mathbb{R}$

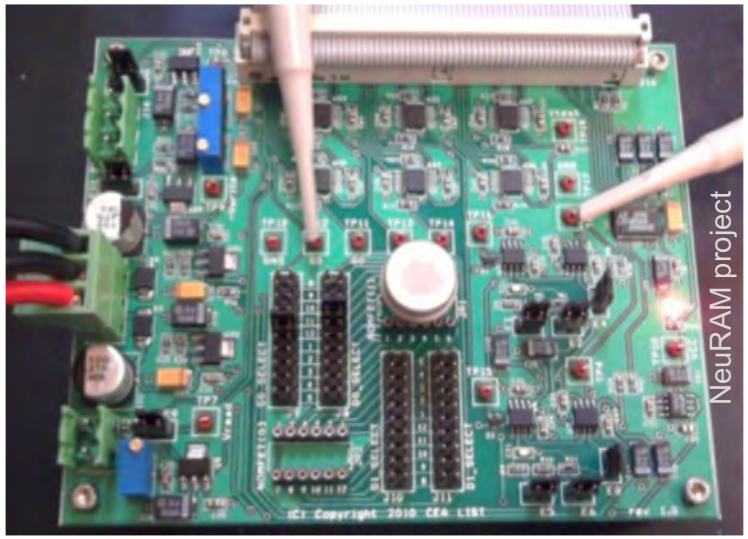
- No global clock
  - continuous time
  - delays
  - synchronization – how?
  - across-chip coordination?

- Parallelism
  - spatio-temporal dynamics
  - causal dependency management
  - multiscale „logic“?

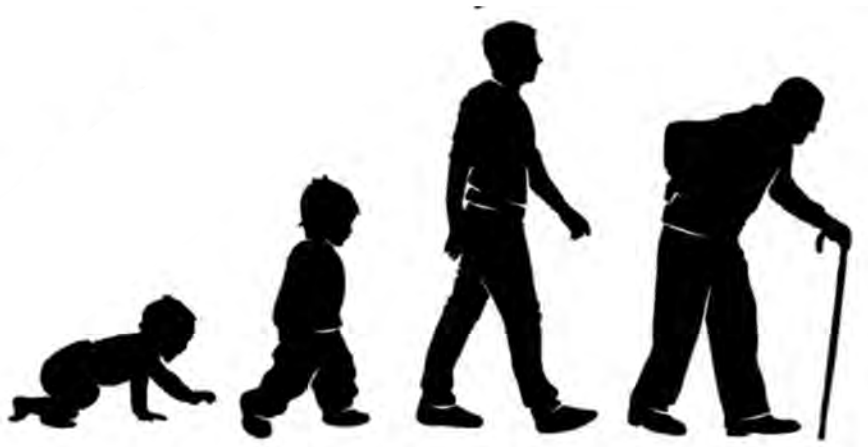
- Stochasticity
  - static: device mismatch, irreproducibility
  - dynamical: spatial and/or temporal averaging?
  - which „information theory“?



- Unobservability
  - only few on-chip physical quantities can be measured
  - measuring attojoule effects distorts them



- Drift, aging, limited endurance
  - life-long adaptation
  - component death

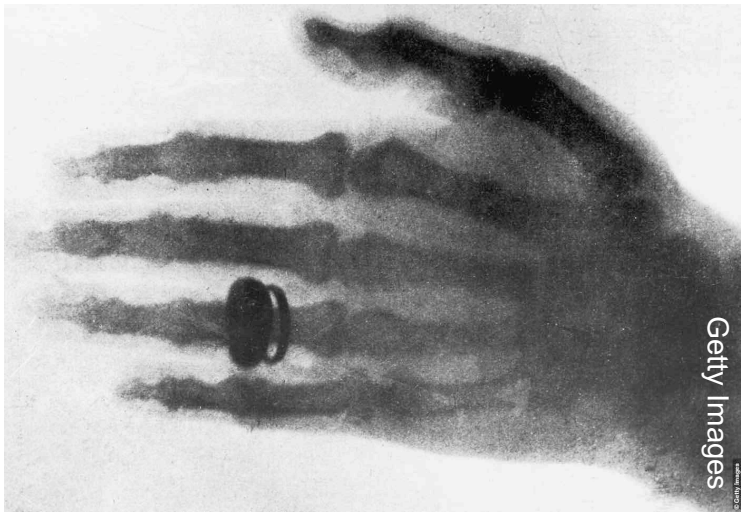


- Temperature sensitivity
  - precise T stabilization...
  - or homeostatic regulation
- room temperature challenge

- Always on
  - no reset state
  - no zero-power memory
  - sleep?

- Utilization attitude
  - not: “tool design & use”
  - rather: “autonomous companions”
  - not 100% predictable or controllable

- Use cases
  - online adaptive sensing ”cognitive”
  - emancipate from DC thinking
  - start with insect ganglion thinking
  - new kind of use culture



Current status of this (not-yet-)field

- Funding boost in industry: Intel's Loihi chips, IBM's TrueNorth and NorthPole
- Funding boost in academia: CogniGron center founded 2019 with 12 new professorships and 20 PhD positions
- Funding boost in National and European programmes
- Great intellectual experience, deep questions, very cooperative social dynamics

- Progress is slow
- Expectations were created that cannot be fulfilled
  - Industry customers want "AI to put on drones"
- In particular, no economically relevant applications yet
- Field is far from unification or consolidation

Why talk with logicians?

System engineers should learn from digital computing (DC) rather than from brains

- DC is overwhelmingly successful as an engineering discipline

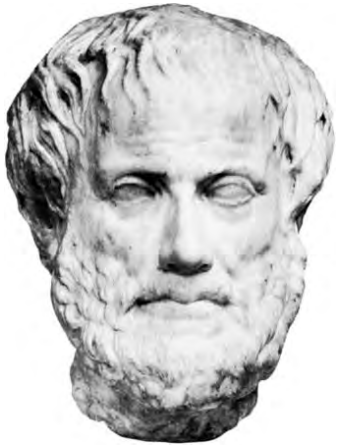
https://www.flickr.com/photos/kimstovring/15674061412

- Neuroscientists cannot give us a functional blueprint for scalable practical computing systems

Here is the heart of it

Sources of pictures given in separate hidden slides, visible in shared version of this talk.

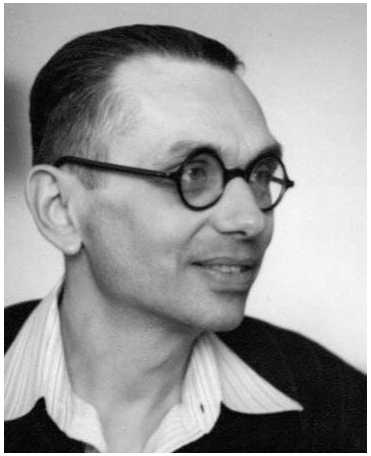
And here the spirit and soul

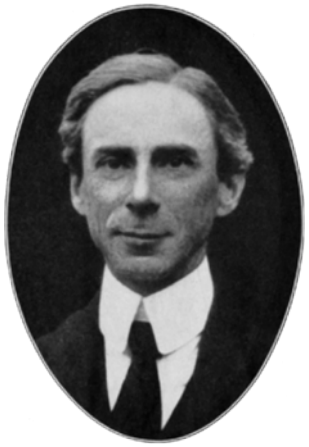


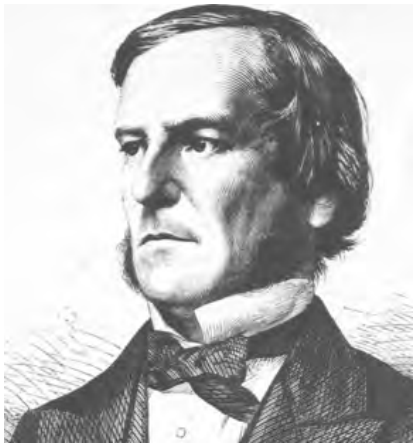
Aristotle (384-322 BC) *"All men are mortal. All Greeks are men. Hence, all Greeks are mortal"* – Syllogistic logic reasoning as basis of irrefutable reasoning from truth to truth.

Leibniz (1646-1716) *Characteristica Universalis* and *Calculus Ratiocinator* – Vision of a universal logical language and mechanical rules of argumentation

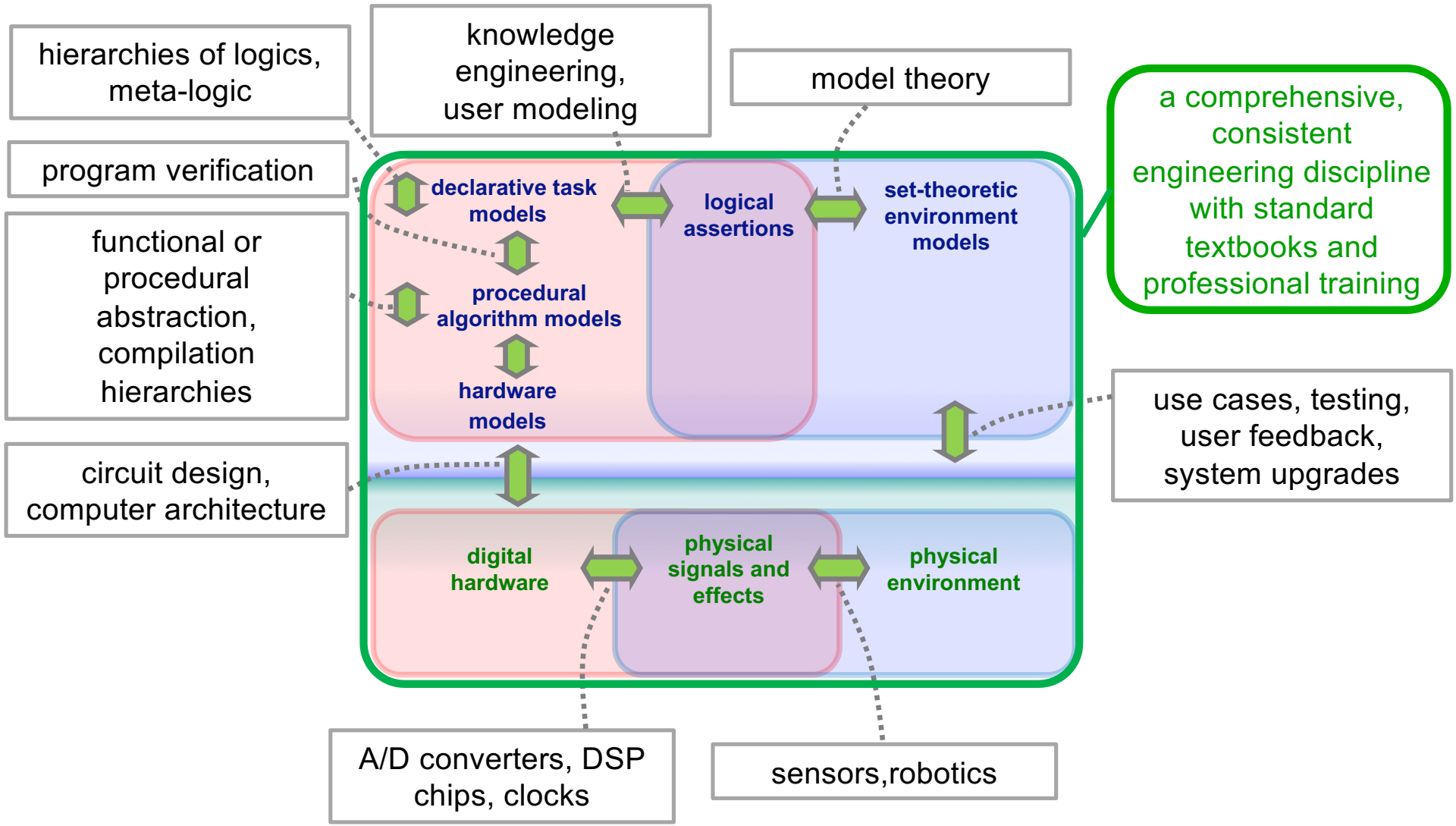
Boole, Frege, Hilbert, Russell, Gödel (~1850'ies to 1930'ies) *mathematical logic systems* – dream of mechanically deciding all mathematical questions







And here is what comes out of hart + soul



More detail in [1, 3, 4]

The grand essentials of digital computing theory

- deep roots in philosophical and mathematical history
- “computing” = logico-mathematical reasoning
- algorithms as models of a mathematician’s mental processes

  $\Longrightarrow$ any formal scientific model can be simulated on a digital computer

  $\Longrightarrow$ necessarily symbolic-logic-like

“Computing” is the essence of rational reasoning
… at least, the symbolic kind of ”computing”

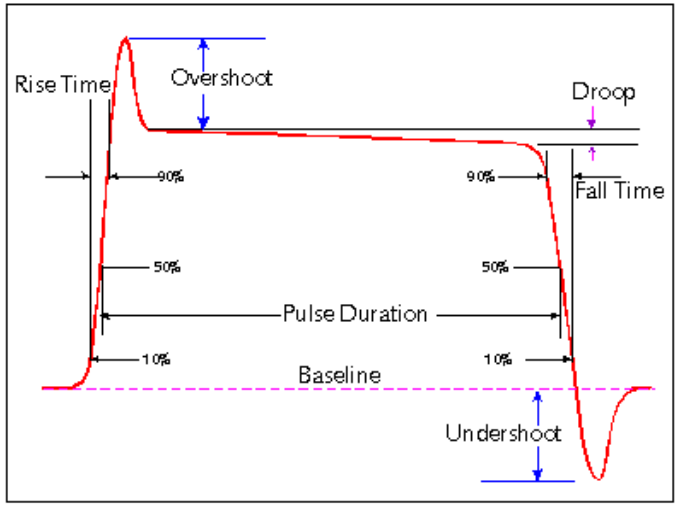
Hence, if “we” (the neuromorphic crowd) wants to think about the roots of “computing”, we must talk with logicians.

But why should the logicians want to talk with “us”?

What symbolic computing theory is *not*

- a theory of physical brains or brainlike physics
  - update steps model logical inference steps, not physical dynamics
  - Turing says ‘mind’, not ‘brain’
  - CS theory textbooks do not use the real-valued timeline t, nor mention the word “second”

- a guide for exploiting physical phenomena at large for information processing
  - the only exploitable physical effect is finite state-switching
  - a tiny niche in the world of physical phenomena



Source lost

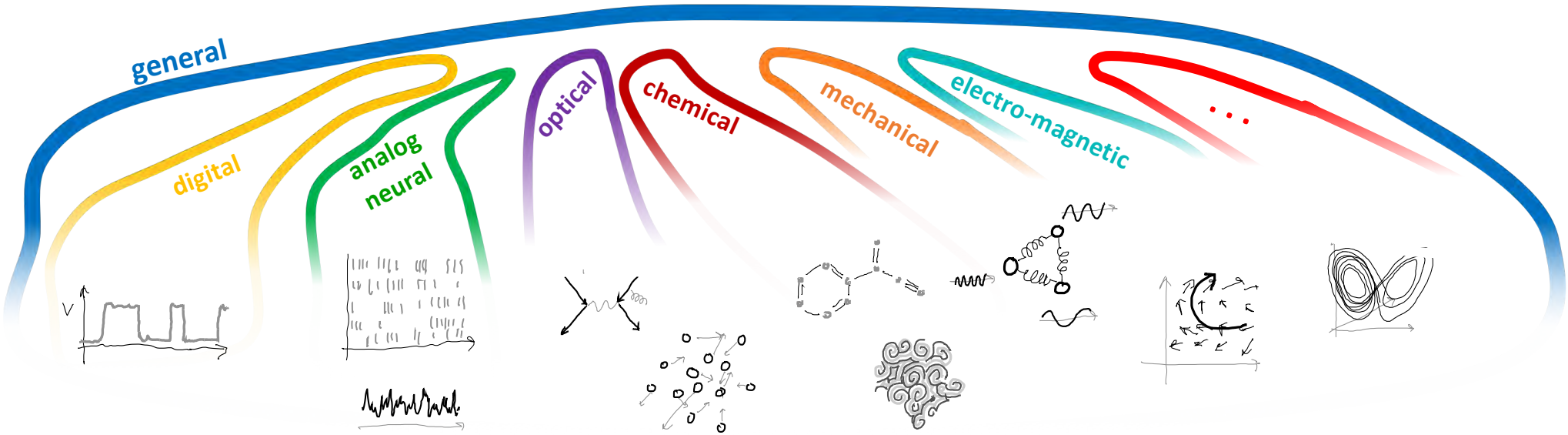
Hence, if one wants to make progress with understanding physical computing, one must get logicians interested.

What we … –

cognitive neuroscientists, microchip engineers, materials scientists, theoretical physicists, dynamical systems mathematicians, complex systems people, neuromorphic computing pioneers, fearless theoretical computer scientists, philosophers of mind and matter and information, etc., –

need

Vision of a general formal theory (GFT) of “computing” in physical systems



- Unified terminology across disciplines
- Model translations
- Functional invariances and translations in/between physical phenomena
- Simulation models
- System classification
- DC as special case
- Describe natural systems as information-processing

(more in [3,4])

Two ways to go

Digital/symbolic computing: top-down

- starting from disembodied rational reasoning,
- imposing a formal model of that on the physics at the bottom

Unconventional / in-materio / neuromorphic… 'computing': bottom-up

- starting from physical phenomena
- evolving ways to use them for 'computing'

Candidate theory proposals (selection)

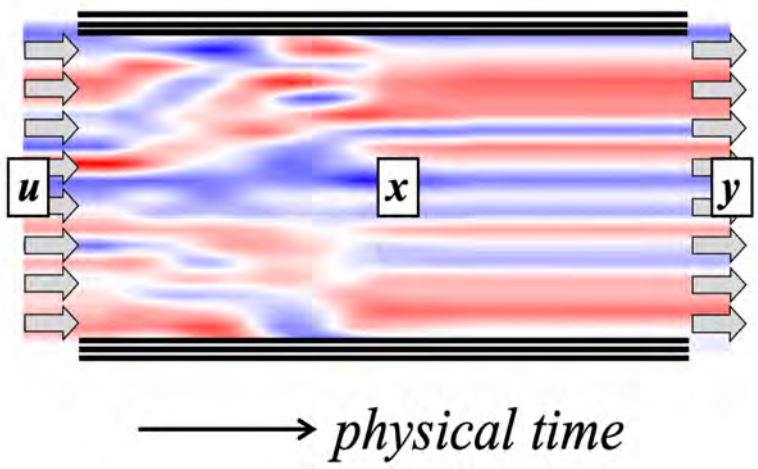
- Ultrastable systems (Ashby)
- Pattern theory (Grenander, Mumford)
- Free energy agent model (Friston)
- Reservoir computing (Maass, Jaeger)
- Stochastic computing (von Neumann)
- Hyperdimensional computing (Kanerva)
- Neural engineering framework (Eliasmith)
- Dynamic fields (Schöner)
- Heteroclinic channels (Rabinovich)
- Neural sampling (Hinton, Maass)
- Neuro-symbolic integration (various)
- Membrane computing (Paun)
- Constructor theory (Deutsch)
- ε-machines (Crutchfield, Packard)
- Wolfram physics (Wolfram)
- Causal sets (Sorkin)
- Commuting diagrams (Horsman, Stepney)
- Neuromorphic compilation hierarchy (Zhang et al)

Too inexpressive
Too abstract / “meta”
Too exclusively ”neuro”
Too informal
Too far away from physics
Too unready
Too symbolic / combinatorial

(more in [4])

How to get there

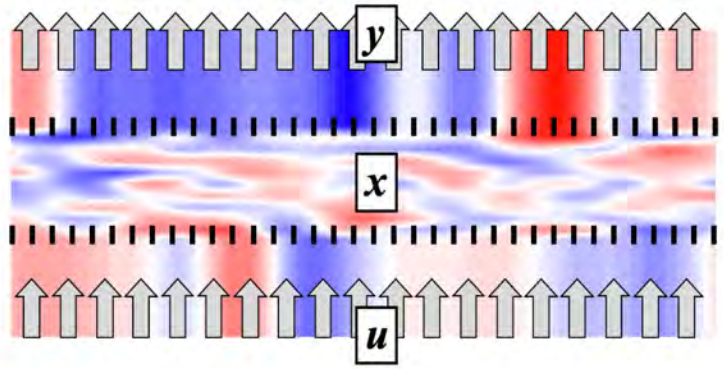
Role model for modeling brains and such: cybernetics



Babbage's arithmetics machine

Digital:

- offline, decoupled in time from task
- input and output: static symbolic structures
- modeling reasoning / minds



Watt's centrifugal governor

Cybernetic:

- online, entrained to physical time $t \in \mathbb{R}$
- input and output: continuous signals
- modeling machines / brains

(workout in [2,4])

Where cybernetics meets, and where it misses, a GFT

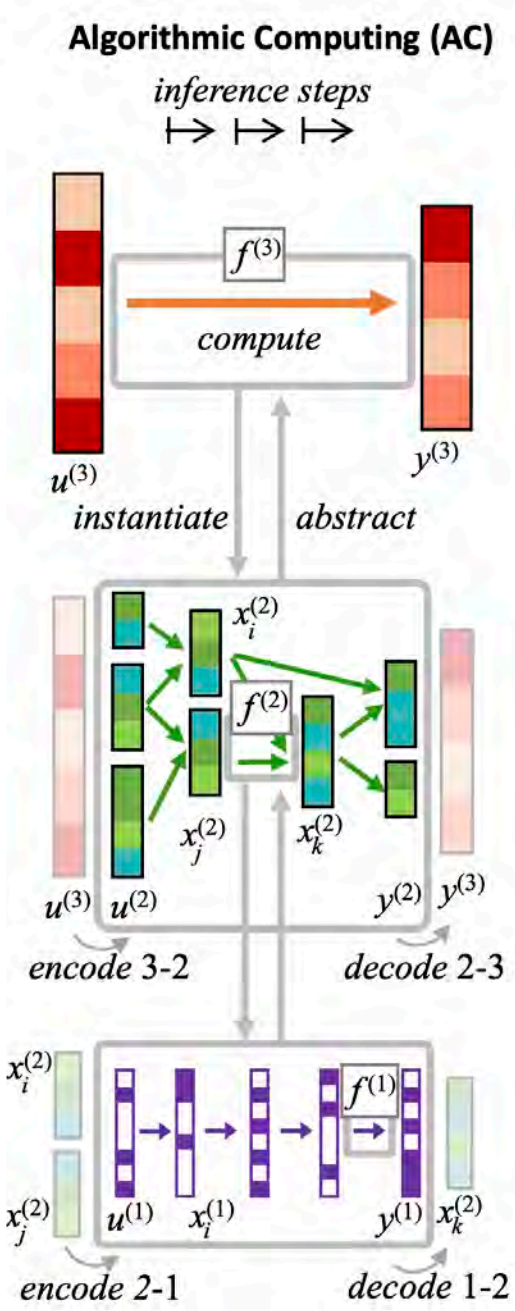
Meets

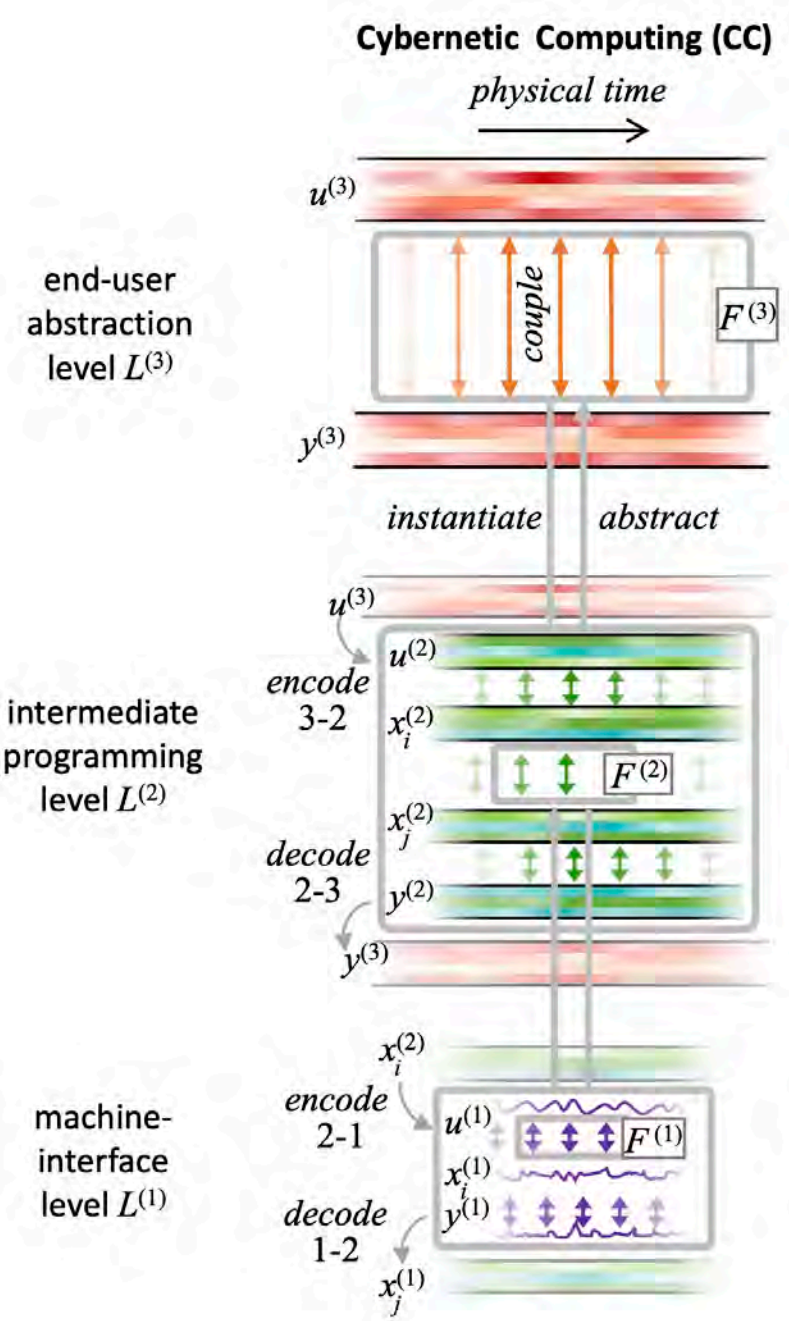
- Continuous time
- Not a priori confined to single sort of root dynamical phenomenon
- Online entrained processing
- Natural science approach, especially in biological cybernetics
- Engineering attitude, especially in signals and systems

Misses

- Spatiotemporal phenomena
- Multiscale dynamics
- No concept of information other than Shannon information – nor of representations or semantics
- No generic methods for scaling system complexity

Strategy: combine scalability of DC with physicality of cybernetics





Motto

From

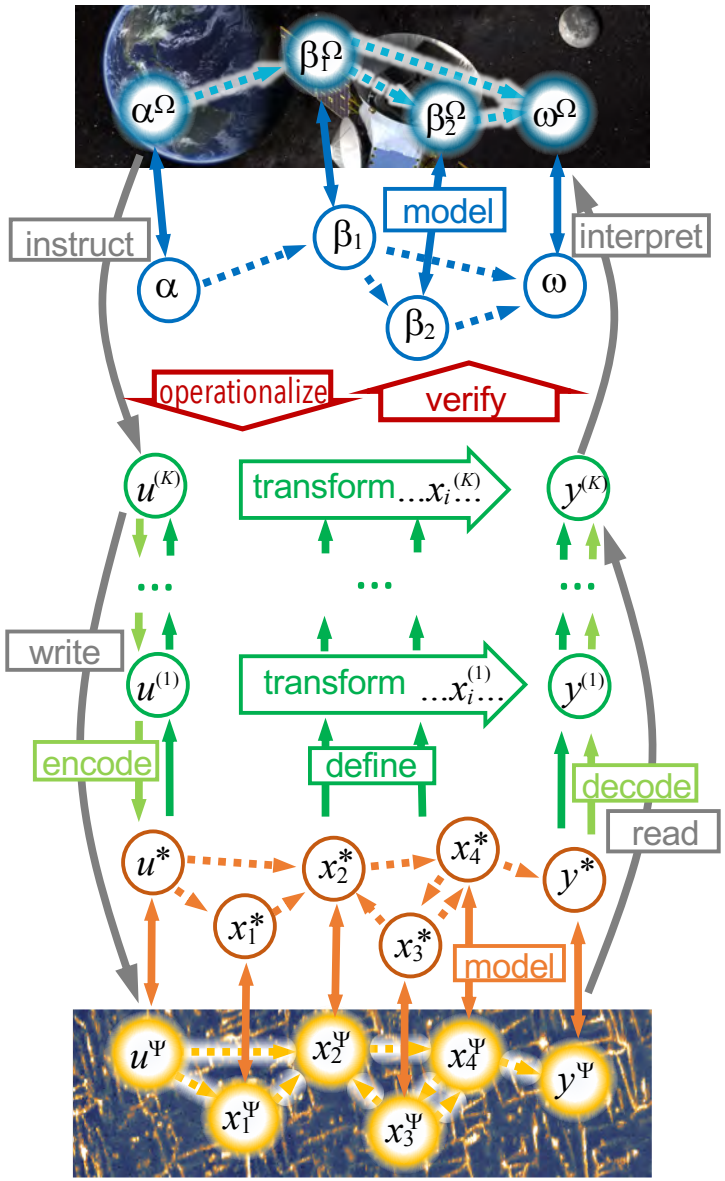
processing structures

to

structuring processes

(workout in [4])

Many things we need



TE
task environment

TM
task model

$CM^{(K)}$
computational model K

...

$CM^{(1)}$
computational model 1

PM
physical system model

PS
physical computing system

physical reality

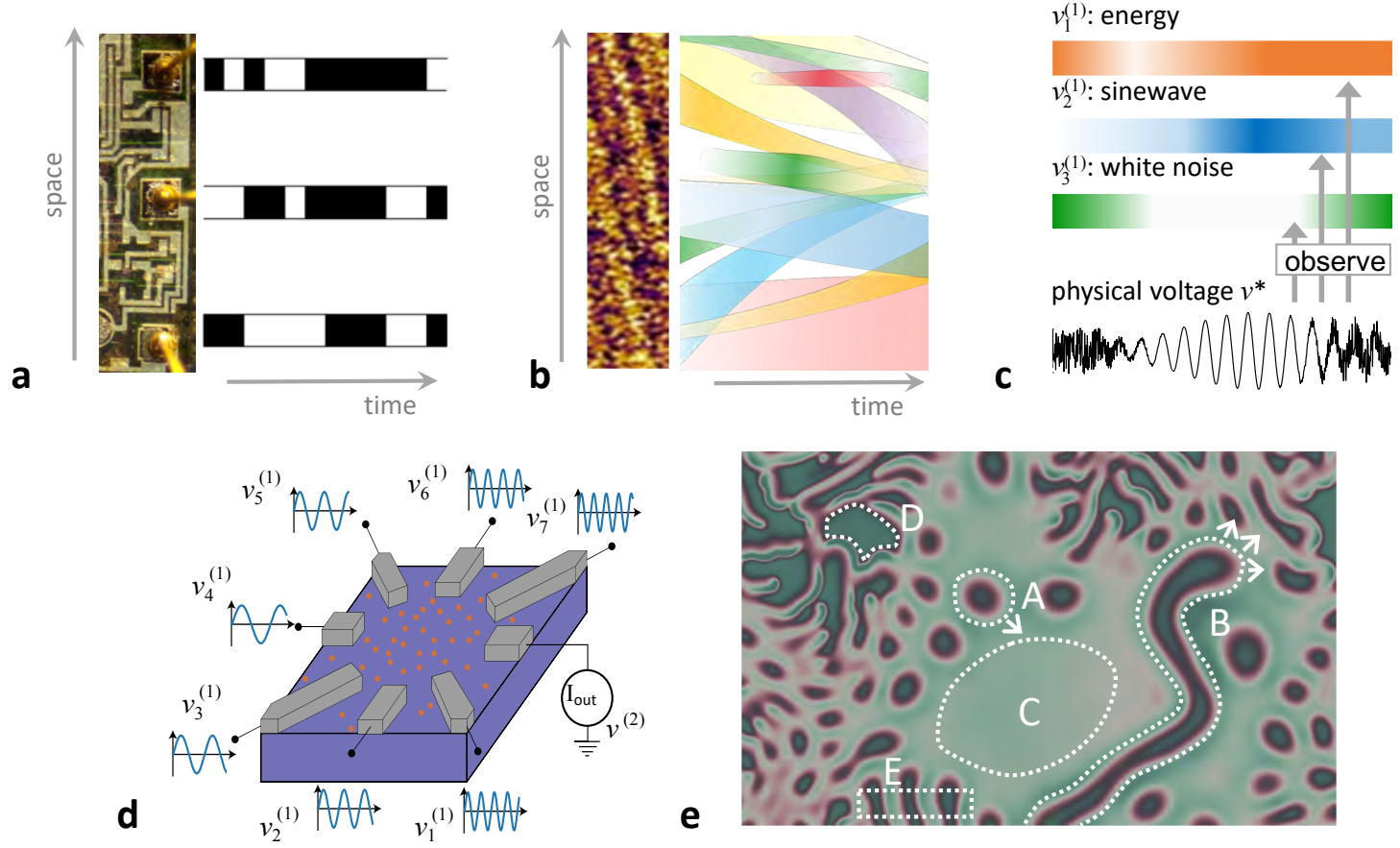
GFT
general formal theory

physical modeling

physical reality

(workout in [4])

Flavor of fluent computing



a. Binary signals as point-localized chronicles

b. Spatiotemporal general observables

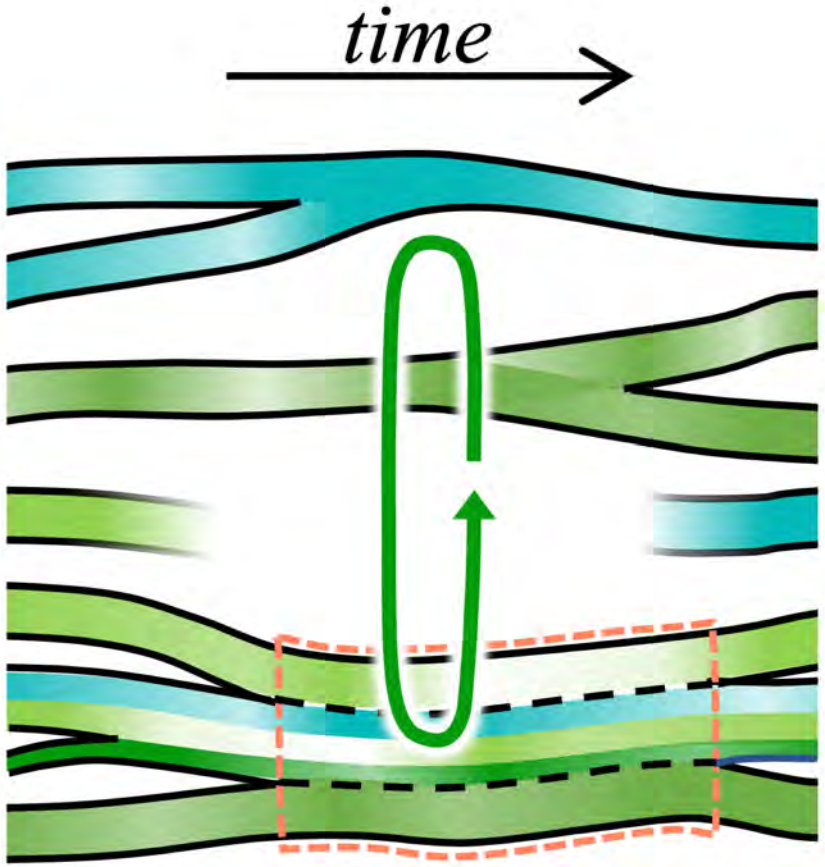
c. A physical signal can be observed in many ways (‘features’, ‘qualities’)

d. A non-digital device (DNPU unit, v. d. Wiel); output is physical observer of inputs

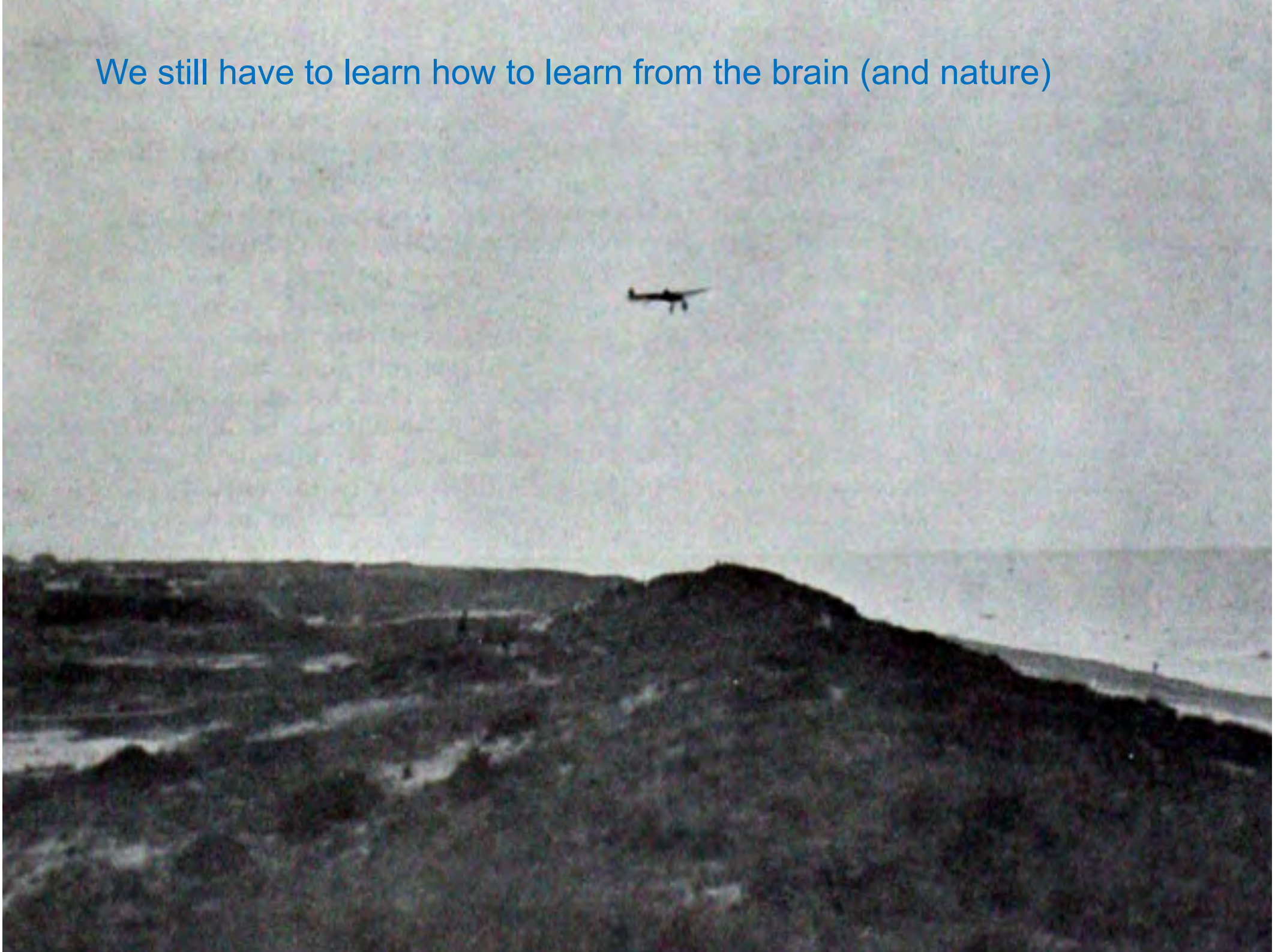
e. Potentially exploitable physical phenomena in reaction-diffusion systems: A moving solitons, B growing filaments, C neutral ground state, D excited field state, E spatiotemporal oscillations

Compositionality is still the key

- Chronicles can hierarchicall bind into compound chronicles
- Unlike symbolic components, chronicles and their components
  - have continuously varying activation
  - have no finite symbolic ‘well-founding’ (they are defined from observables, not names)



We still have to learn how to learn from the brain (and nature)



References

[1] H. Jaeger (2021): Toward a Generalized Theory Comprising Digital, Neuromorphic, and Unconventional Computing. Neuromorphic Computing and Engineering 1(1) (open access article)

[2] H. Jaeger, F. Catthoor (2023): Timescales: the choreography of classical and unconventional computing. (arxiv: 2301.00893, 81 pages)

[3] H. Jaeger, B. Noheda, W.G. van der Wiel (2023): Toward a formal theory for computing machines made out of whatever physics offers. Nature Communications 14, 4911 open access article

- Highlighted in: J. B. Aimone, O. Parekh (2023): The brain's unique take on algorithms. Nature Communications 14, 4910 open access article

[4] H. Jaeger, B. Noheda, W.G. van der Wiel (2023): Toward a formal theory for computing machines made out of whatever physics offers: extended version. (arxiv:2307.15408, 76 pages)