

Universal laws and architecture 2:

Theoretical foundations for complex networks relevant to biology, medicine, and neuroscience?

John Doyle

John G Braun Professor

Control and Dynamical Systems, EE, BE

Caltech

Thanks again

Lectures

- 1) Concrete motivation
- 2-3) Universal laws and architectures***
- 4) A teensy bit of math

*have you ever heard of anything more pretentious?

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}

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

Lectures

- 1) **Concrete motivation (recap)**
- 2-3) Universal laws and architectures*
- 4) A teensy bit of math

*have you ever heard of anything more pretentious?

Human complexity

Robust

- 😊 Metabolism
- 😊 Regeneration & repair
- 😊 Immune/inflammation
- 😊 Microbe symbionts
- 😊 Neuro-endocrine
- 📄 Complex societies
- 📄 Advanced technologies
- 📄 Risk “management”

Yet Fragile

- 😞 Obesity, diabetes
- 😞 Cancer
- 😞 AutoImmune/Inflame
- 😞 Parasites, infection
- 😞 Addiction, psychosis,...
- 💀 Epidemics, war,...
- 💣 Disasters, global &!%\$#
- 💣 Obfuscate, amplify,...

Accident or necessity?

Human complexity

Robust

Yet Fragile

- | | |
|-------------------------|-------------------------|
| ☺ Metabolism | ☹ Obesity, diabetes |
| ☺ Regeneration & repair | ☹ Cancer |
| ☺ Immune/inflammation | ☹ AutoImmune/Inflame |
| ☺ Microbe symbiosis | ☹ Parasitic infection |
| ☺ | ☹ Fat accumulation |
| ☺ | ☹ Insulin resistance |
| ☺ | ☹ Proliferation |
| ☺ | ☹ Inflammation |
| ☺ Risk "management" | ☹ Obtusate, amplify,... |

Accident or necessity?

Robust

☺ Metabolism

☺ Regenerati

☺ Healing wo

Fragile

☹ Obesity, diabetes

☹ Fat accumulation

☹ Insulin resistance

☹ Proliferation

☹ Inflammation

une/Inflame

- 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?



Robust

Modular

Simple

Plastic

Evolvable

and

~~**xor**~~

Fragile

Distributed

Complex

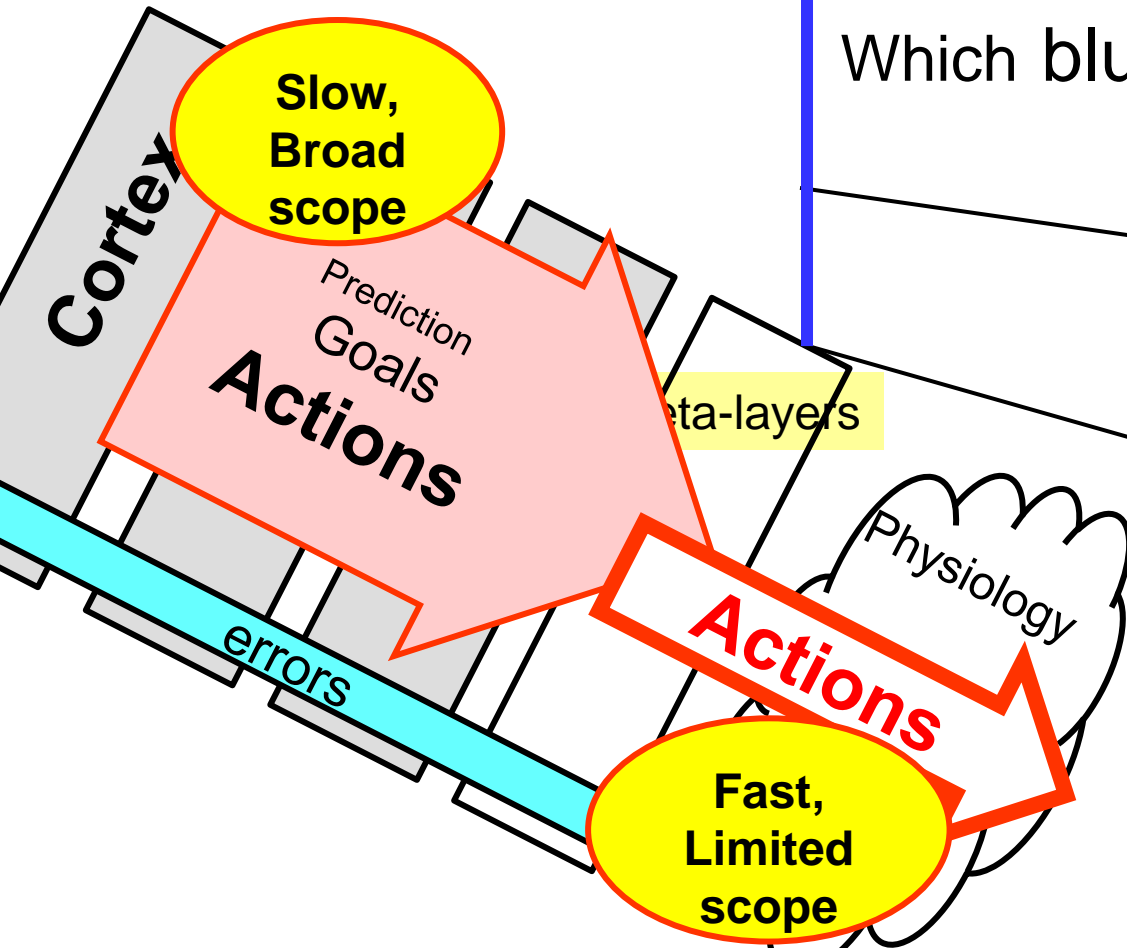
Frozen

Frozen

tradeoffs

“Seeing is dreaming?”

“Seeing is believing?”



Which blue line is longer?

**Fast
Inflexible**

Actions

errors

Prediction
Goals
Actions
Reflex

Reflect

Reflex

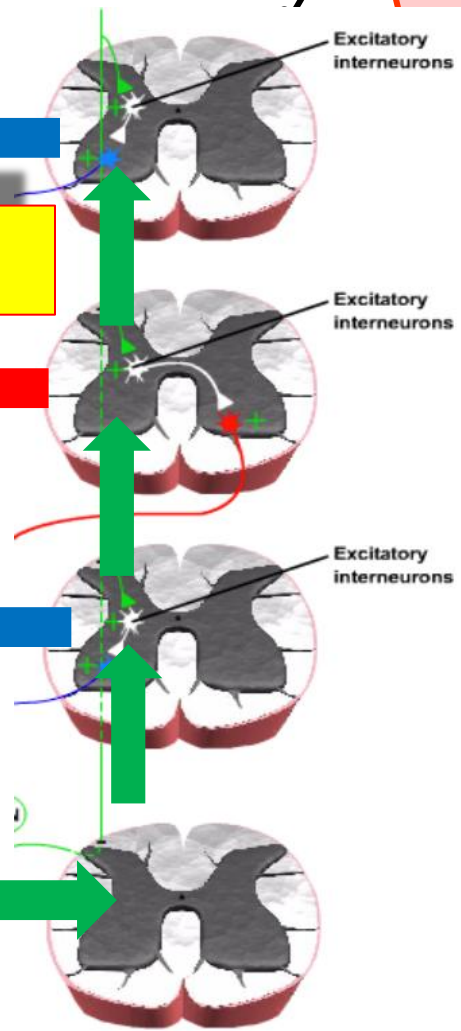
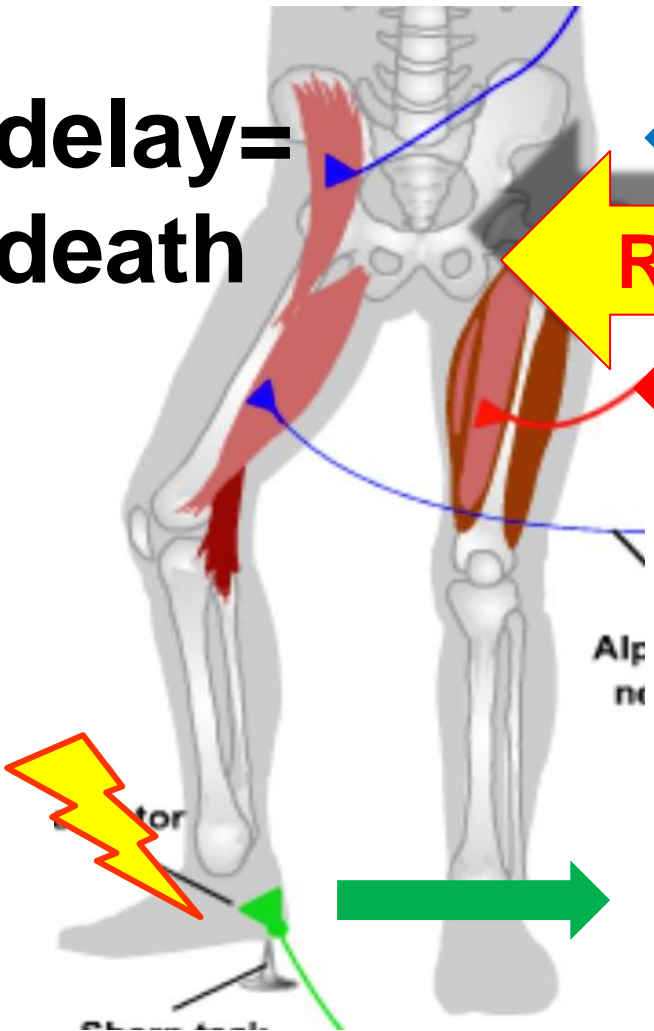
Excitatory interneurons

Excitatory interneurons

Excitatory interneurons

Alp
nt

**delay=
death**



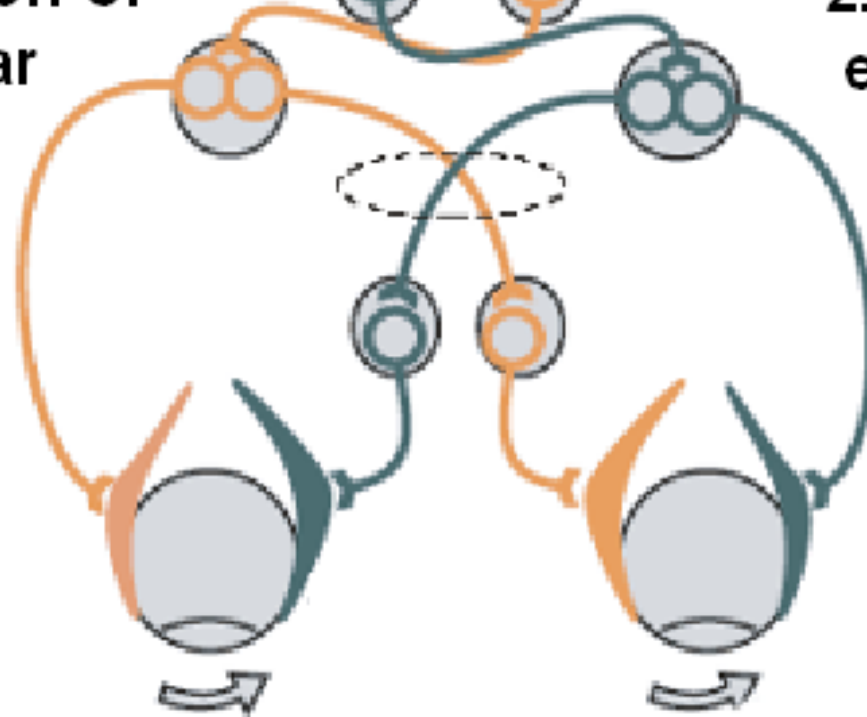
Vestibulo-ocular reflex

1. Detection of rotation

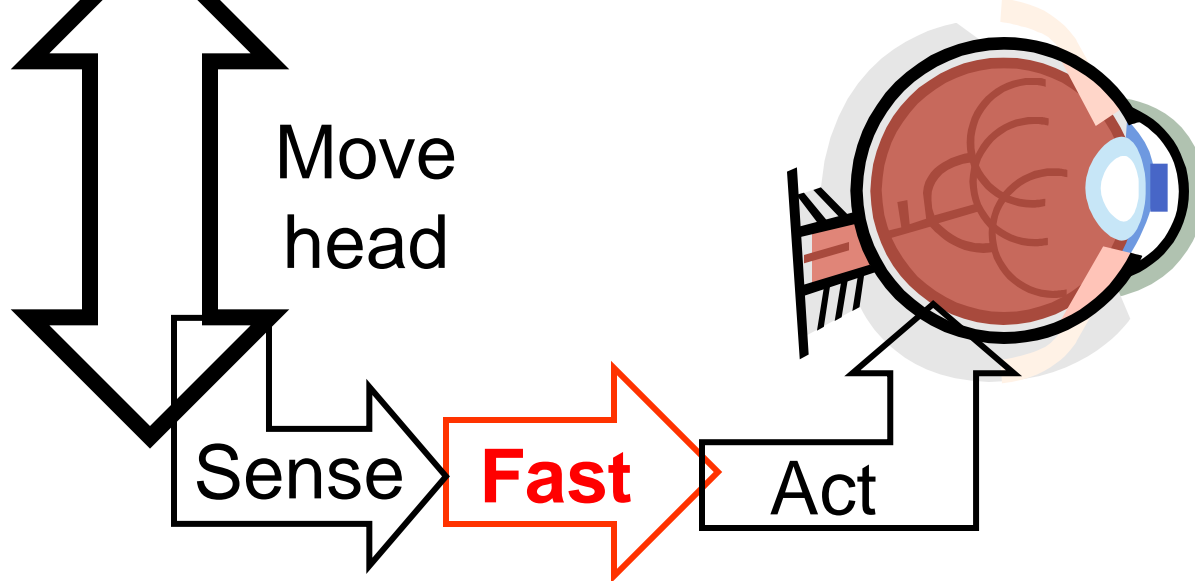


2. Inhibition of extraocular muscles on one side.

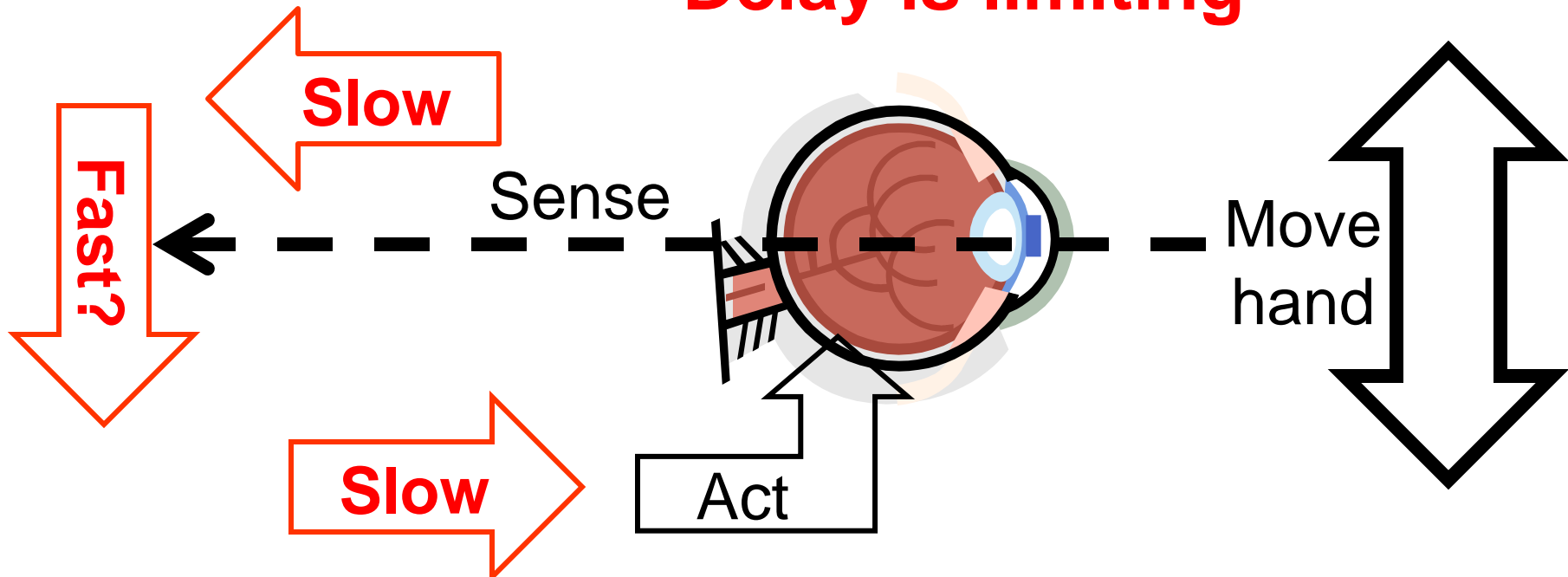
2. Excitation of extraocular muscles on the other side



3. Compensating eye movement



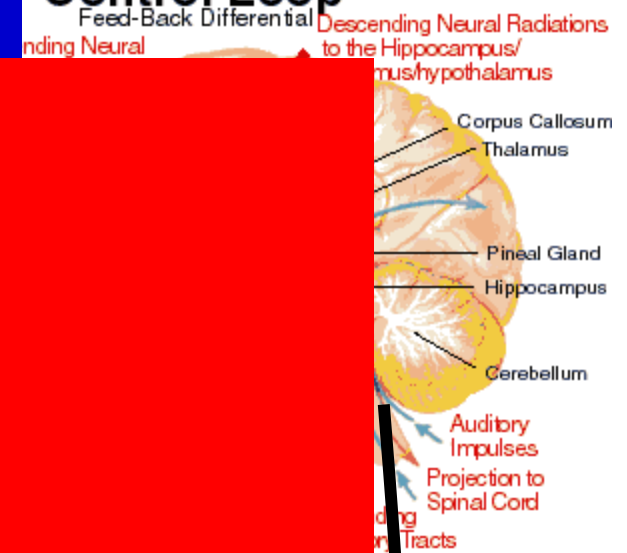
Same actuators
Delay is limiting



Reflect

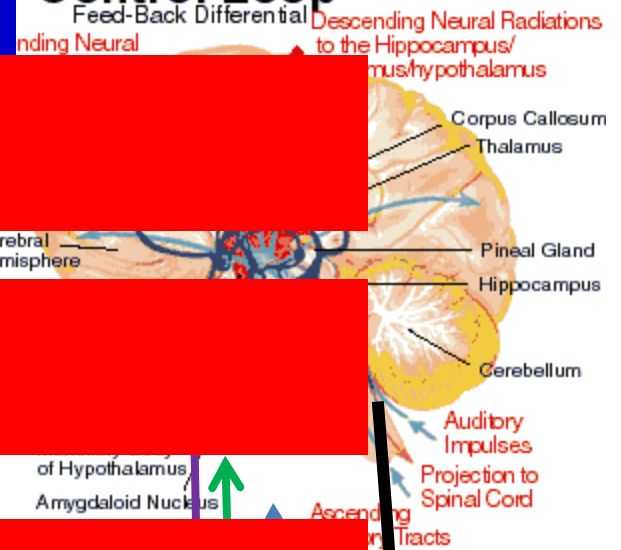
Reflex

Control Loop



Reflect

Control Loop



Layered

Reflex

sense

move

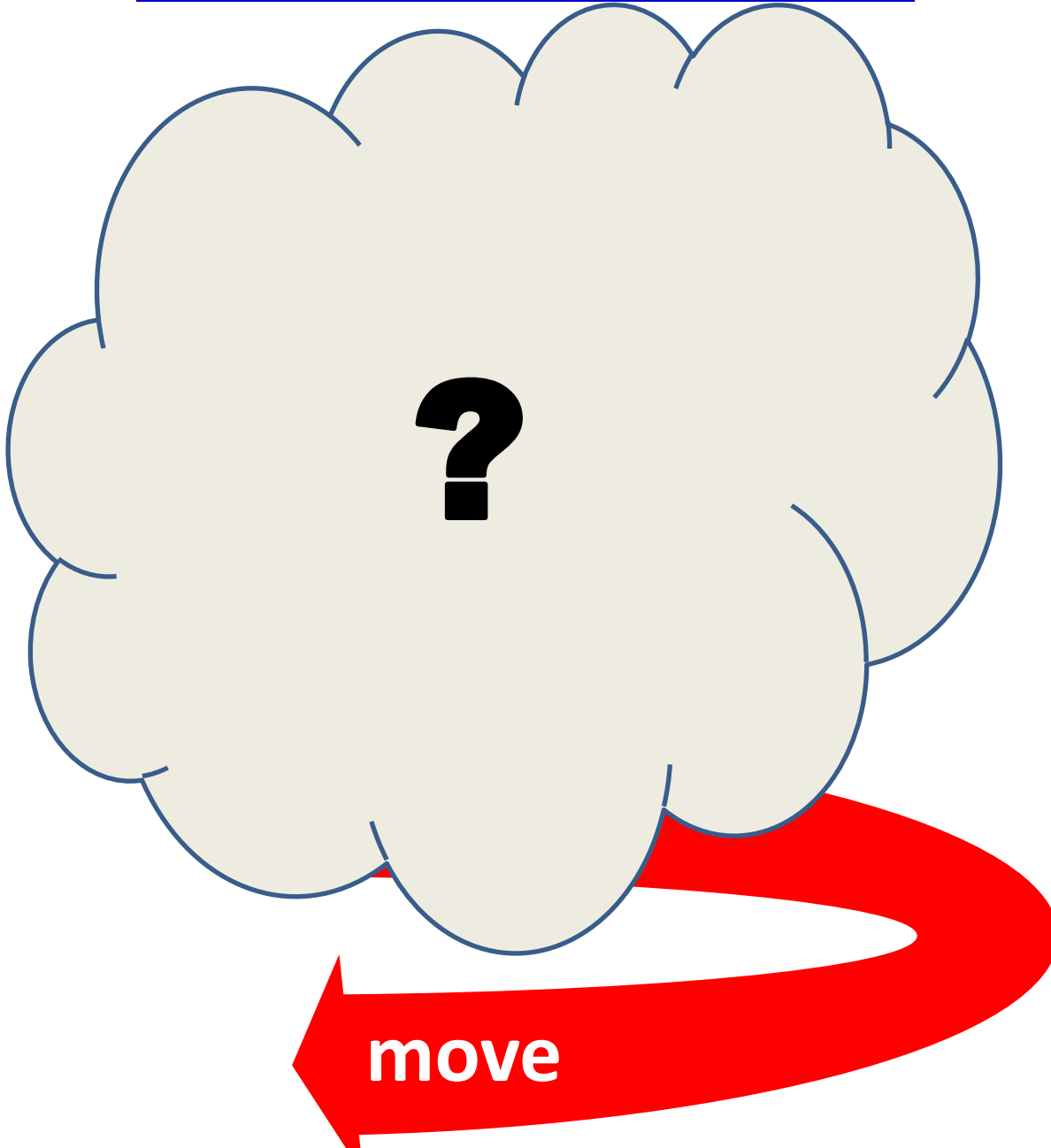
Spine



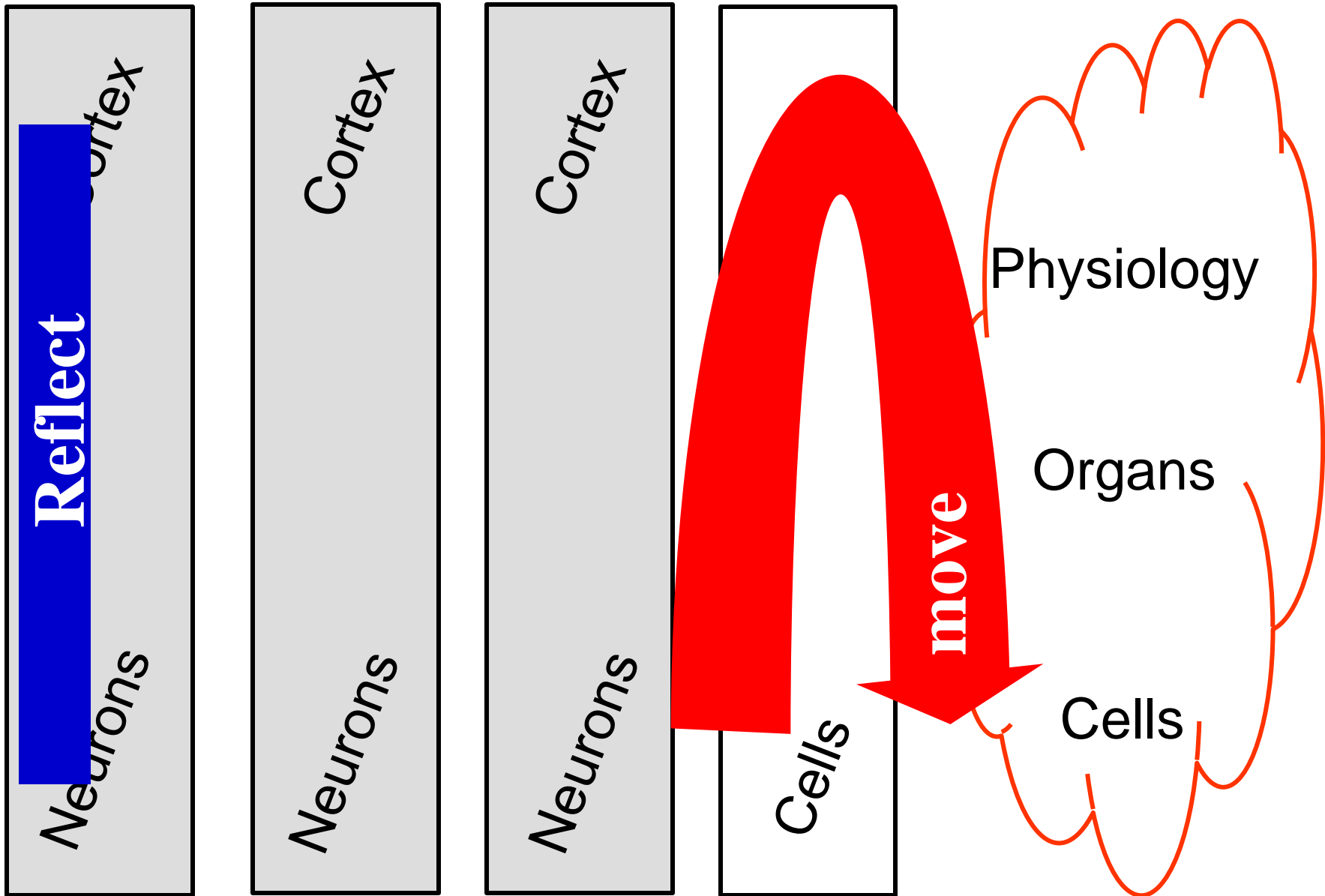
Reflect

?

move



Layered architectures



Control Loop
Feed-Back Differential
Ascending Neural

Reflect

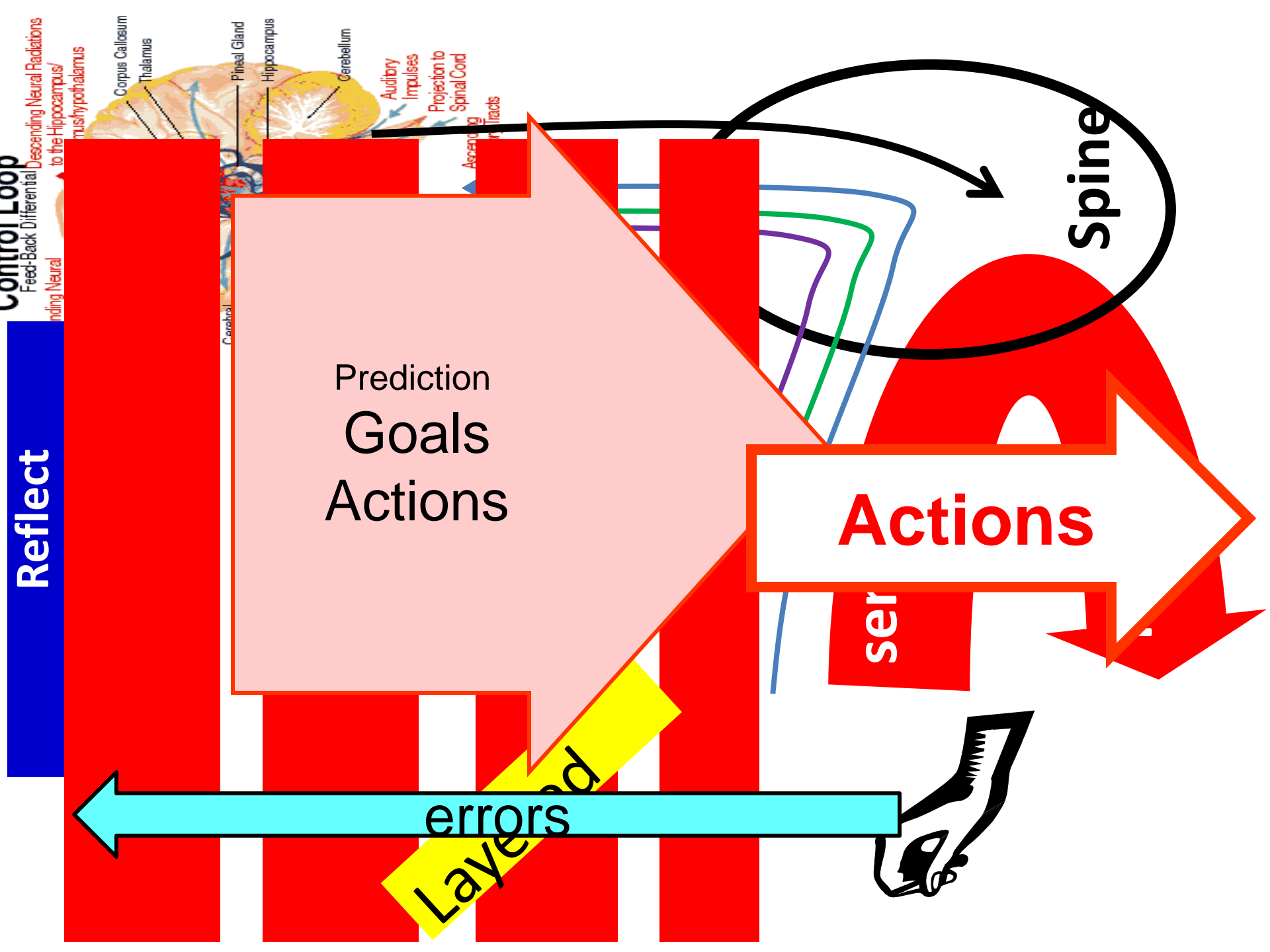
Prediction
Goals
Actions

Actions

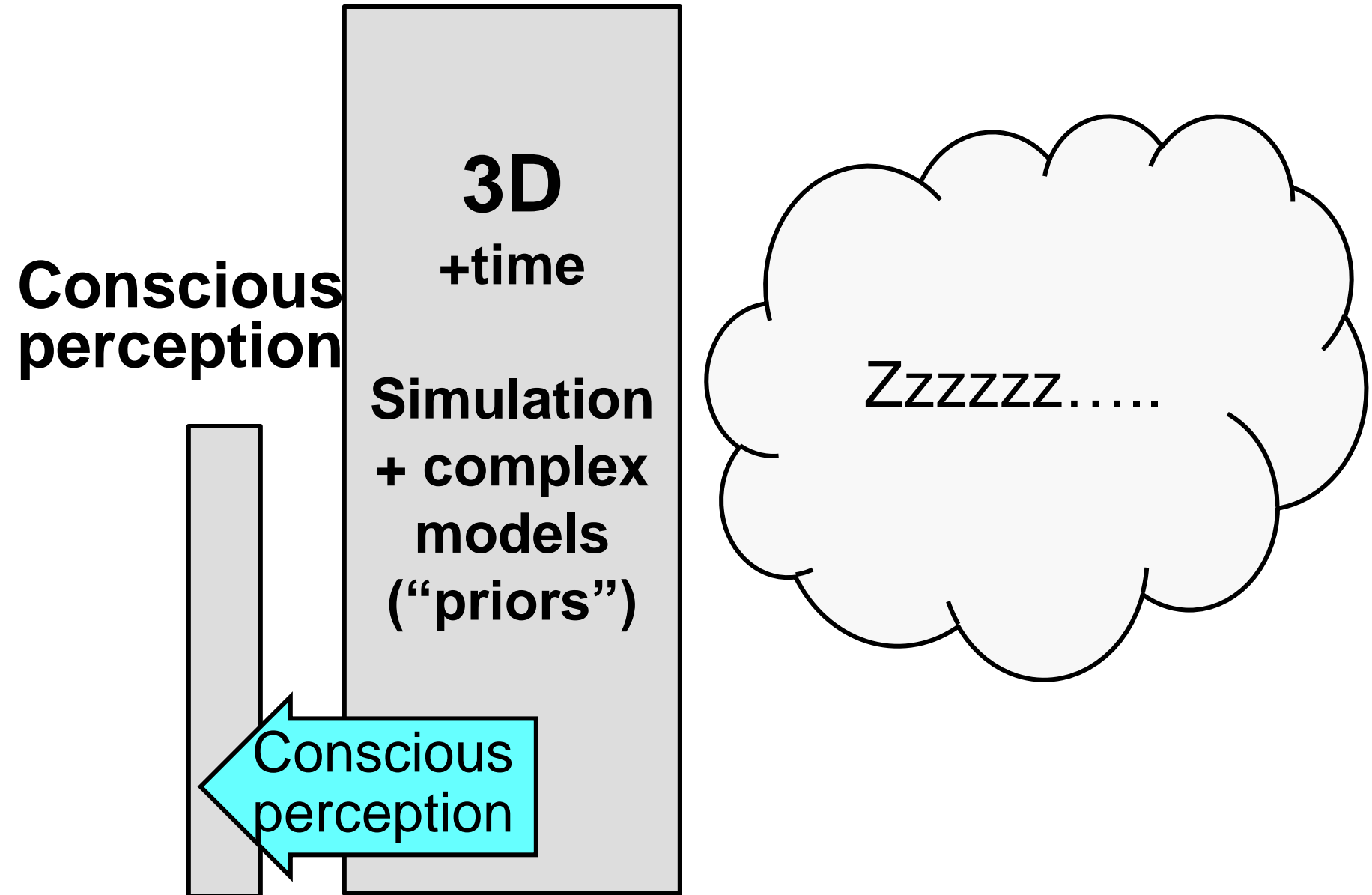
errors

Layered

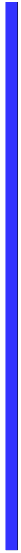
Spine



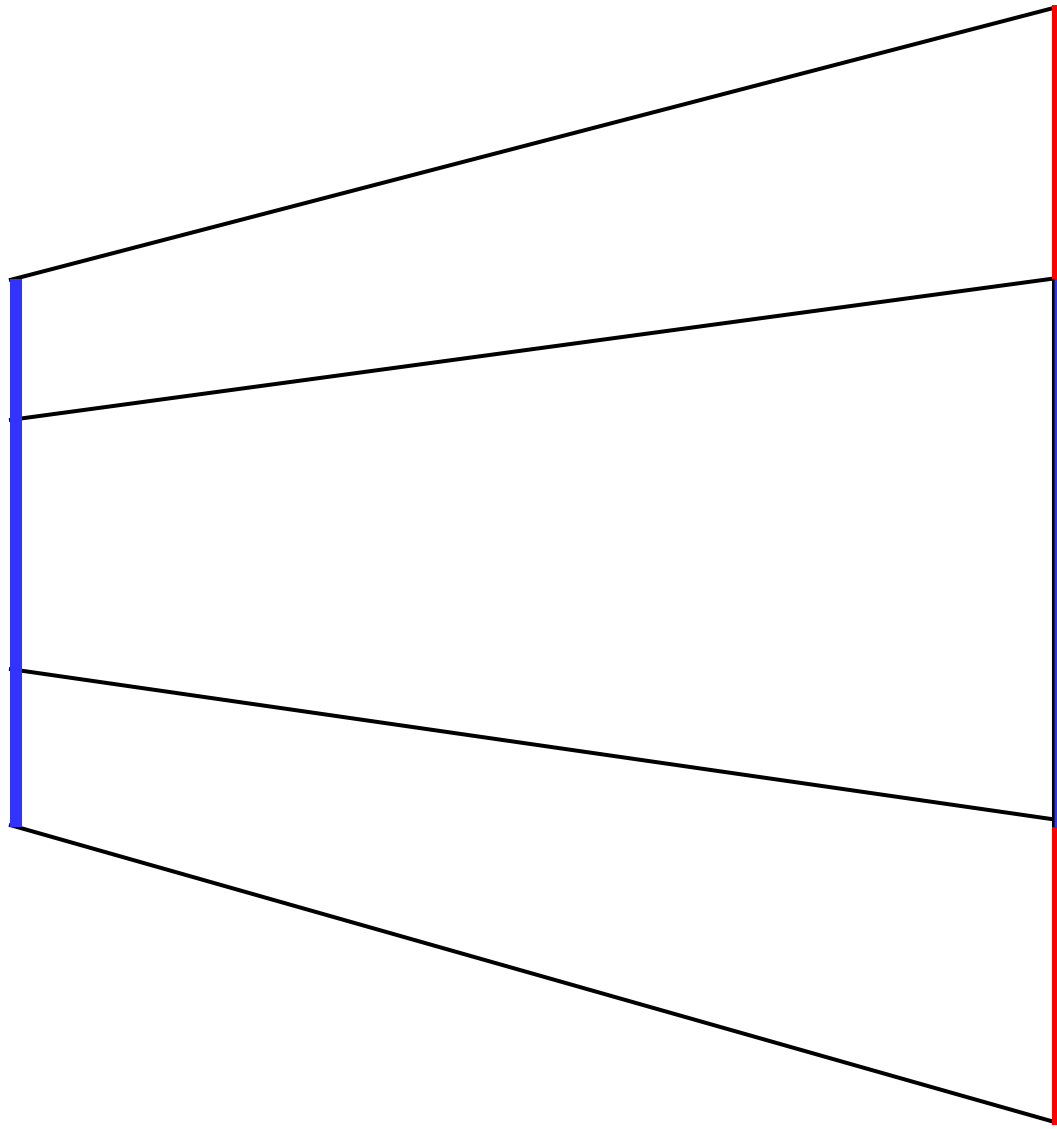
Seeing is *dreaming*



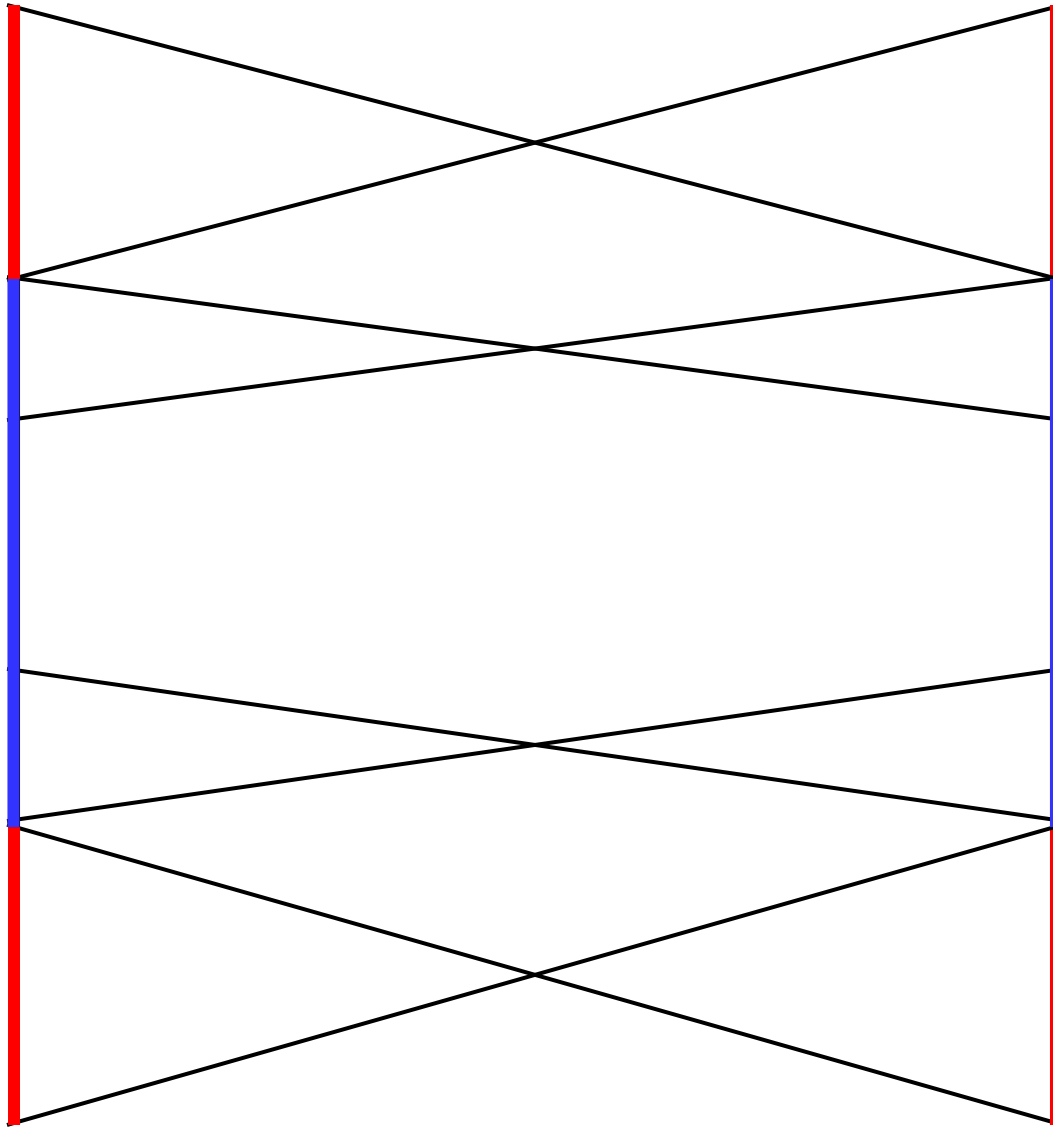
Which blue line is longer?



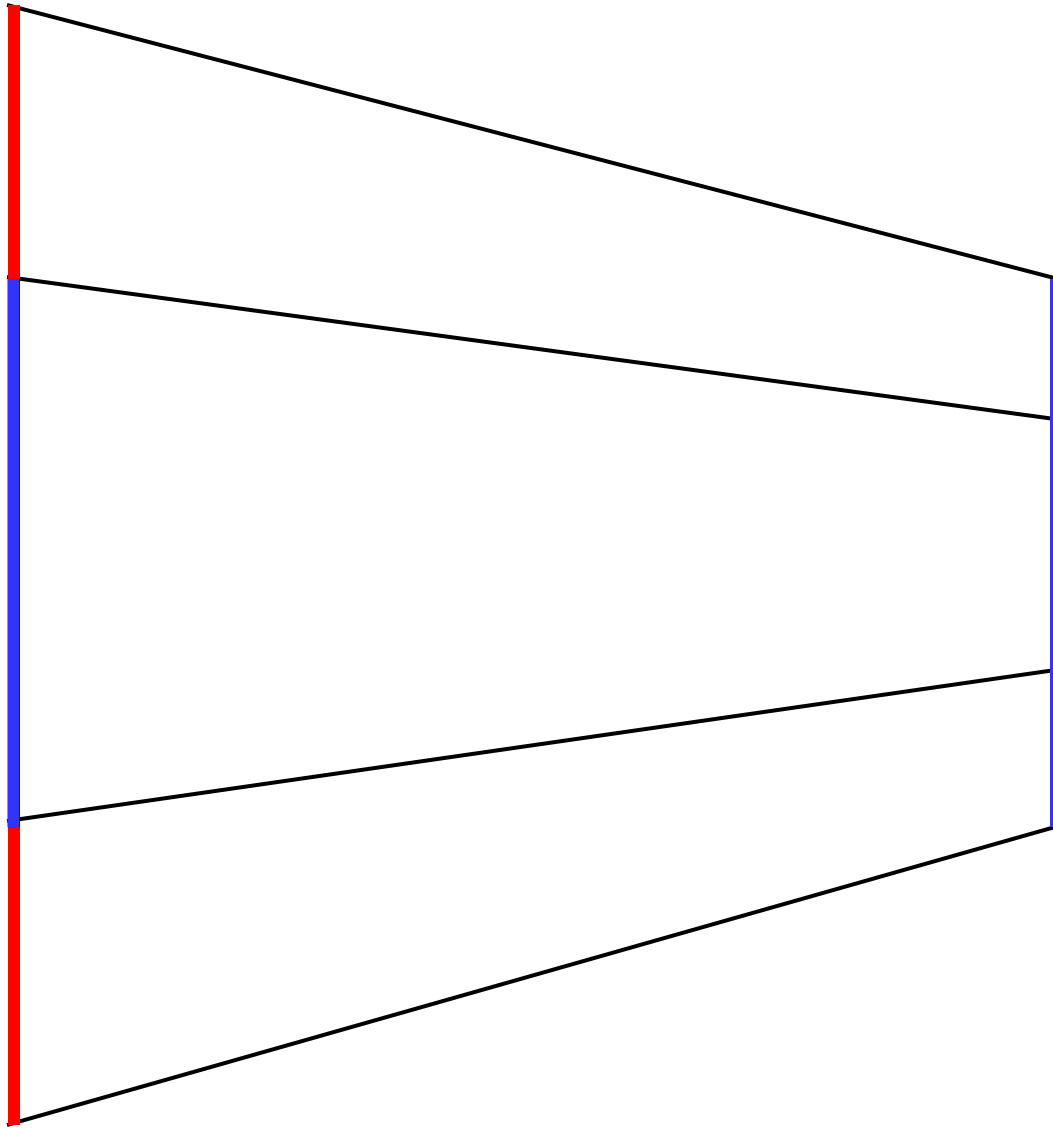
Which blue line is longer?



Which blue line is longer?



Which blue line is longer?

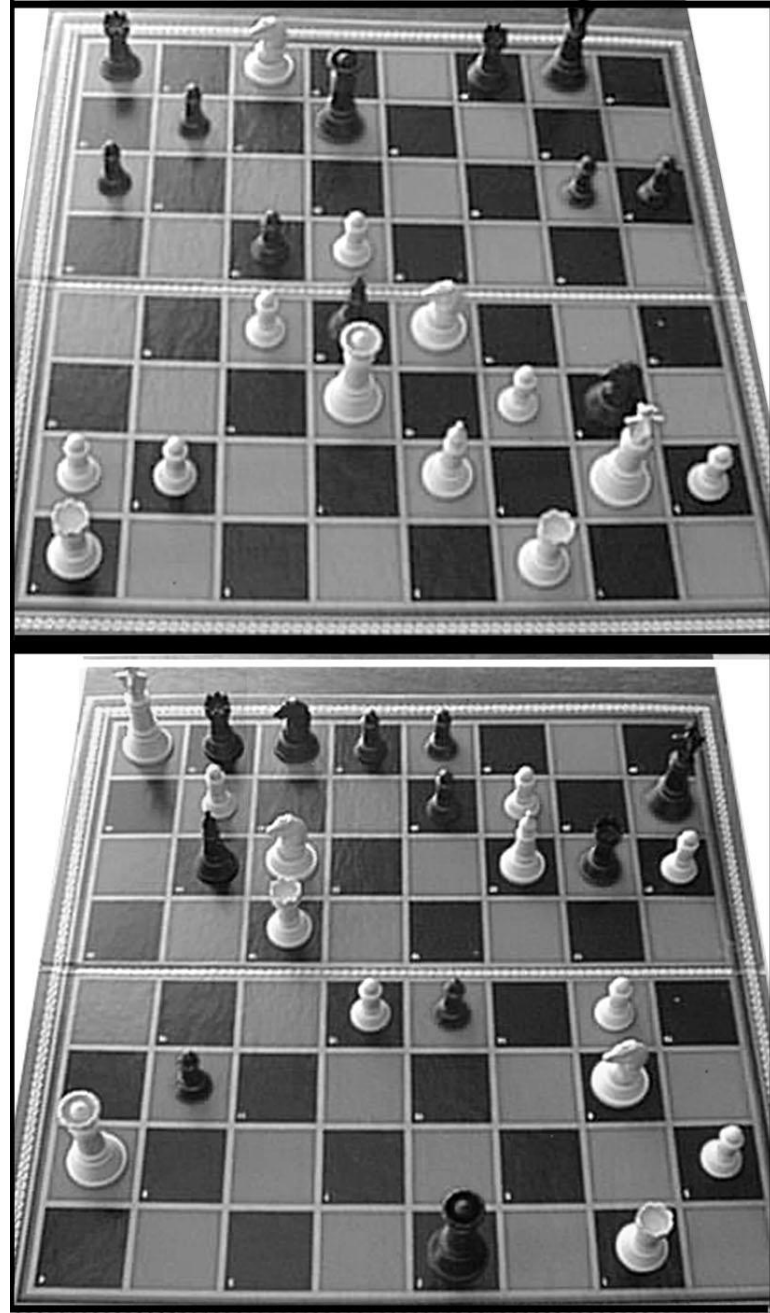




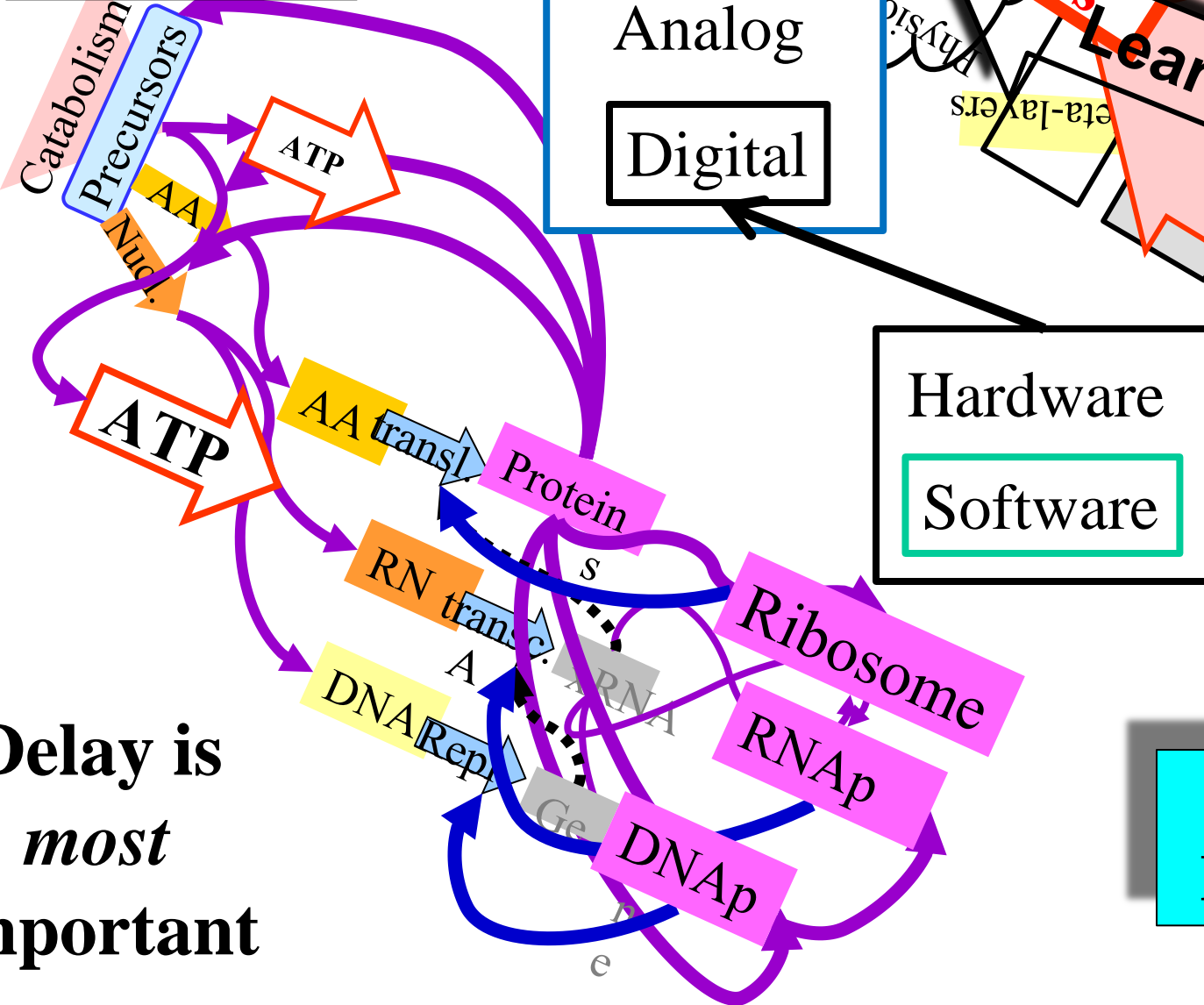
Chess experts

- can reconstruct entire chessboard with $< \sim 5s$ inspection
- can recognize $1e5$ distinct patterns
- can play multiple games blindfolded and simultaneous
- are no better on random boards

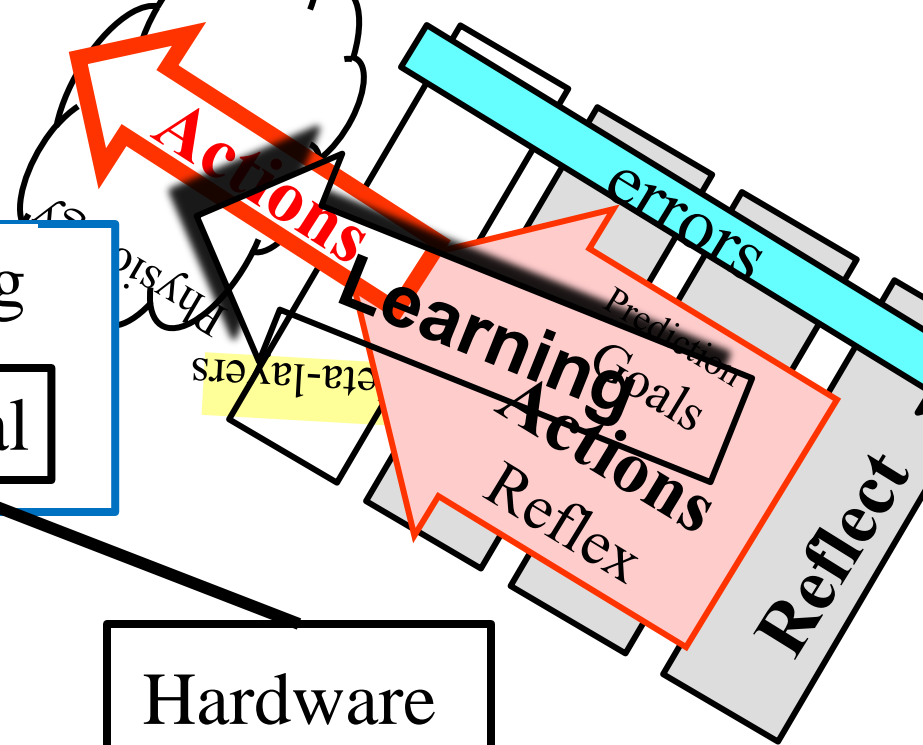
(Simon and Gilmartin, de Groot)



**Fast
Inflexible**

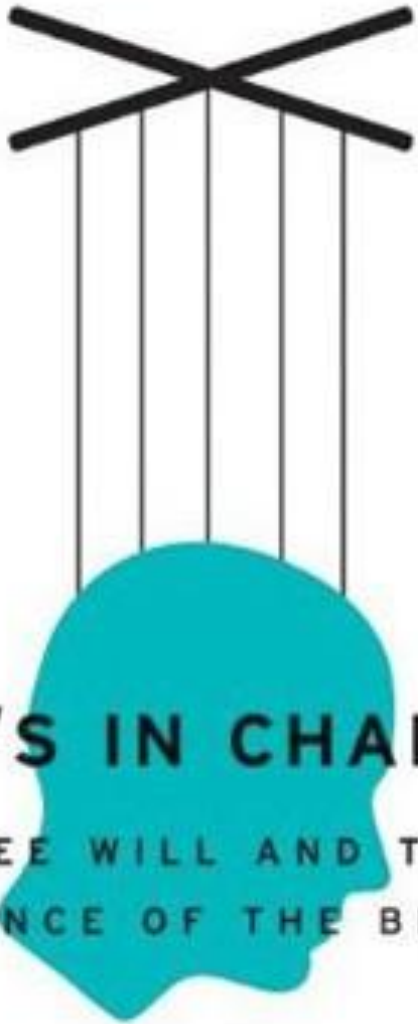


**Delay is
most
important**



**Slow
Flexible**

For more



WHO'S IN CHARGE?

FREE WILL AND THE
SCIENCE OF THE BRAIN

MICHAEL S. GAZZANIGA

author of HUMAN and THE ETHICAL BRAIN



INCOGNITO

THE SECRET LIVES
OF THE BRAIN

**DAVID
EAGLEMAN**

AUTHOR OF SUM

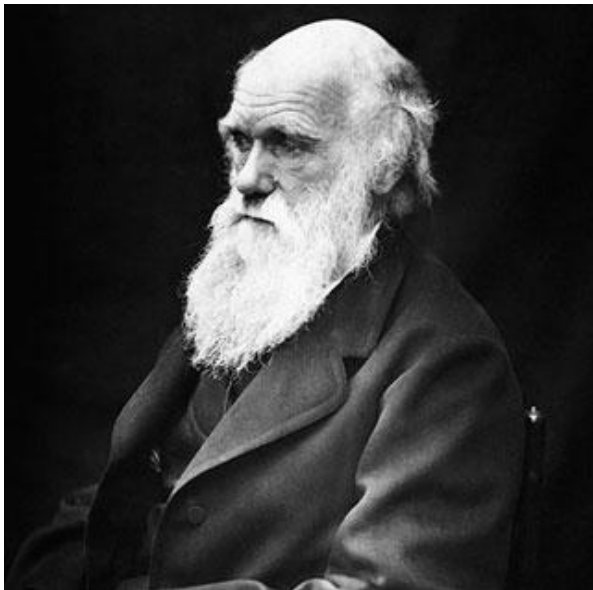
Evolution

Facilitated variation

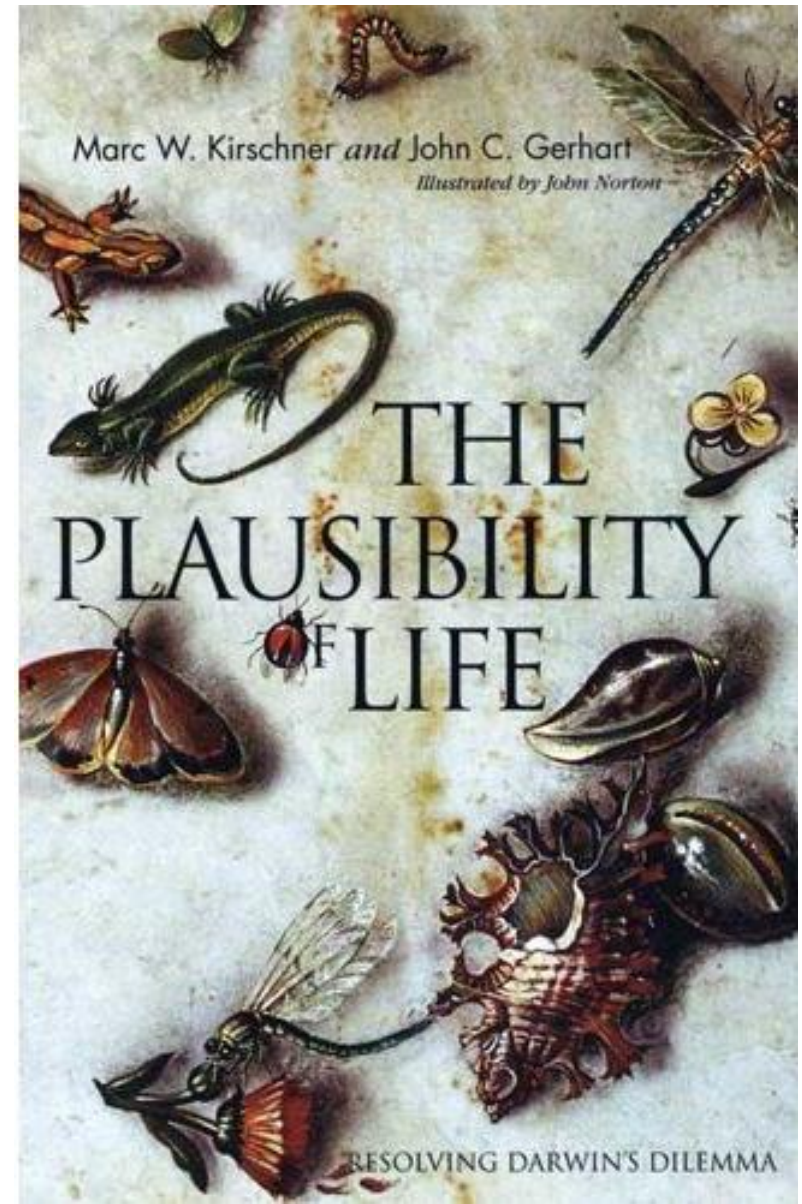
Architecture =

Constraints that deconstrain

- Weak linkage
- Exploratory mechanisms
- Compartmentalization



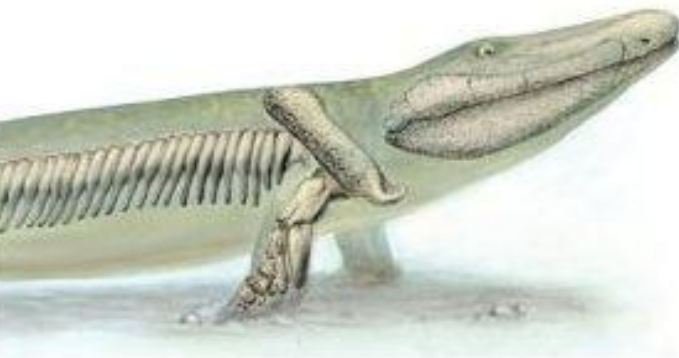
Kirschner and Gerhart



Unfortunately, not
intelligent design

YOUR INNER FISH

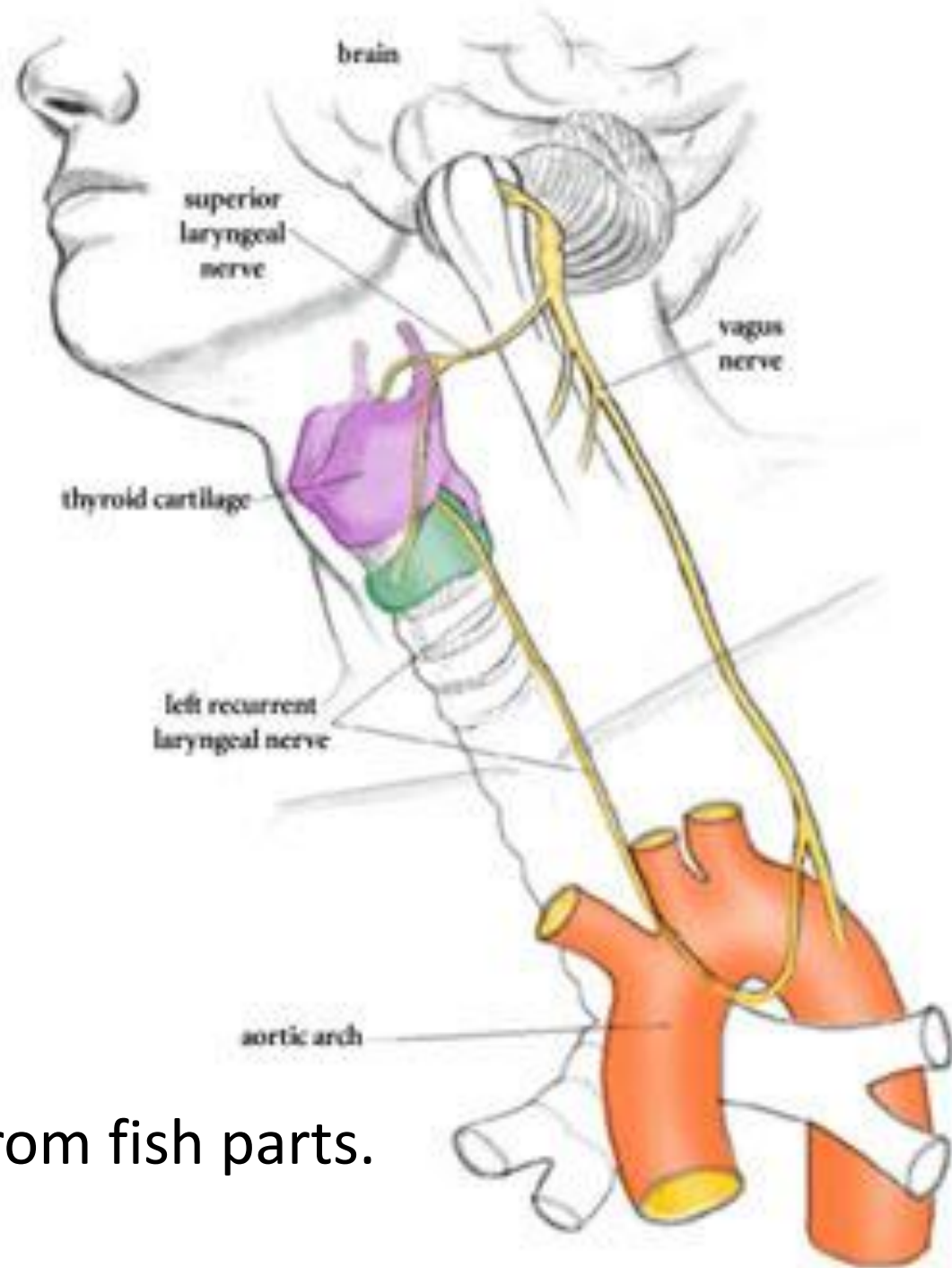
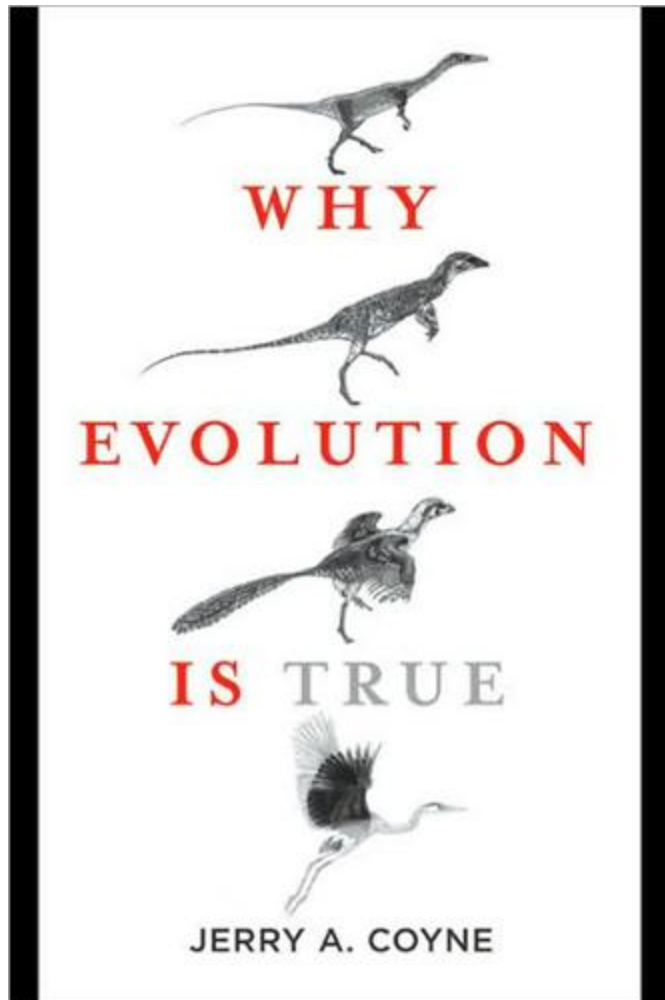
A JOURNEY INTO
THE
3.5-BILLION-YEAR HISTORY
OF THE
HUMAN BODY



NEIL SHUBIN

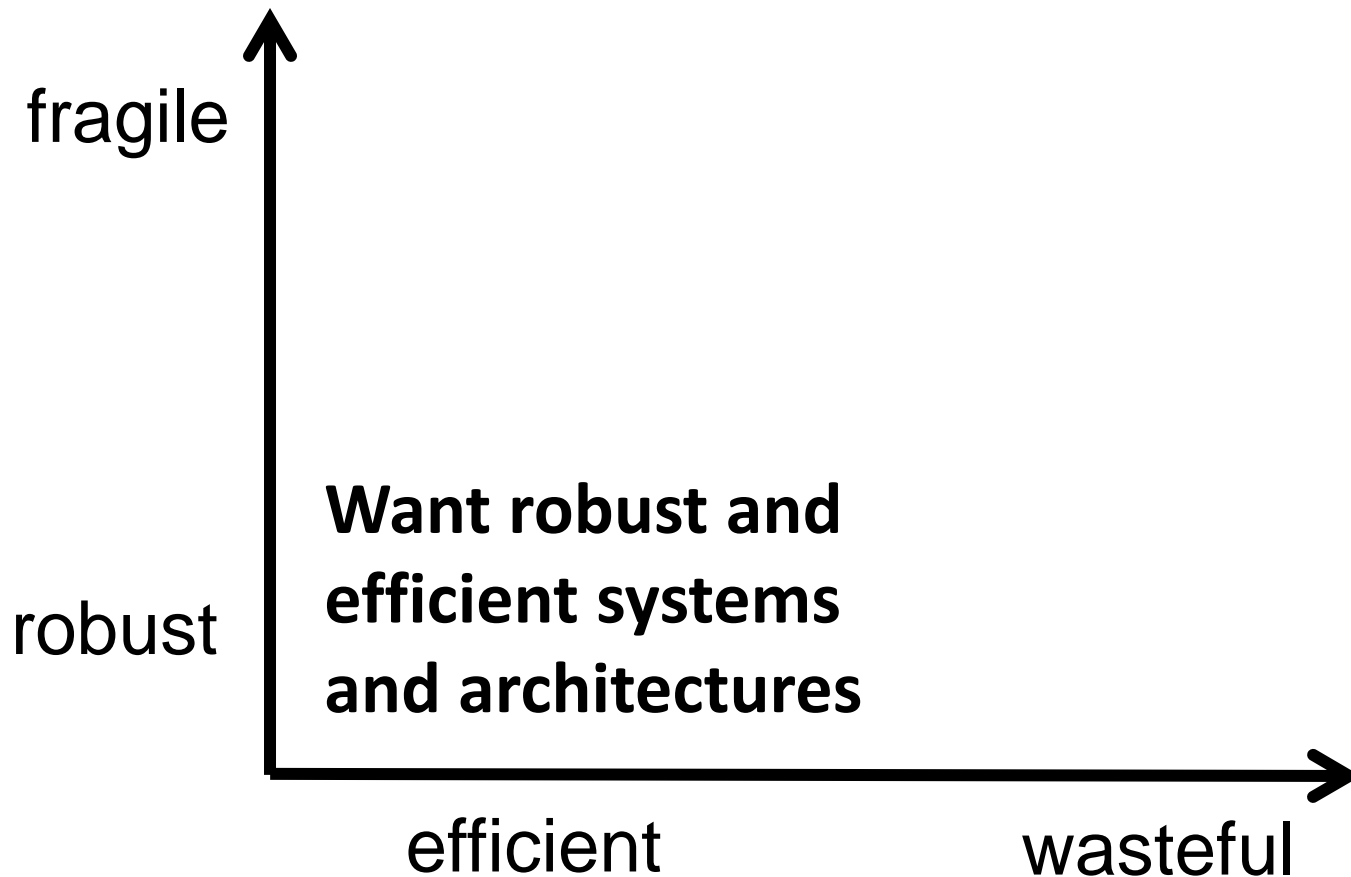


Ouch.

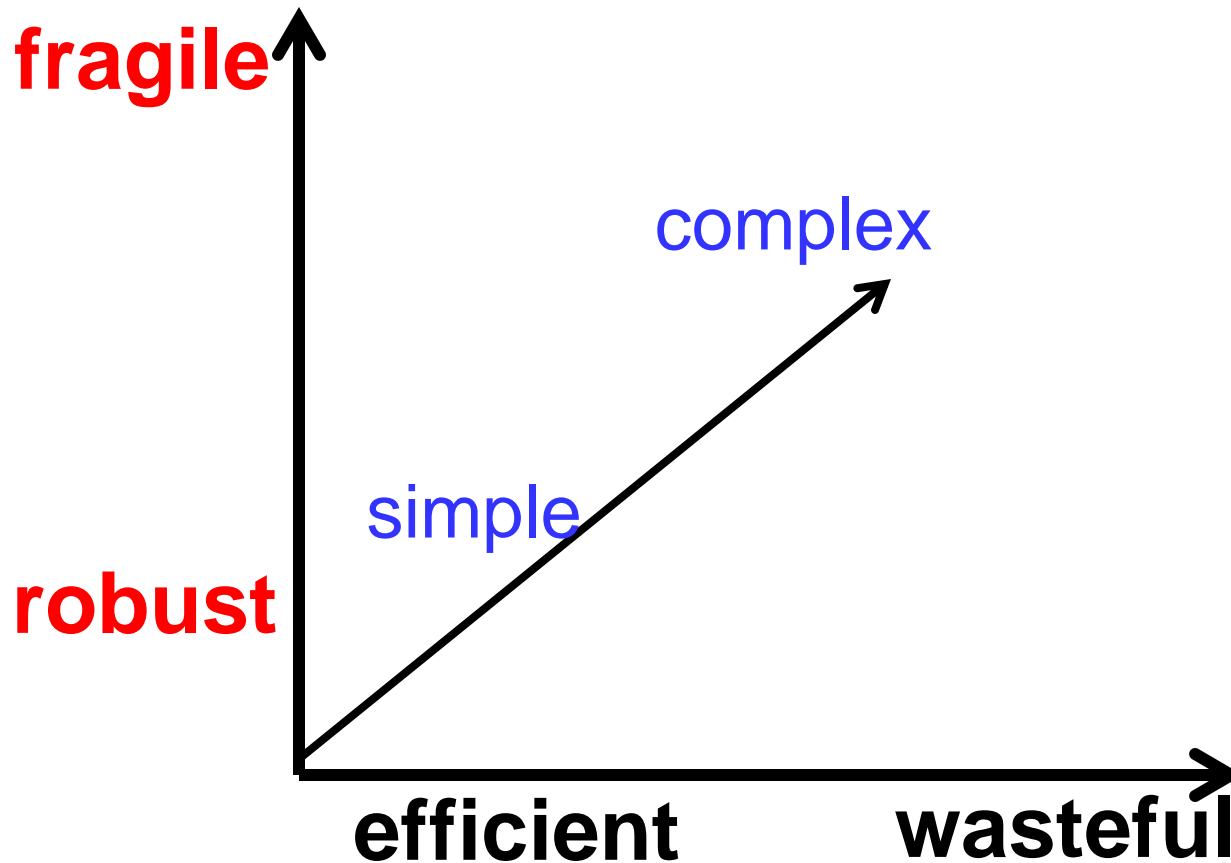


Making humans from fish parts.

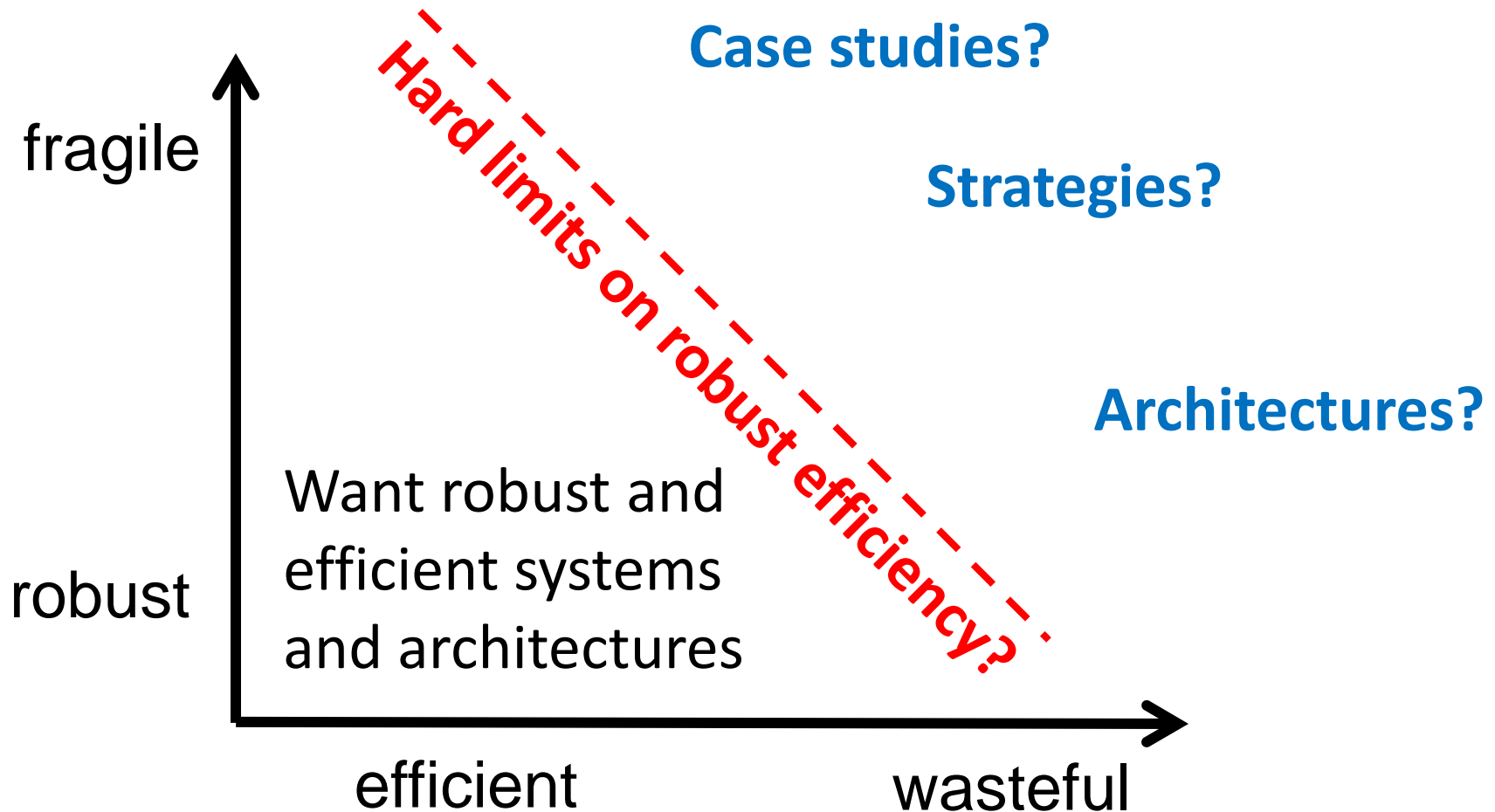
Want to understand the space of systems/architectures



Requirements on systems and architectures



Want to understand the space of systems/architectures



Control, OR

Kalman

Comms

Bode

Pontryagin

Shannon

Nash

Theory?

Deep, but fragmented,
incoherent, incomplete

Von
Neumann

Carnot

Turing

Boltzmann

Godel

Heisenberg

Compute

Einstein

Physics

Control

Comms

Bode

Shannon

fragile?

slow?

?

wasteful?

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

Carnot

Turing

Boltzmann

Godel

Heisenberg

Compute

Einstein

Physics

UG biochem, math,
control theory

Glycolytic Oscillations and Limits on Robust Efficiency

Fiona A. Chandra,^{1*} Gentian Buzi,² John C. Doyle²

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.

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

Chandra, Buzi, and Doyle

Most important paper so far.



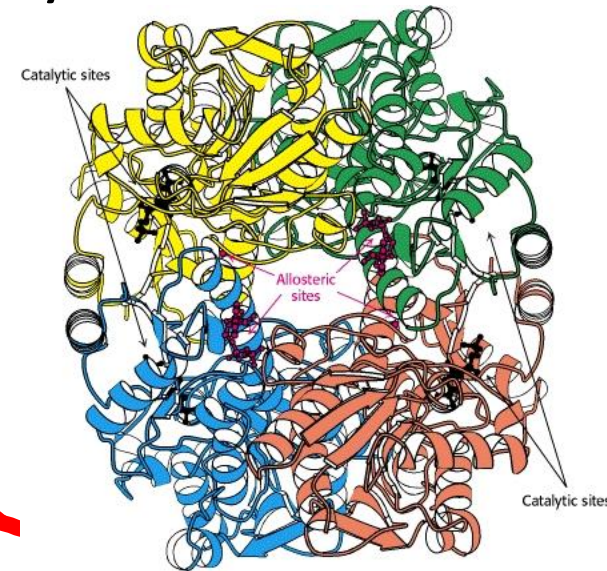
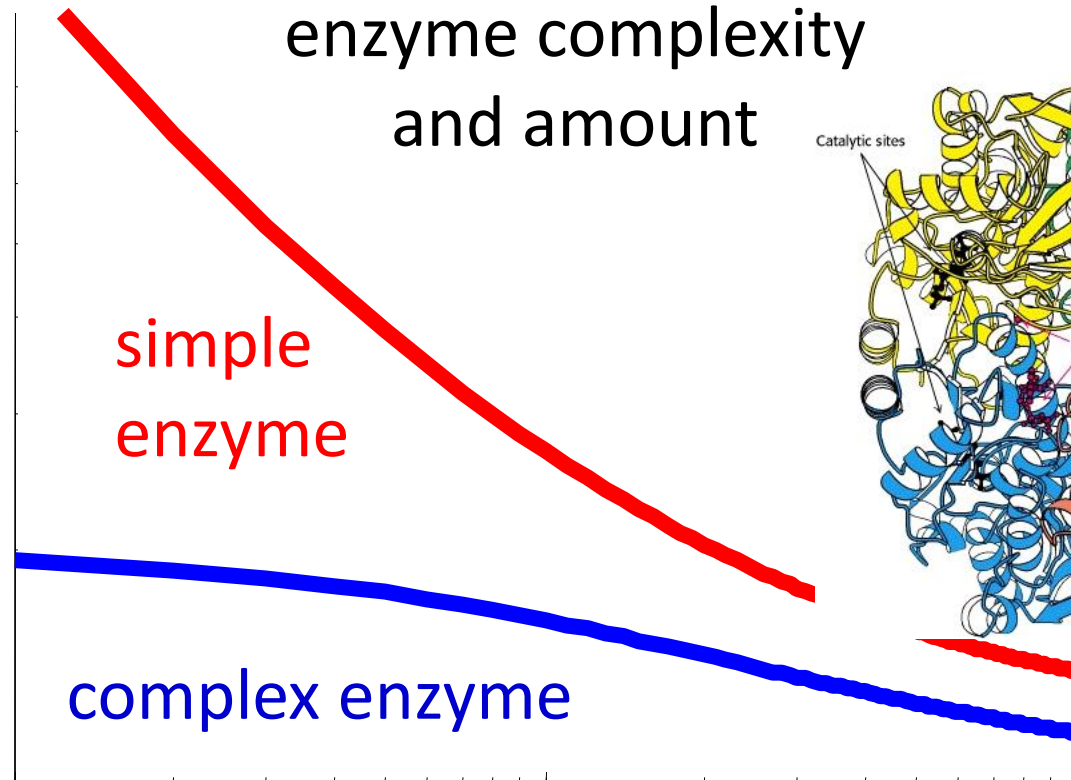
Theorem!

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

z and p functions of
enzyme complexity
and amount

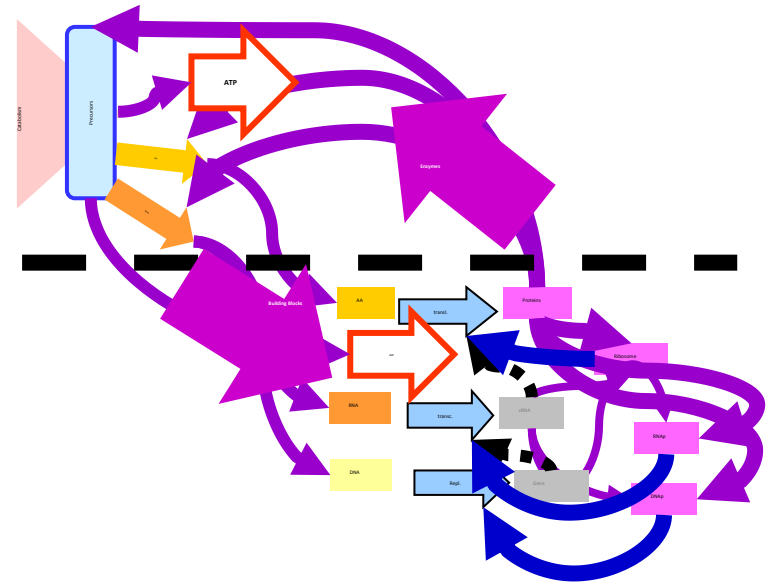
Fragility

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



Enzyme amount

i.e. hard limits and architecture



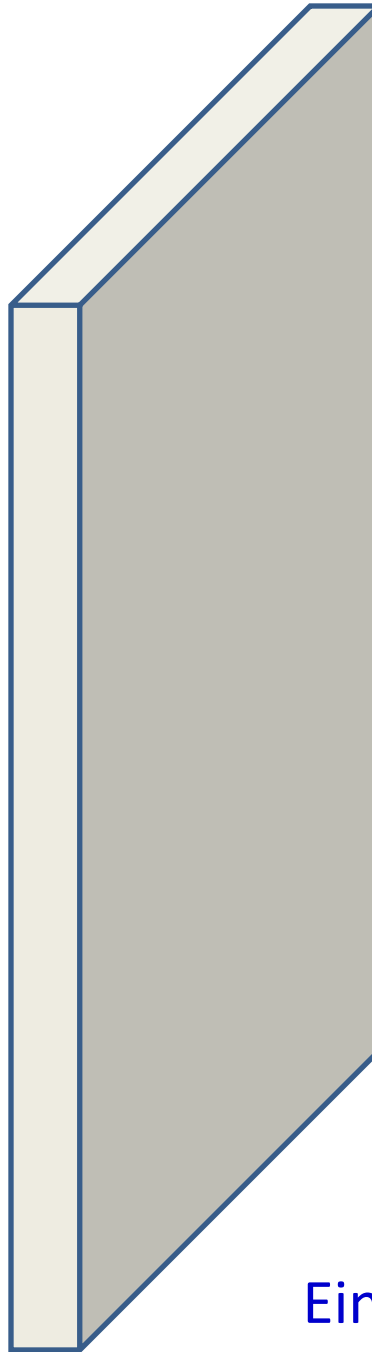
Control, OR

Bode

Delay is
most
important

Turing

Compute



Communications

Shannon

Delay is
least
important

Carnot

Boltzmann

Heisenberg

Einstein

Physics

Control, OR

Bode

**Delay is
most
important**

Turing

Compute

Communications

Shannon

**Delay is
~~*least*~~
important**

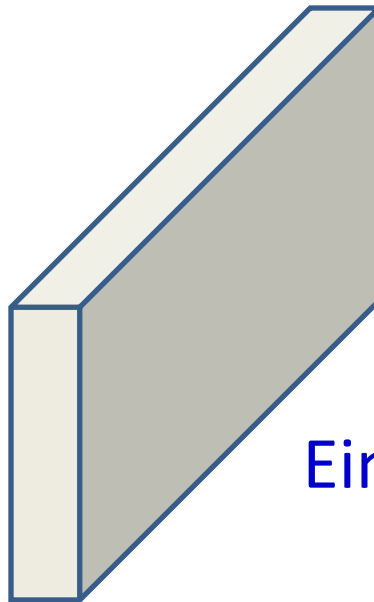
Carnot

Boltzmann

Heisenberg

Einstein

Physics



- 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

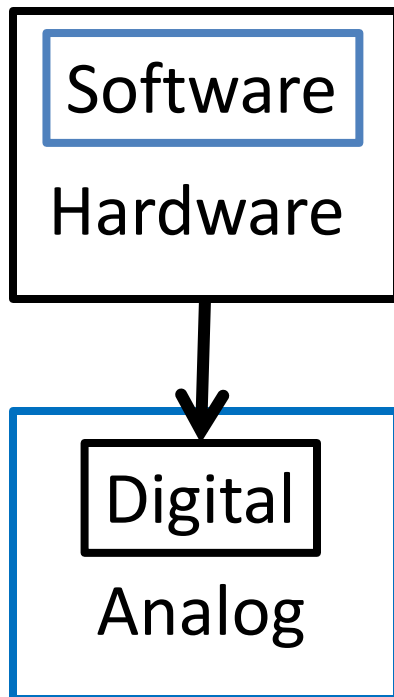
*Also world-class runner.



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?)

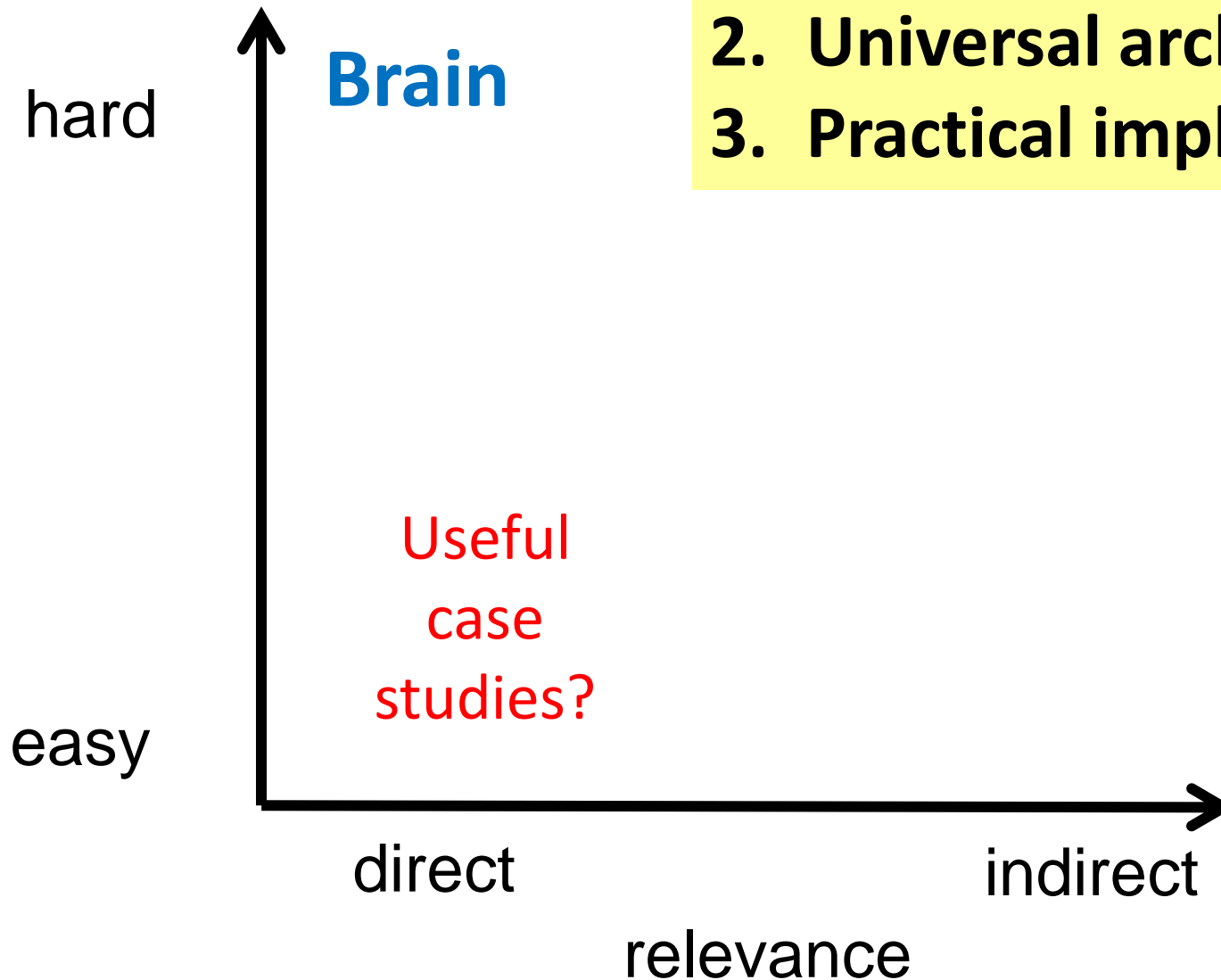
Essentials:

0. Model

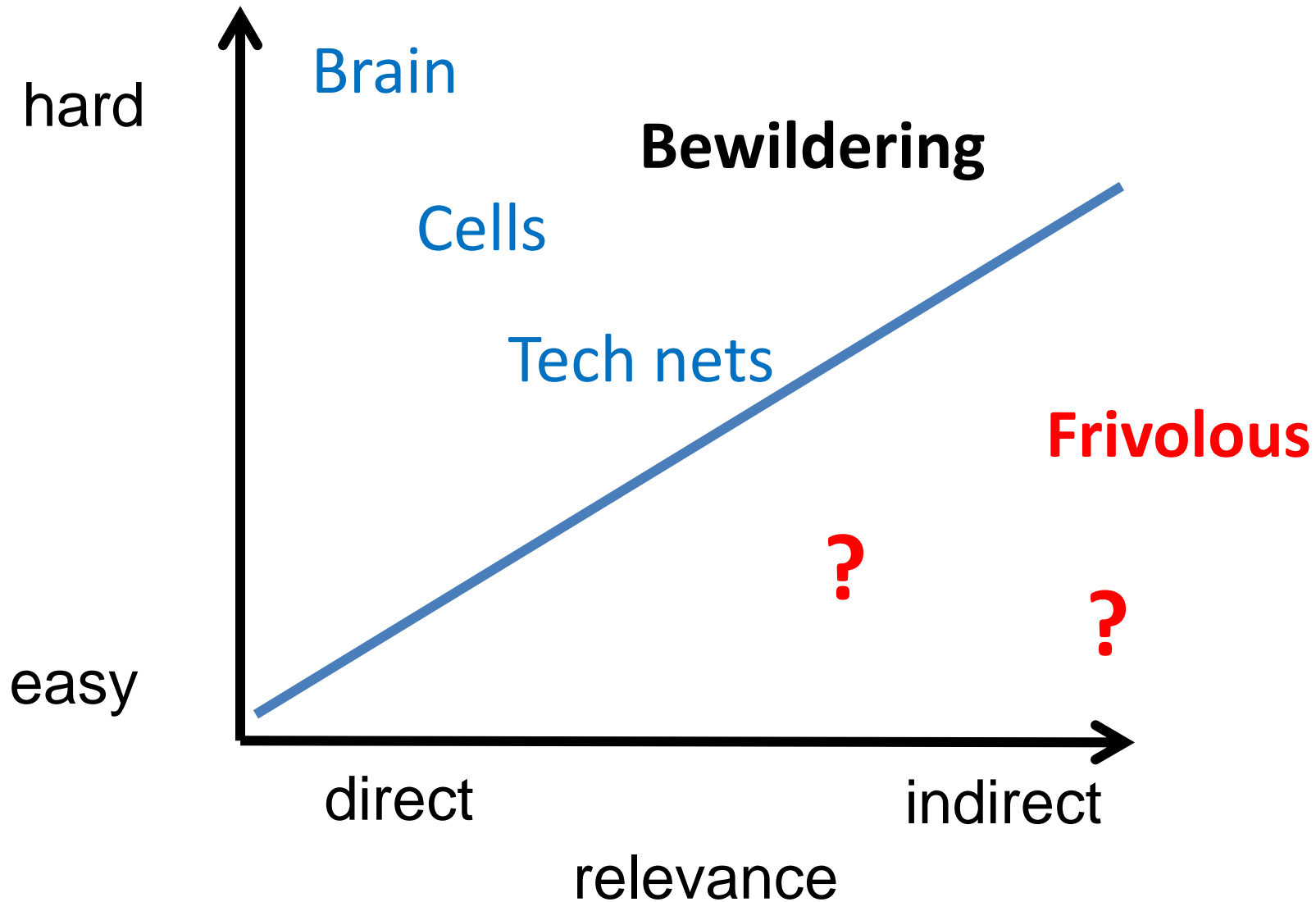
1. Universal laws

2. Universal architecture

3. Practical implementation



- 3. Universal architecture
- 4. Practical implementation



Layered architectures

Essentials

Deconstrained
(Applications)

Few global variables

Don't cross layers

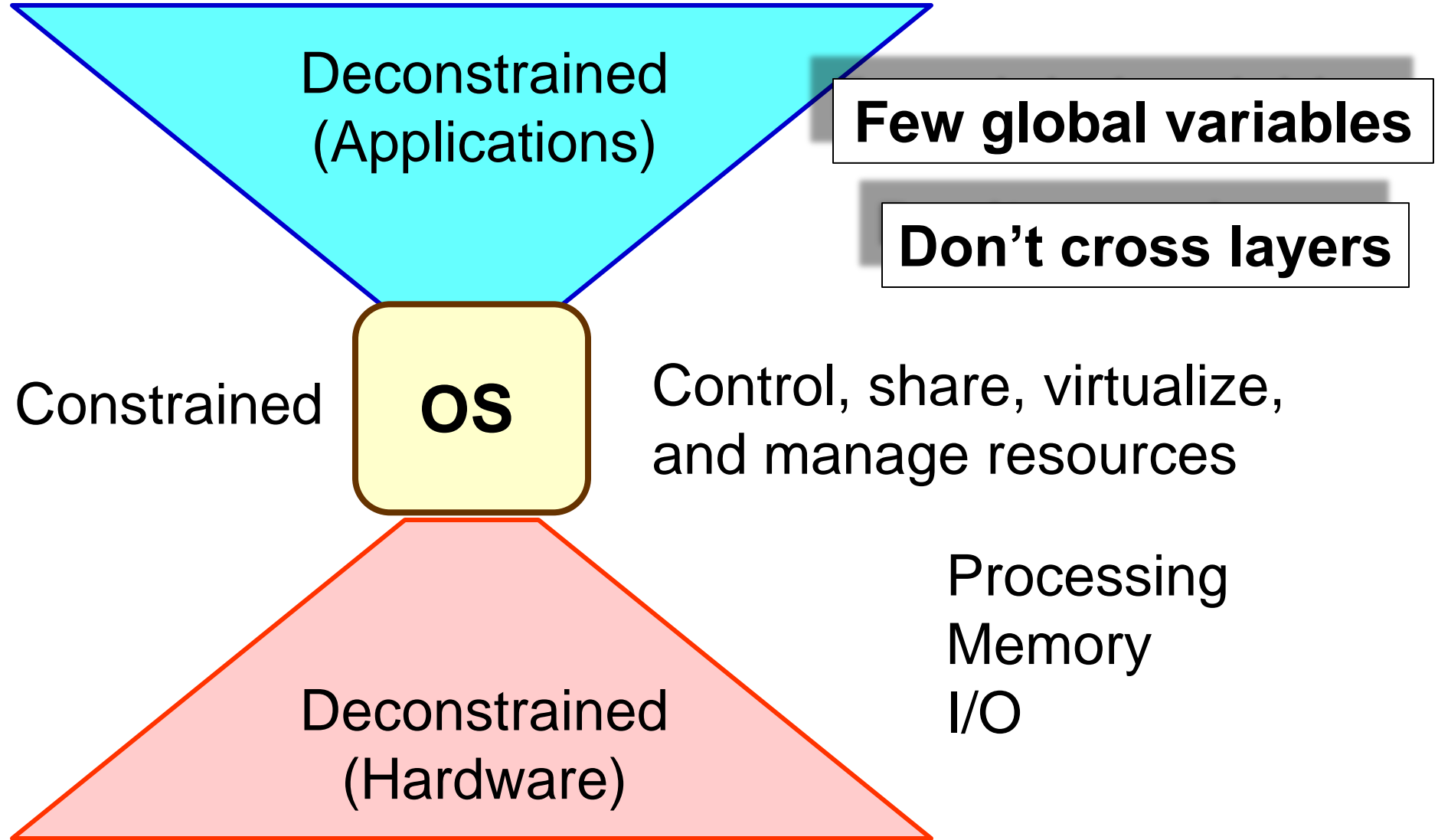
Constrained

OS

Control, share, virtualize,
and manage resources

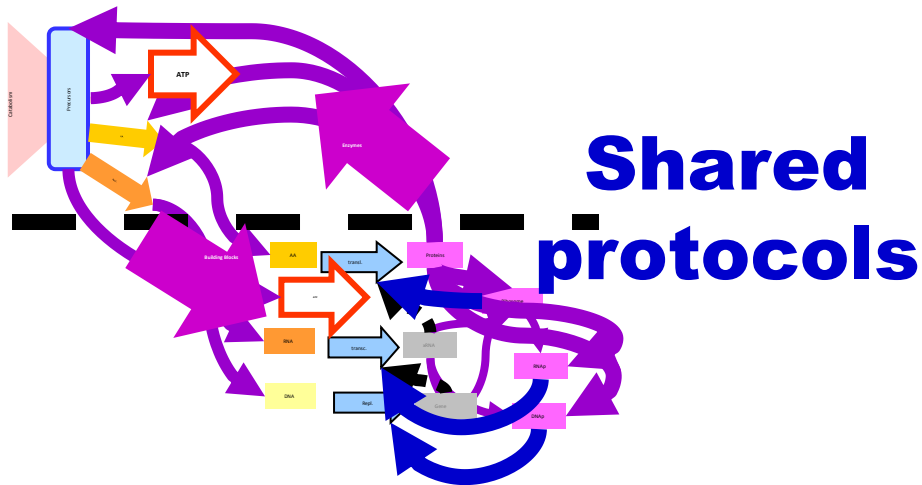
Processing
Memory
I/O

Deconstrained
(Hardware)



Layered architectures

Deconstrained
(diverse)
Environments

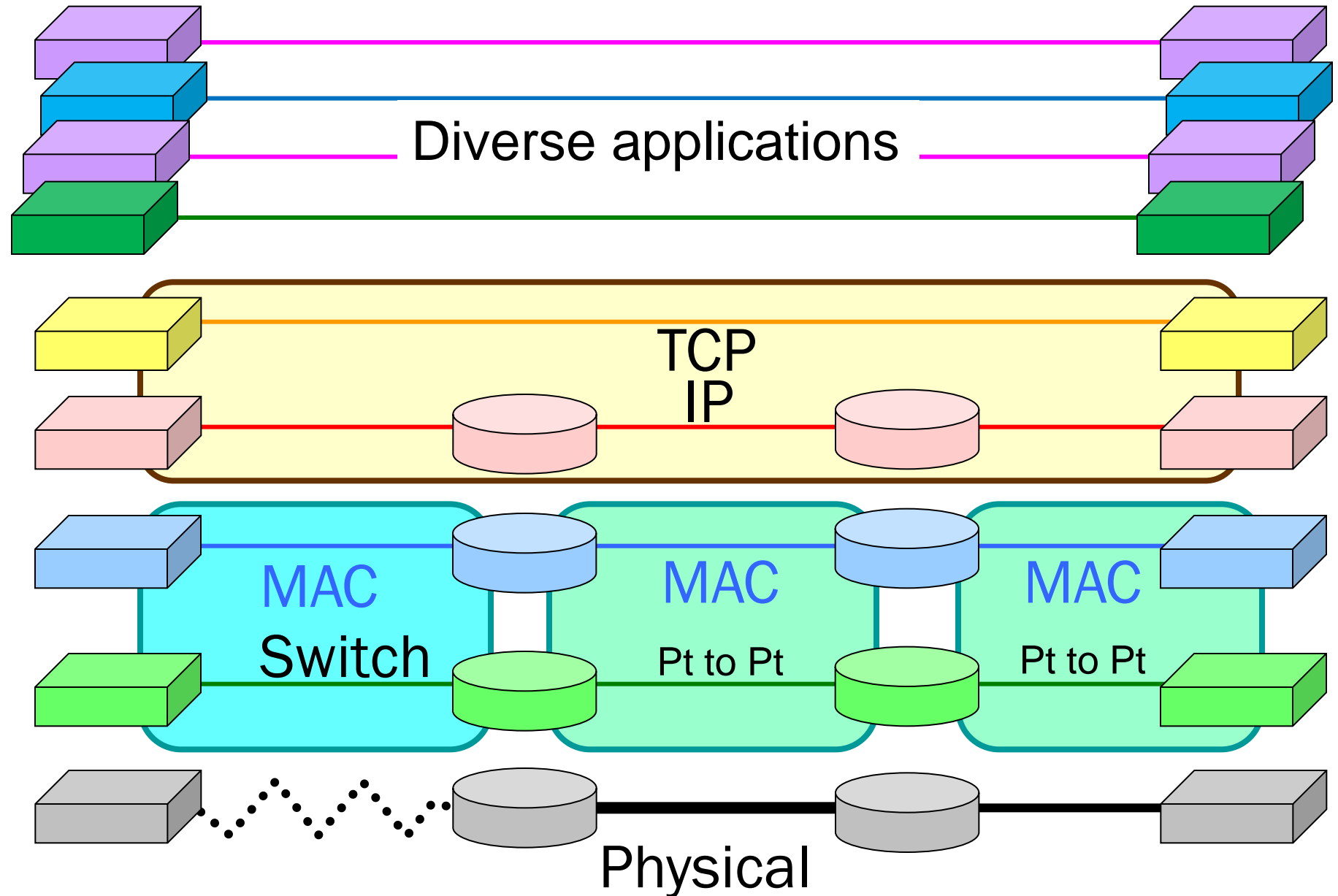


Deconstrained (diverse)
Genomes

Bacterial biosphere

Architecture
=
Constraints
that
Deconstrain

Layered architectures

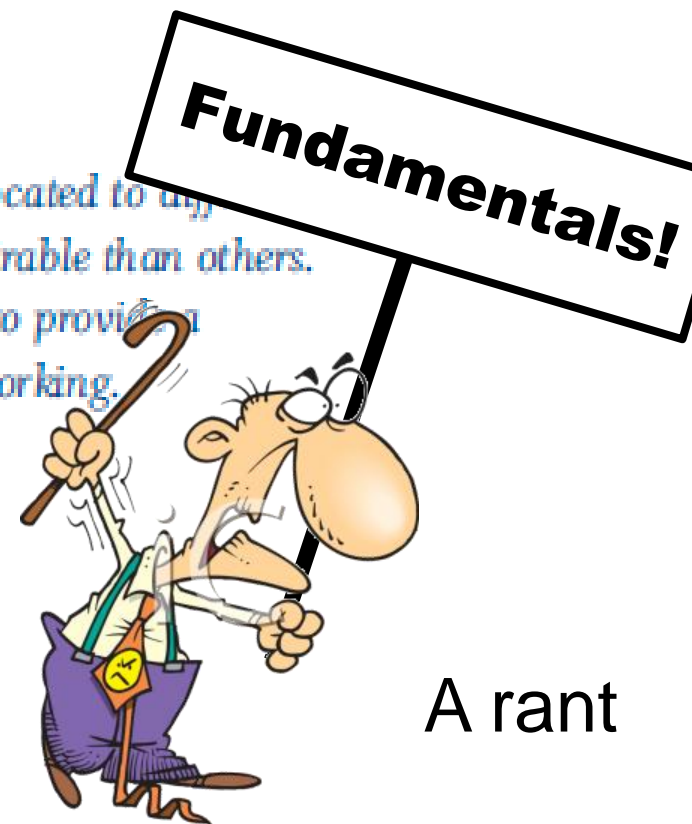


Layering as Optimization Decomposition: A Mathematical Theory of Network Architectures

There are various ways that network functionalities can be allocated to different layers and to different network elements, some being more desirable than others. The intellectual goal of the research surveyed by this article is to provide a theoretical foundation for these architectural decisions in networking.

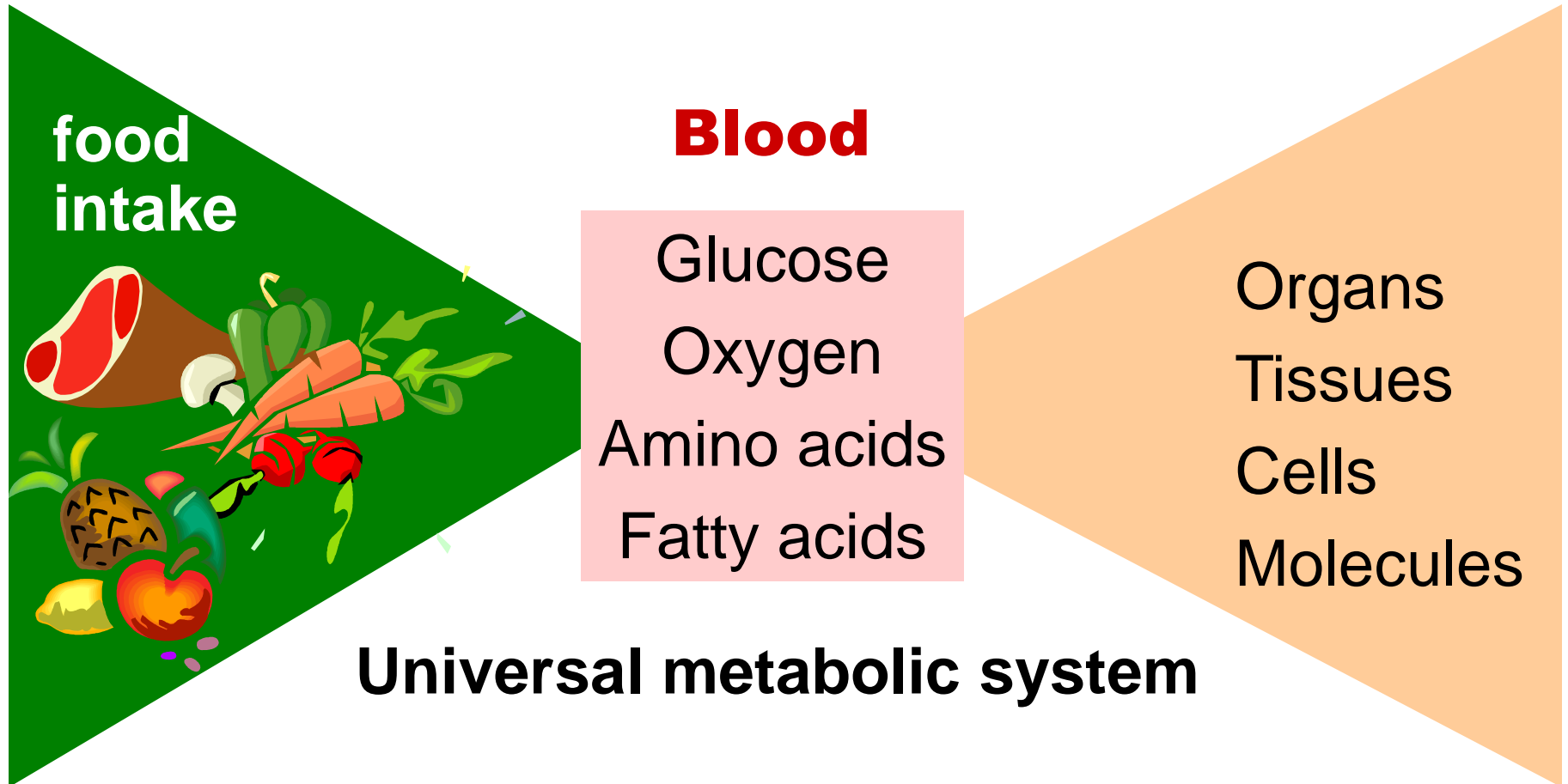
By MUNG CHIANG, Member IEEE, STEVEN H. LOW, Senior Member IEEE,
A. ROBERT CALDERBANK, Fellow IEEE, AND JOHN C. DOYLE

Chang, Low, Calderbank, Doyle



A rant

Peter Sterling and Allostasis



food
intake



Blood

Glucose
Oxygen
Amino acids
Fatty acids

Organs
Tissues
Cells
Molecules

Organs
Tissues
Cells
Molecules

Blood

Glucose
Oxygen
Amino acids
Fatty acids

food
intake



**Highly
variable
supply**

Robust

**Highly
variable
demand**

**food
intake**



Efficient

Organs
Tissues
Cells
Molecules

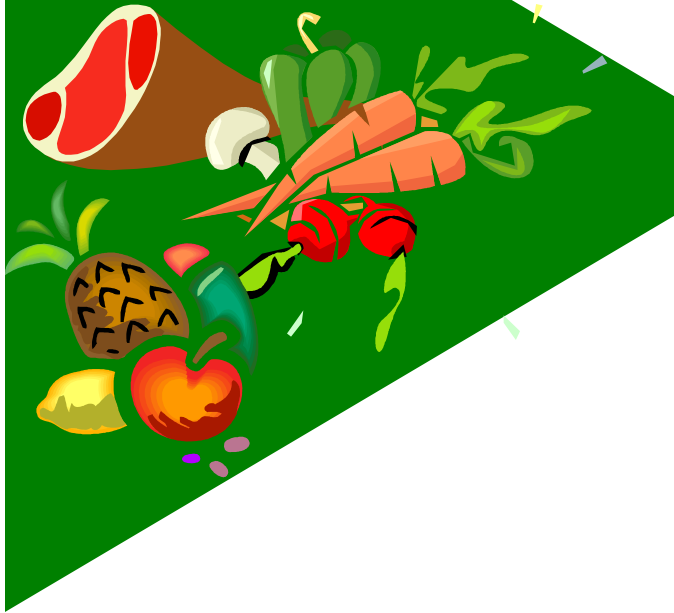
**evolving
diet**

Evolv able

**evolving
function**

Highly
variable
supply

**food
intake**



evolving
diet

**Conserved
core
building
blocks**

Glucose
Oxygen

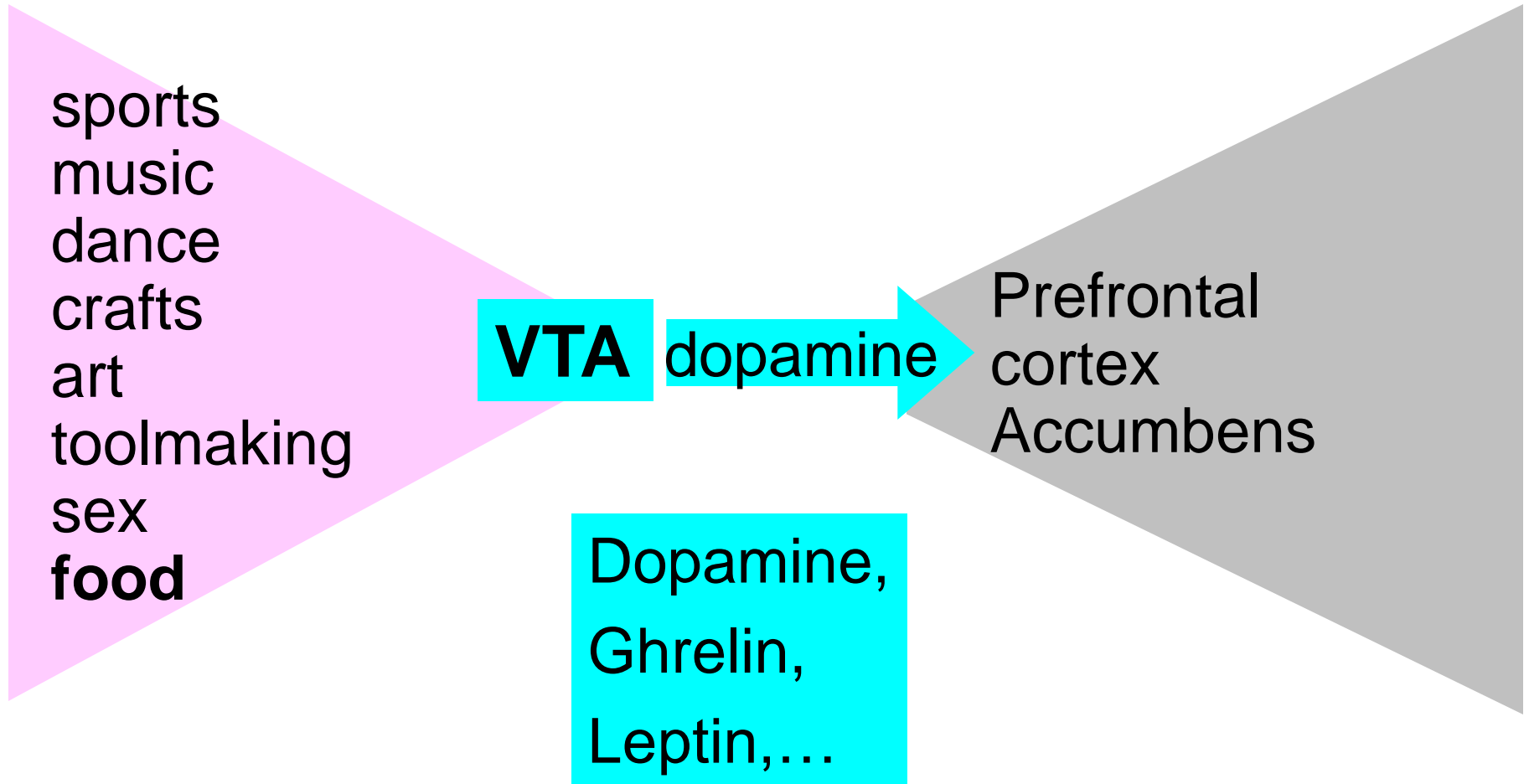
Blood

Highly
variable
demand

Organs
Tissues
Cells
Molecules

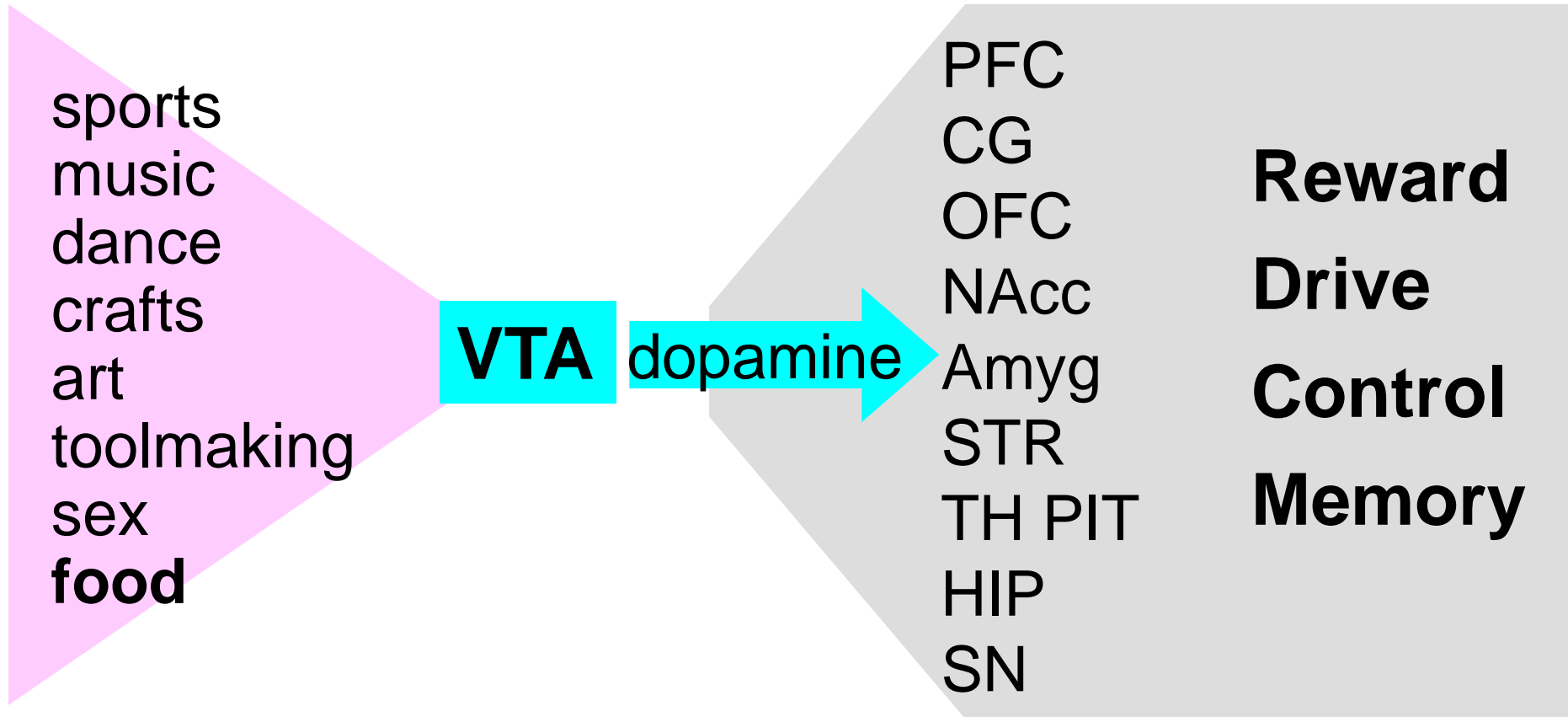
evolving
function

Universal reward systems



Ridiculous oversimplification

Universal reward systems



Robust and evolvable

Universal reward systems

sports
music
dance
crafts
art
toolmaking
sex
food

VTA dopamine

Reward
Drive
Control
Memory

**Constraints
that
deconstrain**

Blood

Glucose
Oxygen

Organs
Tissues
Cells
Molecules

Universal metabolic system



Modularity 2.0

Constraints

dopamine 

Blood

Glucose

Oxygen

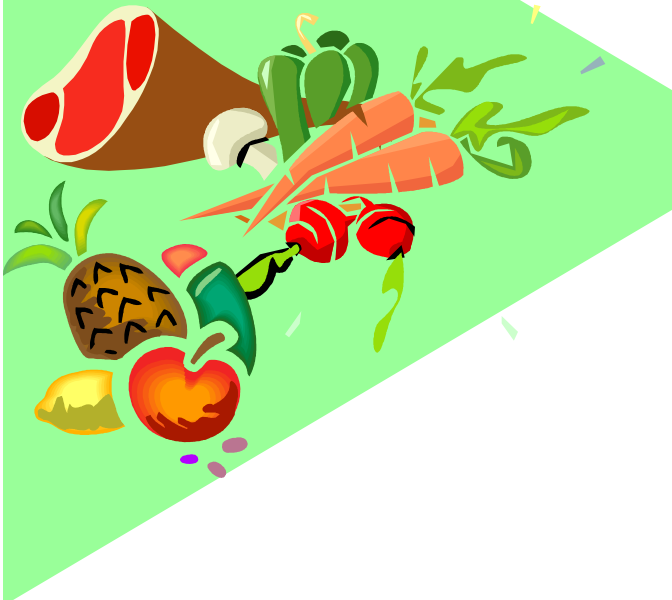
Modularity 2.0

sports
music
dance
crafts
art
toolmaking
sex
food

**that
deconstrain**

Reward
Drive
Control
Memory

Organs
Tissues
Cells
Molecules



Layered architectures



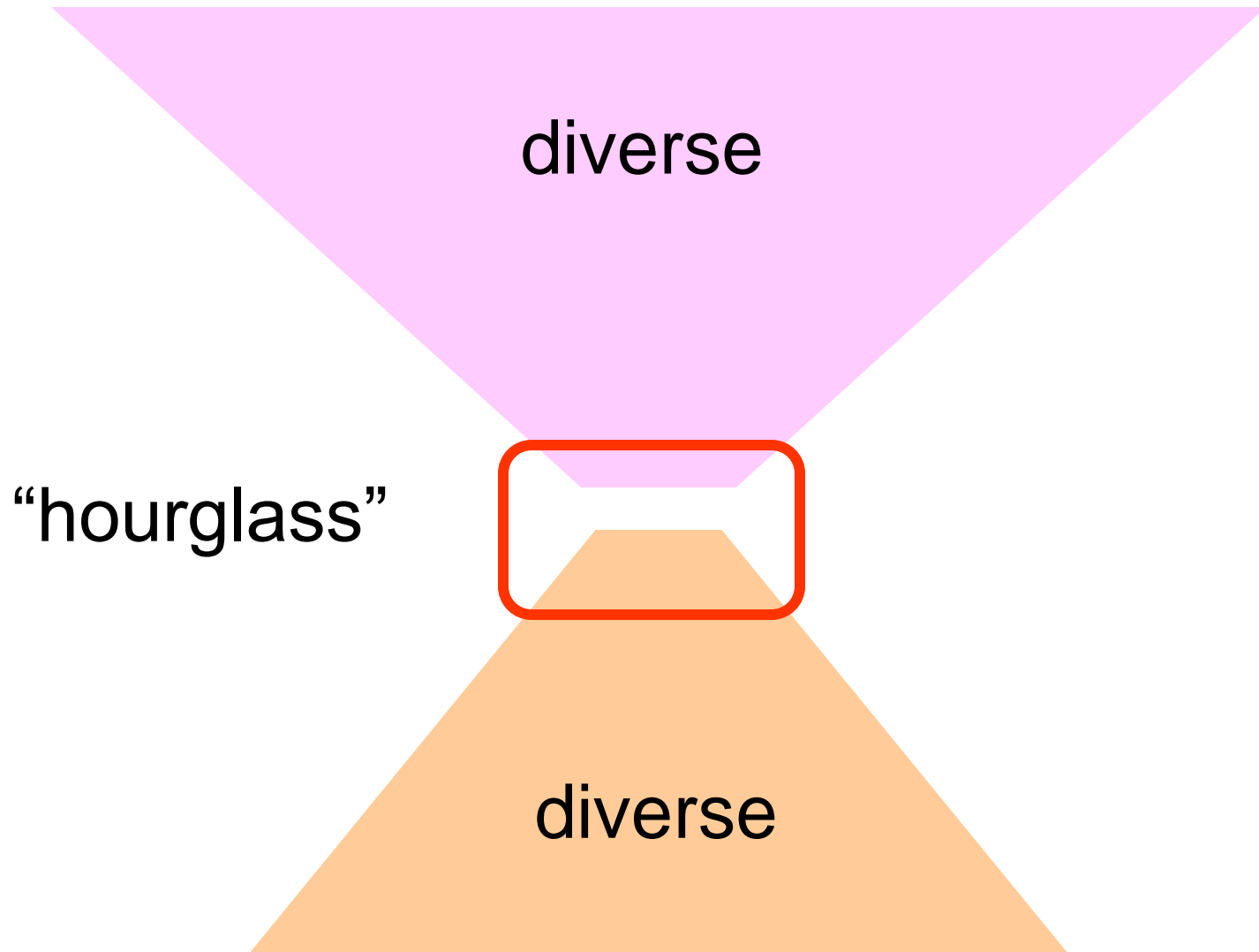
The diagram illustrates a layered architecture. At the top, the title "Layered architectures" is centered. Below it, a central white box with a red border represents an interface or a common layer. To the left of this box is a large pink triangle pointing towards the center, labeled "diverse". To the right of the box is a large orange triangle pointing away from the center, also labeled "diverse". The entire structure is labeled "bow-tie" at the bottom, indicating the shape of the architecture.

diverse

diverse

“bow-tie”

Layered architectures



Universal reward/metabolic systems

work
family
community
nature

food
sex
toolmaking
sports
music
dance
crafts
art

dopamine

Blood

Reward
Drive
Control
Memory

Organs
Tissues
Cells
Molecules

Robust and adaptive, yet ...

Modularity 1.0

work
family
community
nature

food
sex
toolmaking
sports
music
dance
crafts
art

Reward
Drive
Control
Memory

Organs
Tissues
Cells
Molecules

“Weak linkage”

Modularity 2.0

Most important “modules”



***Not* weakly connected to others,
but *highly* connected**

Universal reward/metabolic systems

work
family
community
nature

food
sex
toolmaking
sports
music
dance
crafts
art

dopamine

Blood

Reward
Drive
Control
Memory

Organs
Tissues
Cells
Molecules

Robust and adaptive, yet ...

work
family
community
nature

sex
food
toolmaking
sports
music
dance
crafts
art

cocaine
amphetamine

dopamine

Blood

Reward
Drive
Control
Memory

Organs
Tissues
Cells
Molecules

work
family
community
nature

money

market/
consumer
culture

salt
sugar/fat
nicotine
alcohol

Vicarious

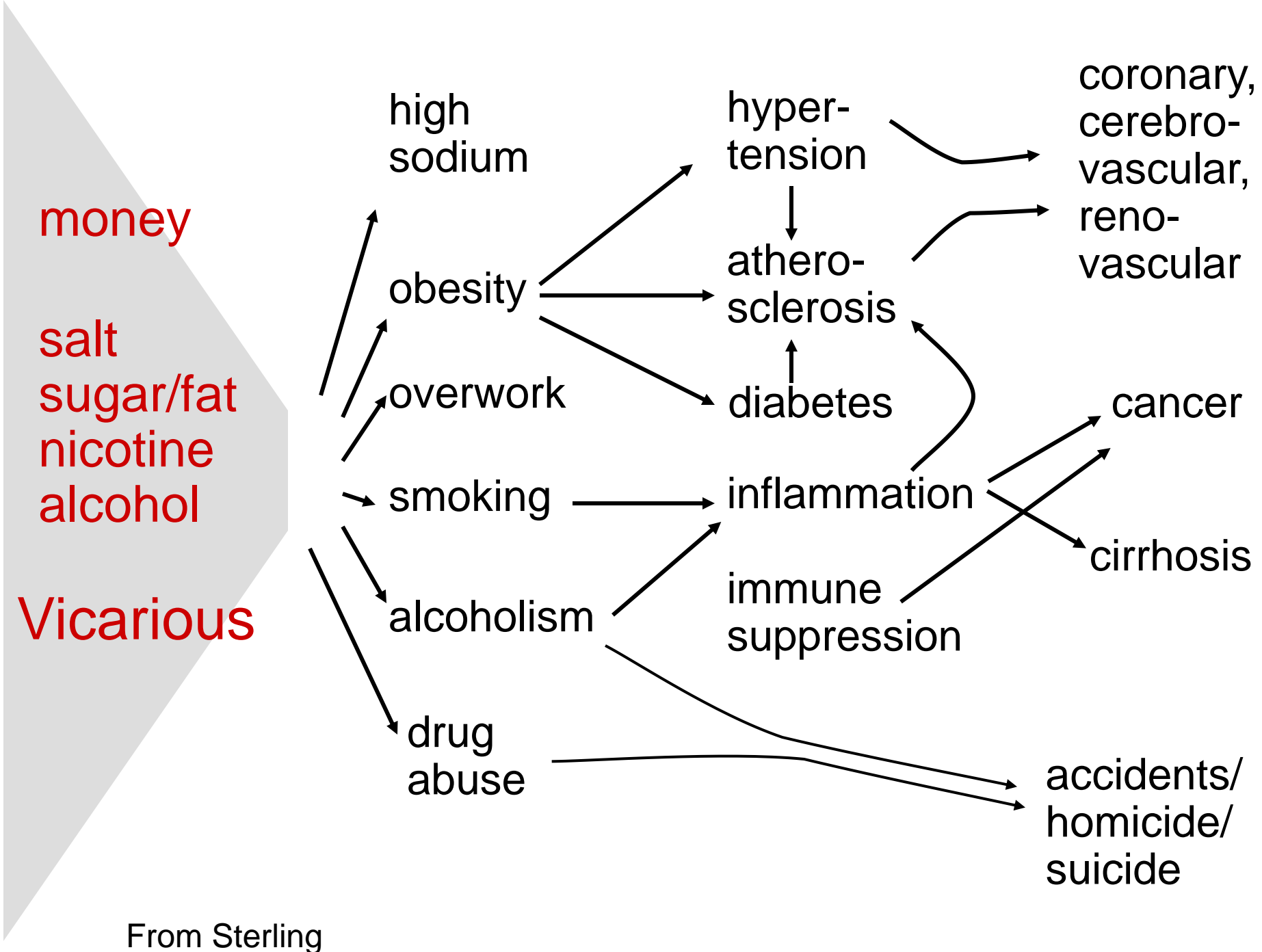
sex
toolmaking
sports
music
dance
crafts
art

industrial
agriculture

dopamine

Reward
Drive
Control
Memory

Organs
Tissues
Cells
Molecules



Universal reward systems

sports
music
dance
crafts
art
toolmaking
sex
food

ROBUST

VTA dopamine

Prefrontal
cortex

Nucleus accumbens

Blood

Glucose
Oxygen

Organs

Tissues

Cells

Molecules

Universal metabolic system

Robust

Yet Fragile

money

salt
sugar/fat
nicotine
alcohol

Vicarious

high
sodium

hyper-
tension

athero-
sclerosis

coronary,
cerebro-
vascular,
reno-
vascular

cancer

cirrhosis

immune
suppression

alcoholism

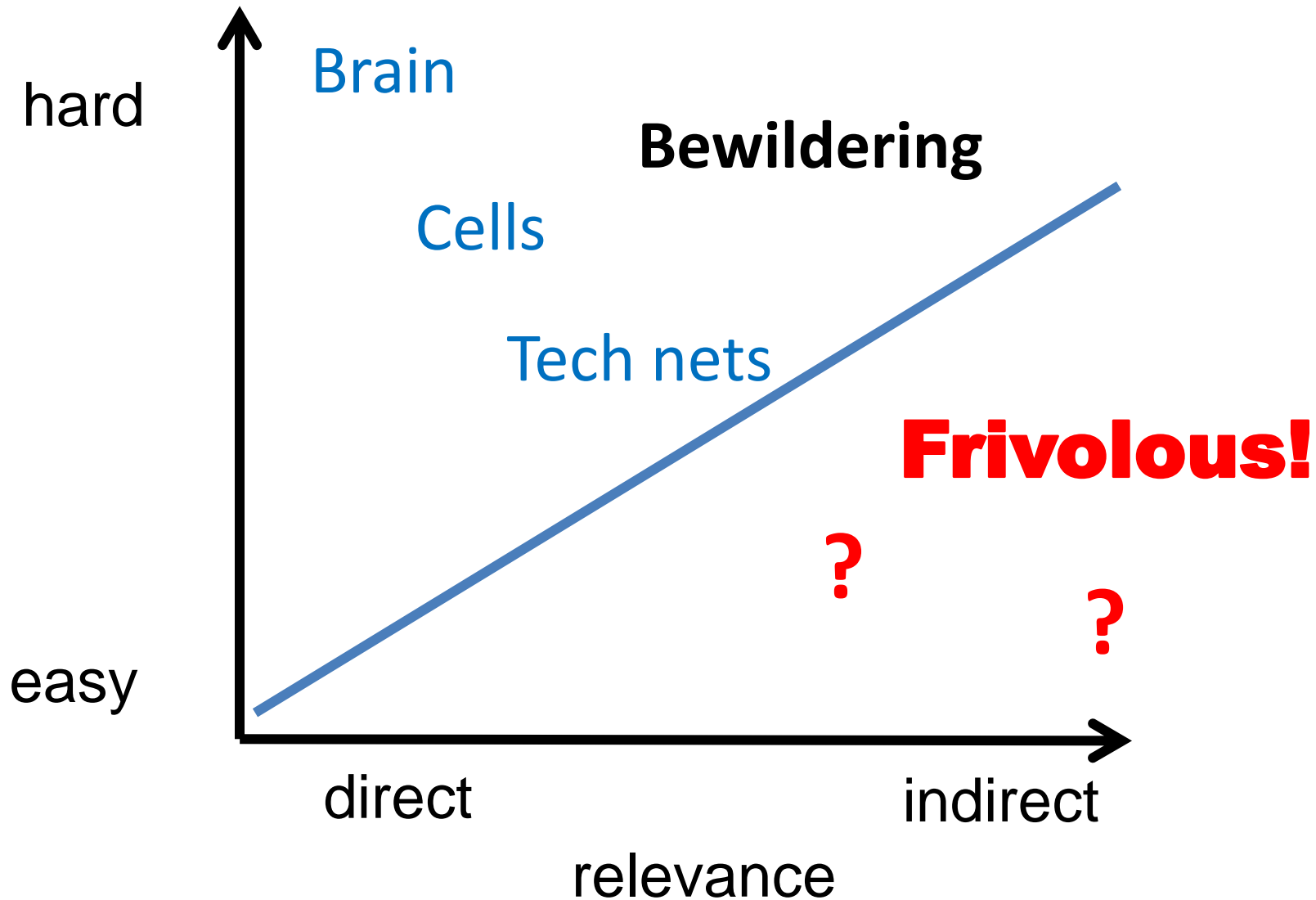
drug
abuse

accidents/
homicide/
suicide

Glucose
Oxygen

clonidine
VTA
dopamine

3. Universal architecture
4. Practical implementation





FASHION WARS

NEW YORK SPRING 2009



Garments

Cloth

Thread

Fiber

Frivolous!



Other examples

Words

Lego

Clothing

Cell biology

Internet

Cyberphysical

Money

Letters and words

- 9 letters: adeginorz
- $9! = 362,880$ sequences of 9 letters
- Only “organized” is a word

1 << (# words) << (# non-words)

large

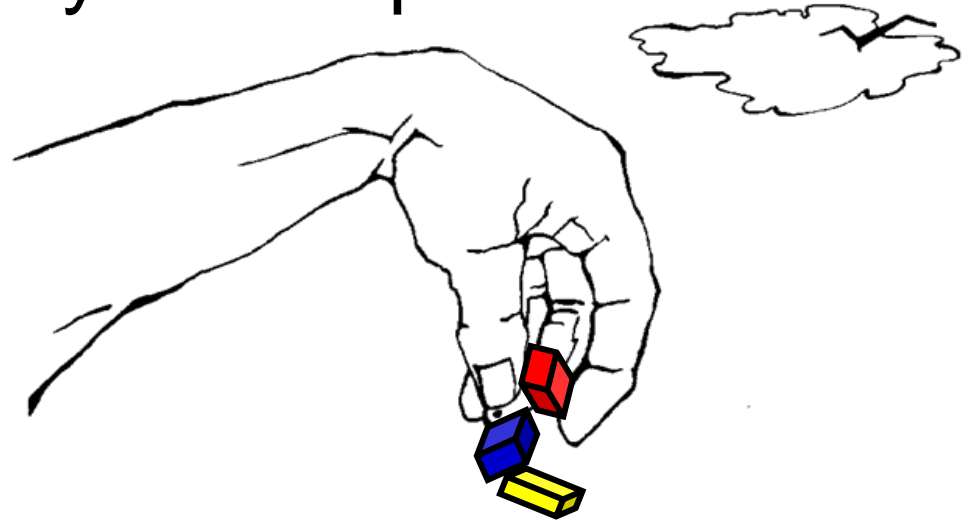
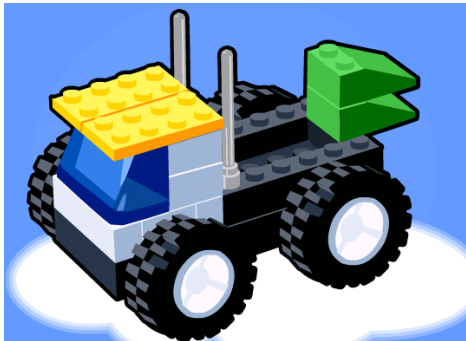
thin

large **thin**

$1 \ll \# \text{ toys} \ll \# \text{ piles}$



toys

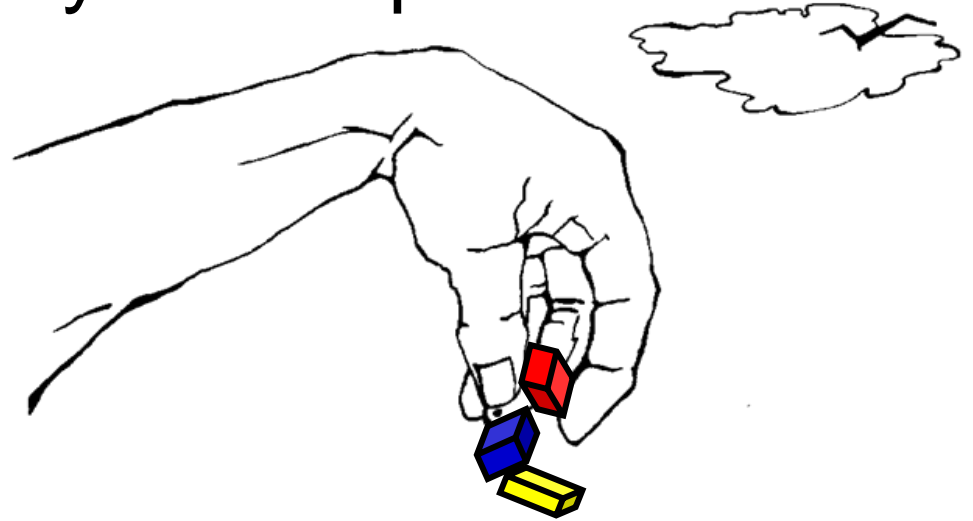


pile

~~“order for free?”~~

~~large thin~~
 ~~$1 \ll \# \text{ toys} \ll \# \text{ piles}$~~

edge of chaos
self-organized criticality
scale-free
???



statistical physics
random ensembles
minimally tuned
phase transitions
bifurcations



Reverse Engineering of Biological Complexity

Marie E. Csete¹ and John C. Doyle^{2*}

Advanced technologies and biology have extremely different physical implementations, but they are far more alike in systems-level organization than is widely appreciated. Convergent evolution in both domains produces modular architectures that are composed of elaborate hierarchies of protocols and layers of feedback regulation, are driven by demand for robustness to uncertain environments, and use often imprecise components. This complexity may be largely hidden in idealized laboratory settings and in normal operation, becoming conspicuous only when contributing to rare cascading failures. These puzzling and paradoxical features are neither accidental nor artificial, but derive from a deep and necessary interplay between complexity and robustness, modularity, feedback, and fragility. This review describes insights from engineering theory and practice that can shed some light on biological complexity.

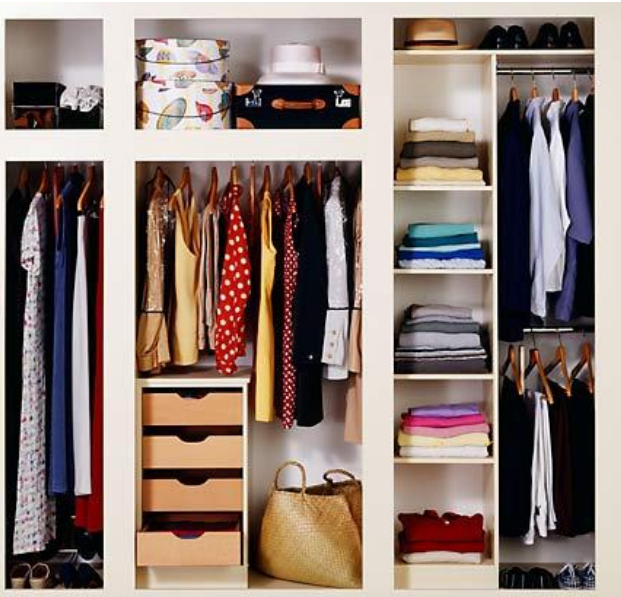
ty in components or the

Biologists and biophysicists find that engineering complex networks often reveals a biological network's (15). They find that "per homeostatic regulation are networks (16, 17), despite organisms" that can seem g (18–20). Some even conclude that organisms and their resulting in engineering (20, 21). It is in the nature of their robustness that biology and advan

Csete and Doyle



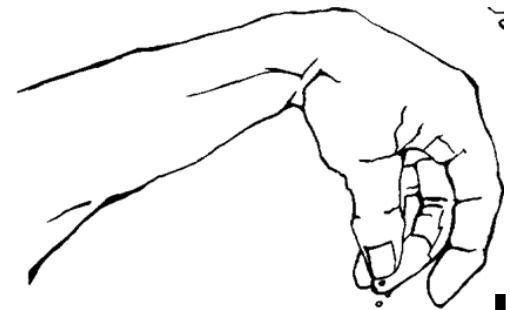
wardrobe



large

thin

1 << # outfits << # heaps



heap



outfit



Cool



Hycreek Layering Guide

This guide is meant as a "suggested" guide only. The amount and type of layers that will keep you warm in any given condition may vary, so you can feel free to adapt it as necessary.

Frigid

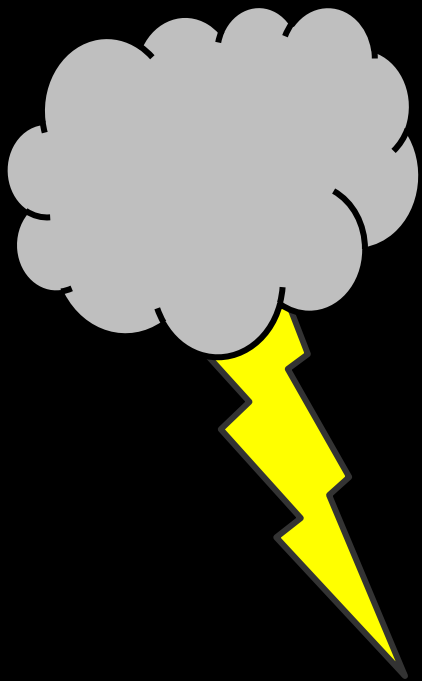
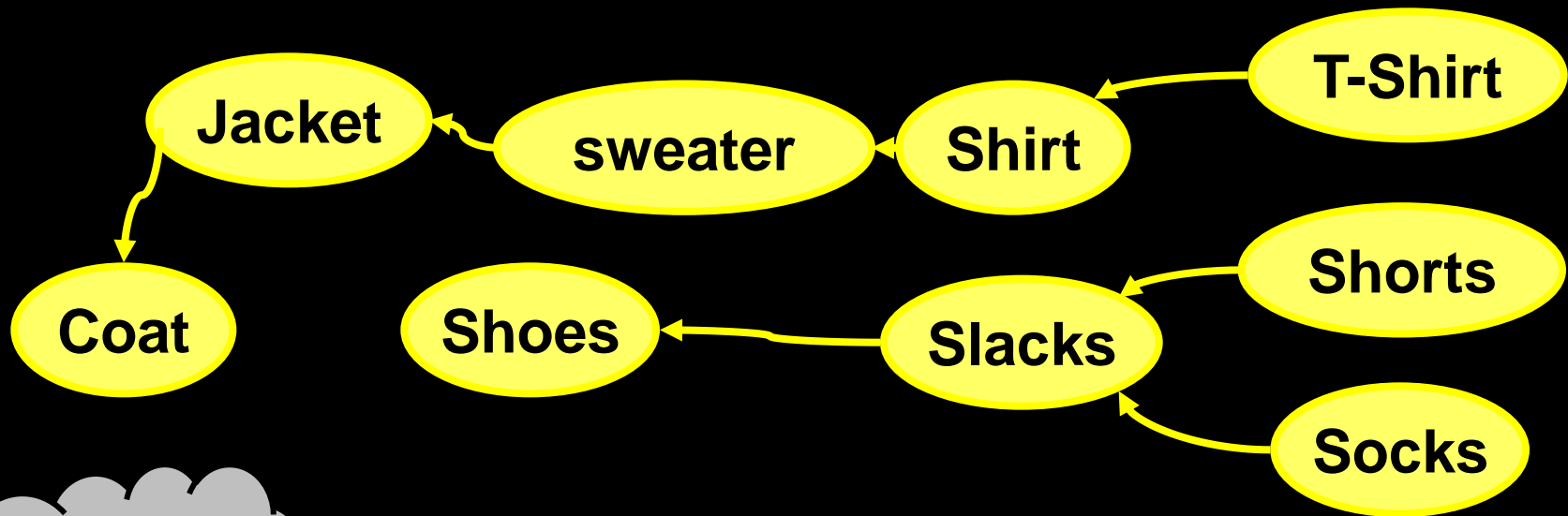
Layering



Tradeoffs

Extreme





Outer

Middle

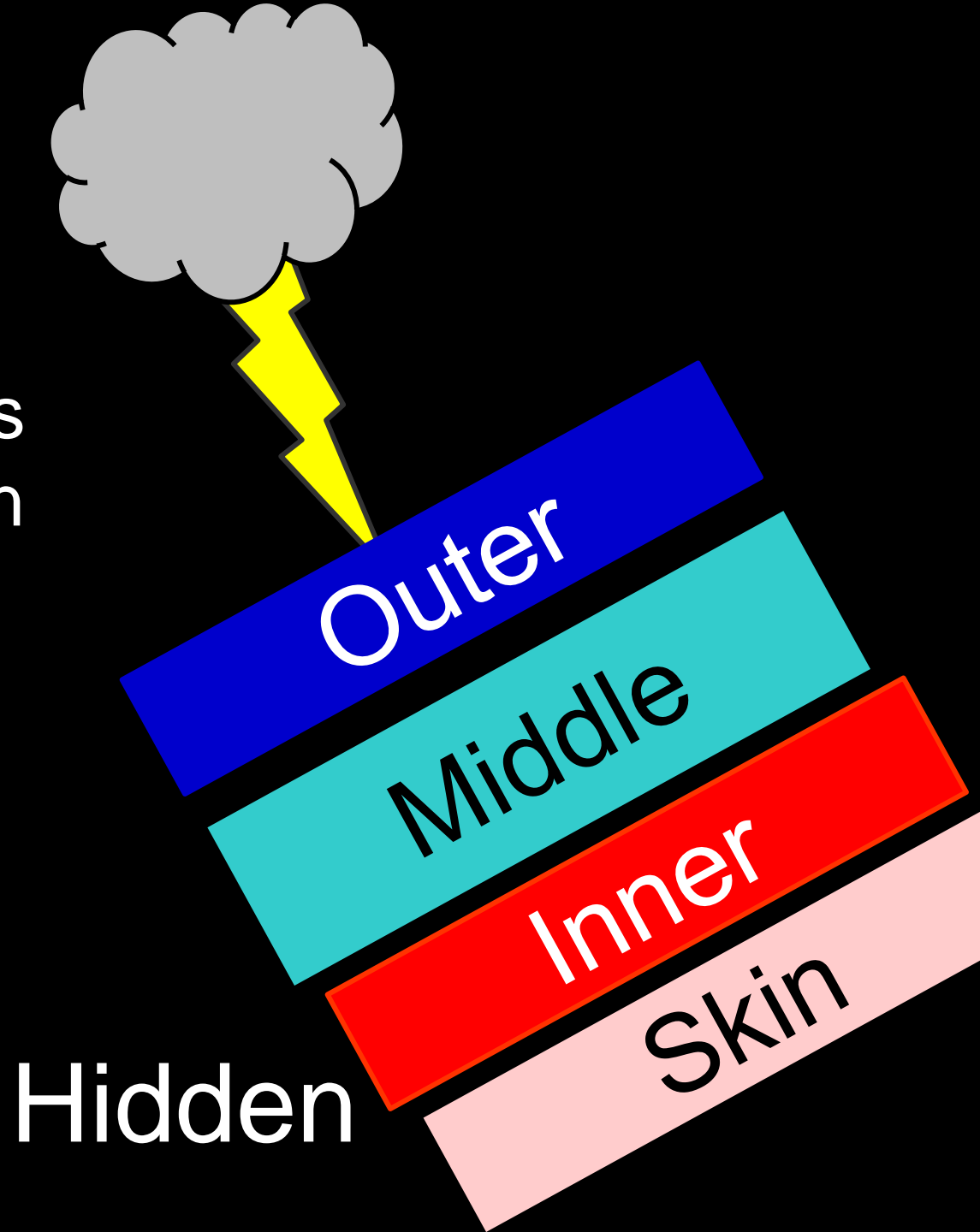
Inner

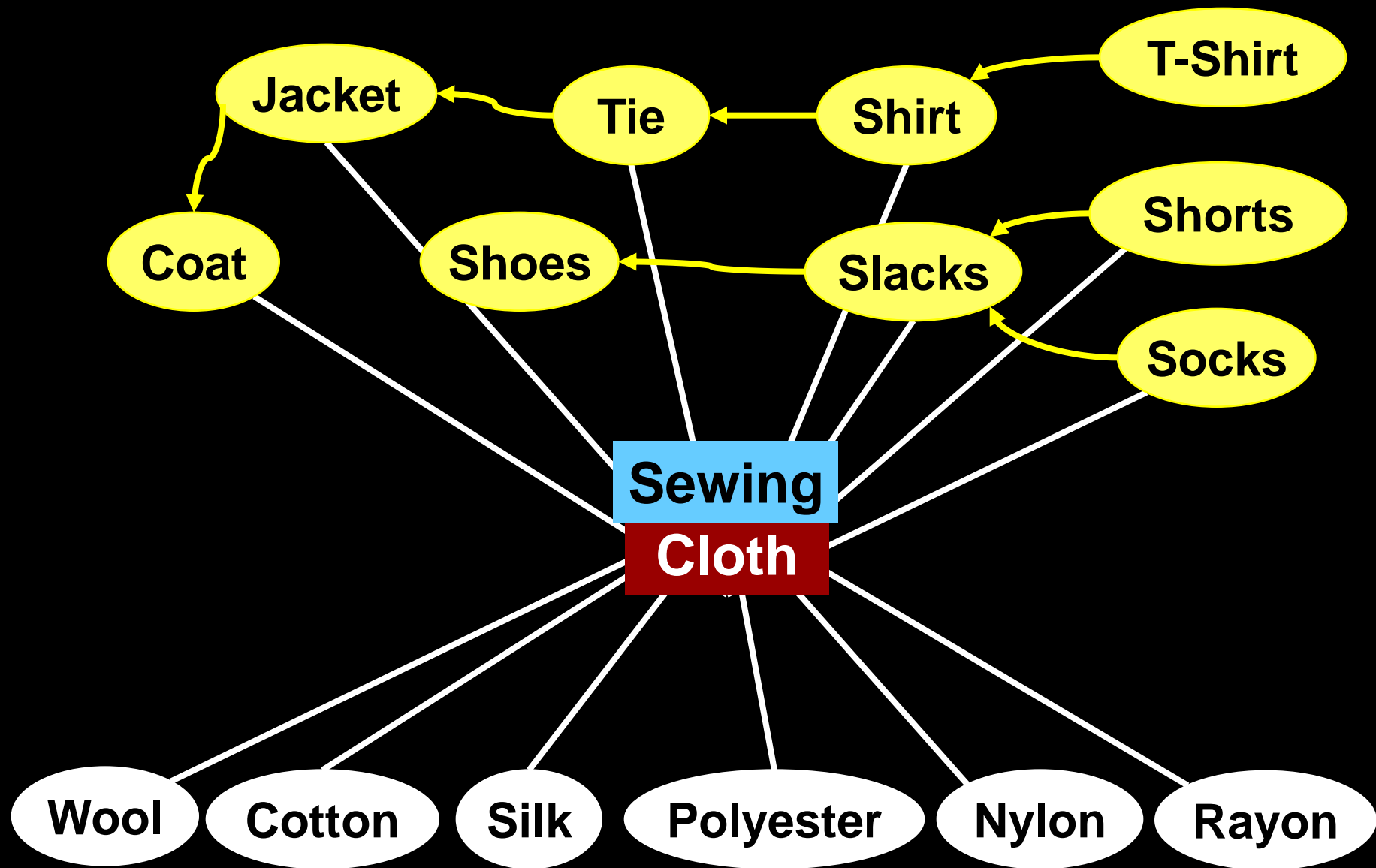
Skin

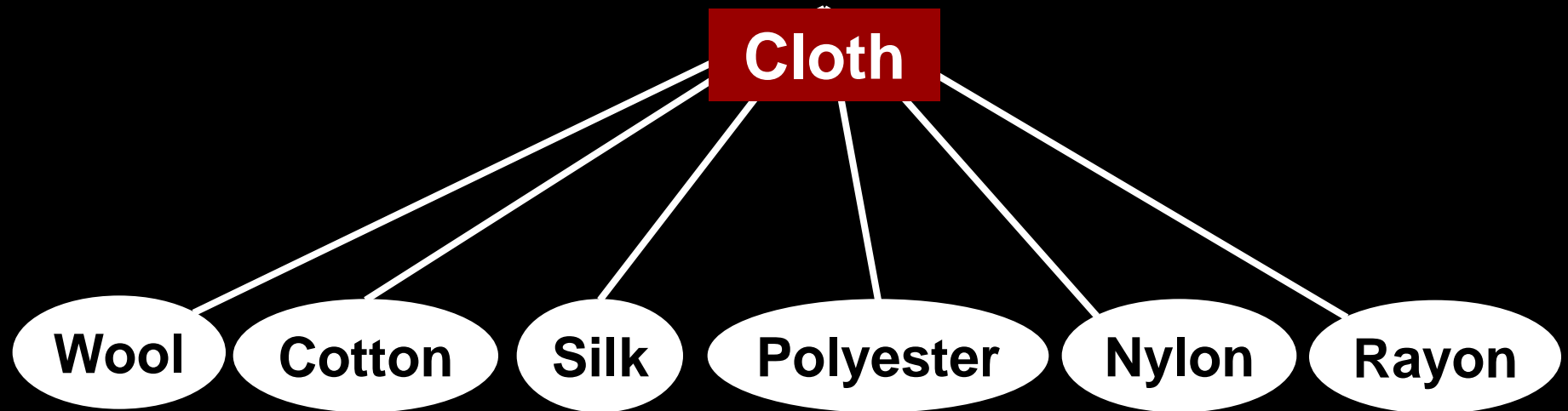
System constraints

Robust to variations and requirements in

- weather
- activity
- appearance
- wear and tear
- washing







Component constraints

Functionally diverse garments

sew

Diverse fabric

knit, weave

Diverse Thread

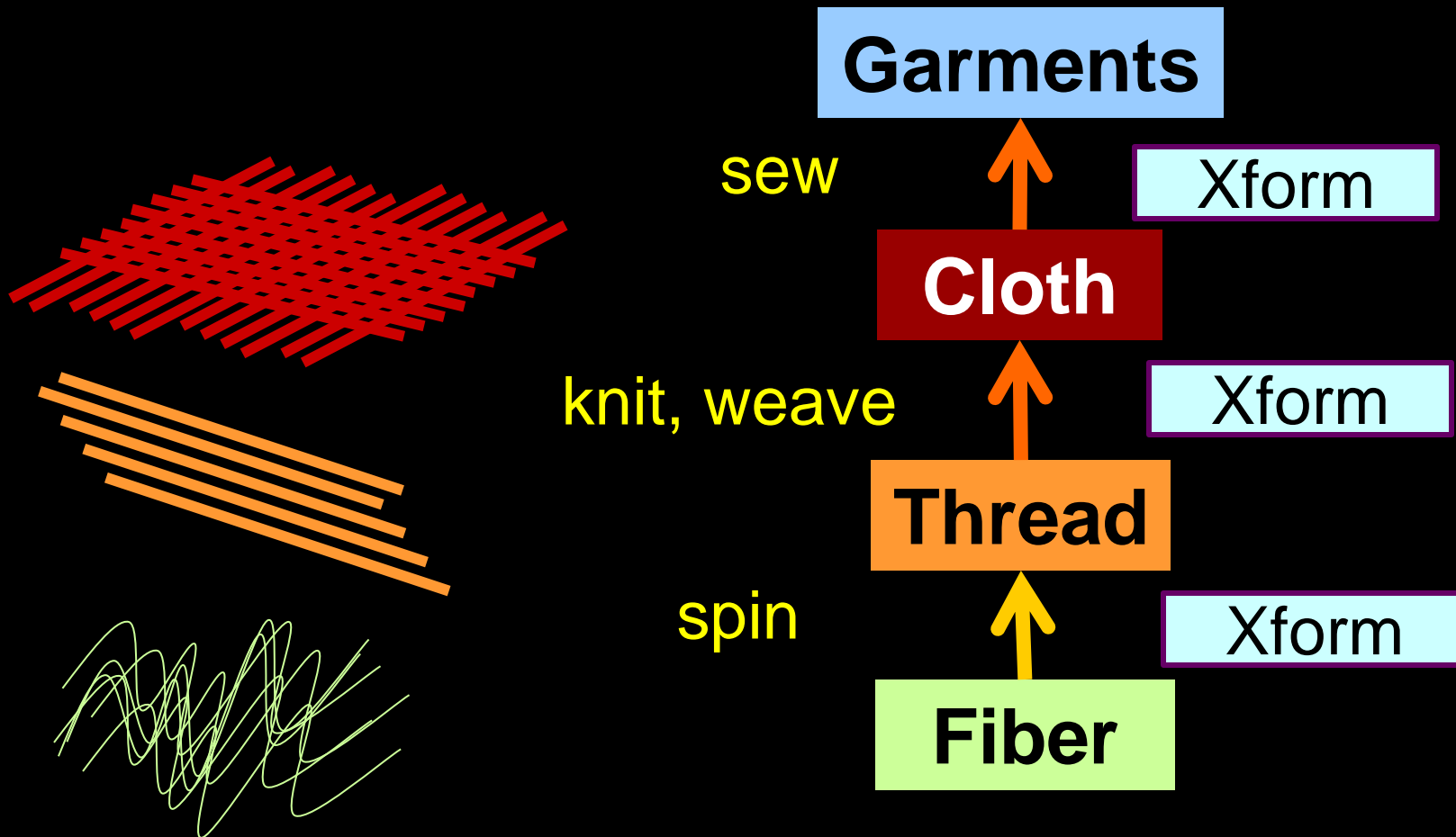
spin

Fiber

Geographically diverse sources

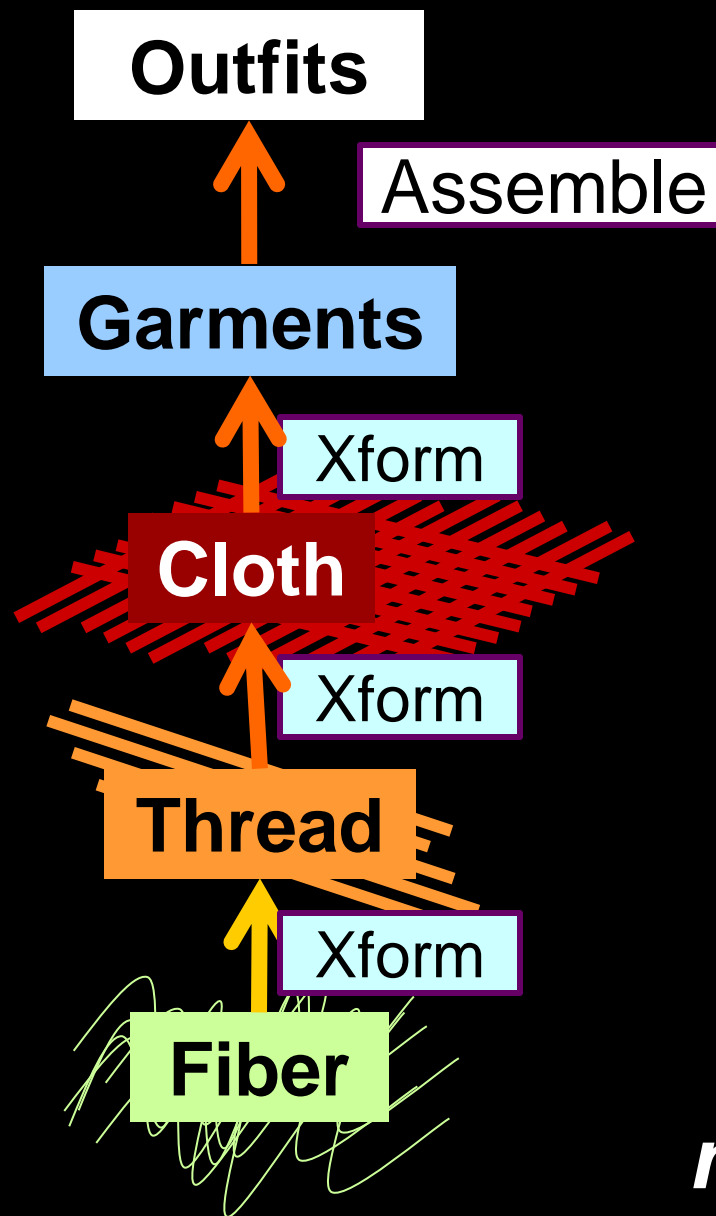
General
purpose
machines

Architecture and Modularity 2.0



Prevents unraveling of lower layers

**Hidden,
large, thin,
nonconvex**

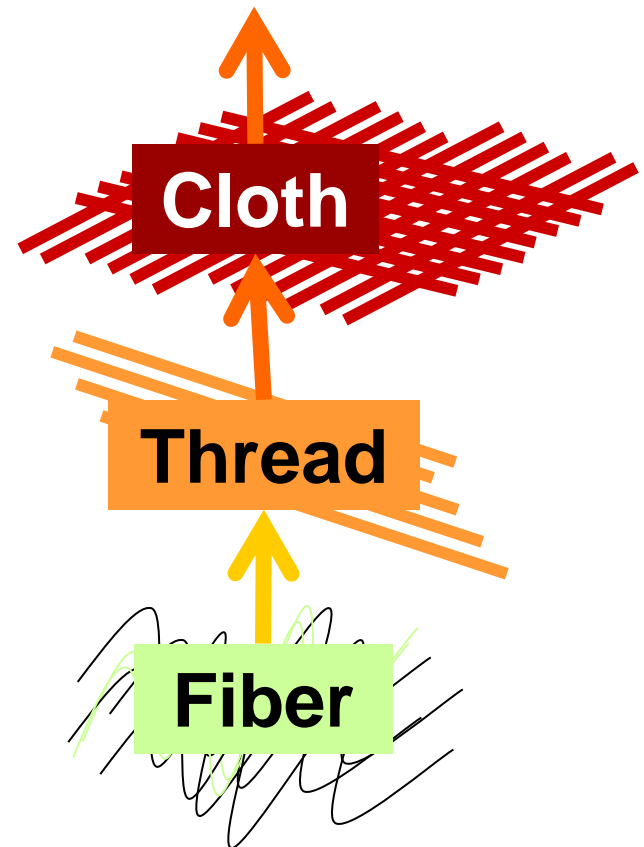
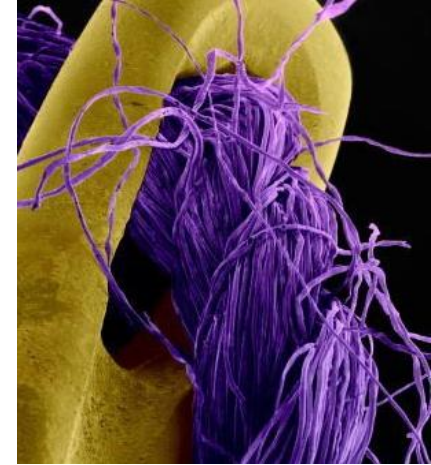
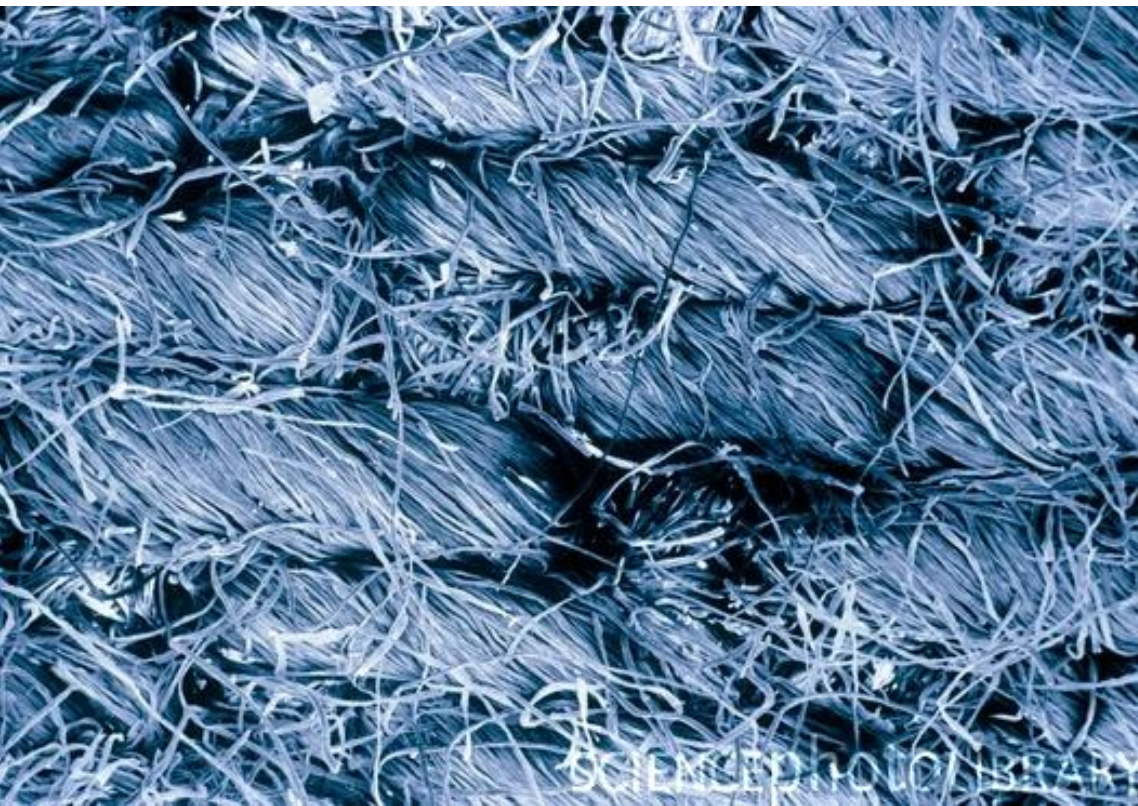


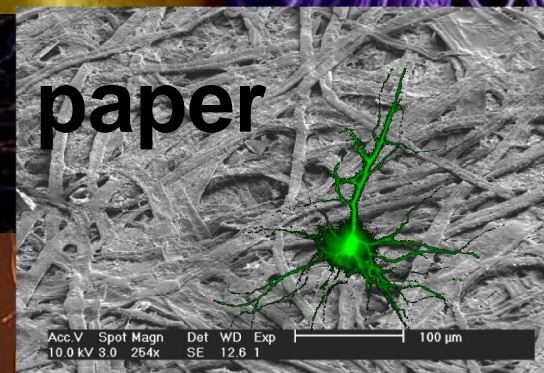
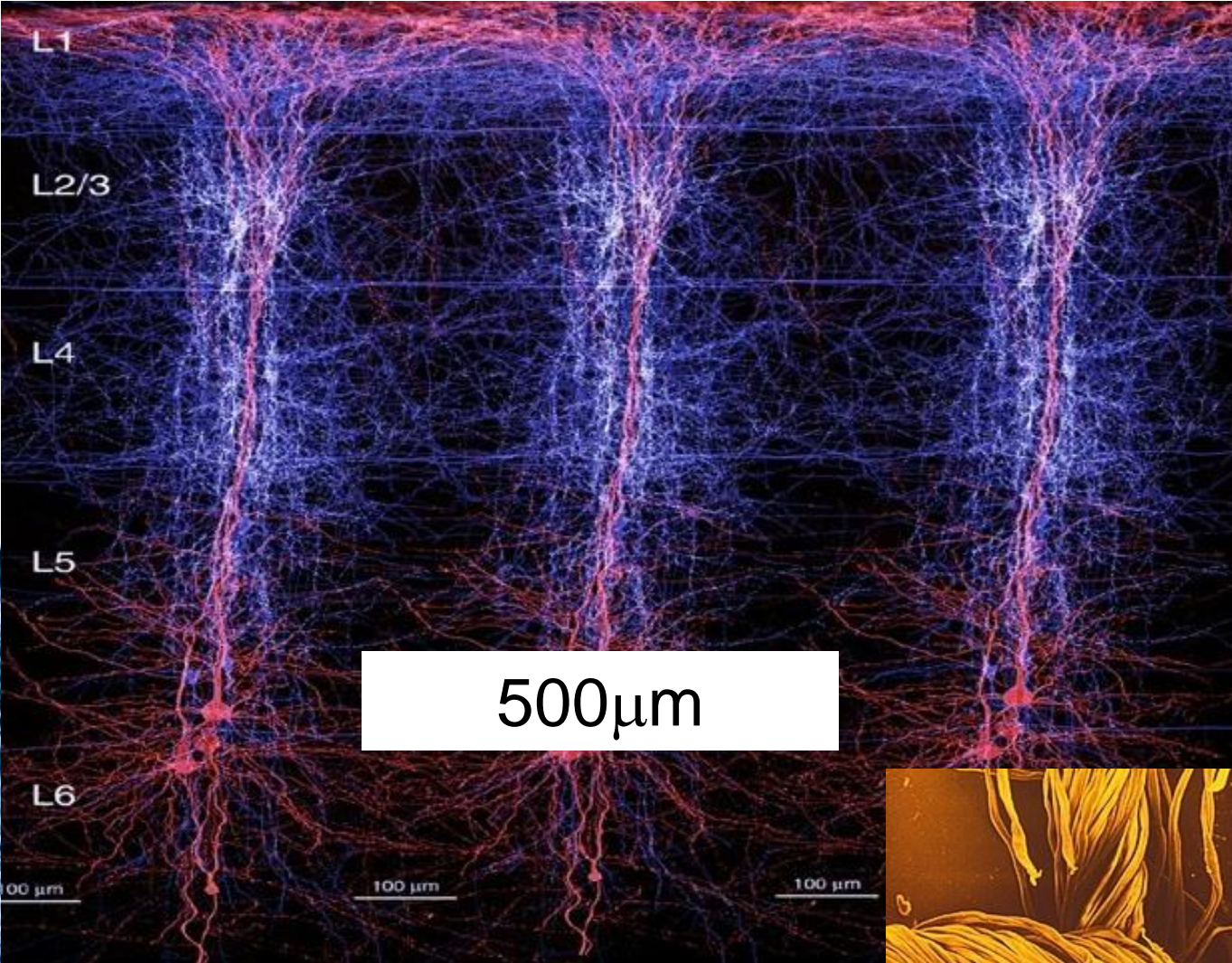
**are
*necessary***

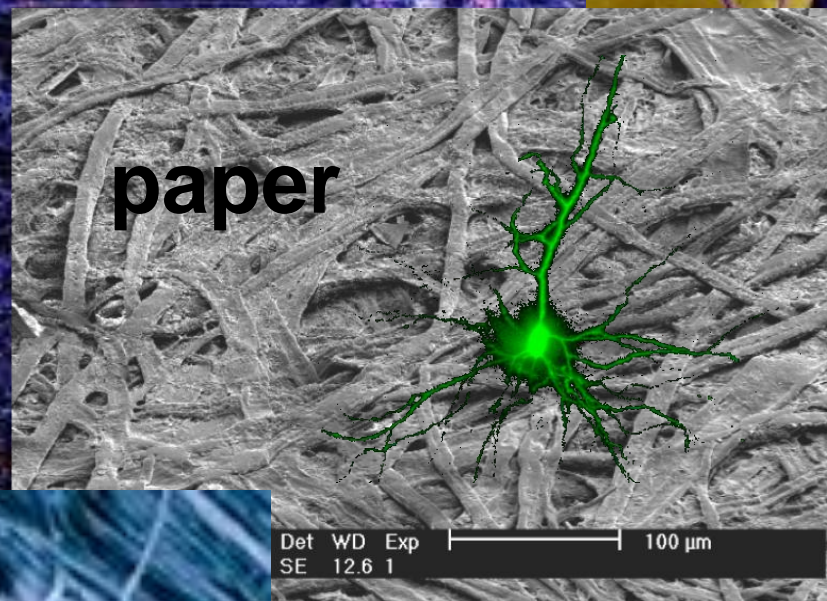
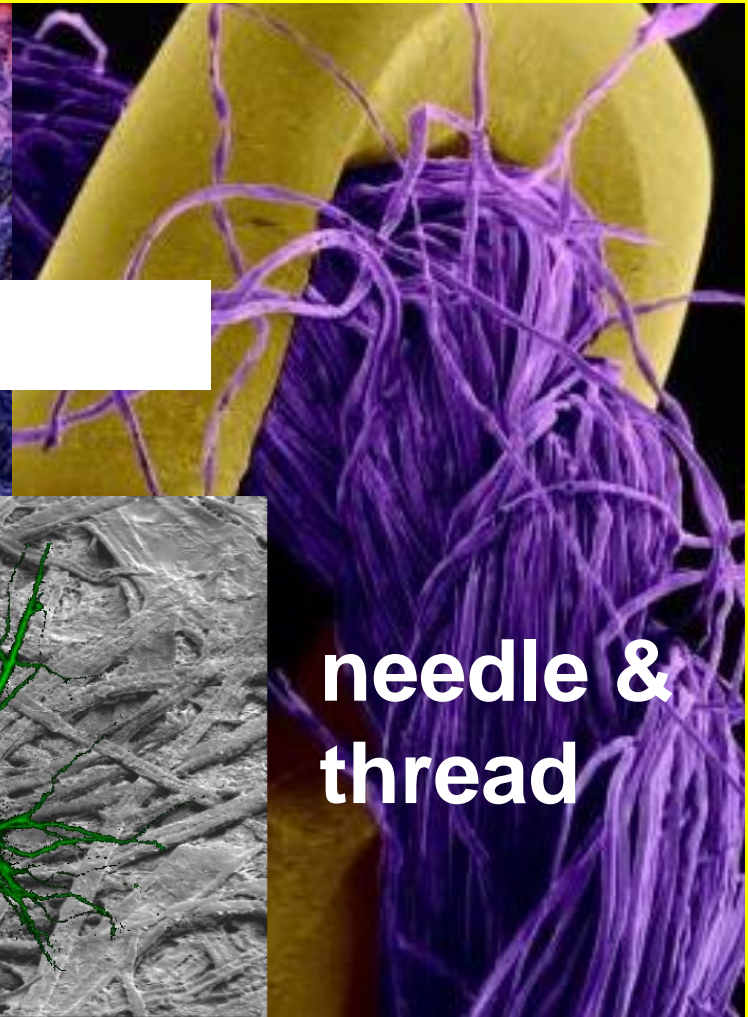
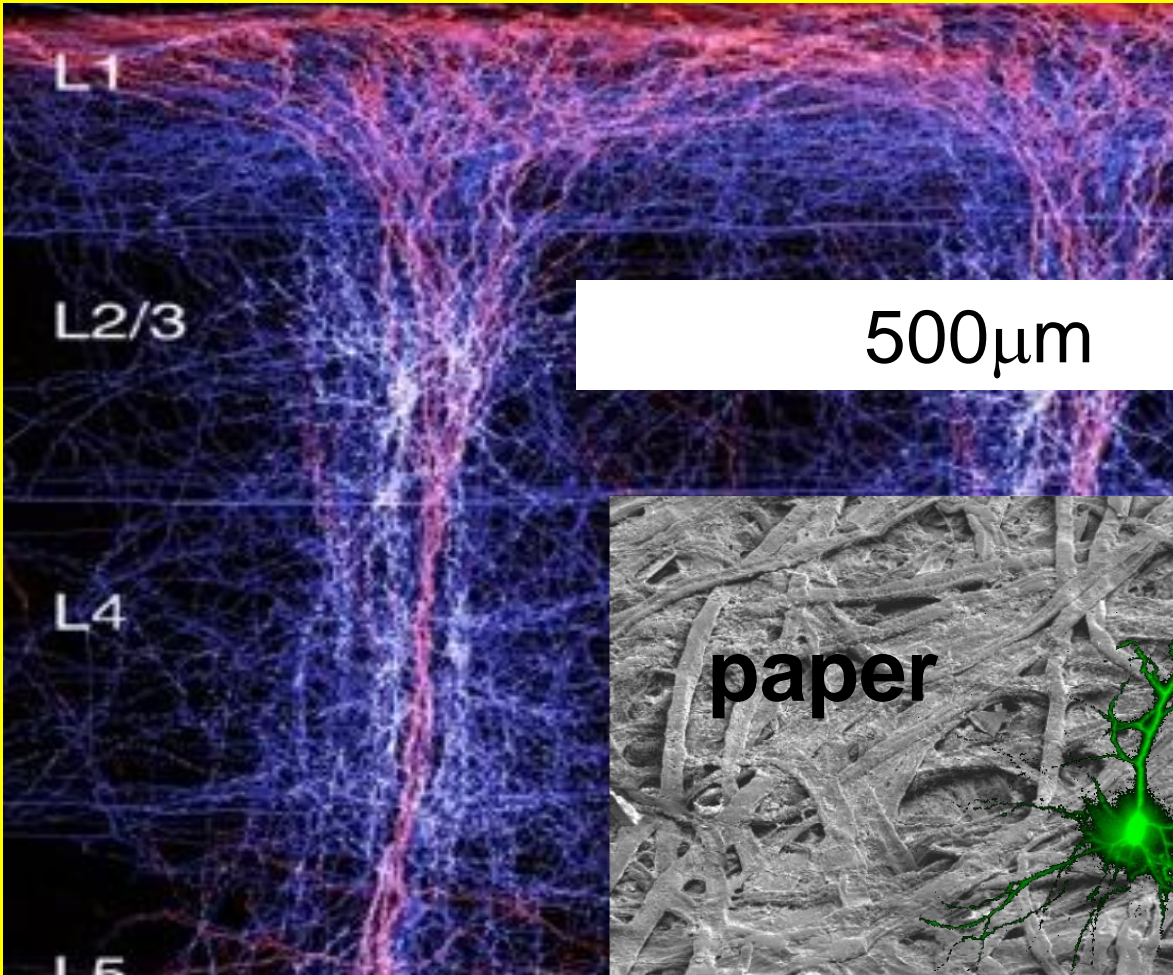
500 μ m

.5mm

denim

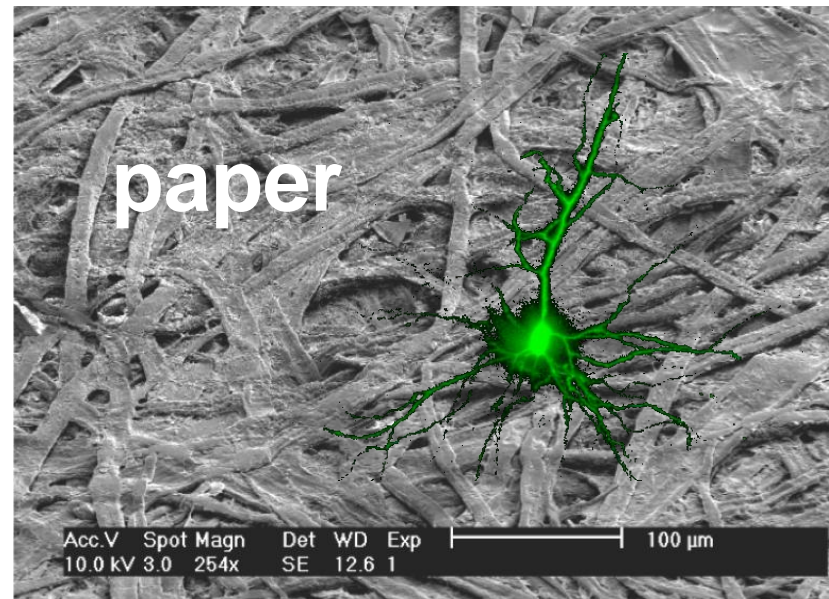






.5mm x .35 mm cotton paper

500 μ m

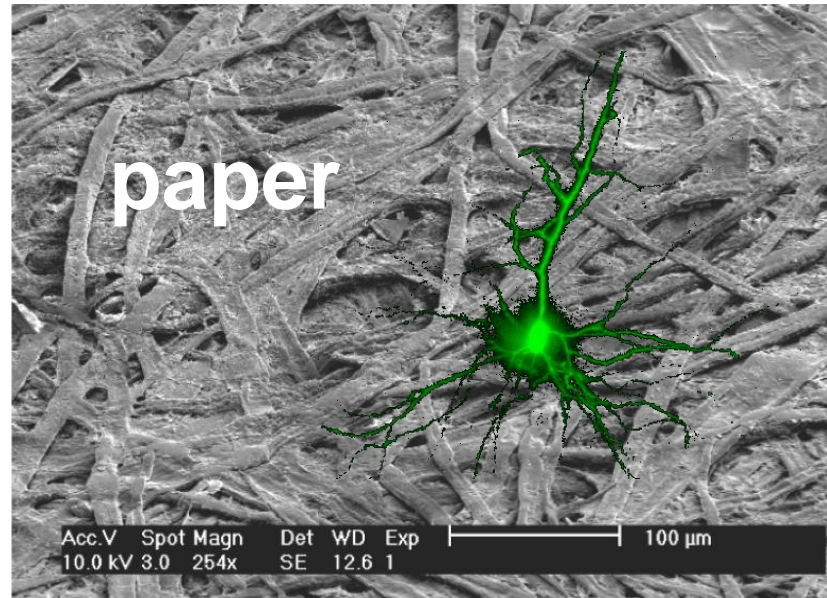


500 μ m

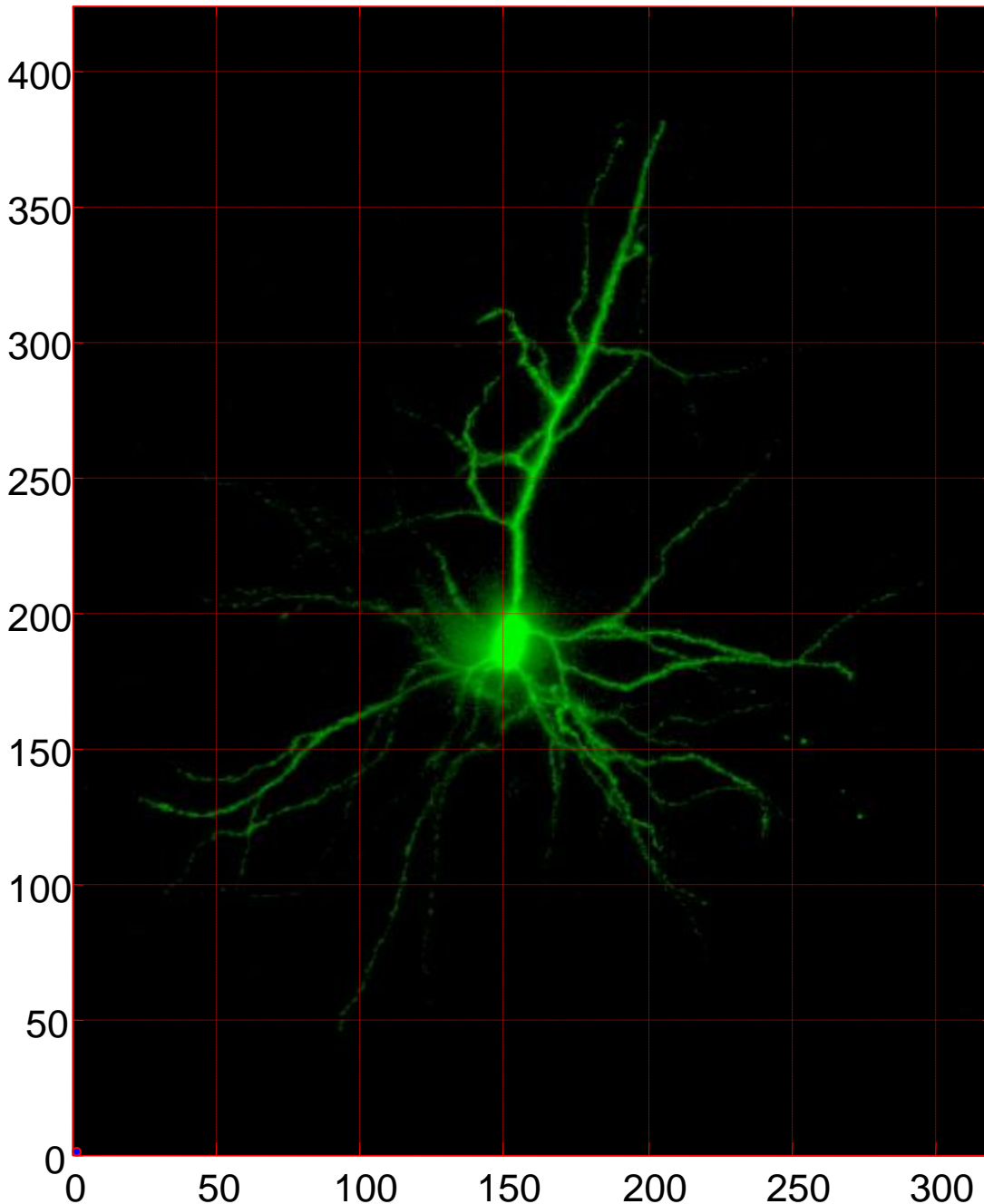
Paper



Fiber

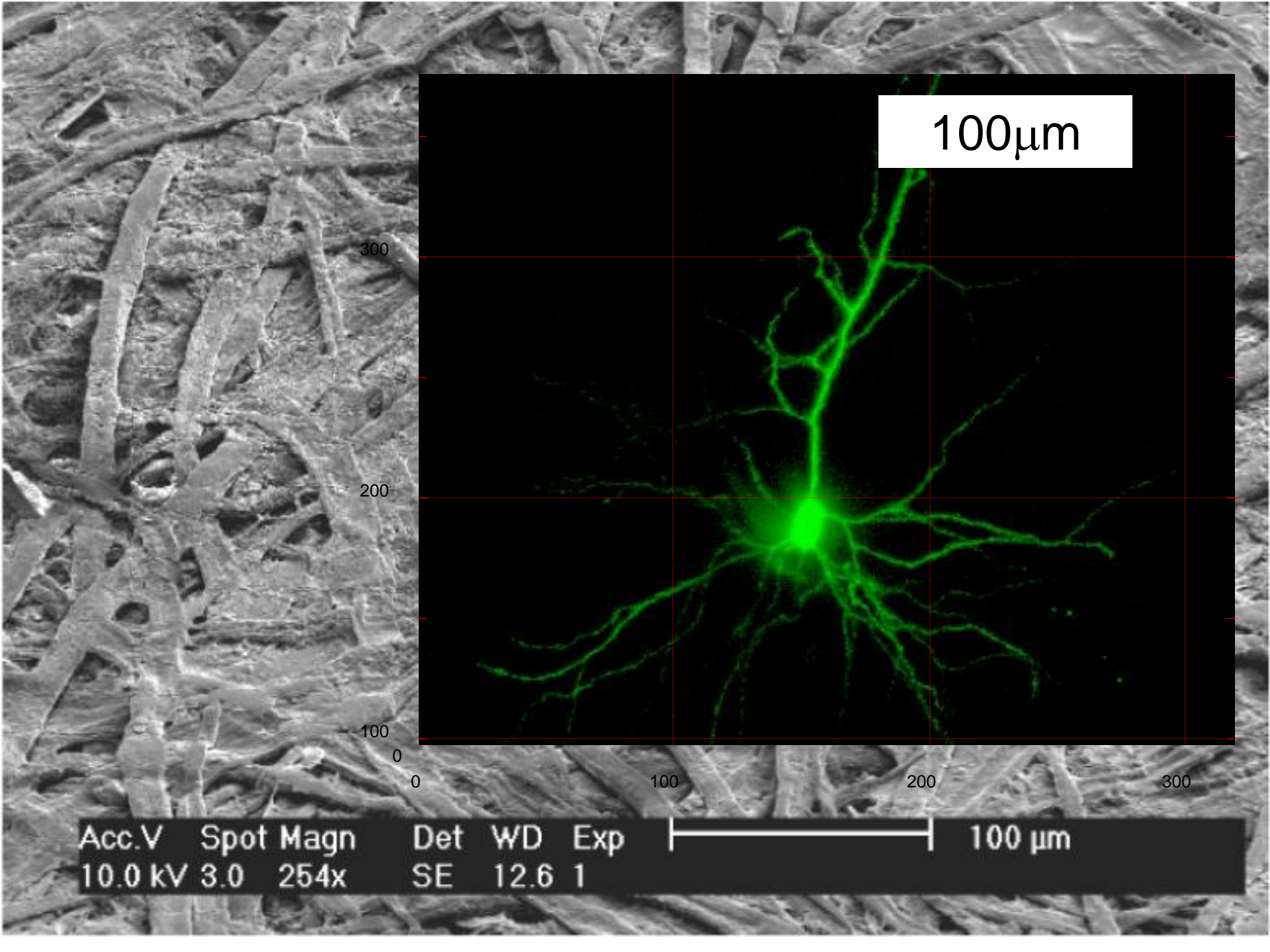


Minimal architecture



100 μ m

A neonatal rat
pyramidal neuron
filled with Lucifer Yellow
imaged on the BioRad
MRC600 confocal
microscope using a 20X oil
objective, NA=0.8. Image
size is 320 x 425 x 120 μ m.



100μm

Acc.V	Spot	Magn	Det	WD	Exp		
10.0 kV	3.0	254x	SE	12.6	1		100 μm

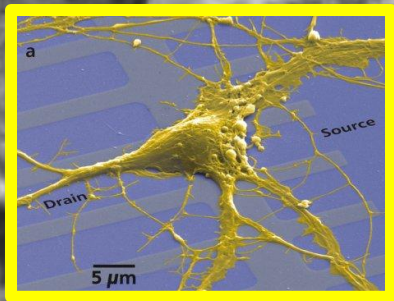
.5mm x .35 mm cotton paper

100 μ m

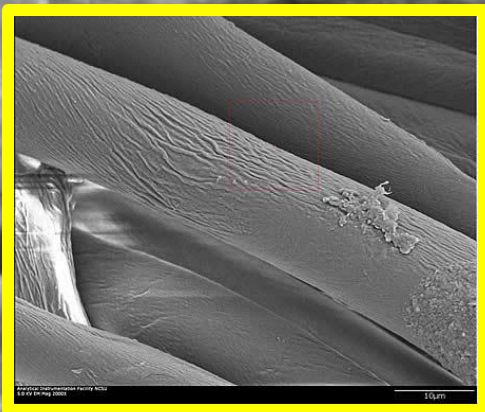
Acc.V	Spot	Magn	Det	WD	Exp
10.0 kV	3.0	254x	SE	12.6	1

100 μ m

.5mm x .35 mm cotton paper

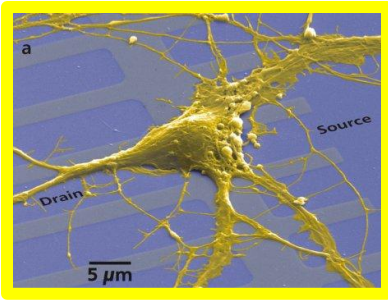


100 μm



EXP

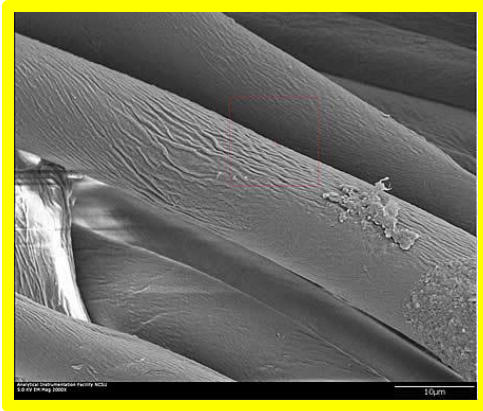
100 μm



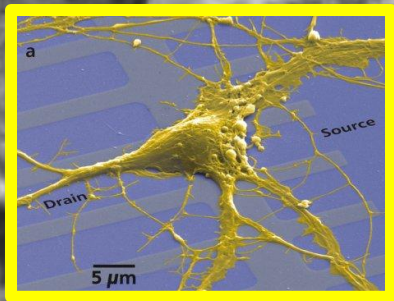
47x35 micron

100μm

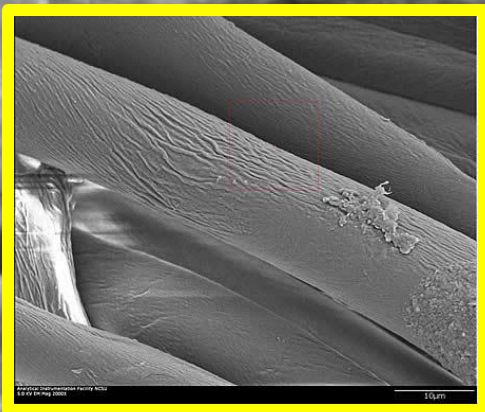
cotton fibers



60x50 microns



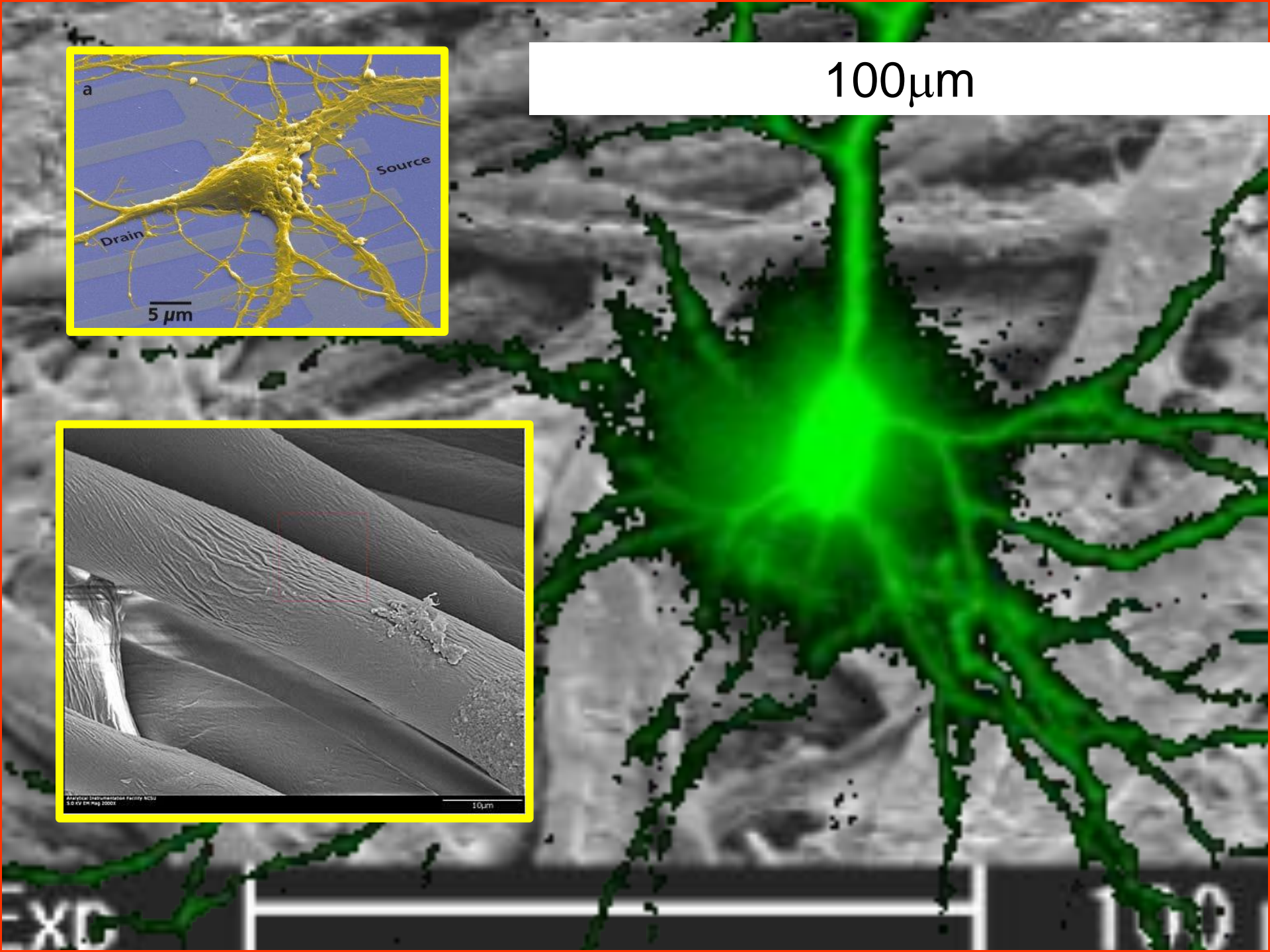
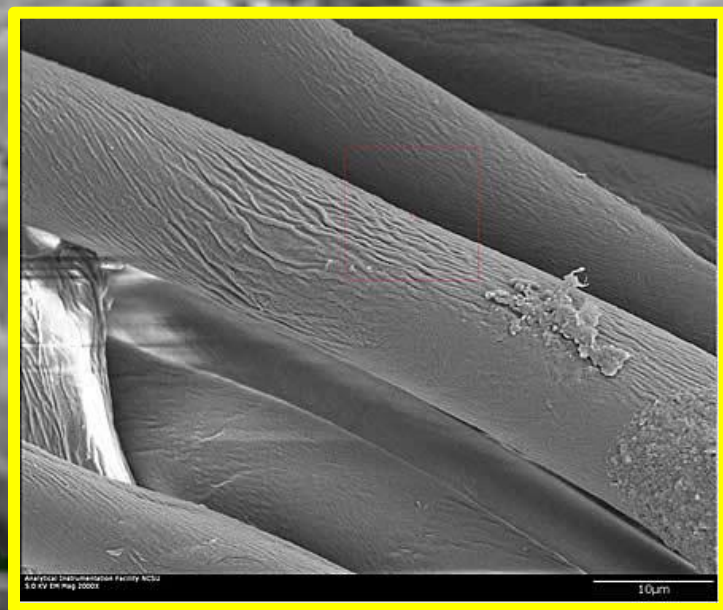
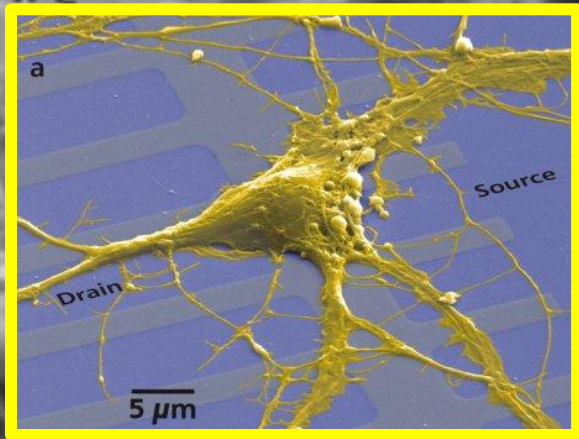
100 μm

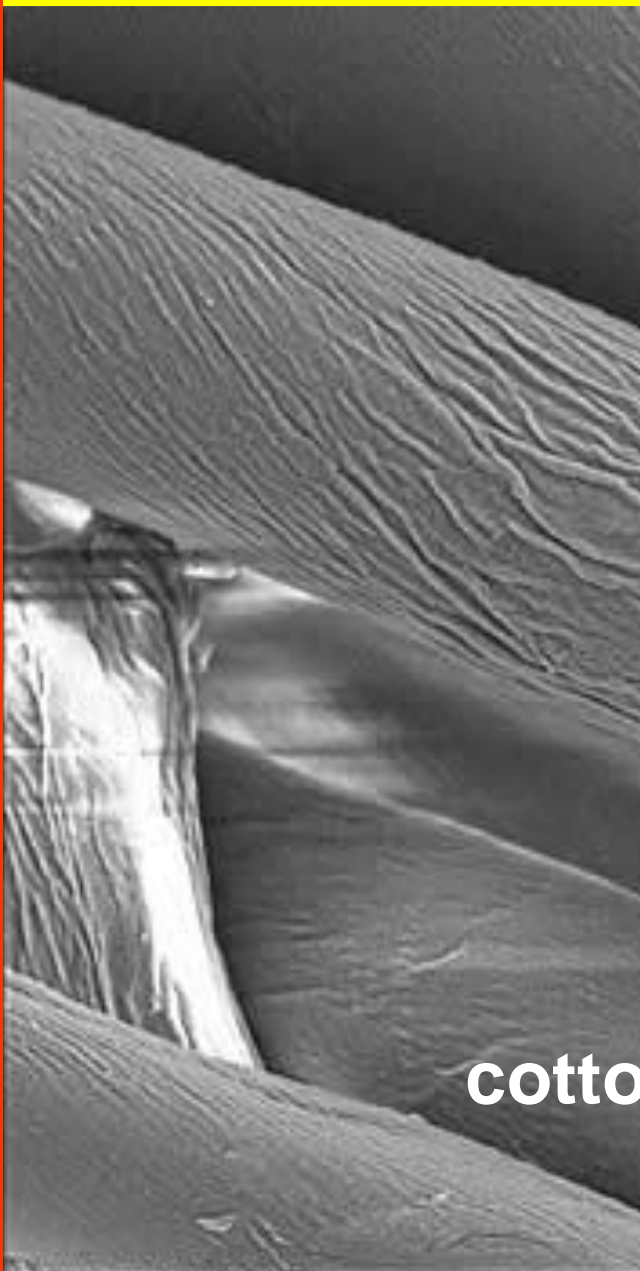


EXD

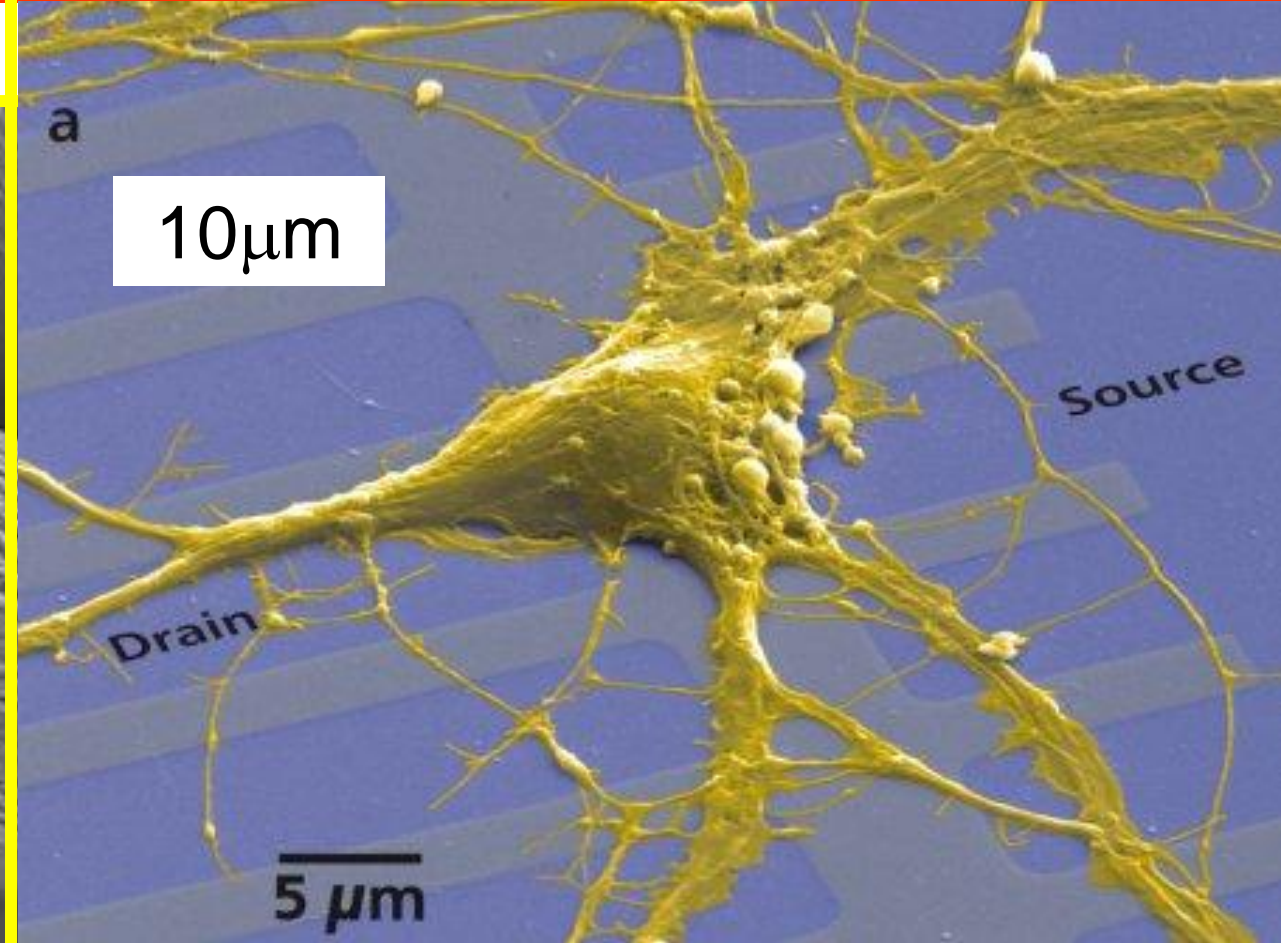
100 μm

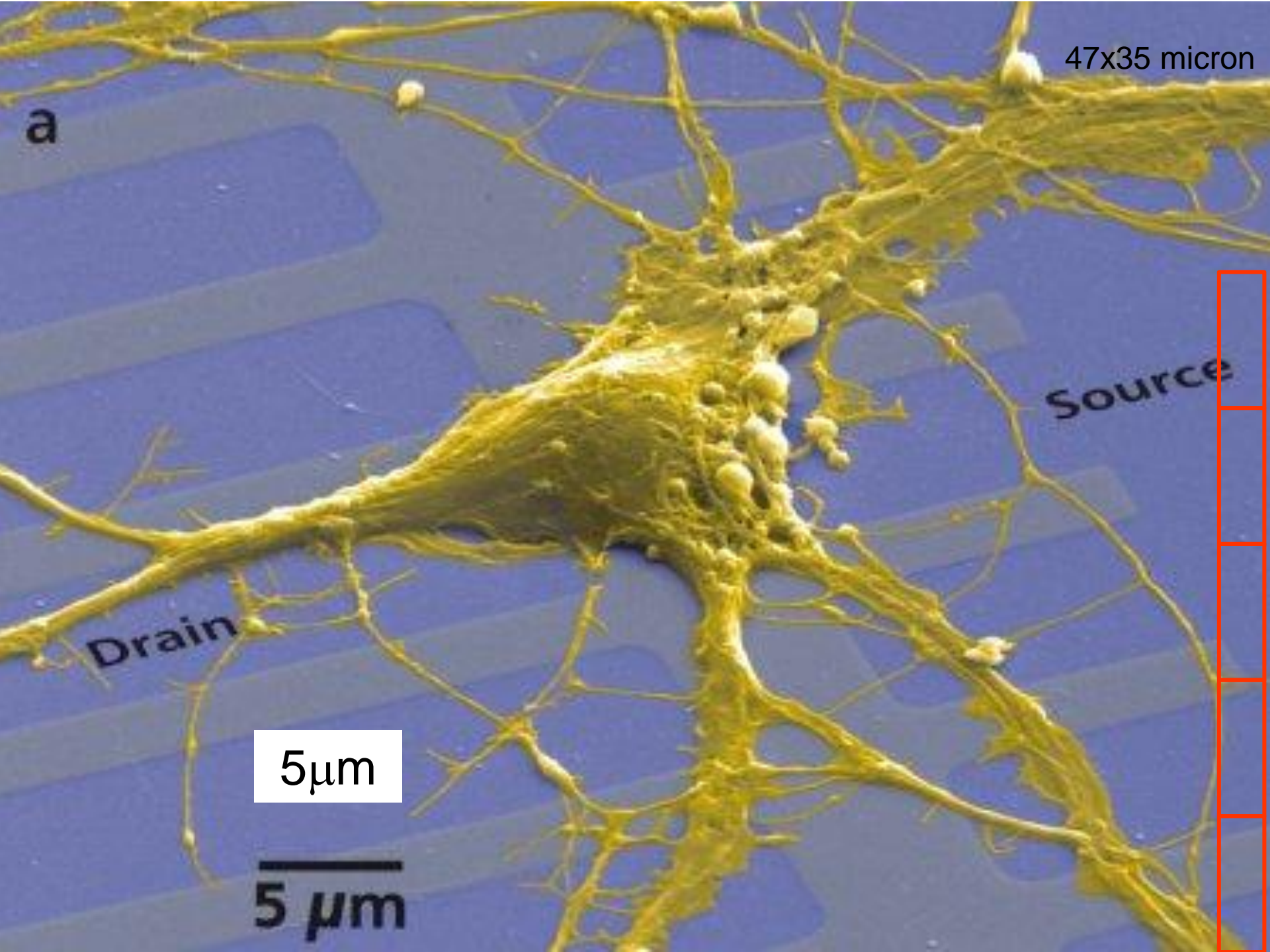
100μm





cotton fibers





47x35 micron

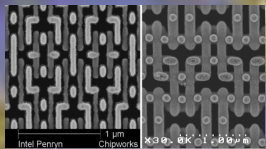
a

Source

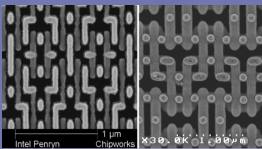
Drain

5 μm

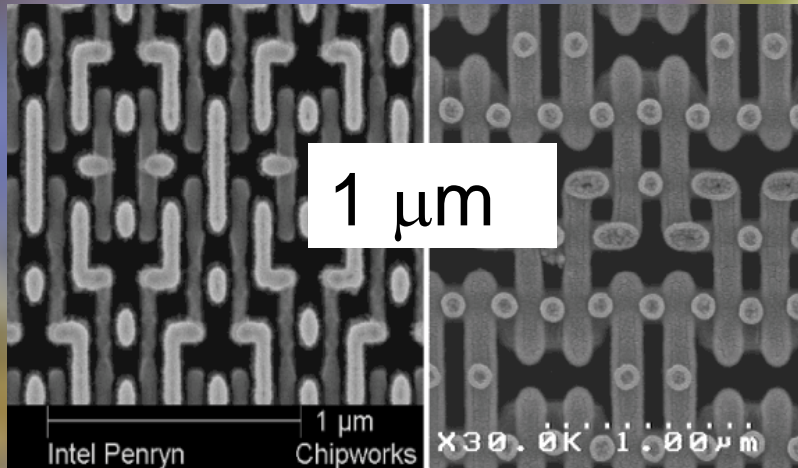
5 μm



5 μm

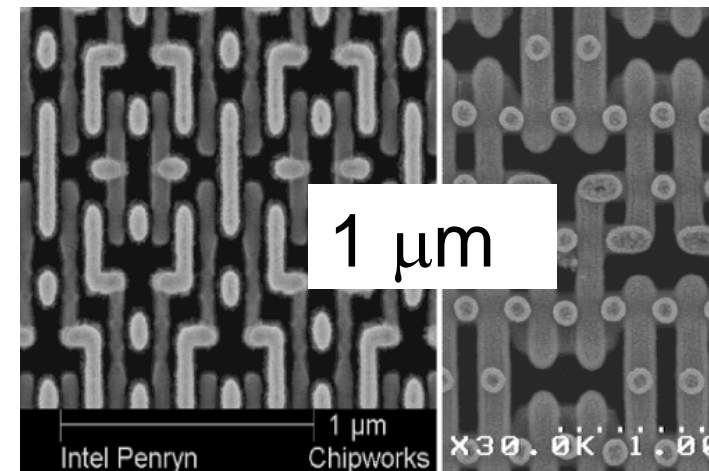
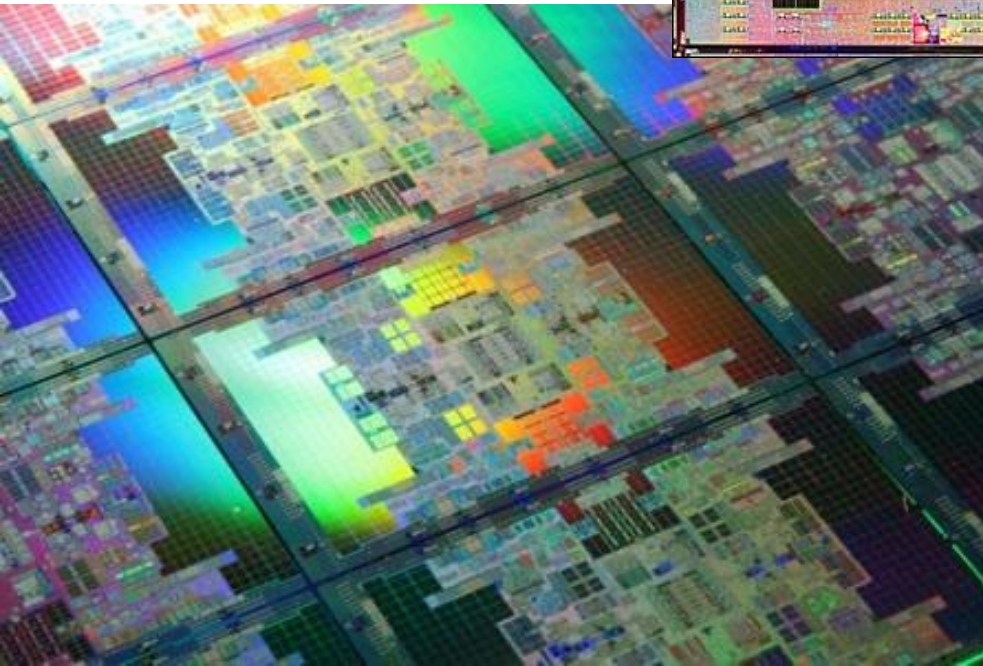
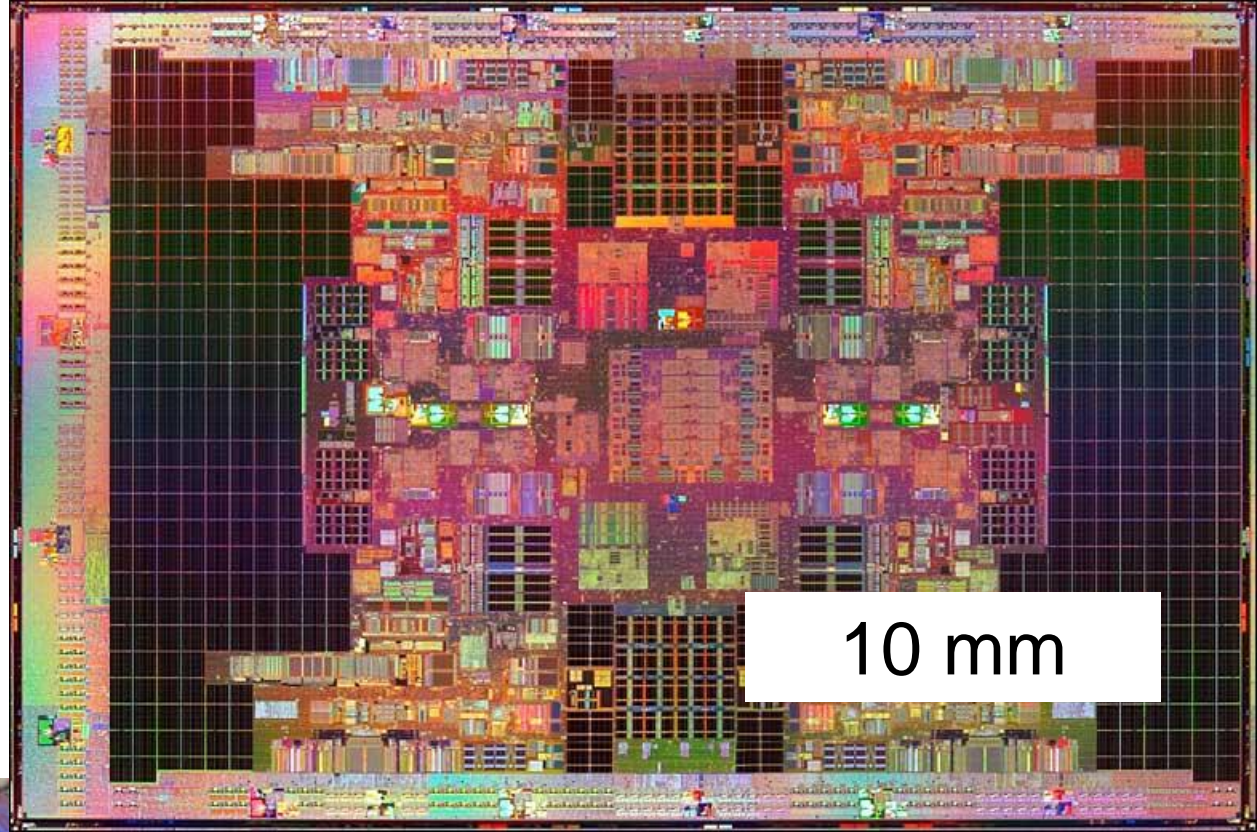


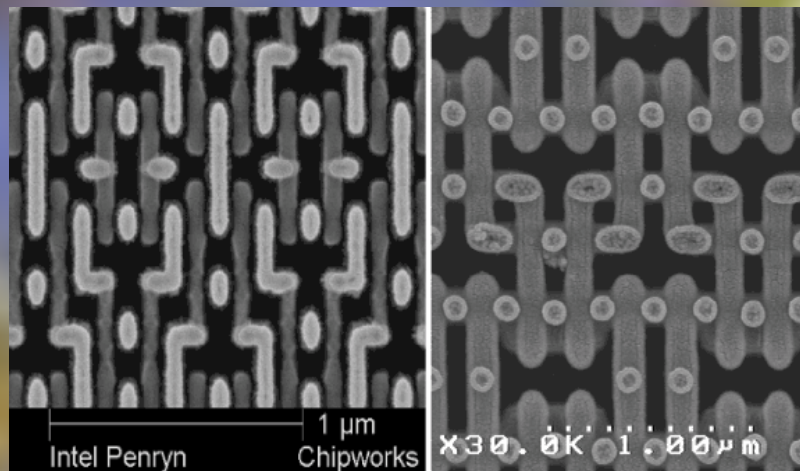
5 μm



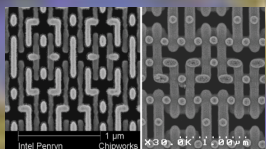
5 μm

**Intel Tukwila
quad core chip
with more than
2 billion
transistors**





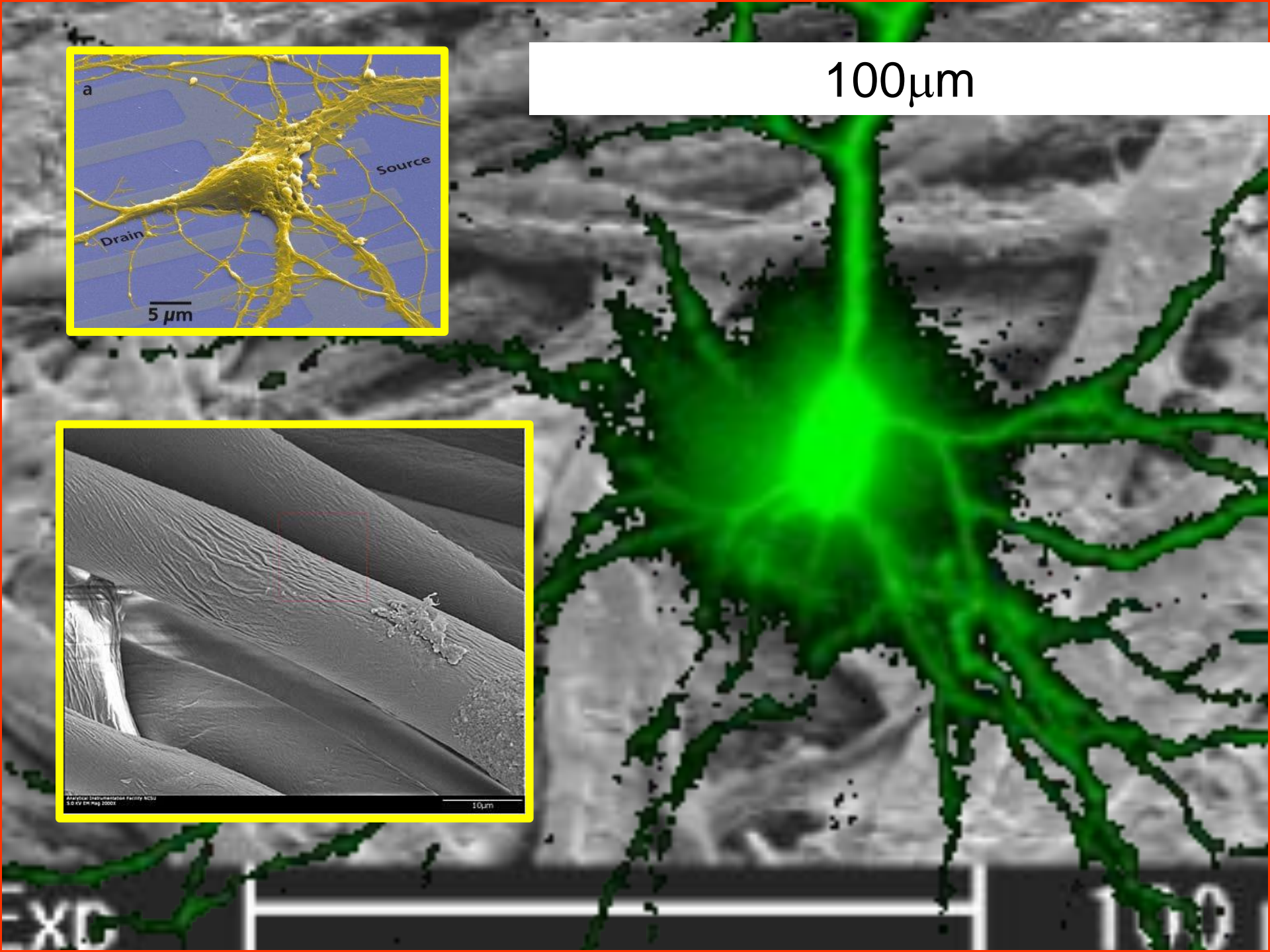
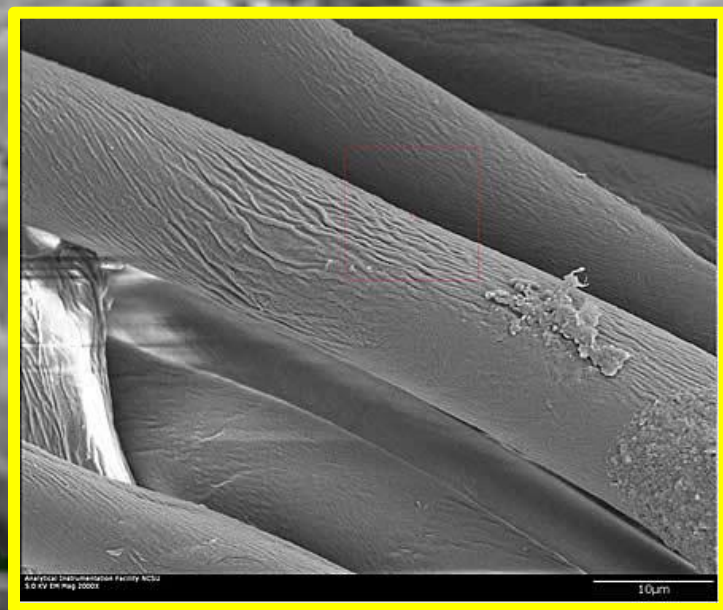
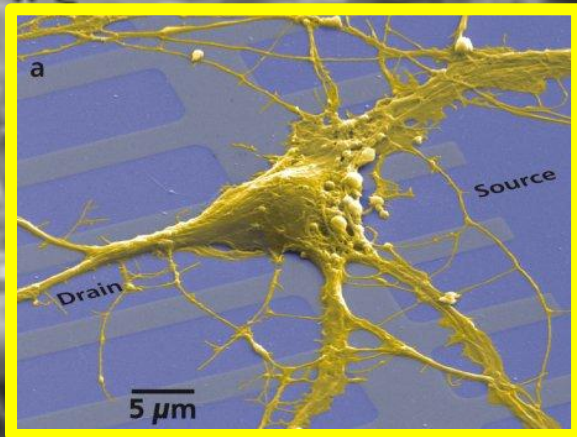
5 μm



5 μm

5 μm

100μm



.5mm x .35 mm cotton paper

100 μ m

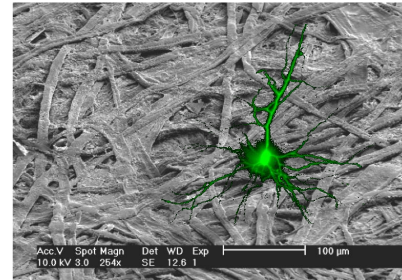
Acc.V	Spot	Magn	Det	WD	Exp
10.0 kV	3.0	254x	SE	12.6	1

100 μ m

.5mm x .35 mm cotton paper

500 μ m

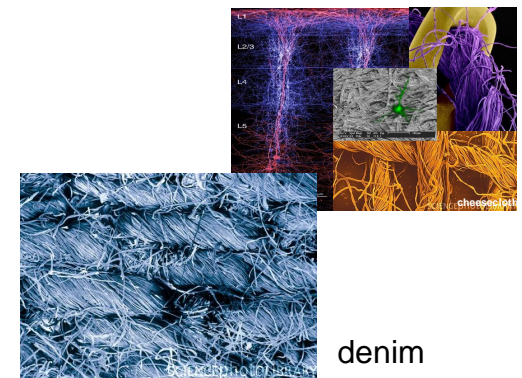
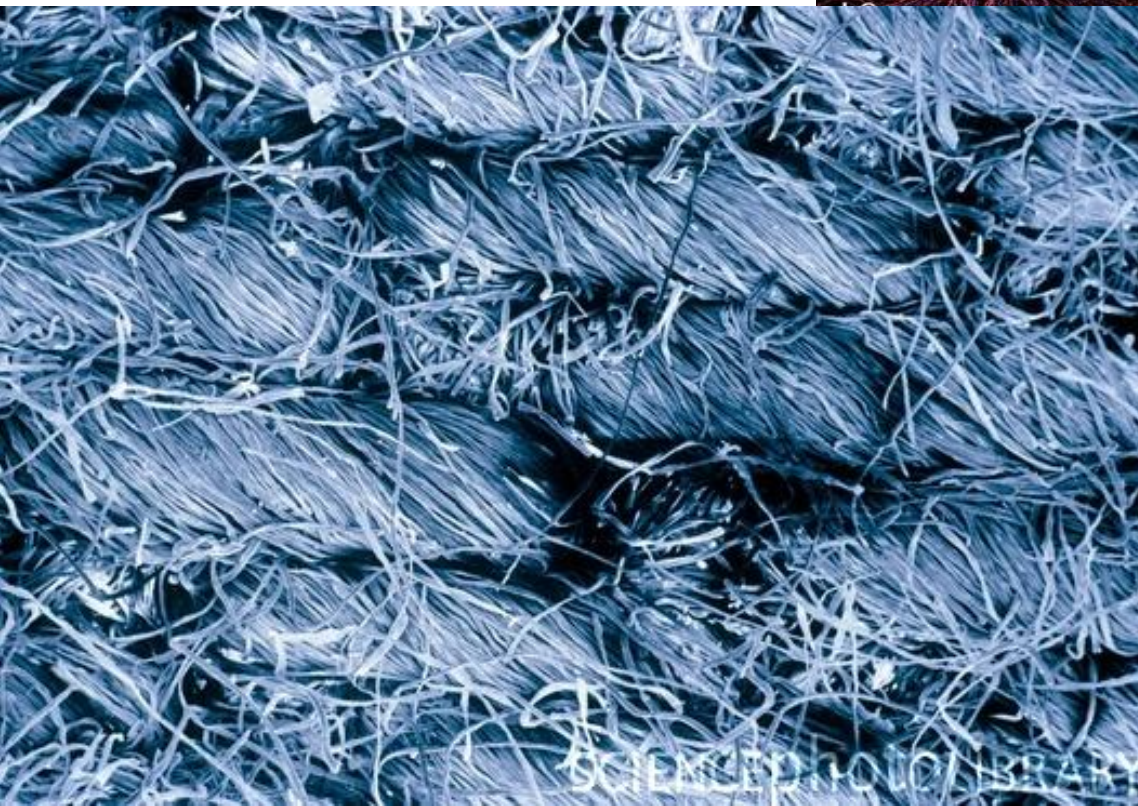
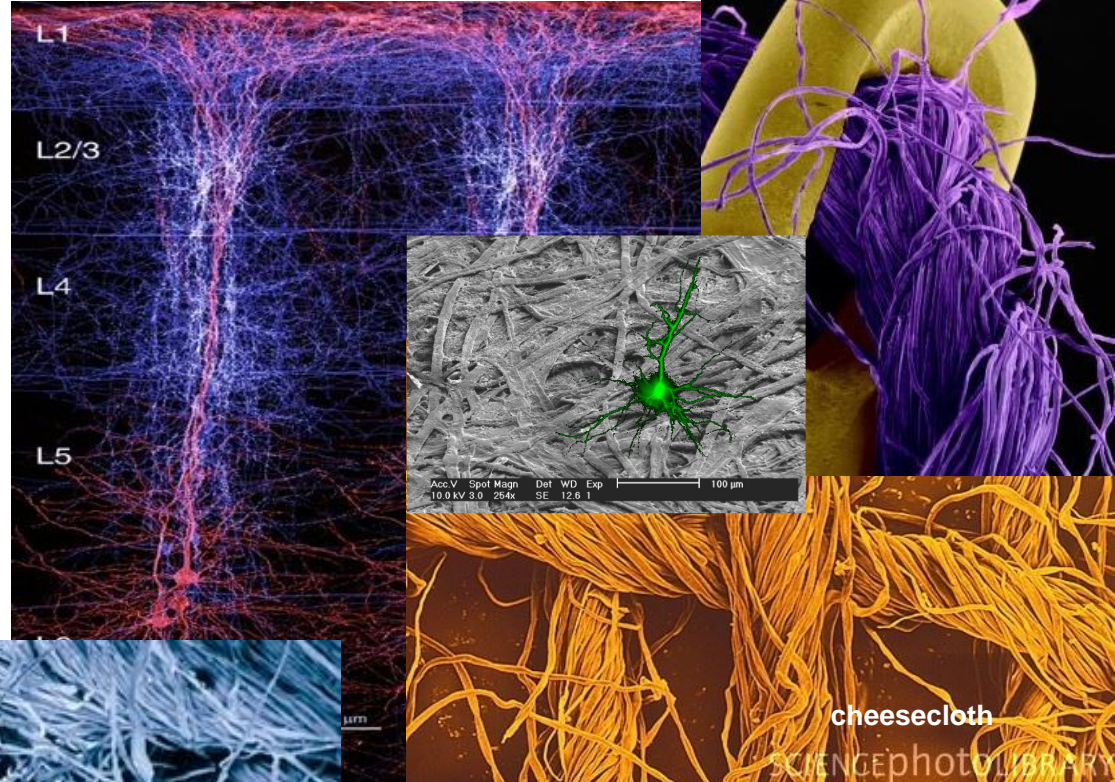
.5mm



500 μ m

.5mm

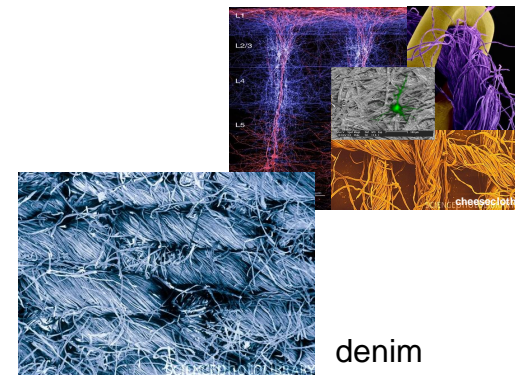
denim





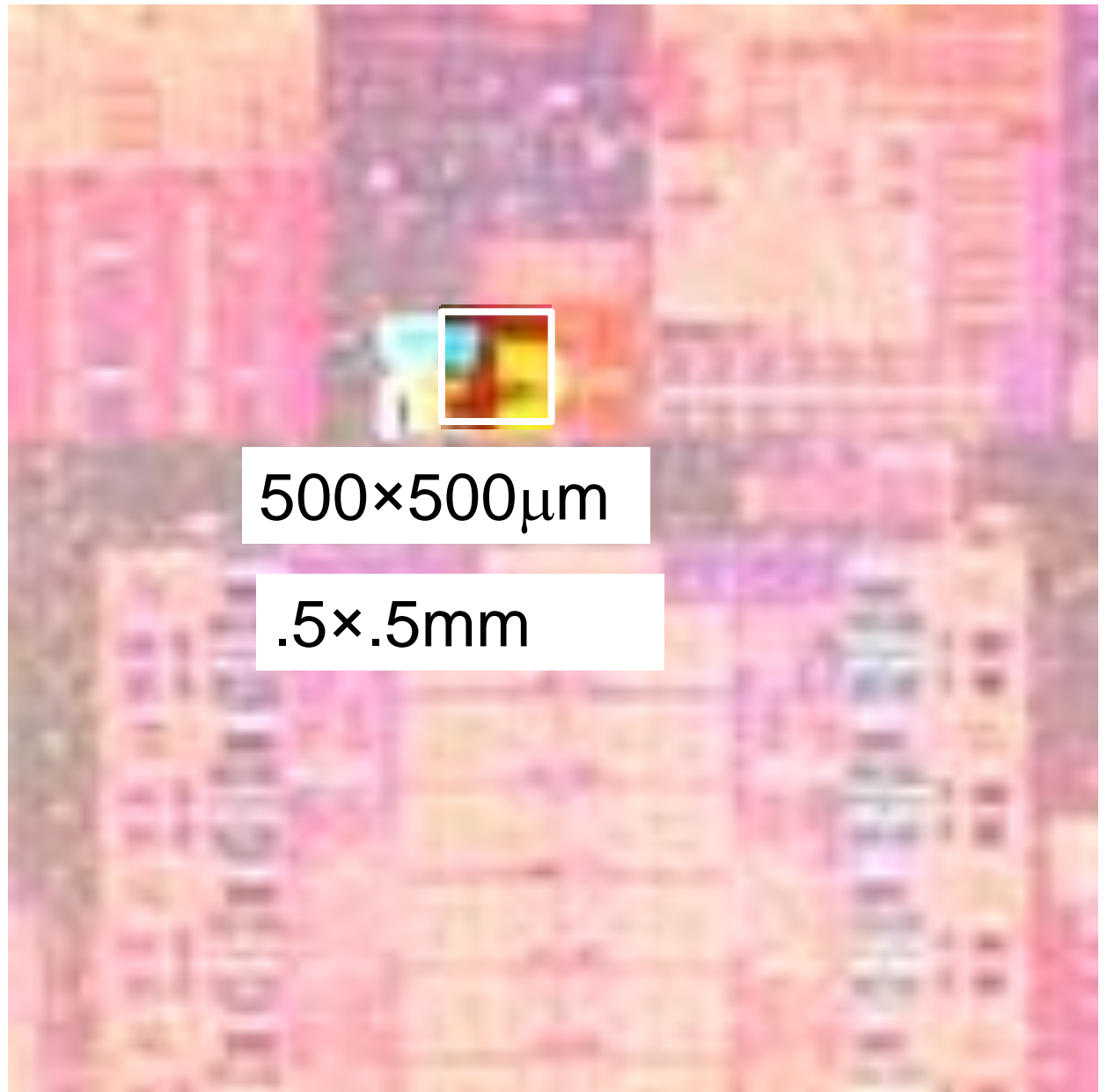
$500 \times 500 \mu\text{m}$

$.5 \times .5 \text{mm}$



denim

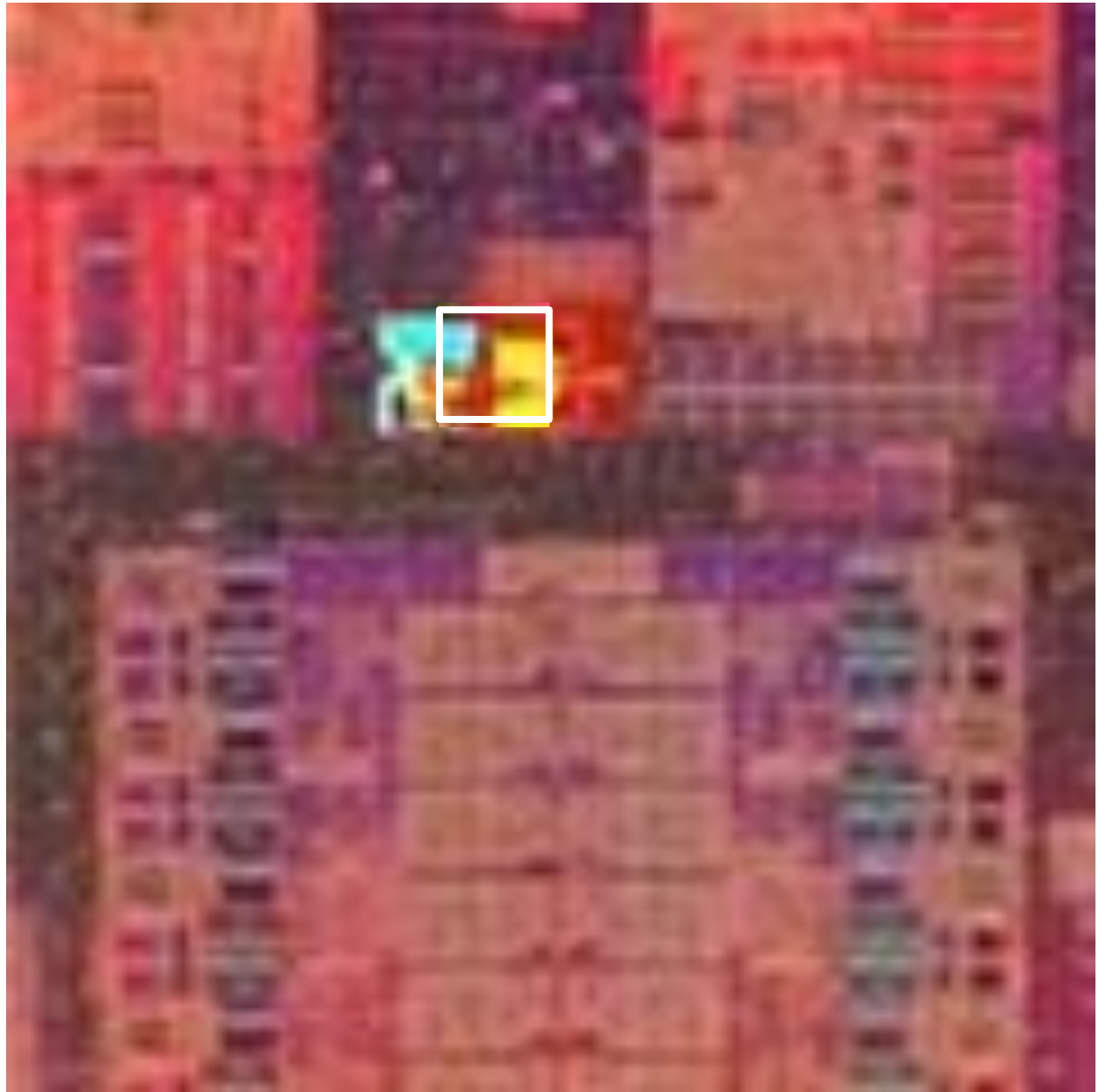
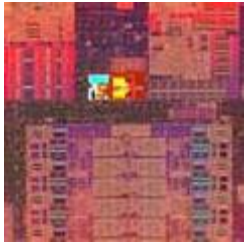
$5 \times 5 \text{ mm}$



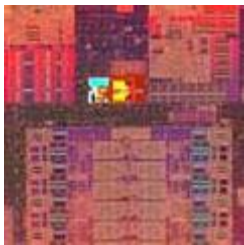
$500 \times 500 \mu\text{m}$

$.5 \times .5 \text{ mm}$

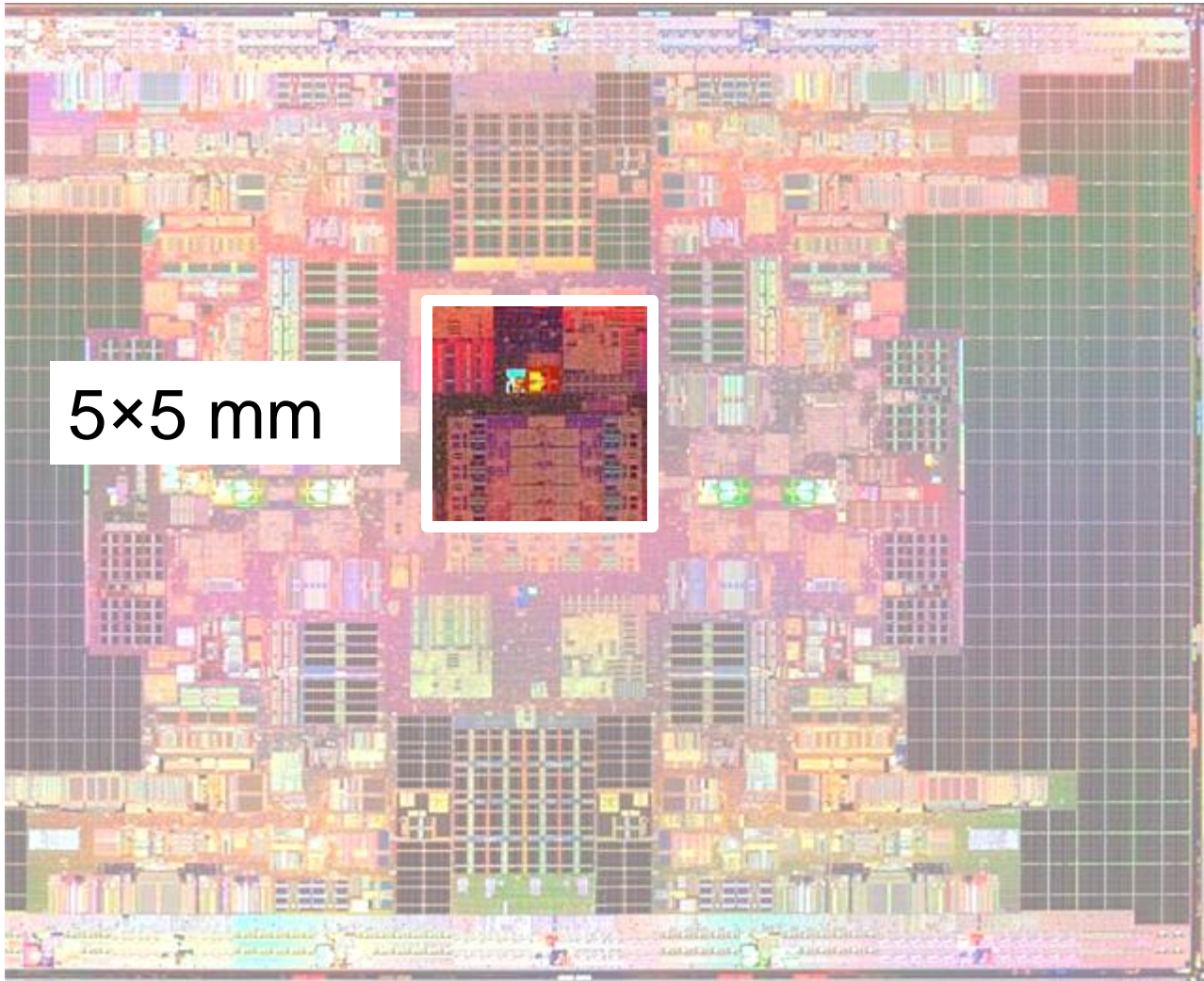
5×5 mm

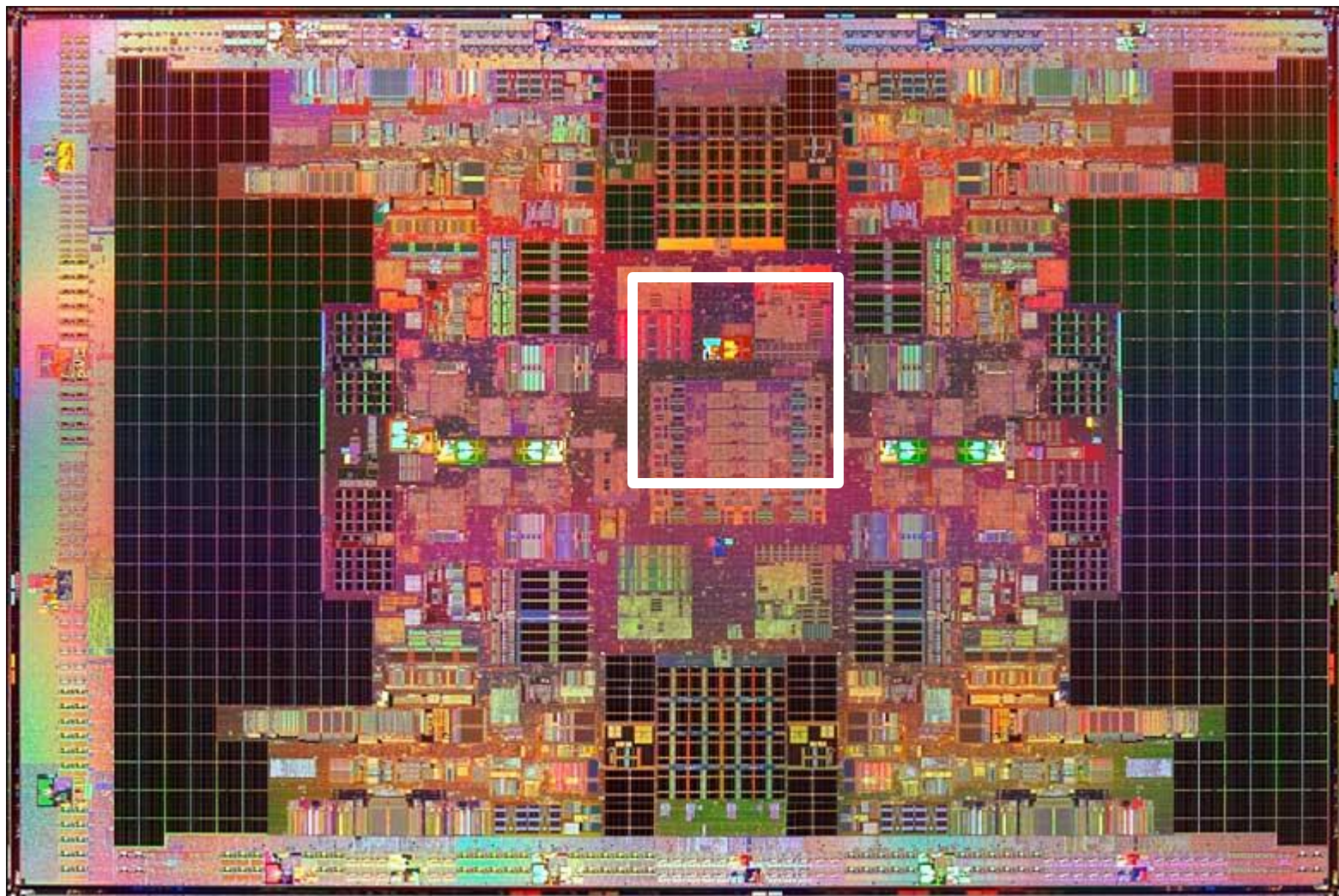


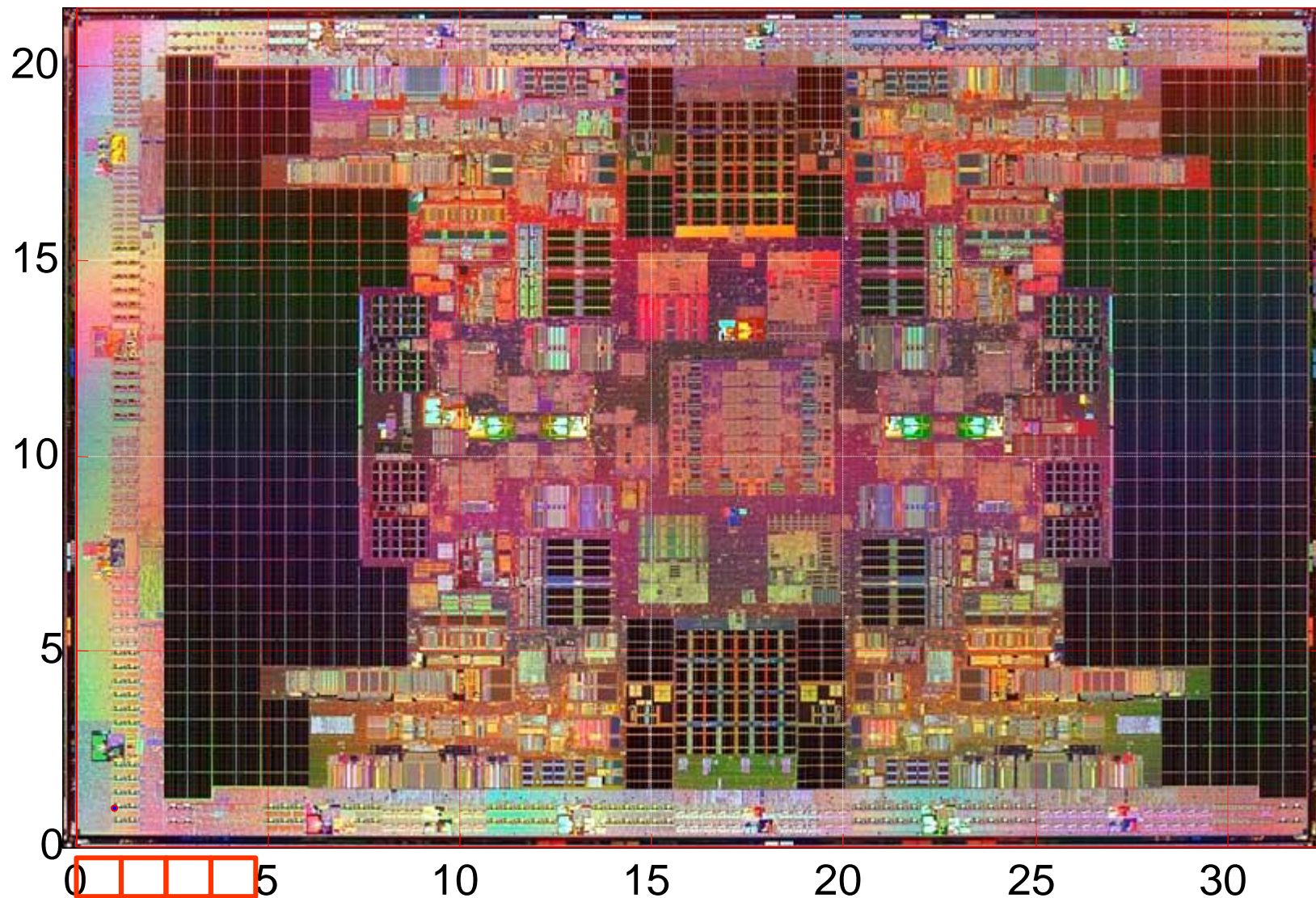
5×5 mm



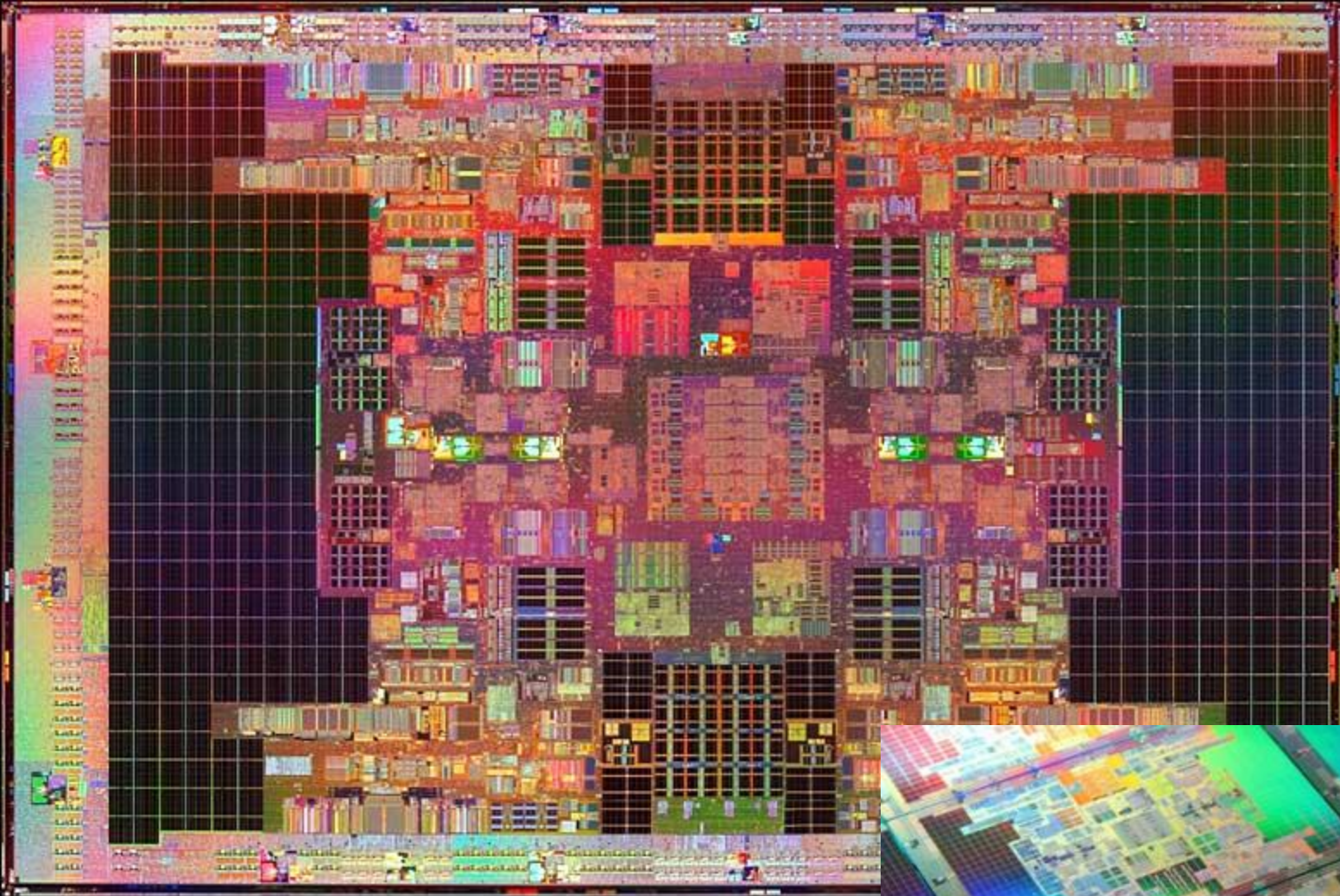
5×5 mm





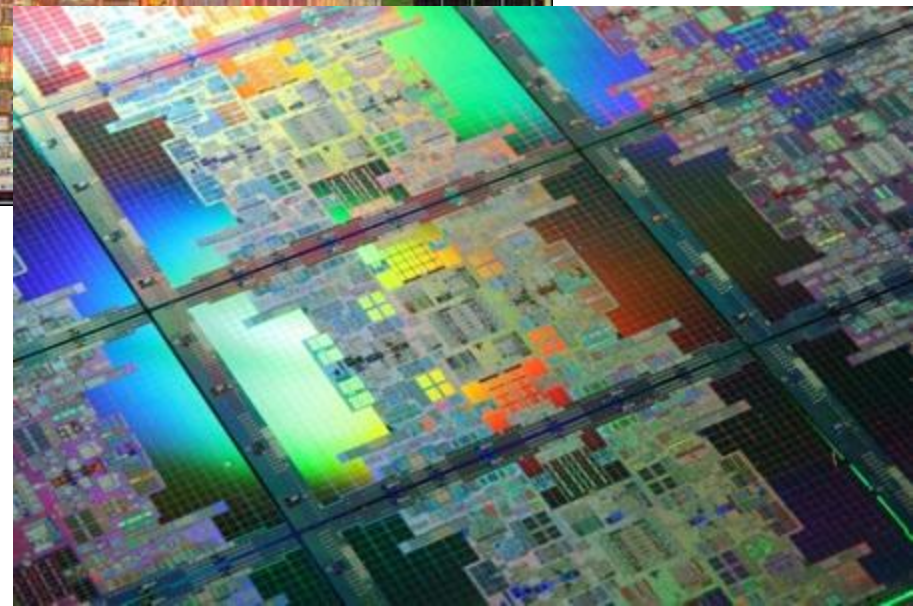


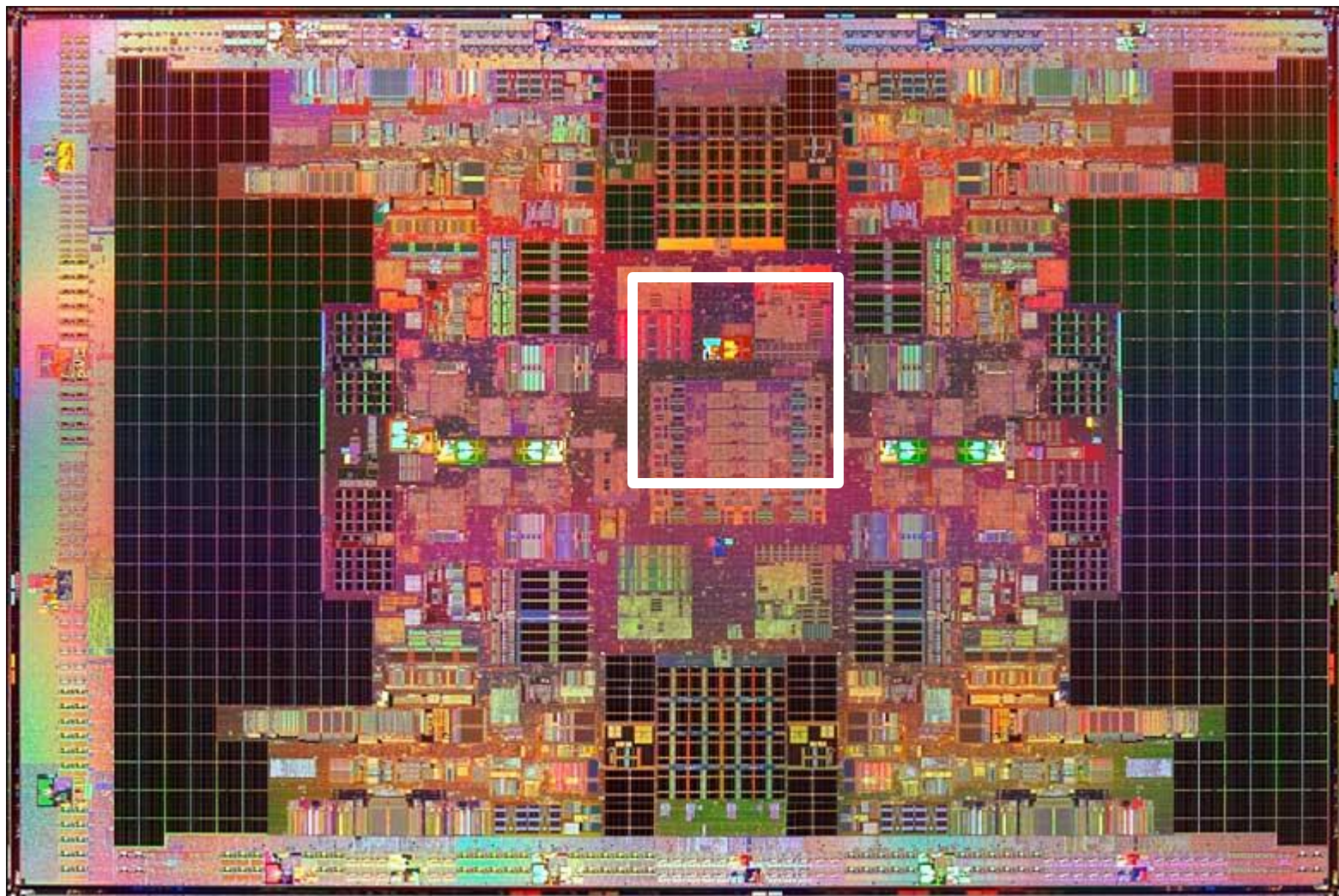
21.5×32.5 mm



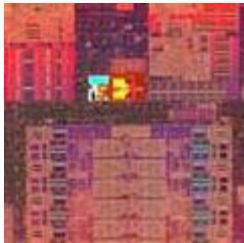
**Intel Tukwila quad core chip with
more than 2 billion transistors**

21.5×32.5 mm

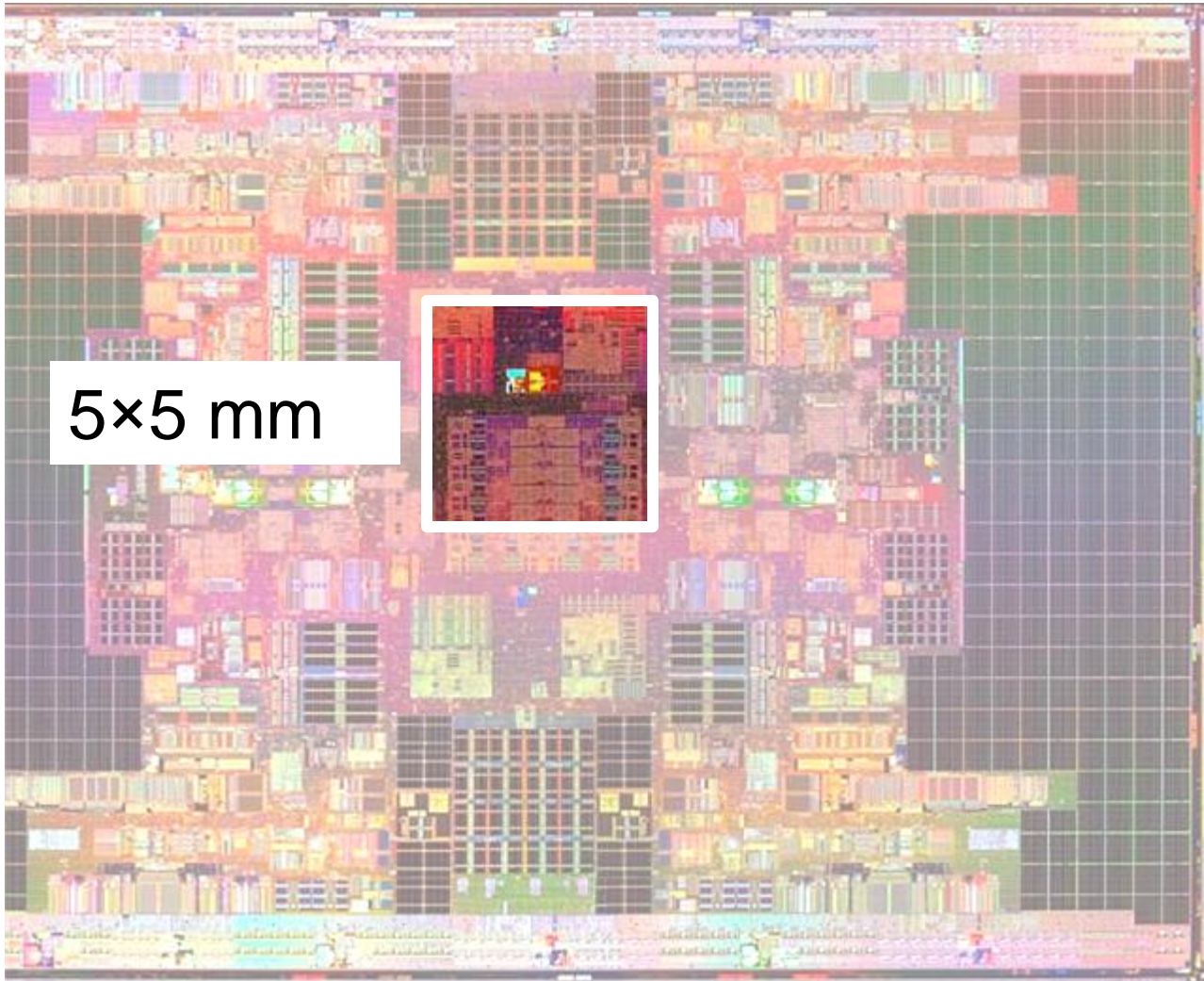
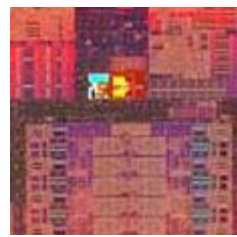




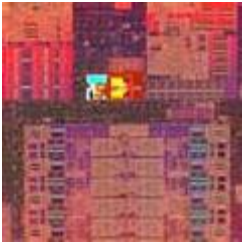
5×5 mm



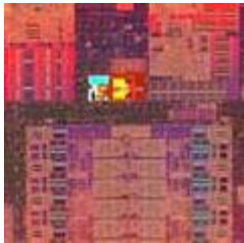
5×5 mm



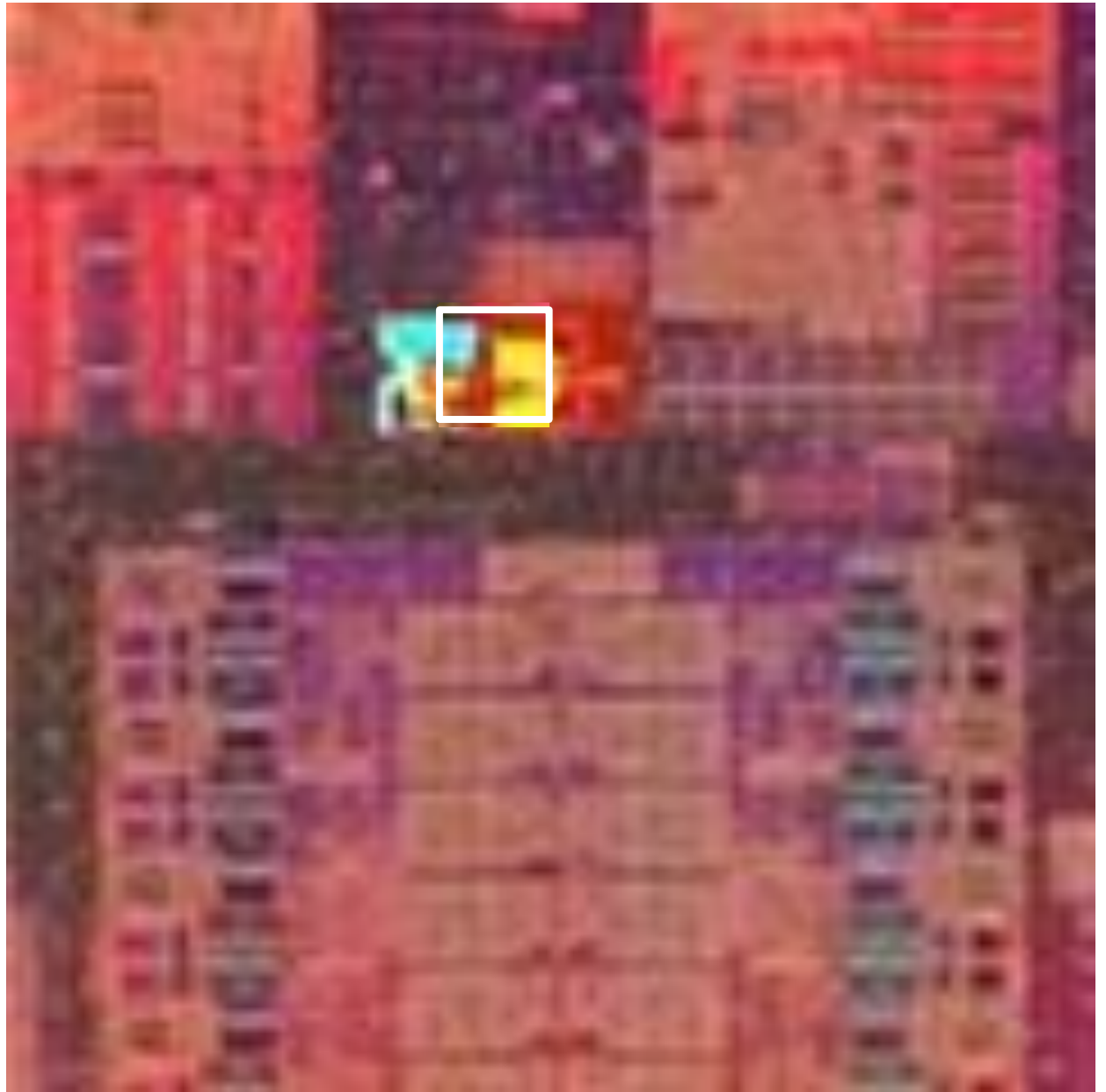
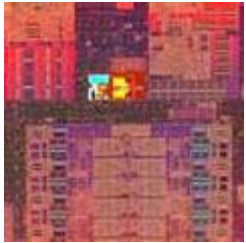
5×5 mm



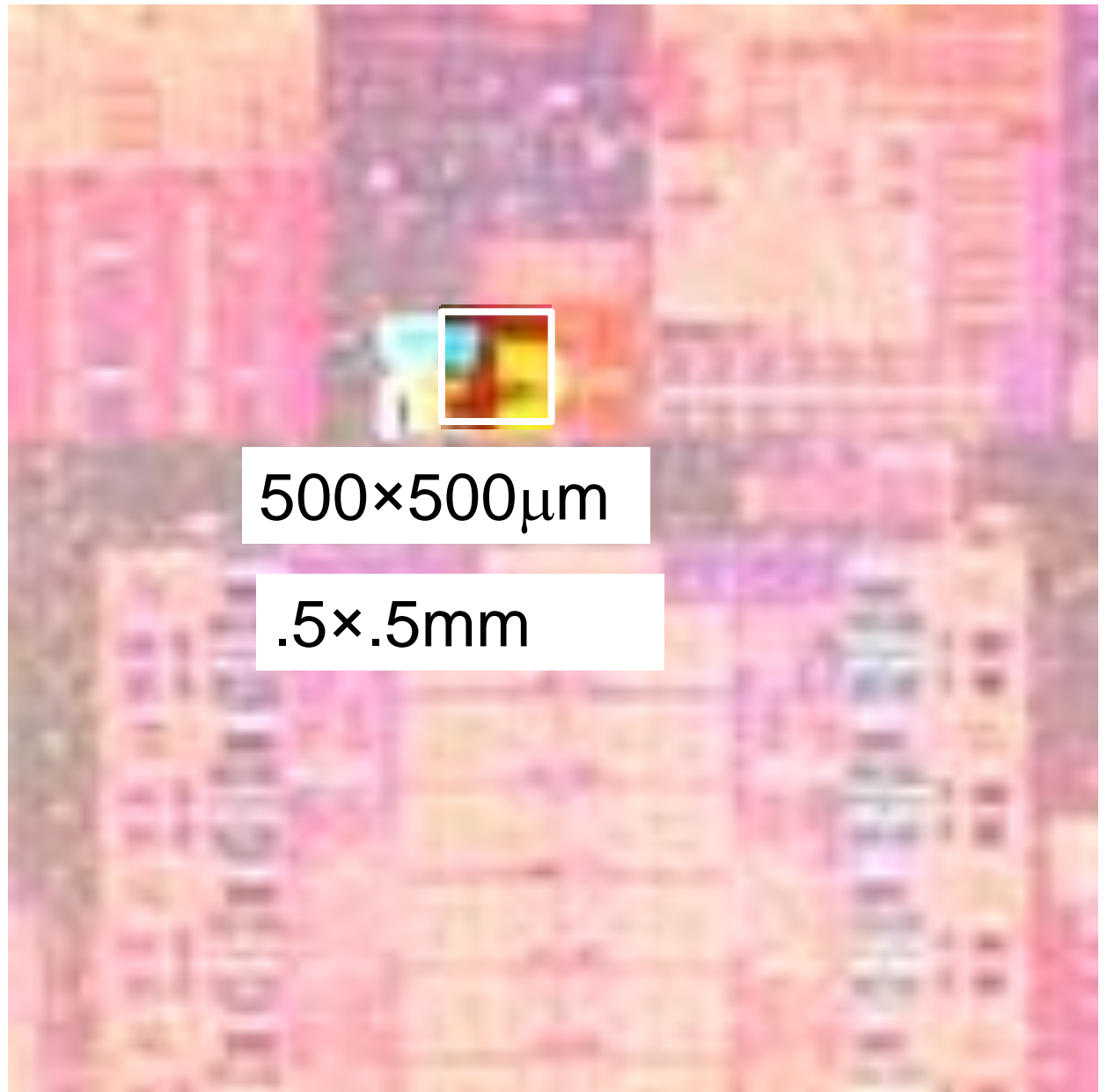
5×5 mm



5×5 mm



$5 \times 5 \text{ mm}$



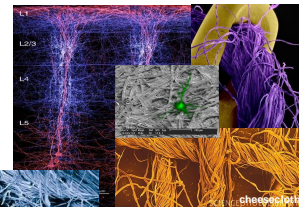
$500 \times 500 \mu\text{m}$

$.5 \times .5 \text{ mm}$



$500 \times 500 \mu\text{m}$

$.5 \times .5 \text{mm}$

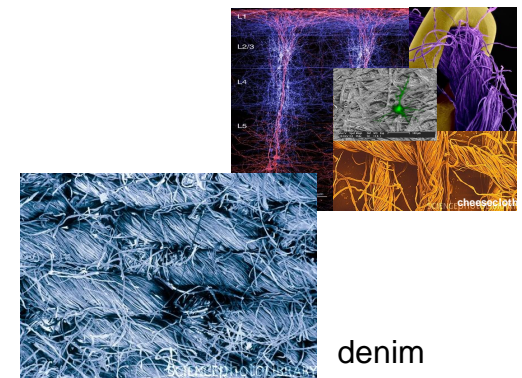
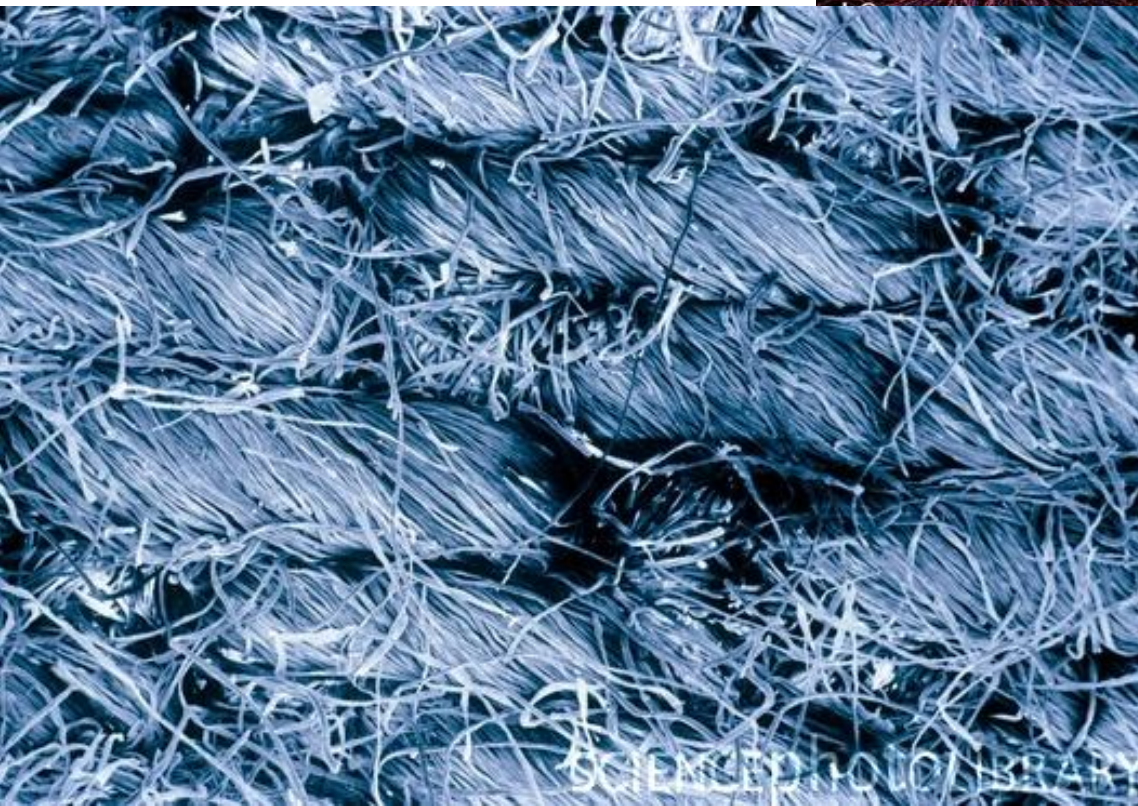
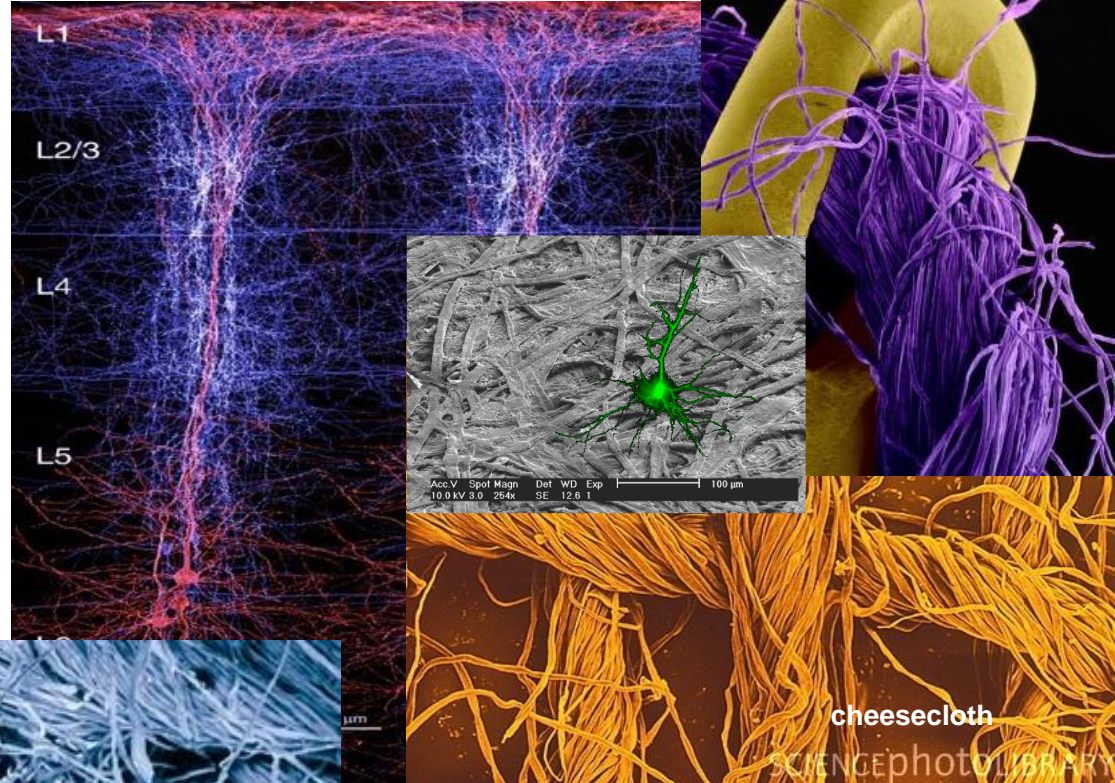


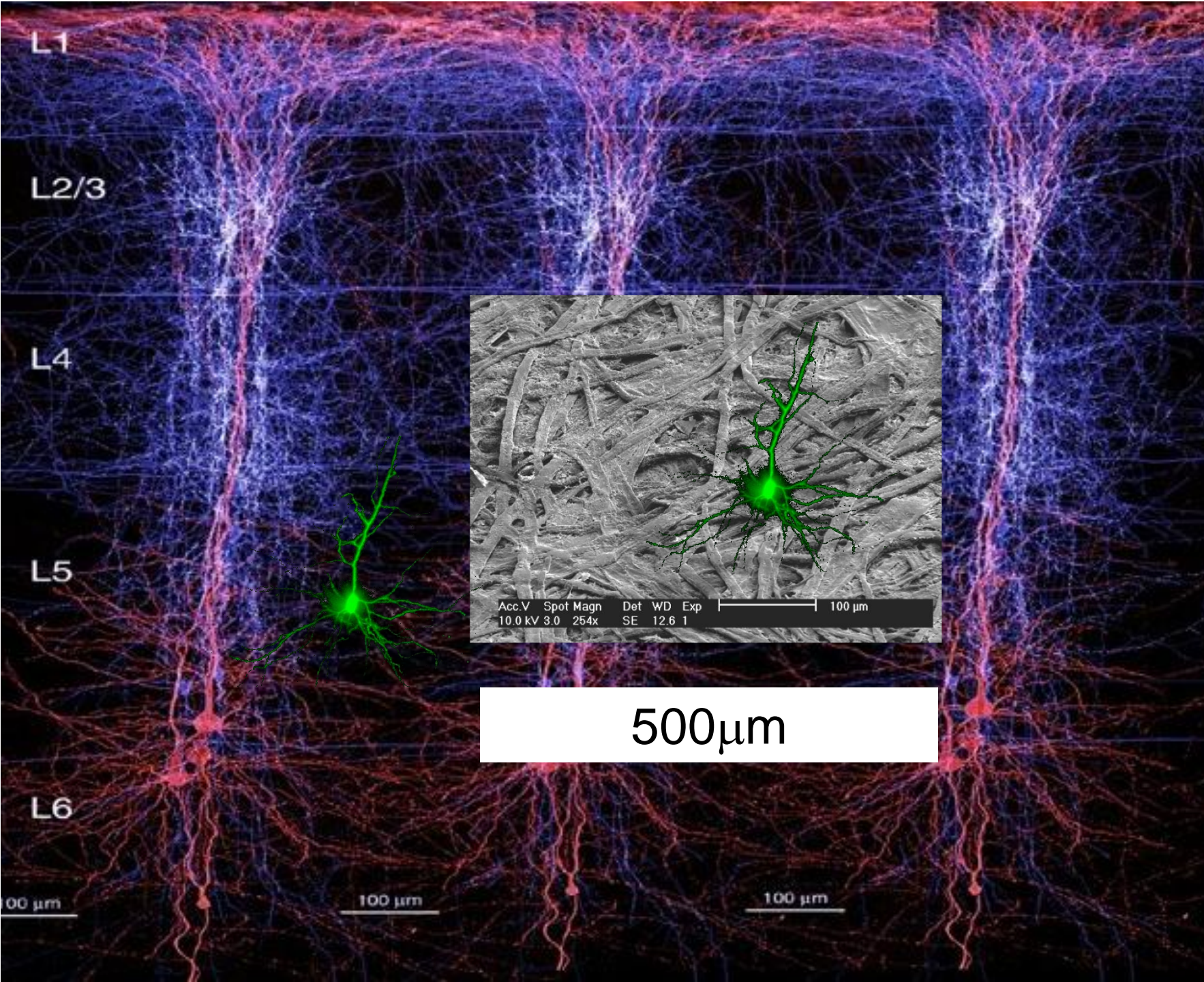
denim

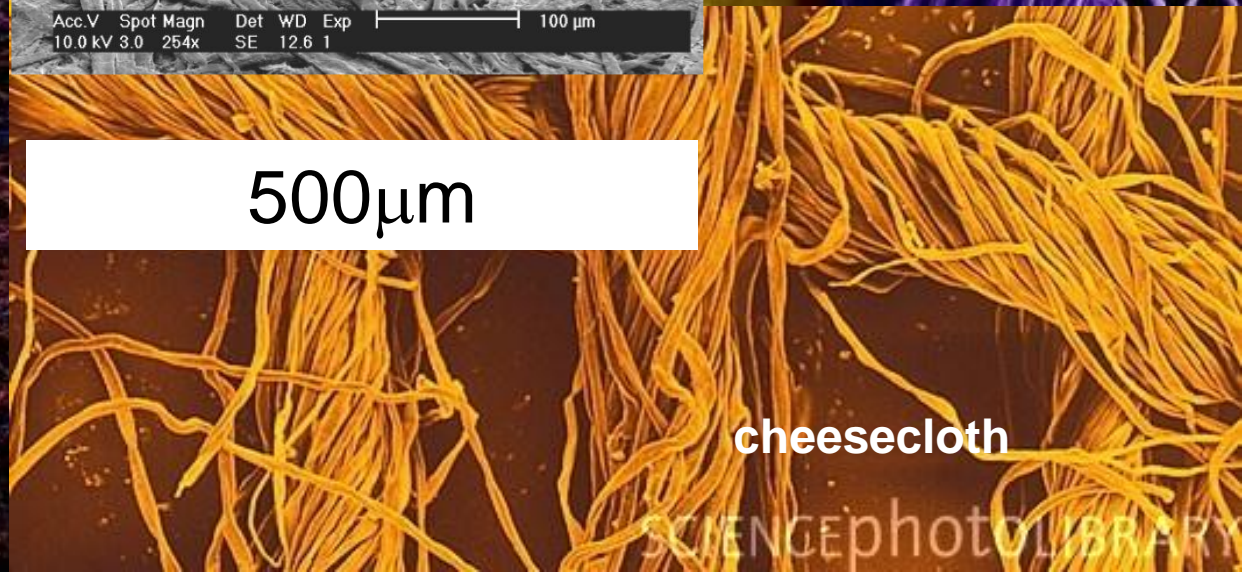
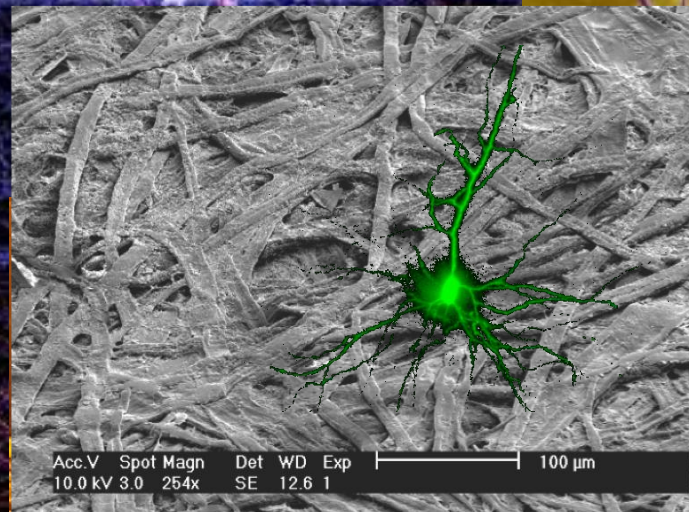
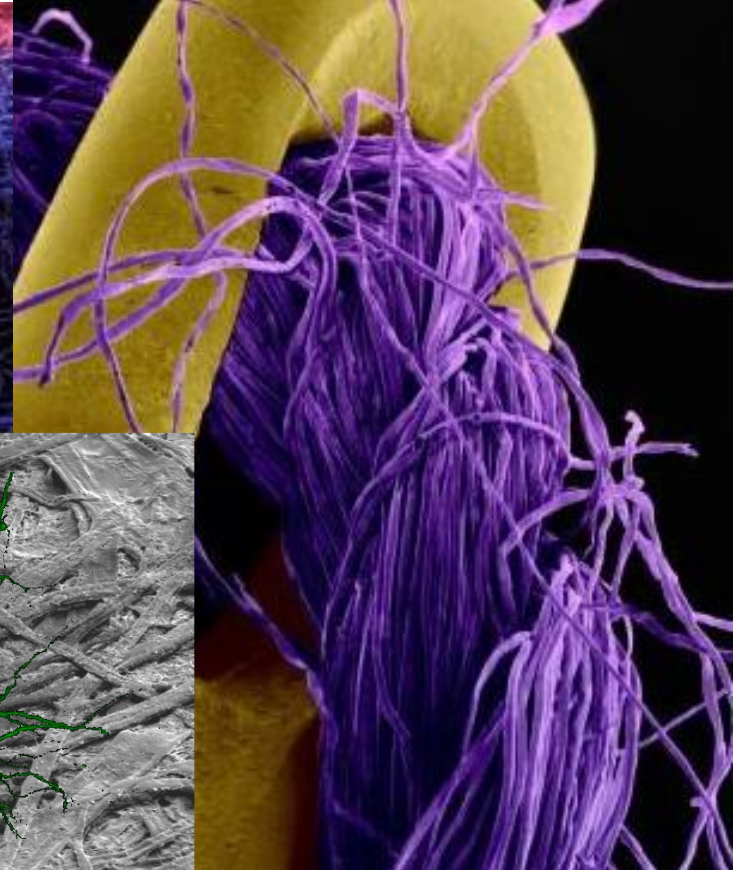
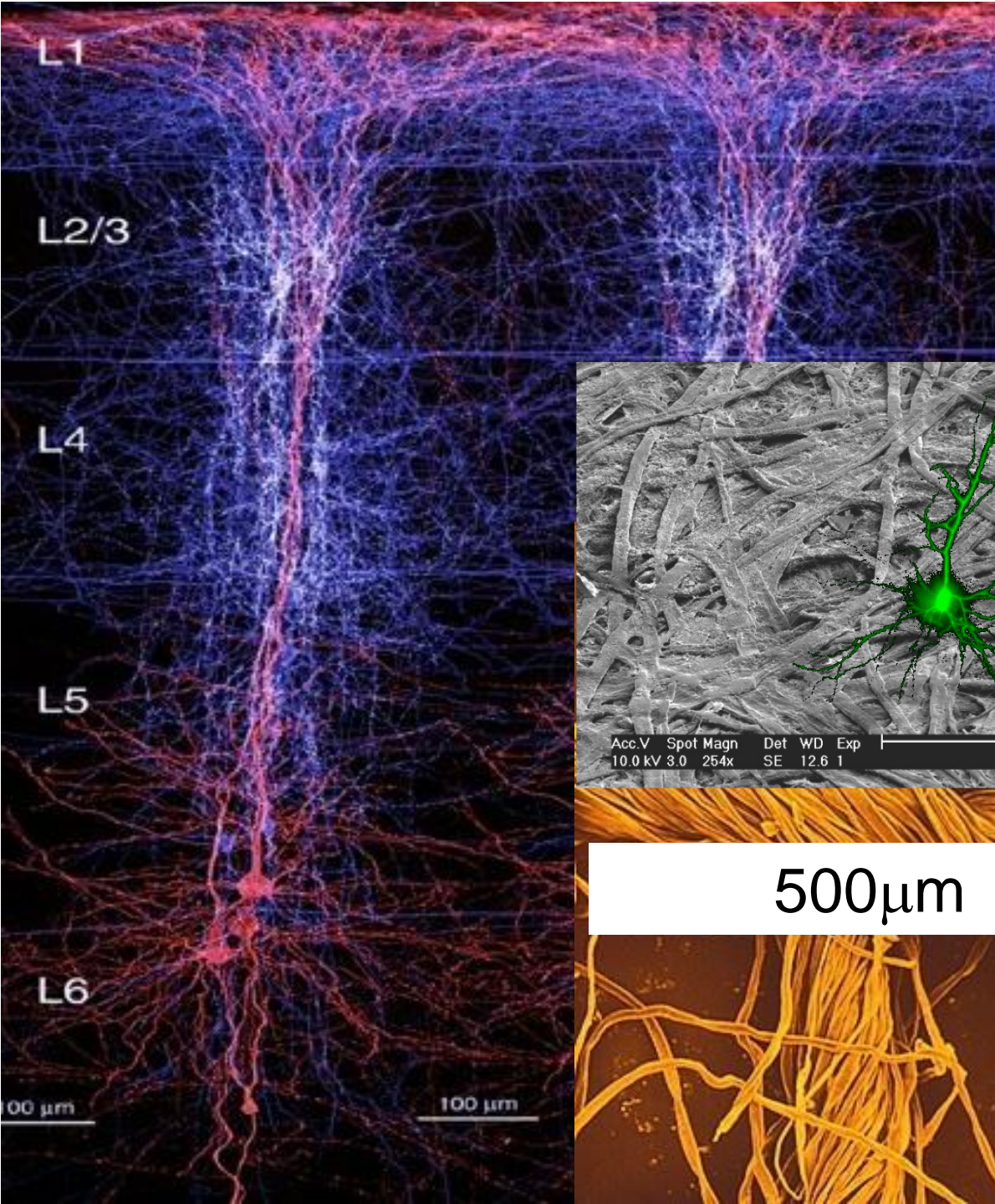
500 μ m

.5mm

denim

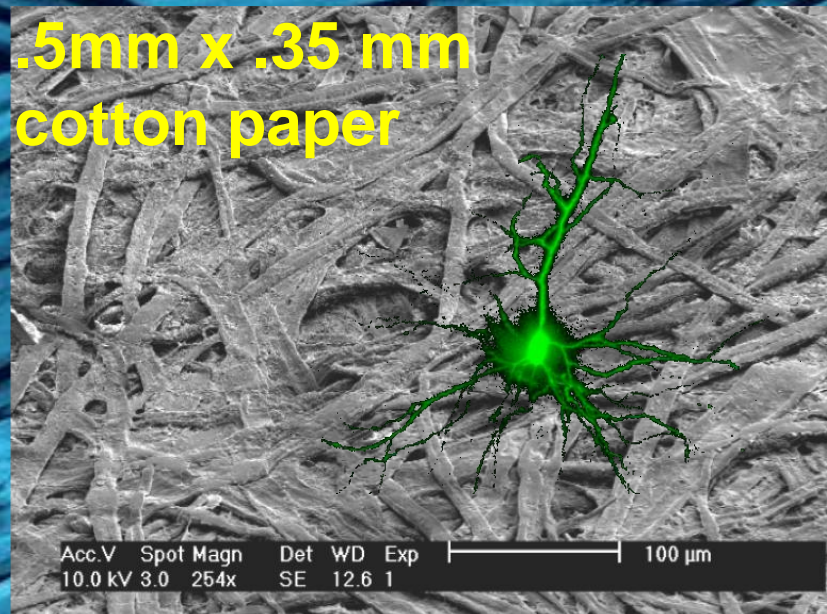






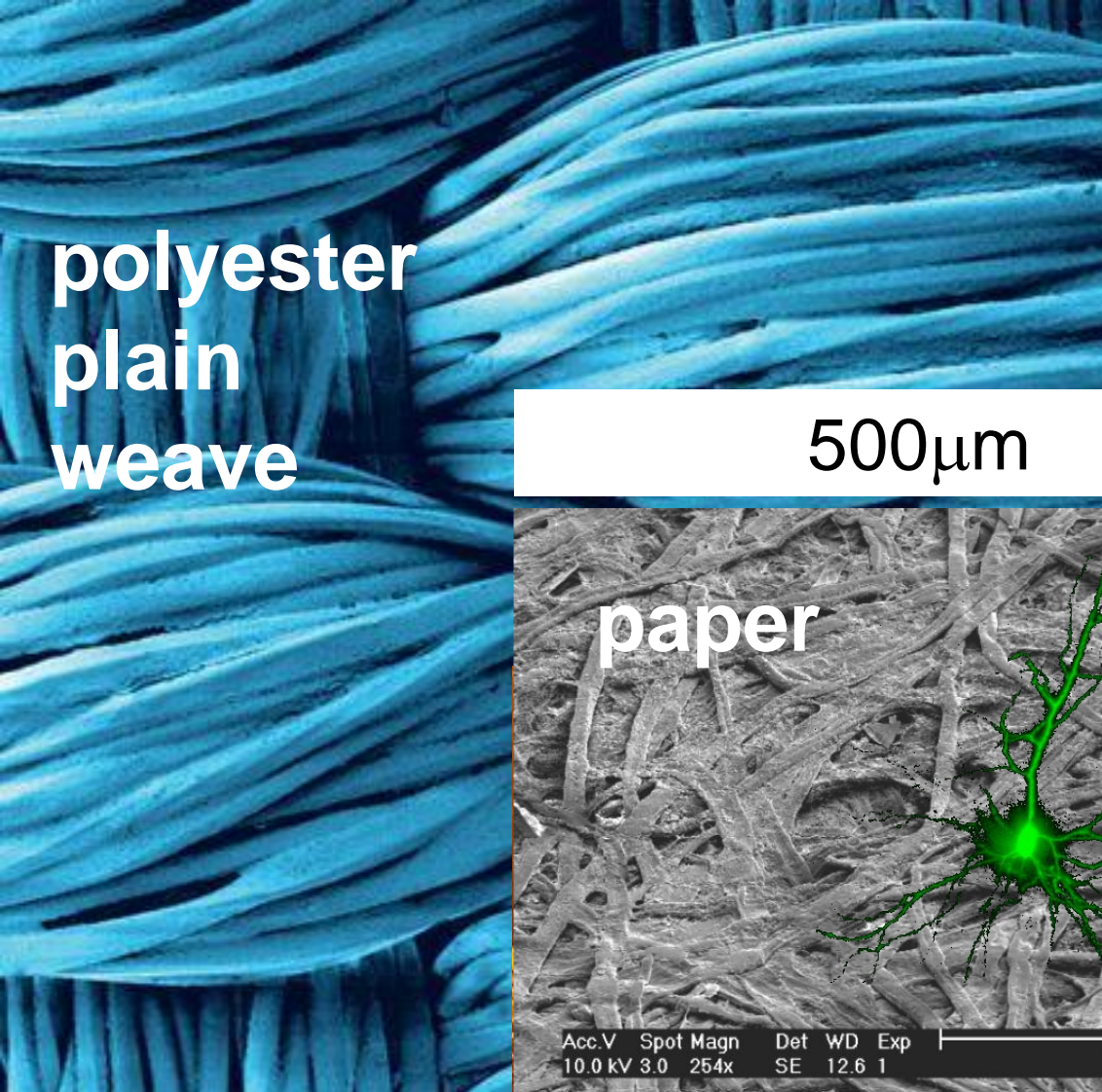
500 μ m

.5mm x .35 mm
cotton paper



1.15mm x .85mm polyester plain weave

500 μ m

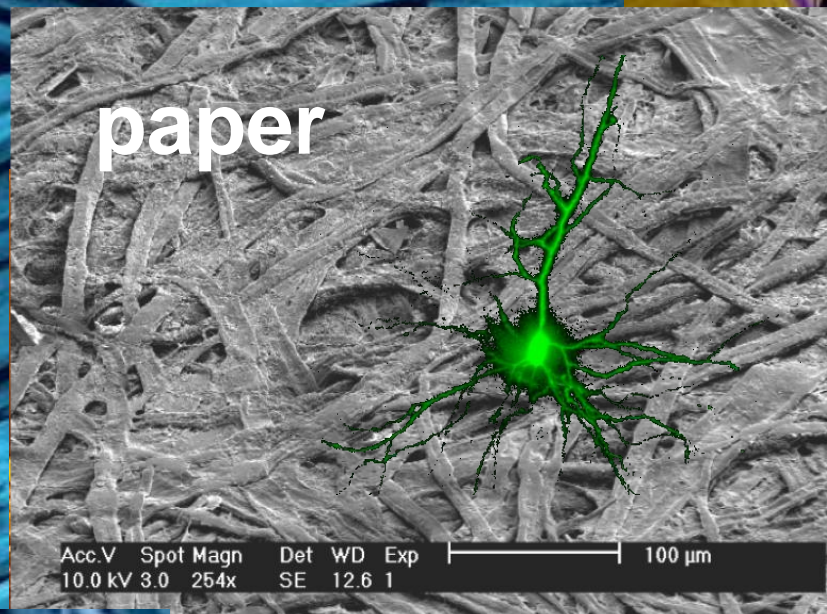


**polyester
plain
weave**

500 μ m



**needle &
thread**



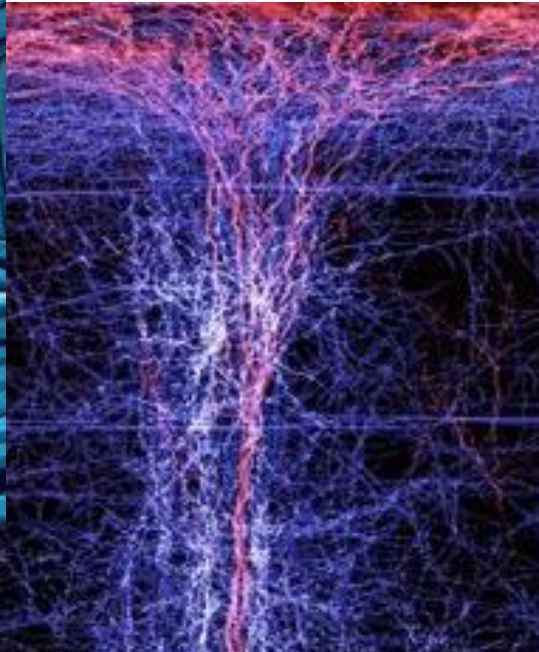
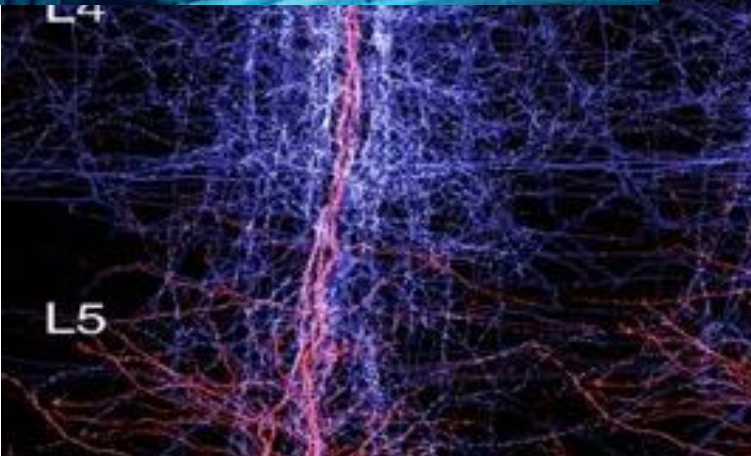
paper



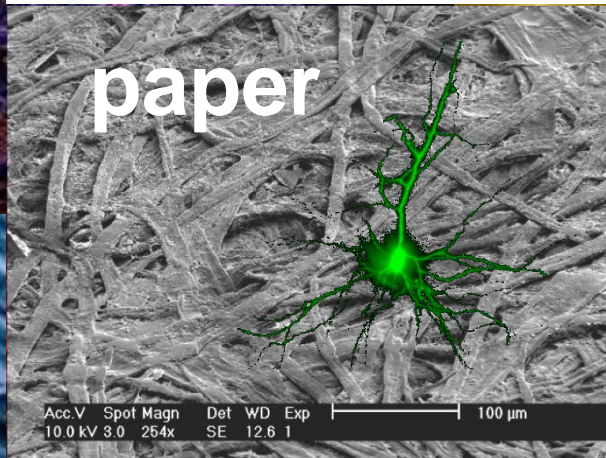
denim



cheesecloth

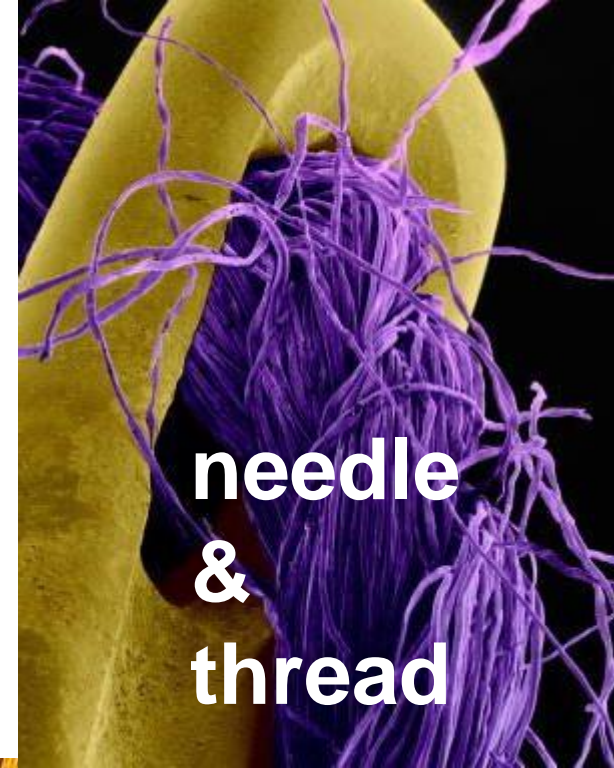
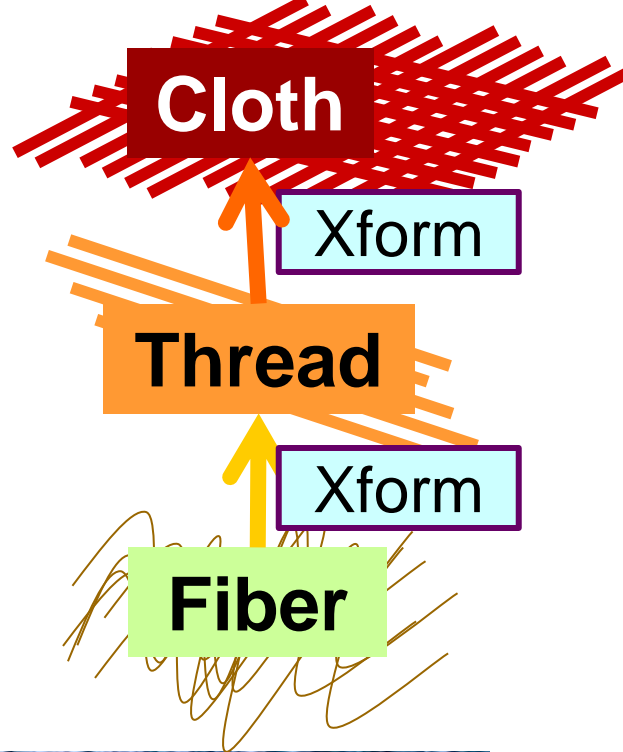


500μm

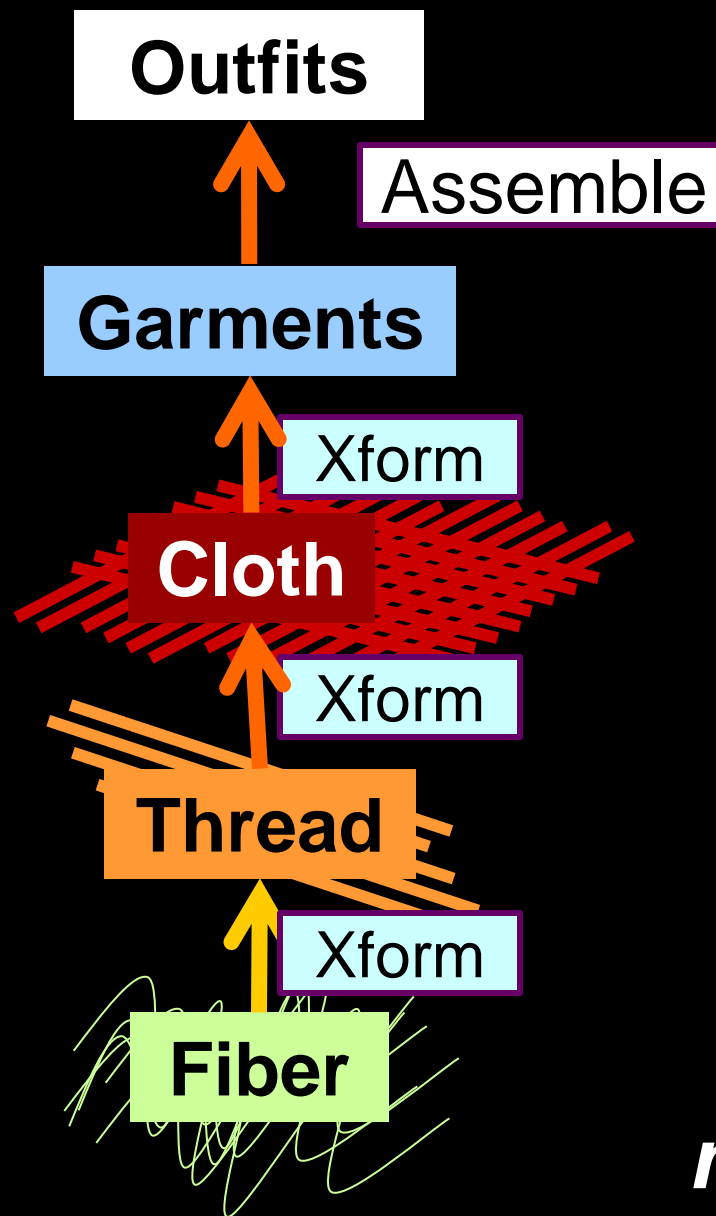


**Hidden,
large, thin,
nonconvex

are
*necessary***



**Hidden,
large, thin,
nonconvex**

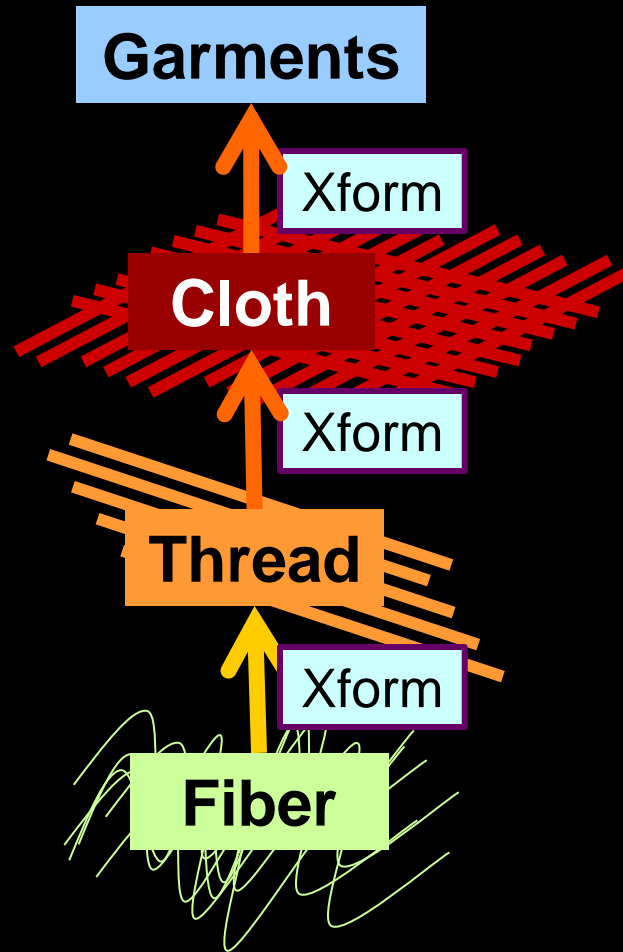


**are
*necessary***

Universal strategies?

Even though garments seem analog/continuous

Garments have limited access to threads and fibers

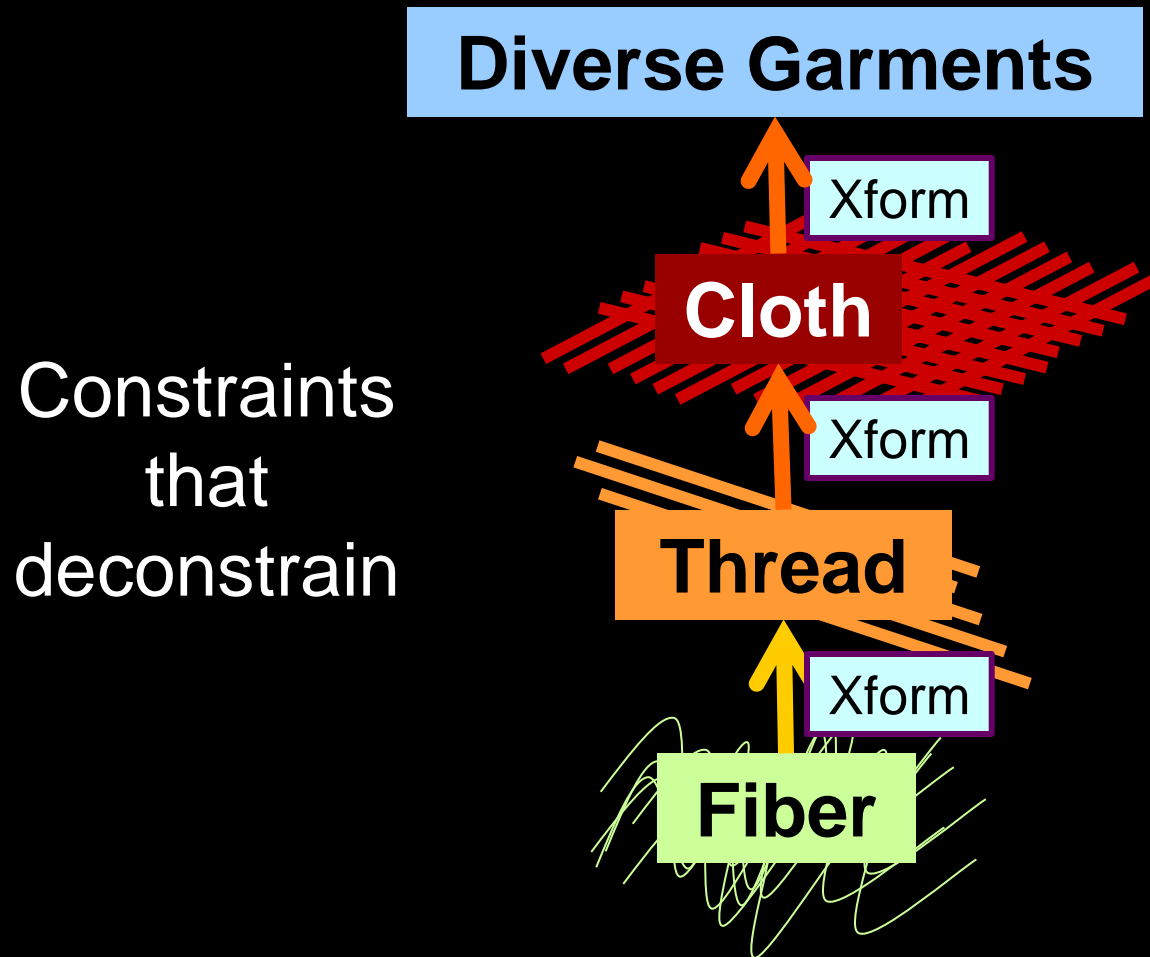


quantization for robustness

constraints on cross-layer interactions

Prevents unraveling of lower layers

Diverse outfits



Geographically diverse sources

**System
constraints**

Diverse outfits

Diverse Garments

Xform

Cloth

Xform

Thread

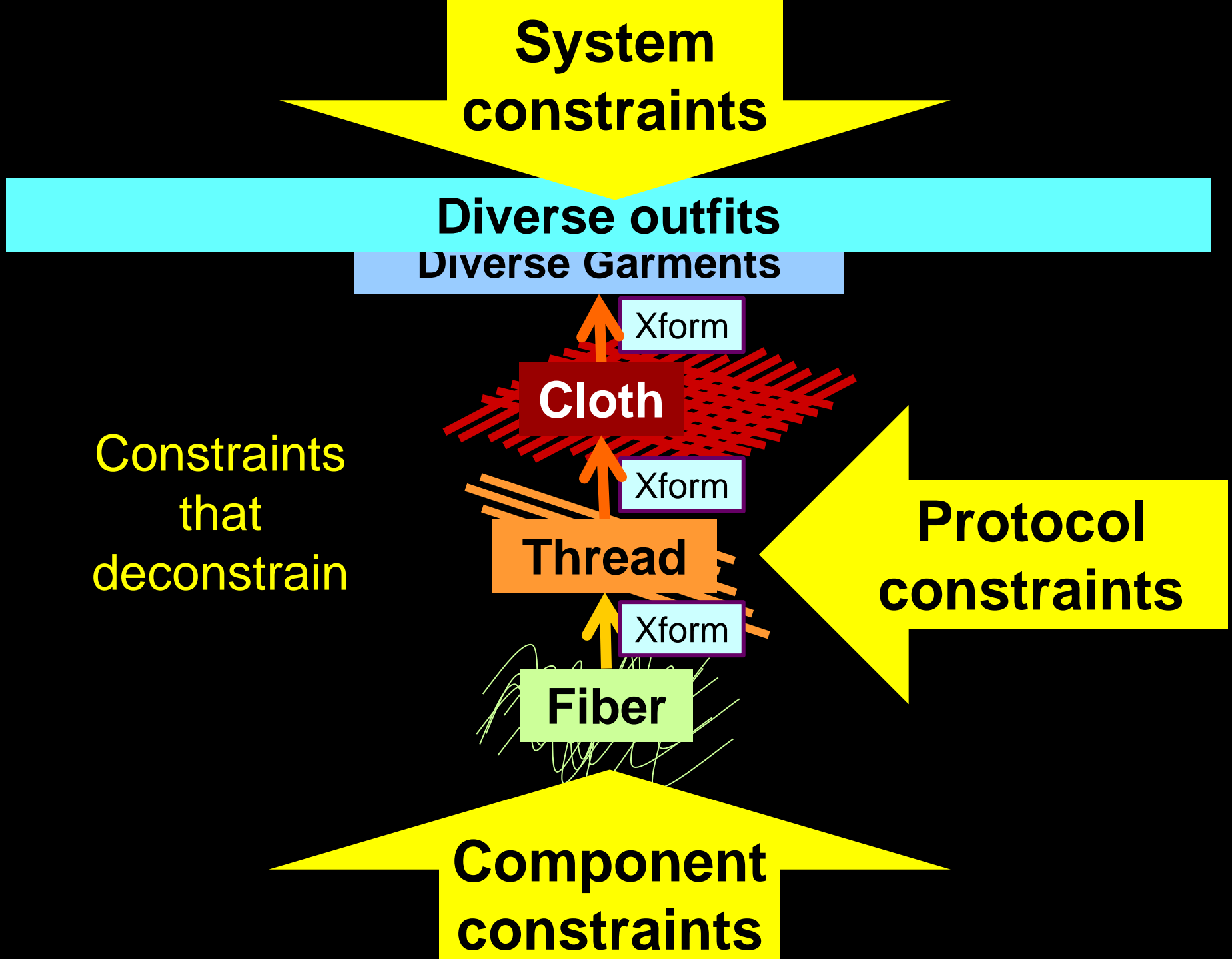
Xform

Fiber

Constraints
that
deconstrain

**Protocol
constraints**

**Component
constraints**



Diverse outfits

Garments

Xform

Cloth

Xform

Thread

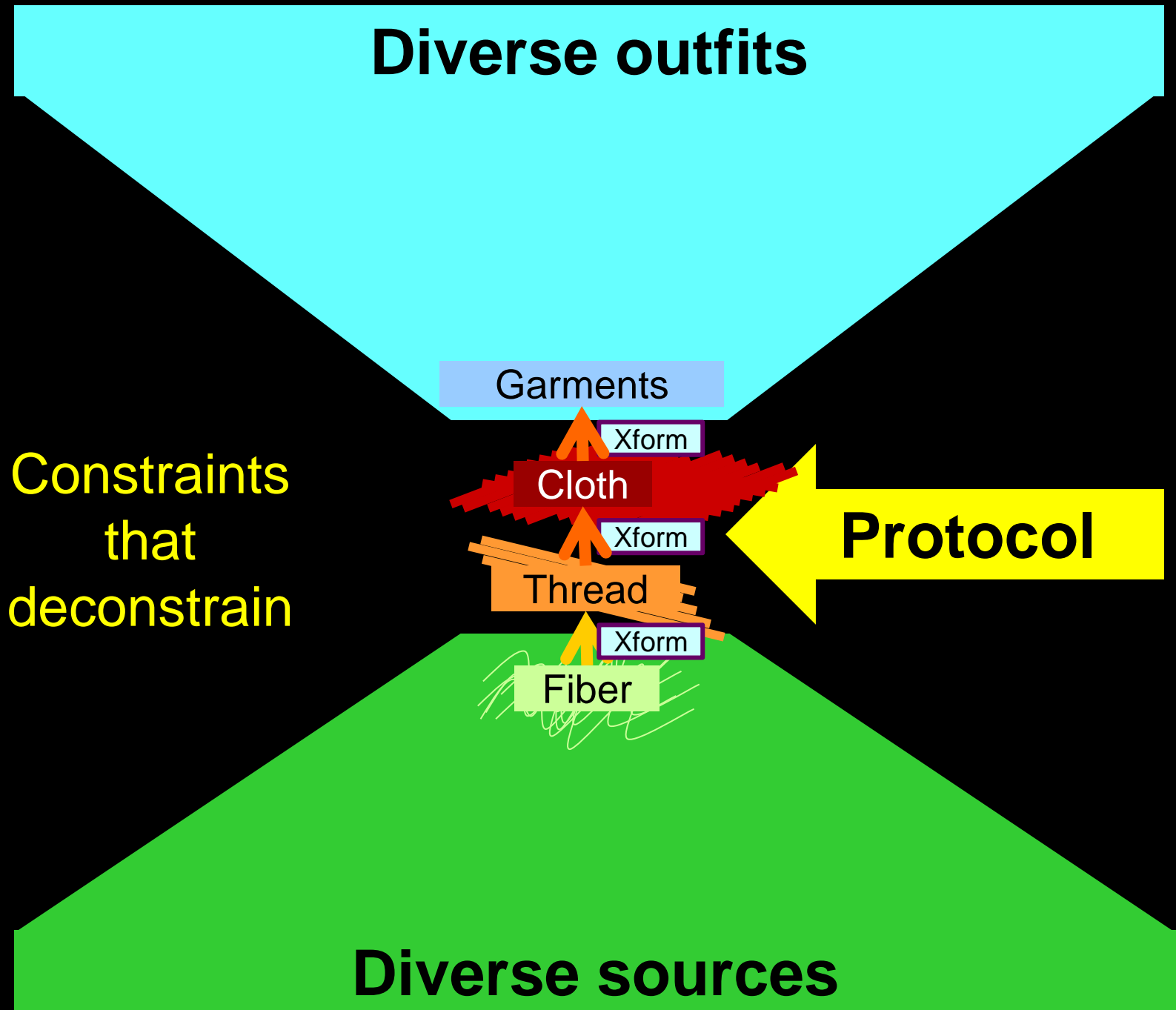
Xform

Fiber

Protocol

Constraints
that
deconstrain

Diverse sources





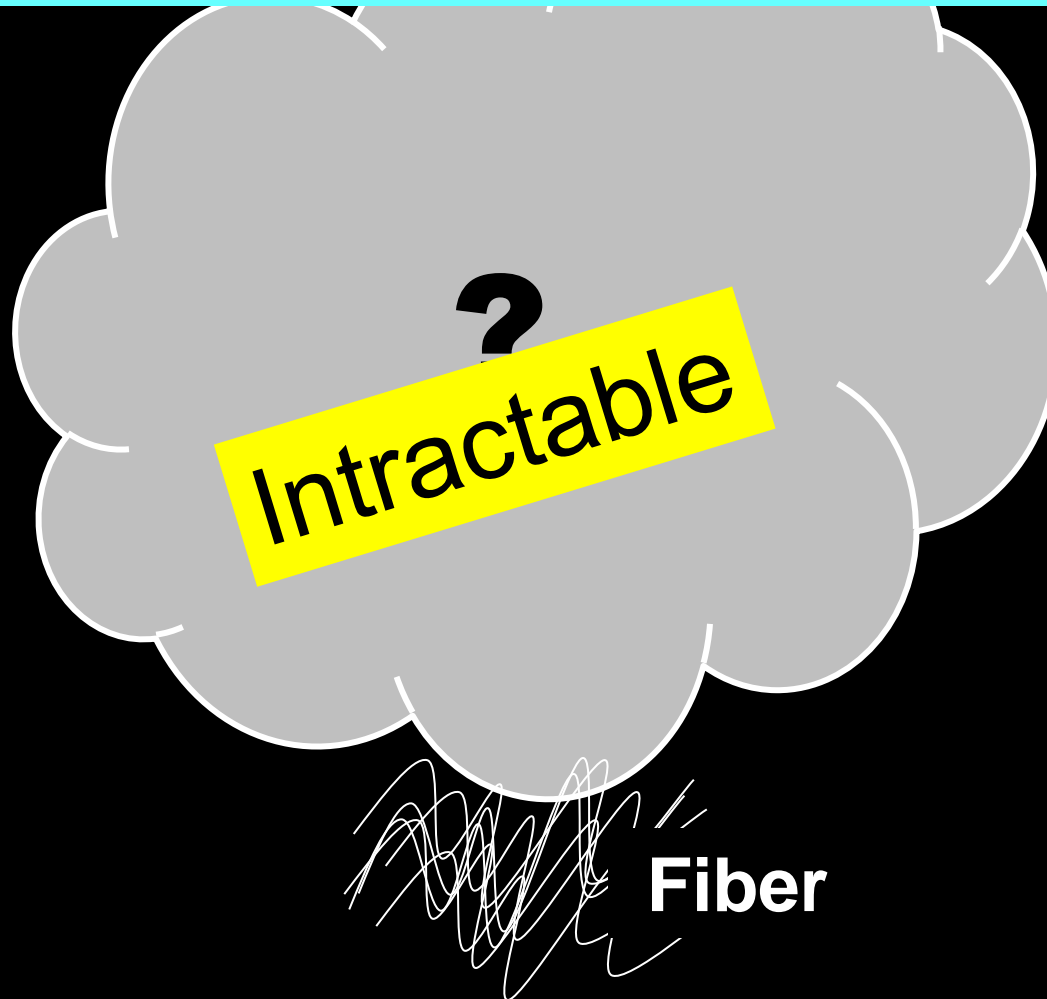
Diverse outfits



?

Fiber

Diverse outfits





SOC/EOC?



Random

Self-Organized Clothing

Edge of Couture

Scale-Free Fashion



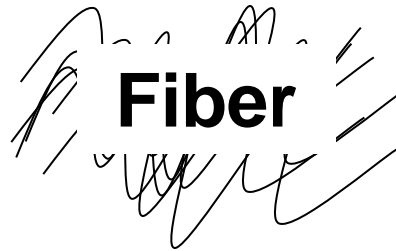
Standard error



Diverse outfits

Small gap

No architecture



Self-Organized Clothing

Edge of Couture

Scale-Free Fashion

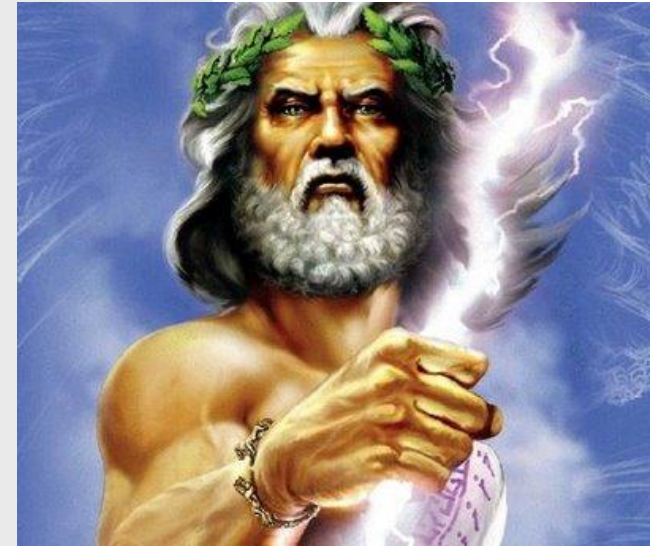


Standard error

Diverse outfits



Huge gap
No architecture
Supernatural



Fiber

Mysteries in the gaps

No architecture

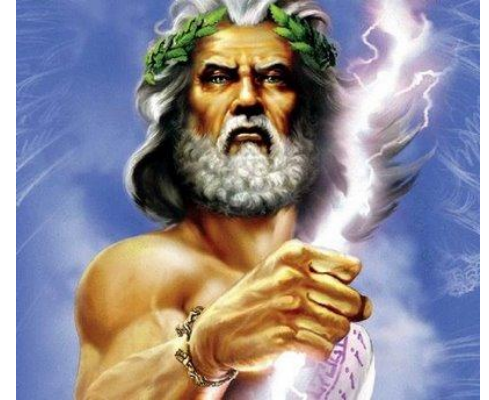


Small gap
Emergence
Self-organized
Phase transition
Edge-of
Scale-free

Diverse outfits



Diverse outfits



Huge gap
Supernatural

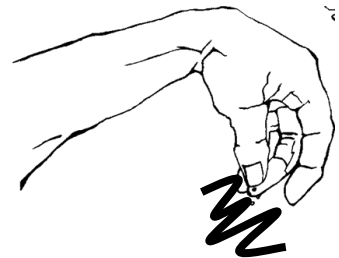
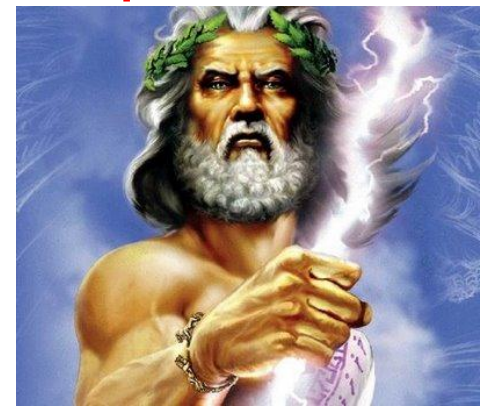


Mysteries in the gaps
No architecture

Huge gap
Supernatural



Small gap
Emergent



Diverse outfits

Diverse Garments

Constraints
that
deconstrain

Cloth

Xform

Thread

Xform

Fiber

Xform

Protocols

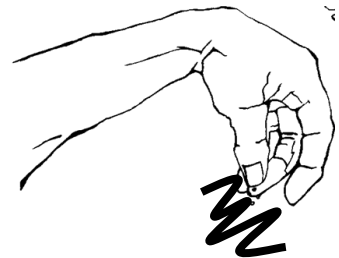
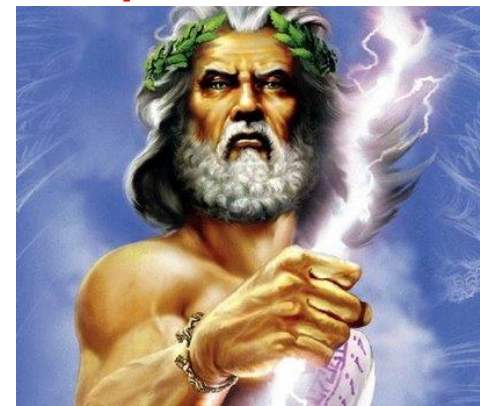
Different worlds

Mysteries in the gaps
No architecture

Huge gap
Supernatural

Mainstream

Small gap
Emergent



Diverse outfits

Diverse Garments

Constraints
that
deconstrain

Cloth

Xform

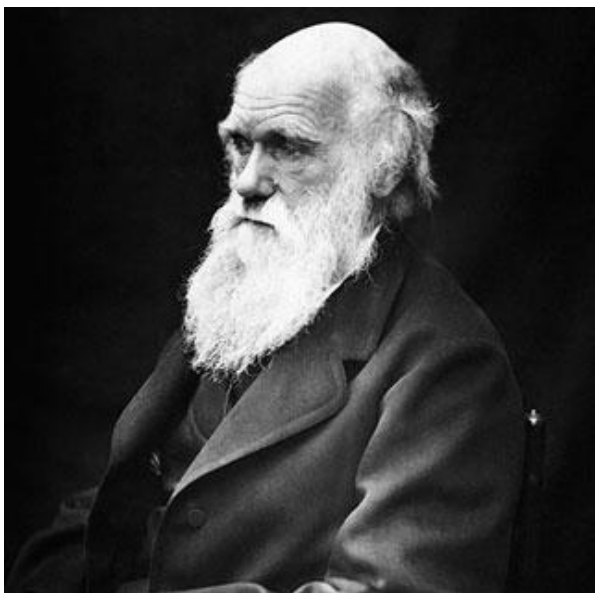
Xform

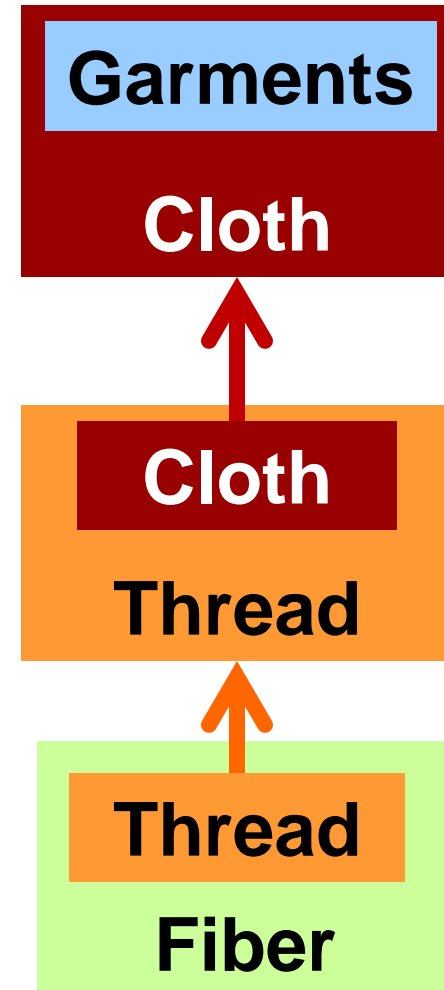
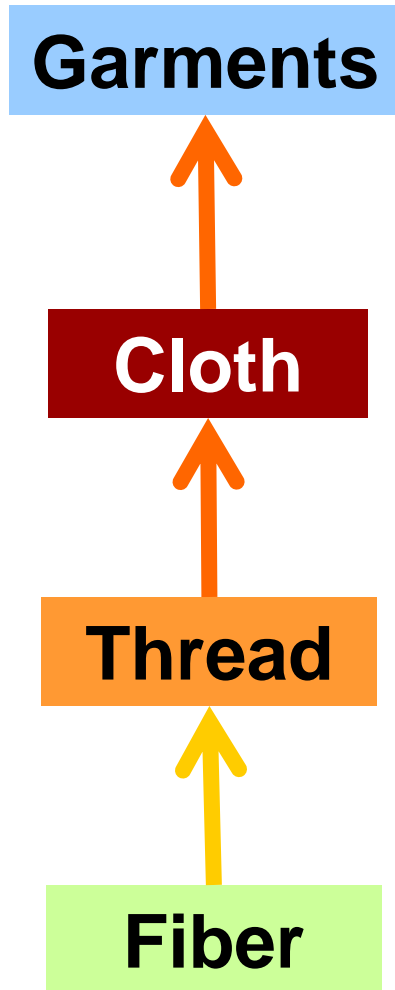
Thread

Xform

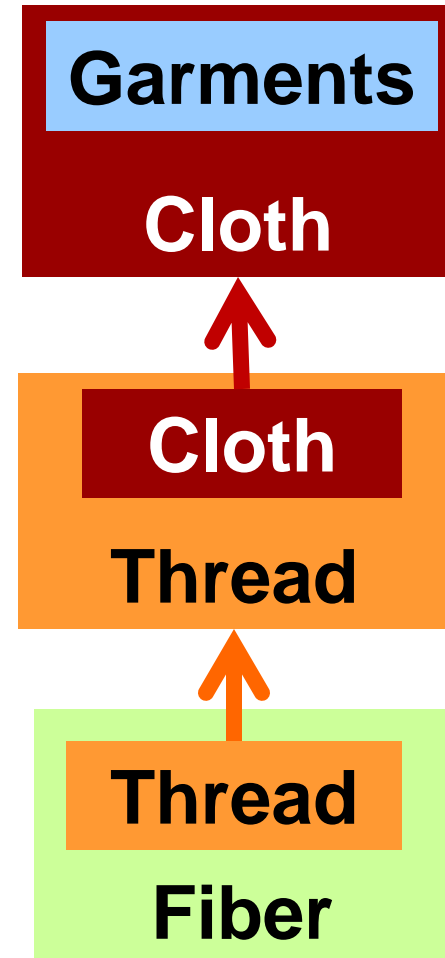
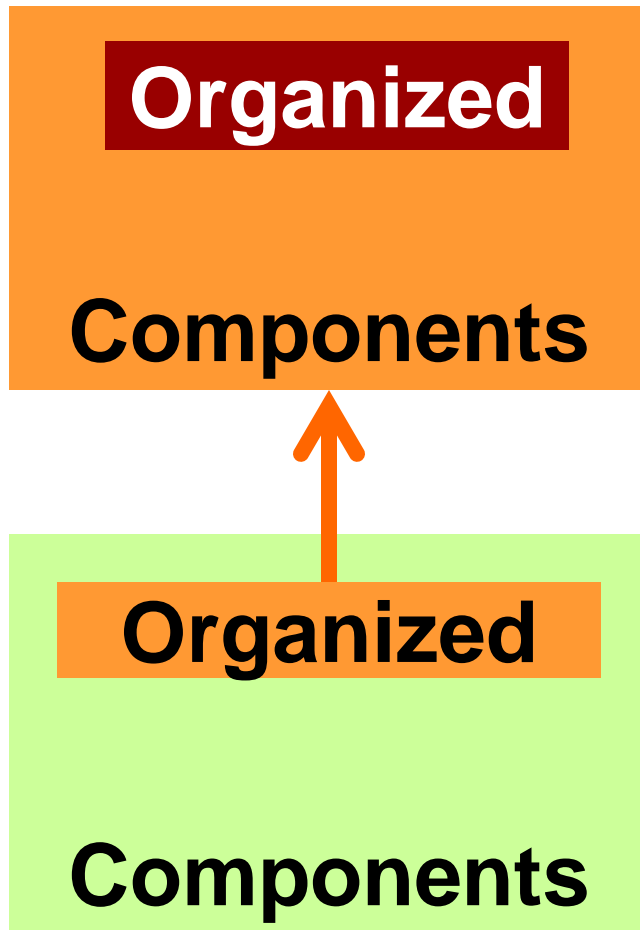
Fiber

Protocols





Layered, large, thin



large

thin

$1 \ll \# \text{ outfits} \ll \# \text{ heaps}$

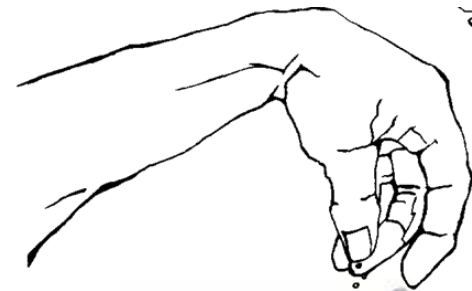
Organized

Components



outfit

Components



heap





large

thin

$1 \ll \# \text{ outfits} \ll \# \text{ heaps}$

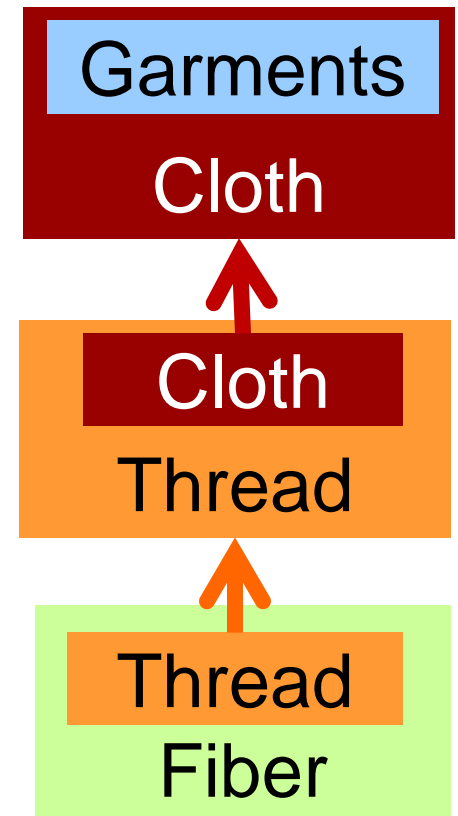
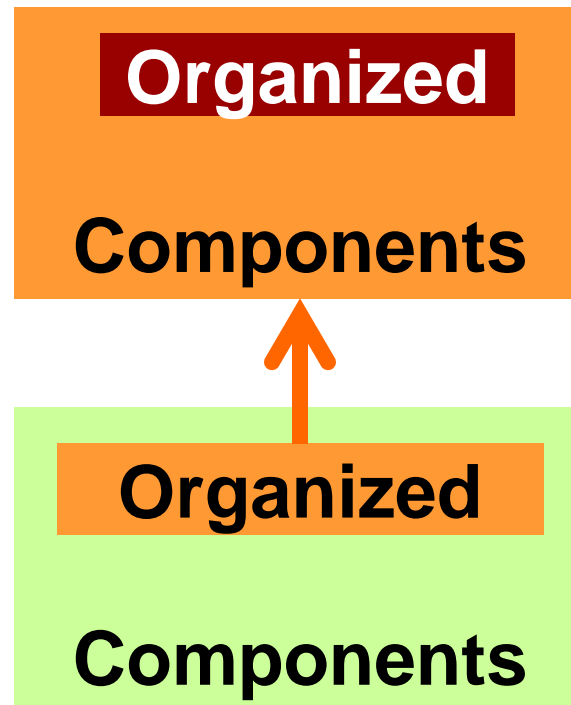
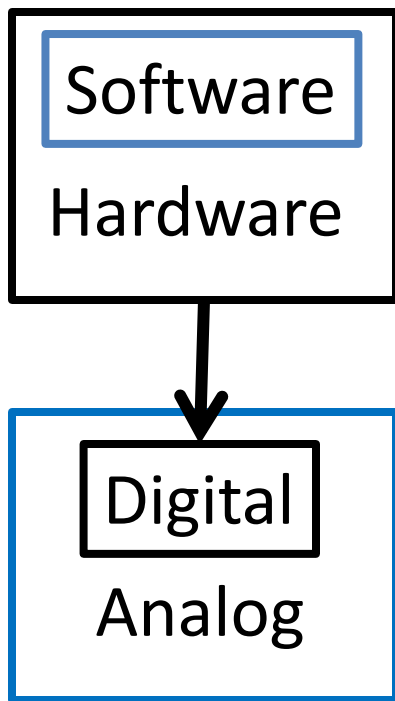
Organized

Components



Architecture

What is the “true functional unit?”



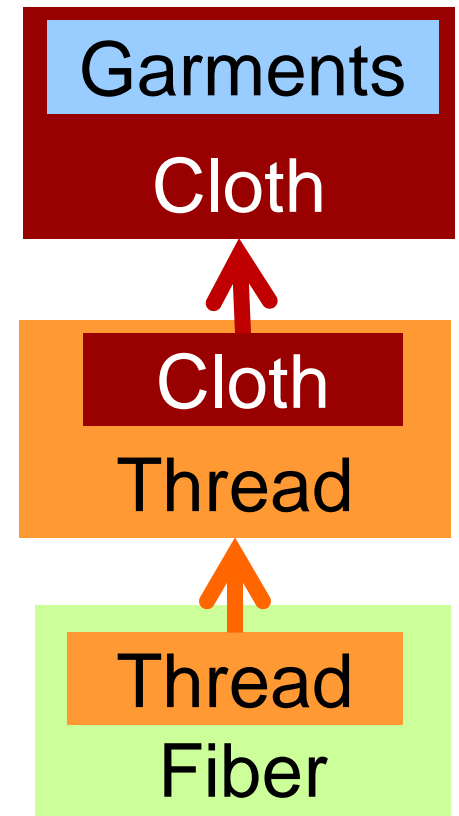
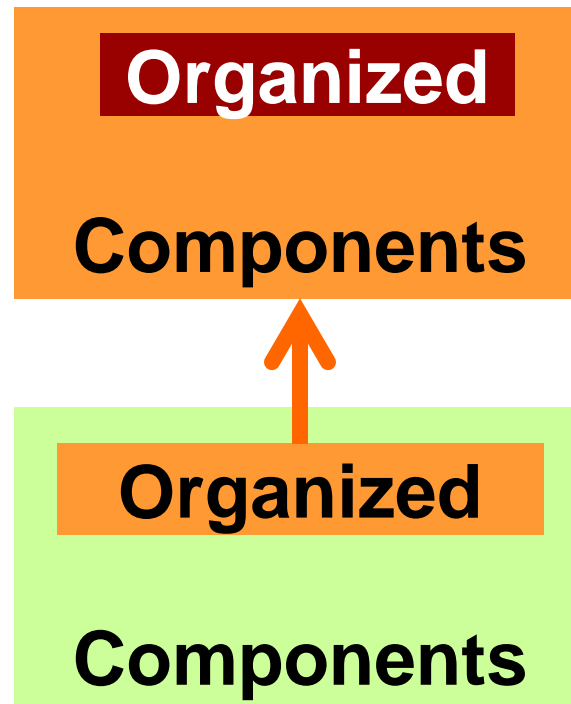
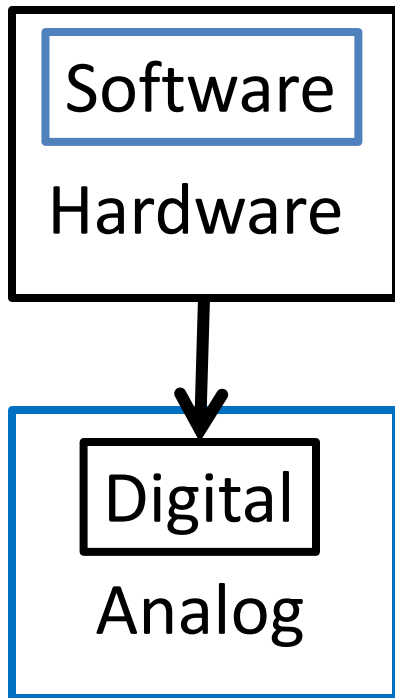
Virtual machines

Software

Organized

Garments

Implementations



Software

Organized

Garments

Virtual machines

Digital

Organized

Cloth

Implementations

Digital

Analog

Organized

Components

Cloth

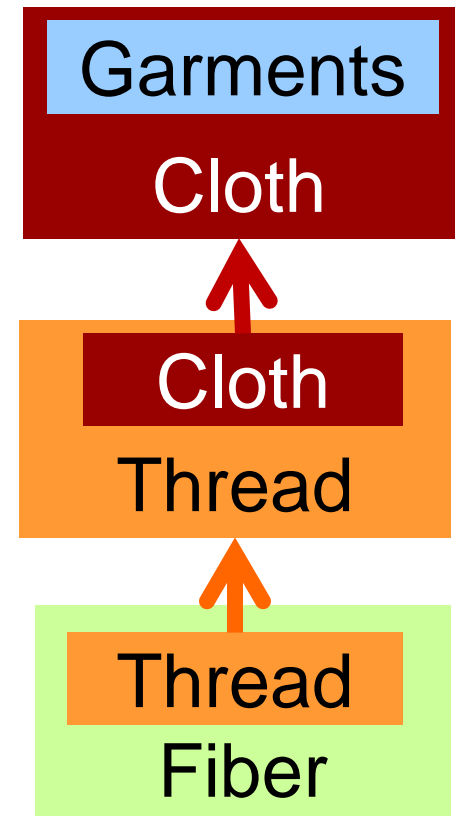
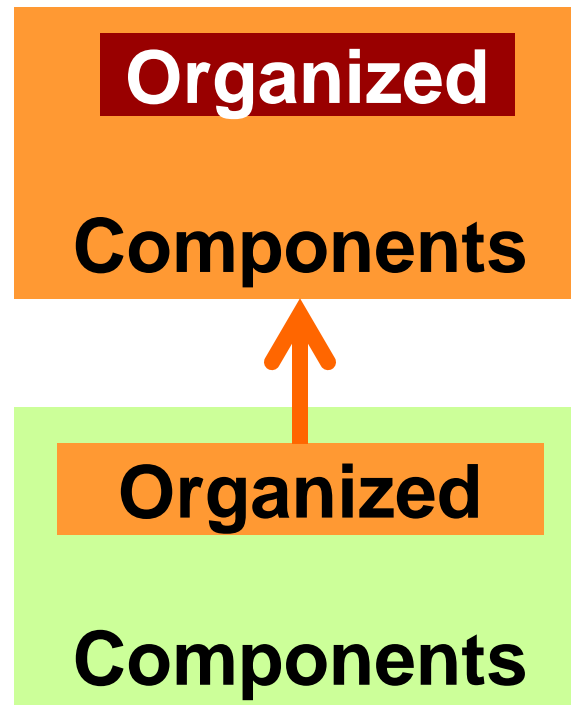
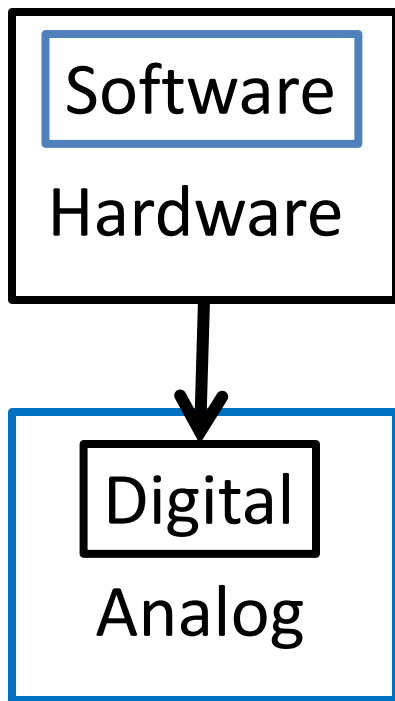
Thread



Thread

Fiber

Layered, large, thin Hidden Virtualized



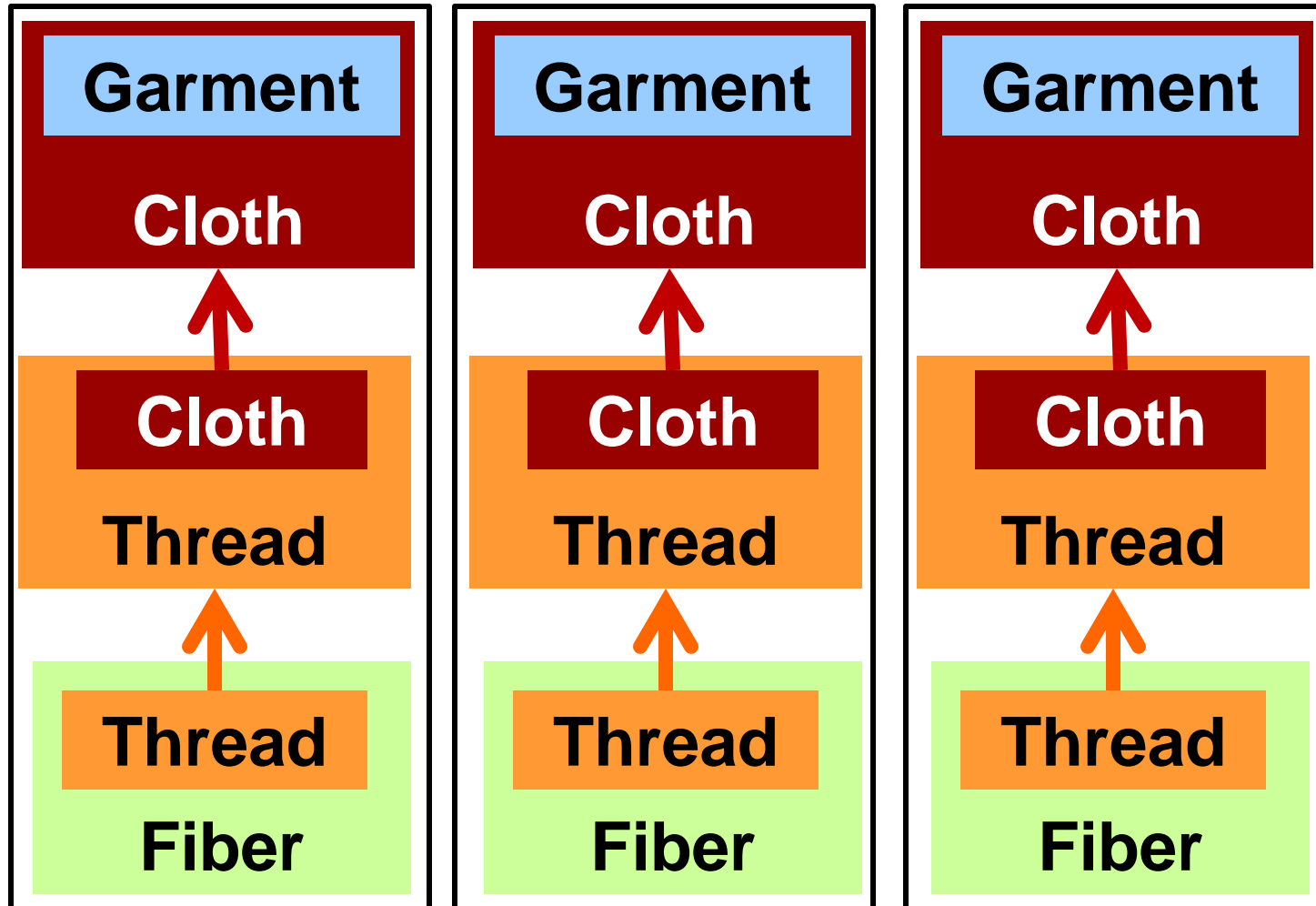
Outfit

Garment

Garment

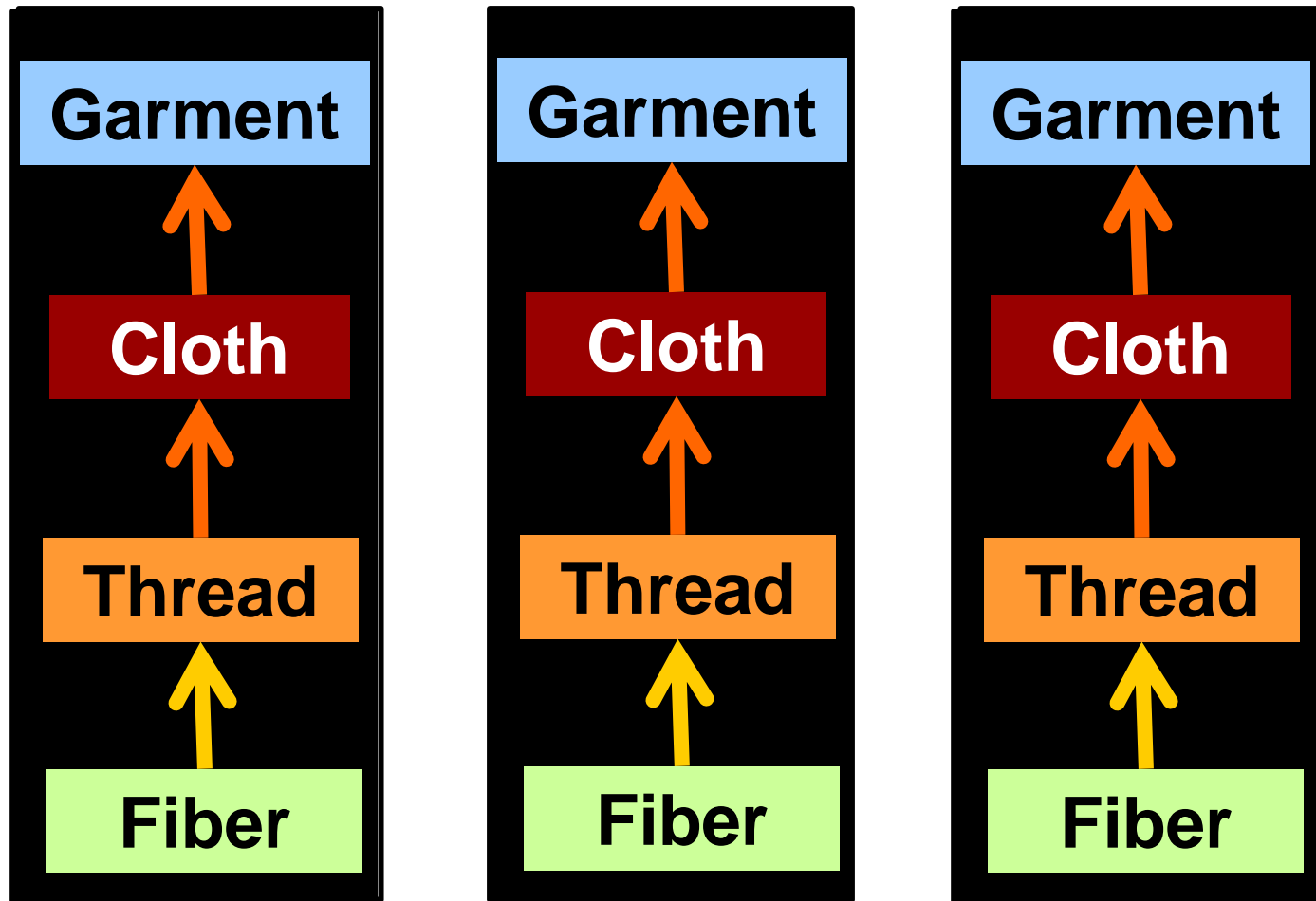
Garment

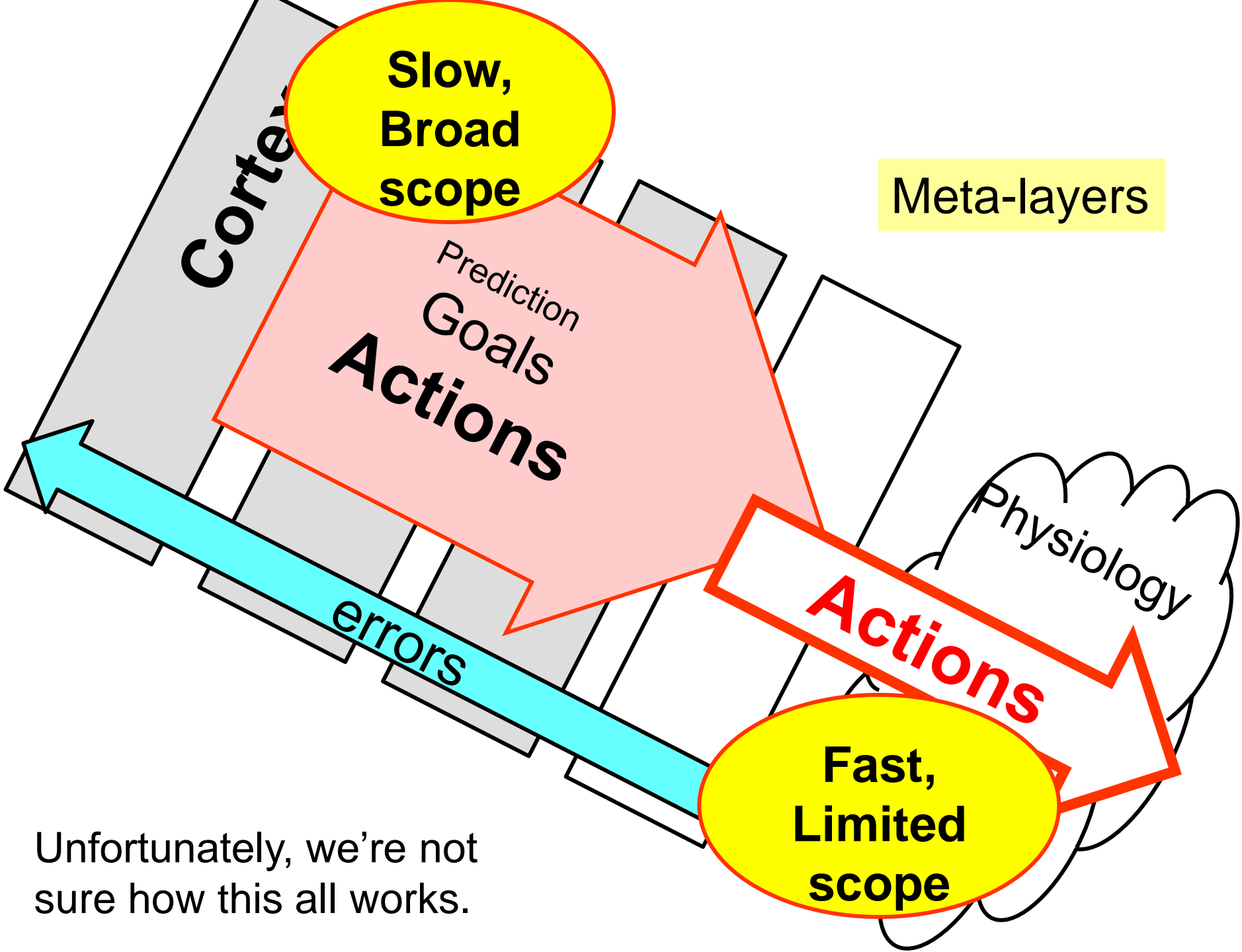
Outfit



Layering within garments (textiles)

Outfit







Outfit

Shell

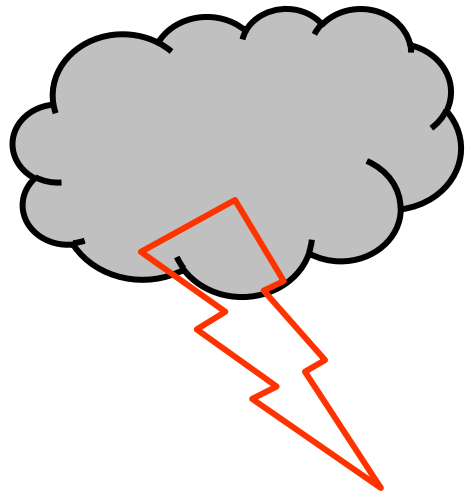
Insulation

Base

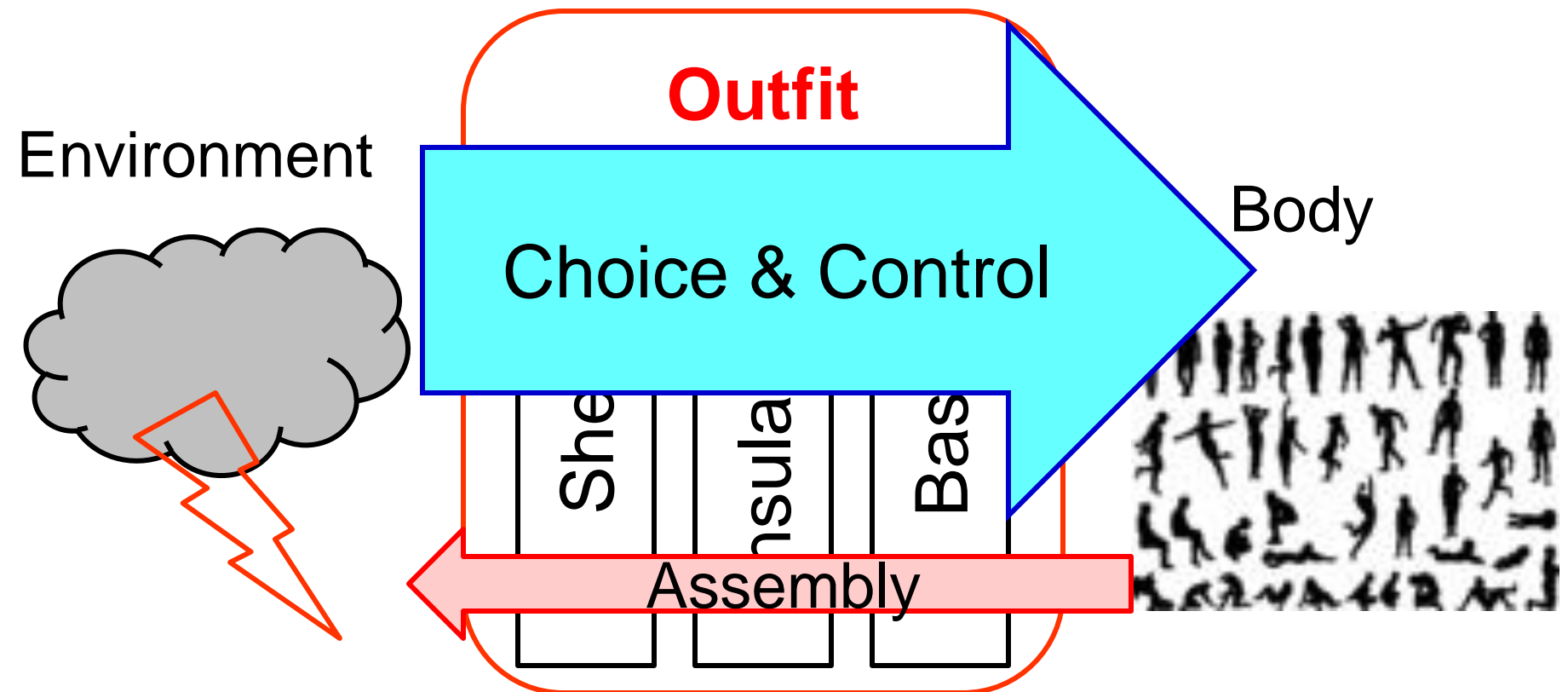
Body

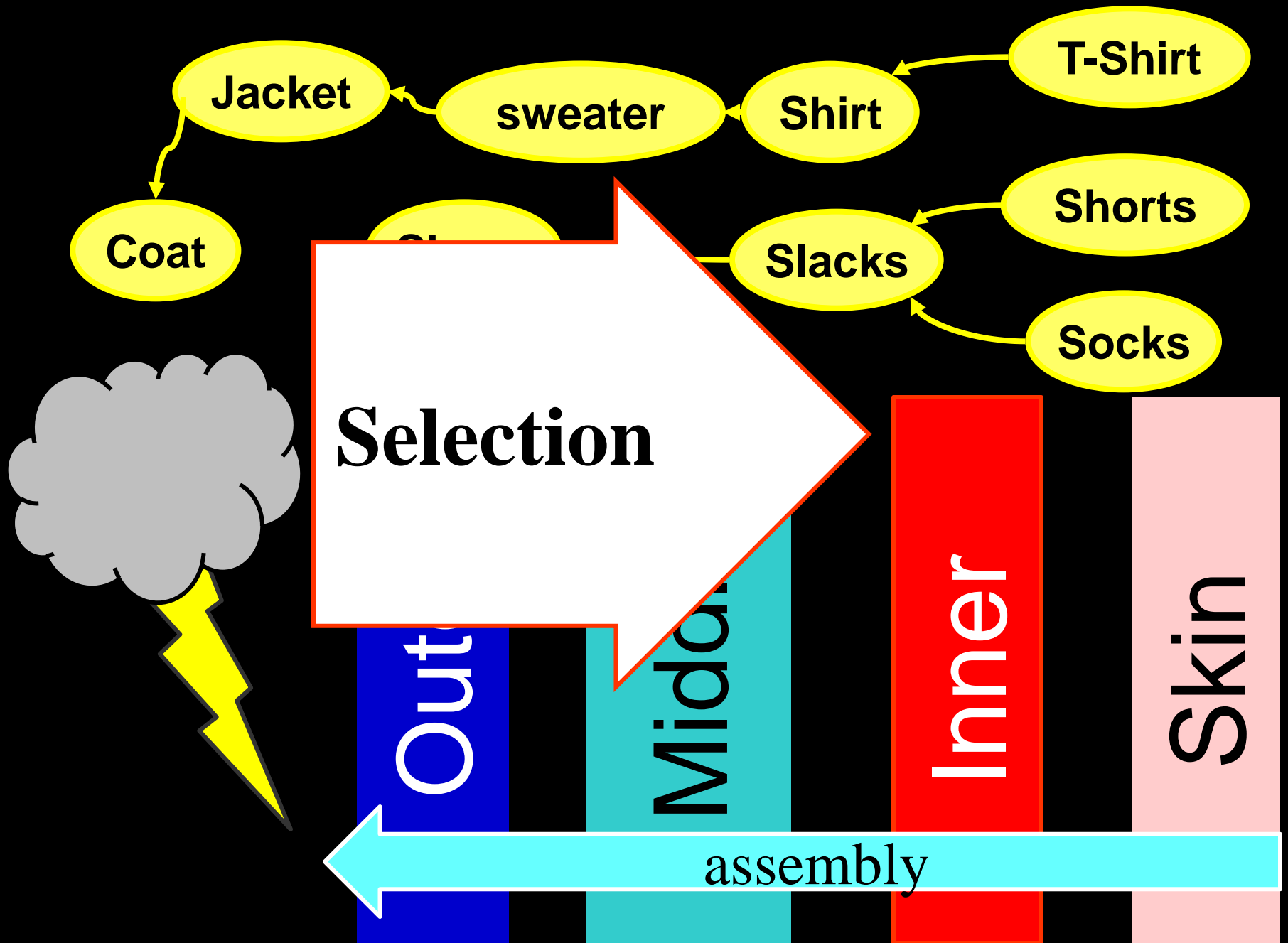


Environment

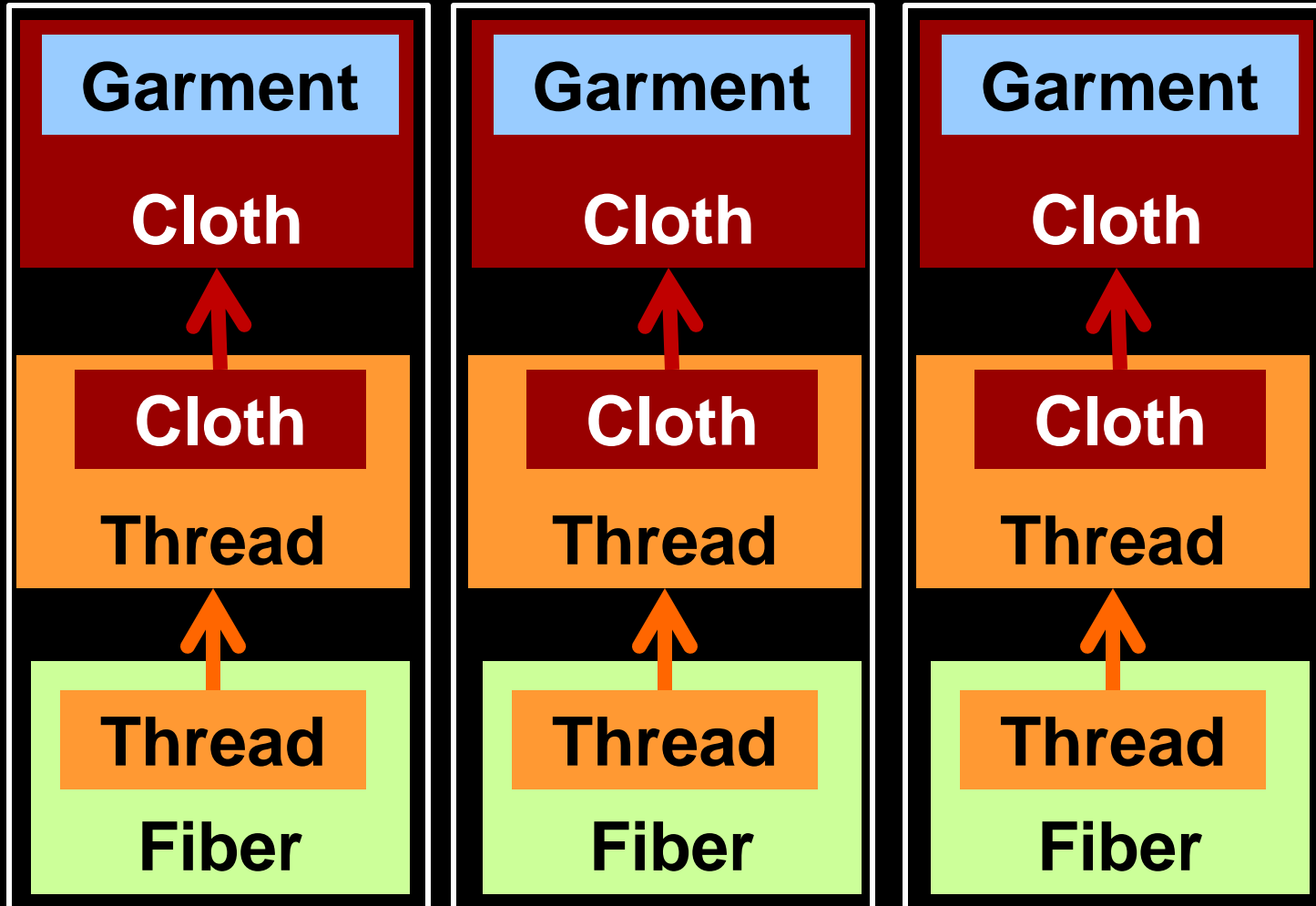


- Complexity \Leftrightarrow Robustness
- Layers must be hidden to be robust
- Choice (management and control) is more complex than assembly





Outfit



Outfit

Assembly

Garment

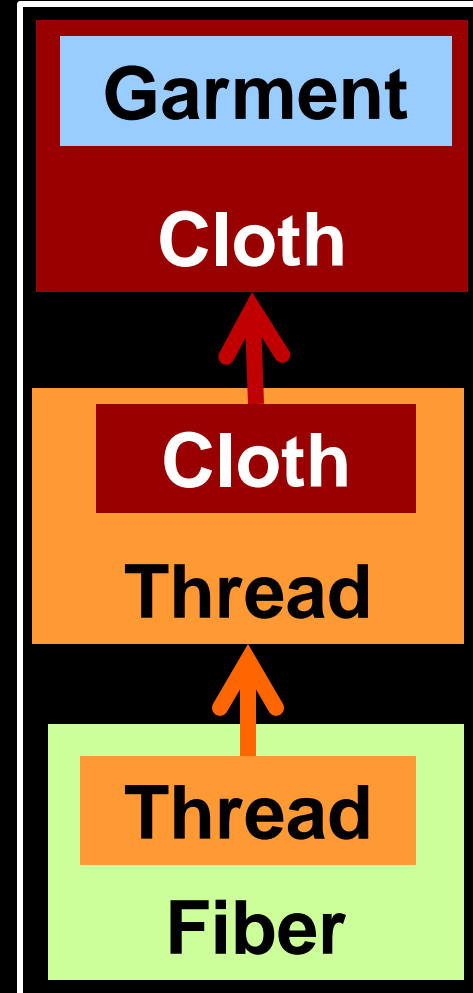
Cloth

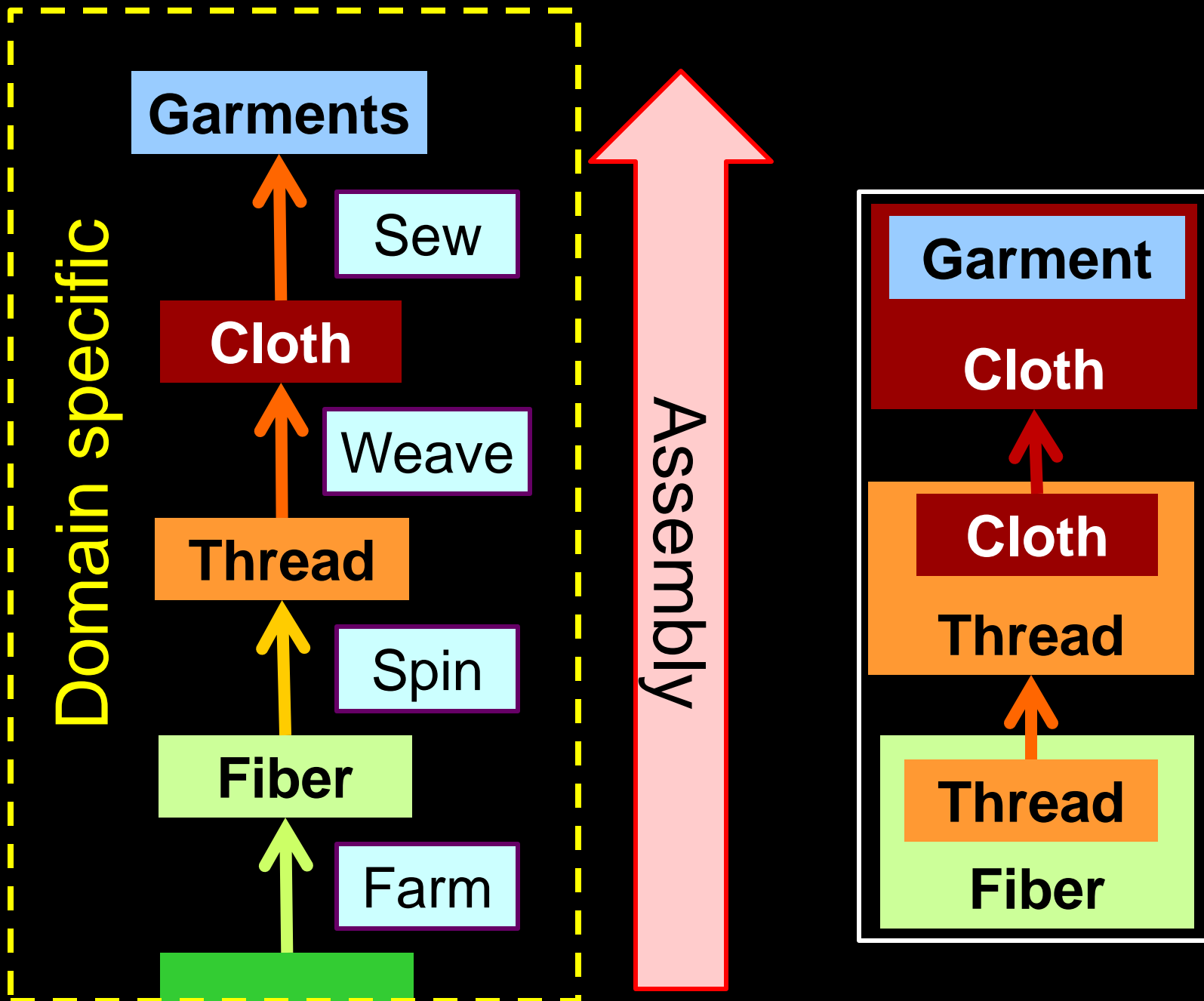
Cloth

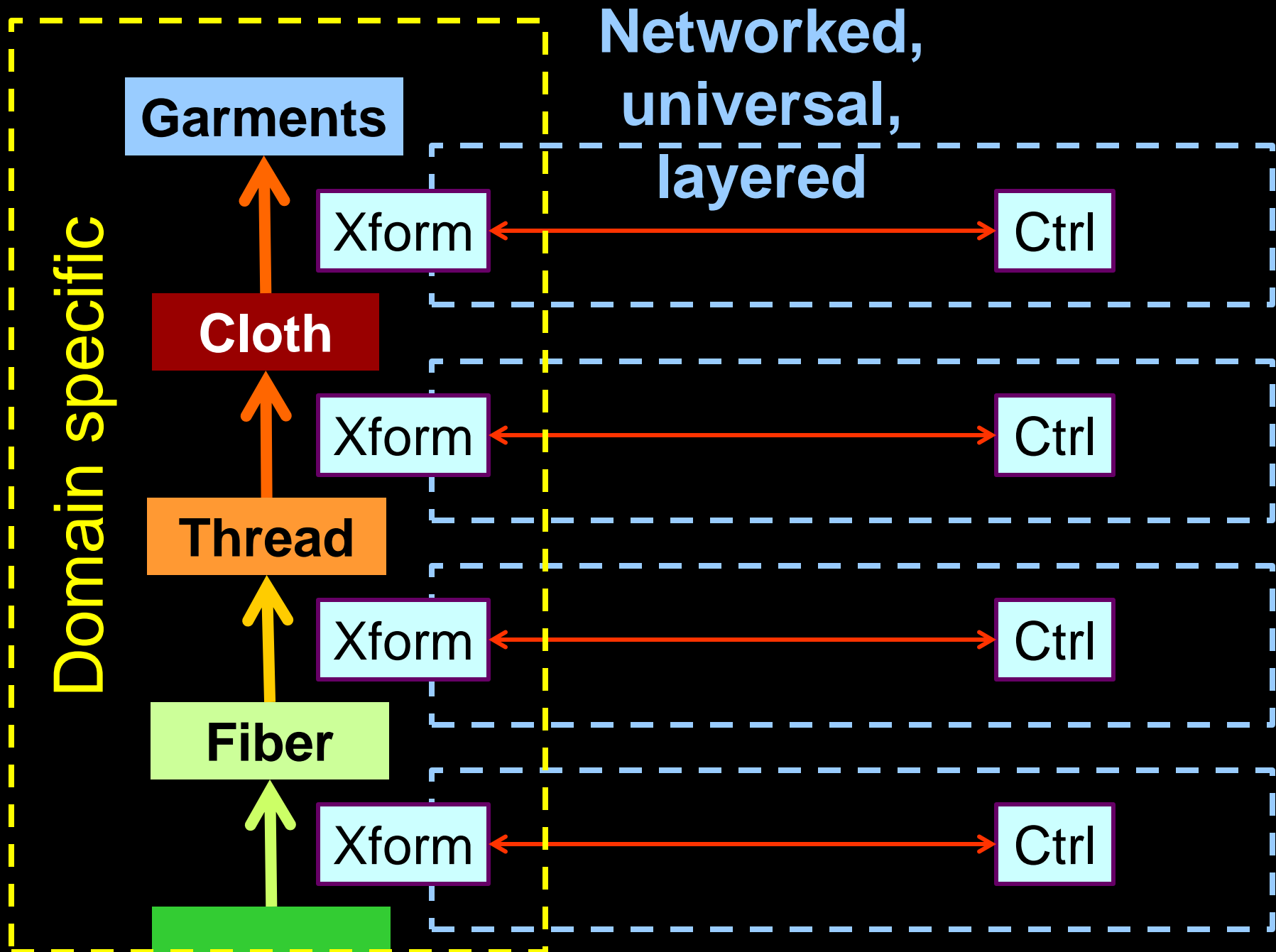
Thread

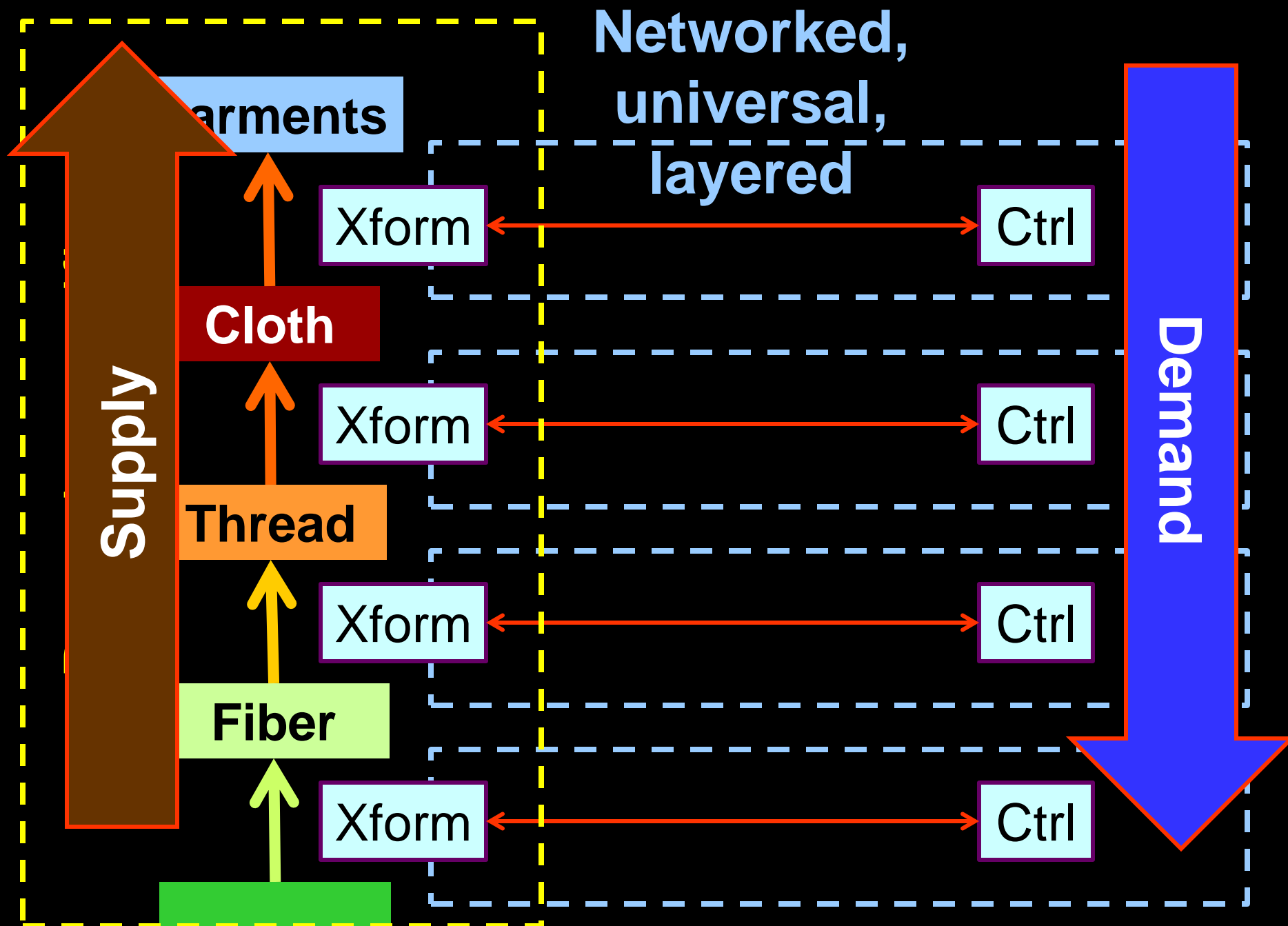
Thread

Fiber

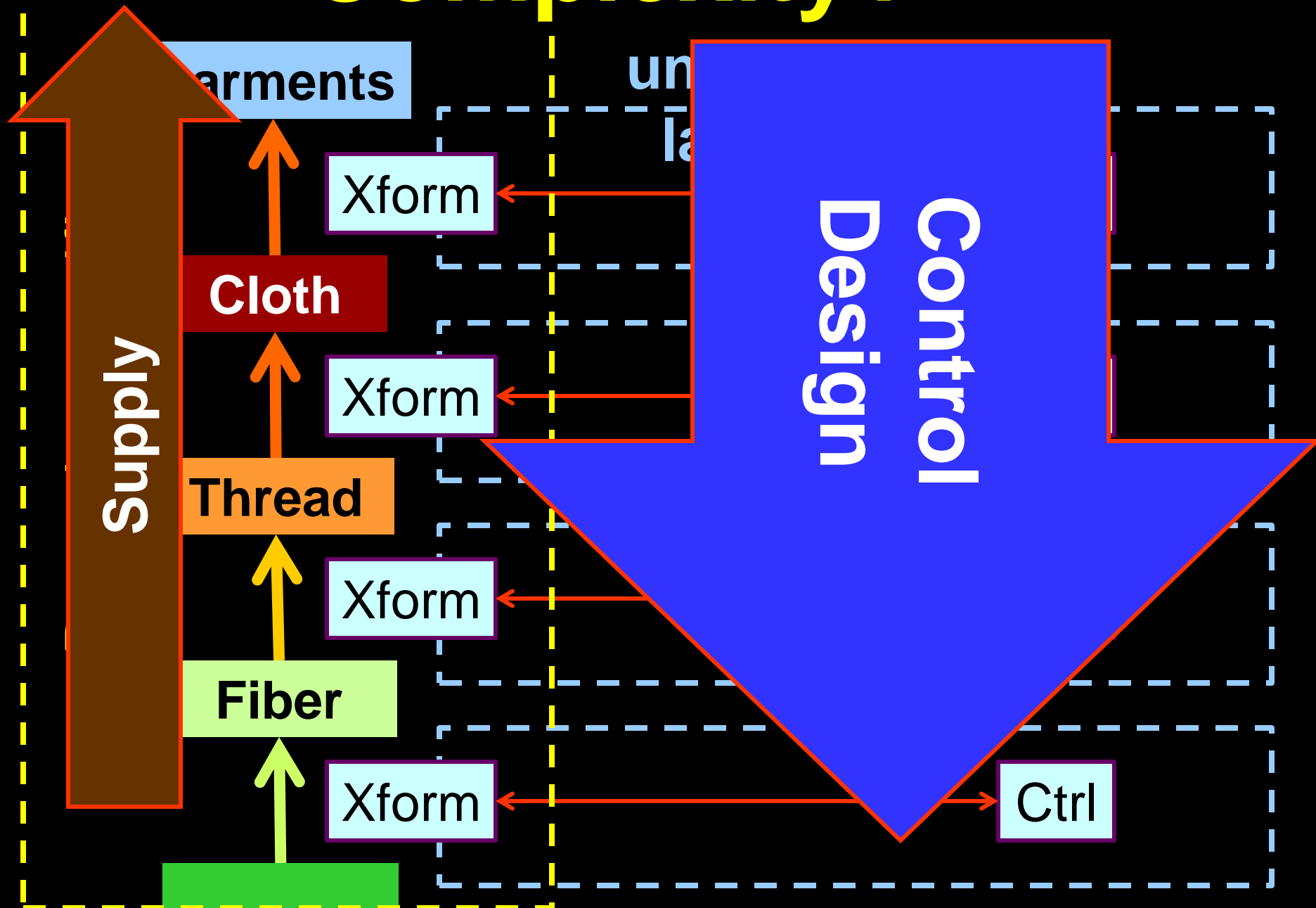








Complexity?



**System
constraints**

Diverse outfits

Diverse Garments

Xform

Cloth

Xform

Thread

Xform

Fiber

**Component
constraints**

**Constraints
that
deconstrain**

**Protocol
constraints**

Assembly

**Control
Design**



System
constraints

**Downward
causation?**

Diverse outfits

Diverse Garments

Xform

Cloth

Xform

Thread

Xform

Fiber

Constraints
that
deconstrain

Protocol
constraints

Control
Design

Component
constraints

Functionally diverse garments

sew

Diverse fabric

General
purpose
machines

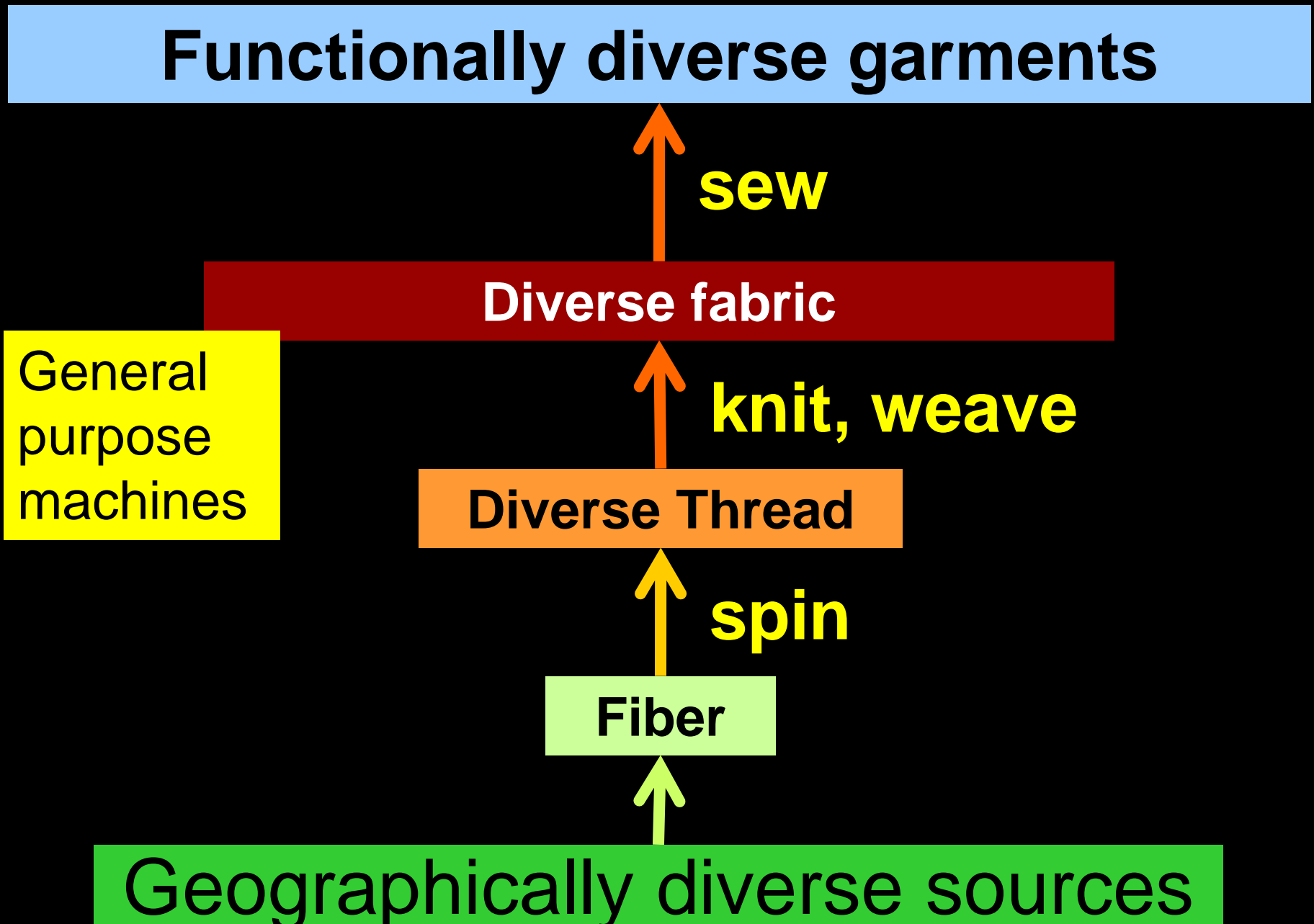
knit, weave

Diverse Thread

spin

Fiber

Geographically diverse sources



Functionally diverse garments



Garments

Fragilities?

Thread

Fiber



Garments



Cloth



Thread



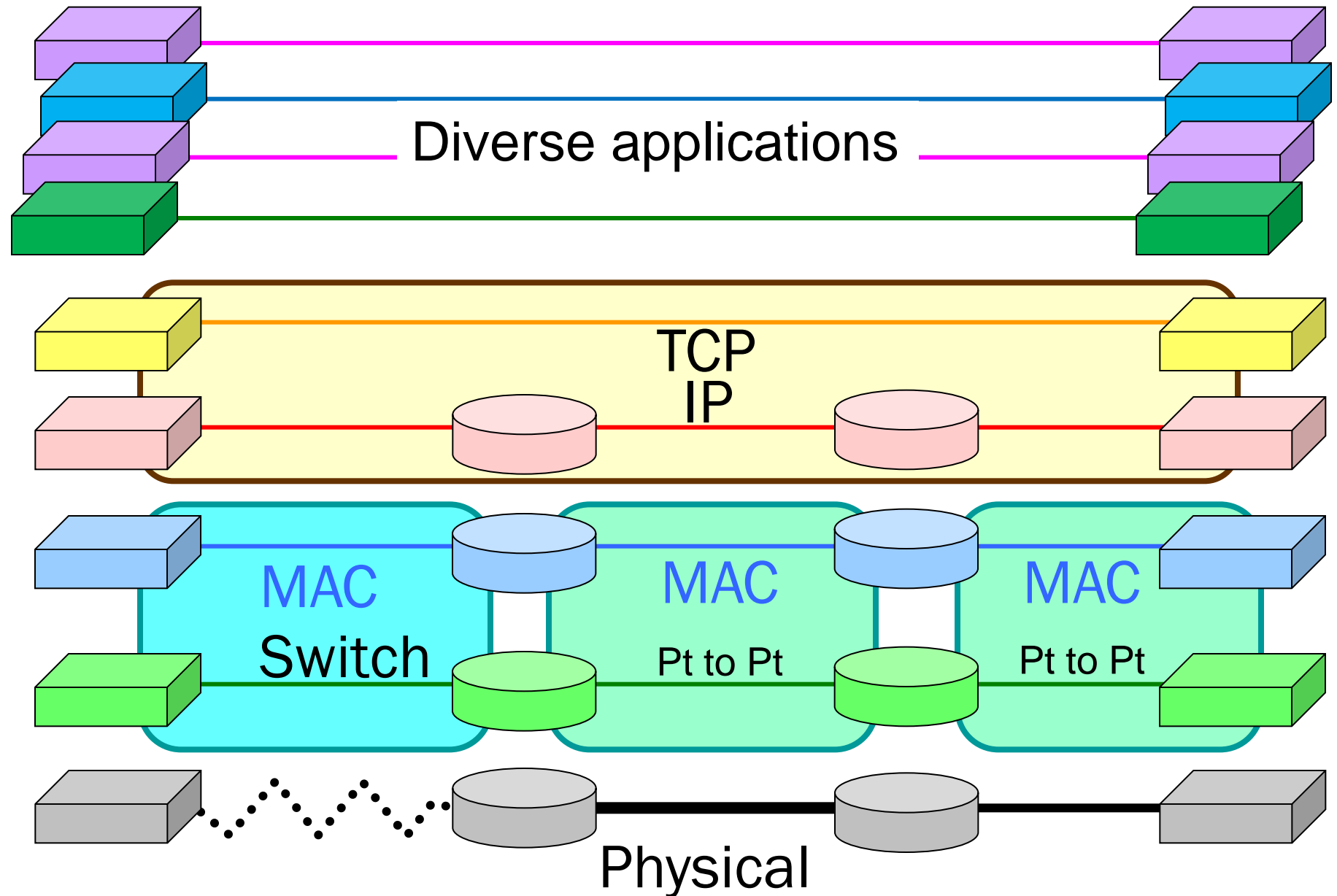
Fiber



Scalable

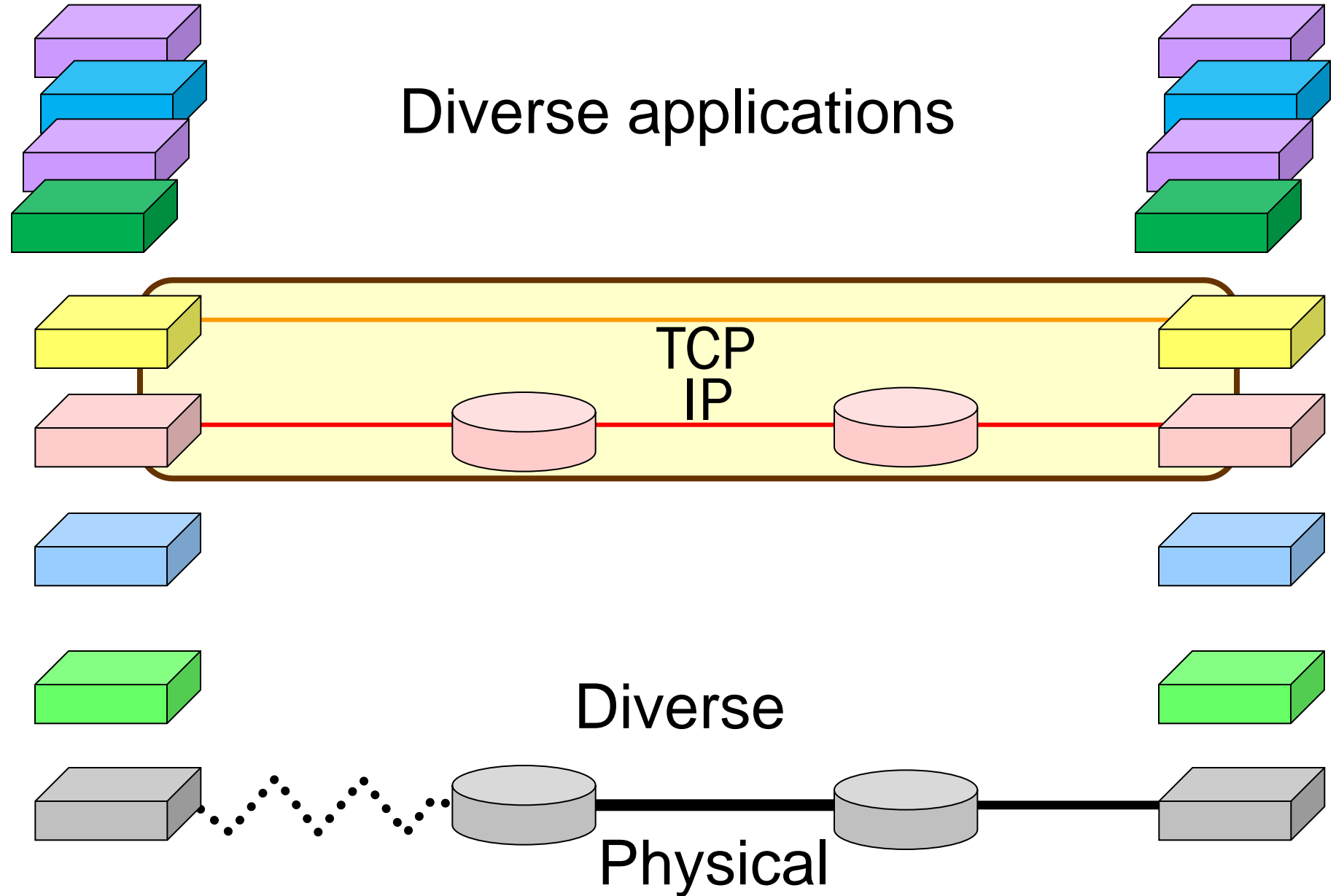
Sustainable?

Layered architectures

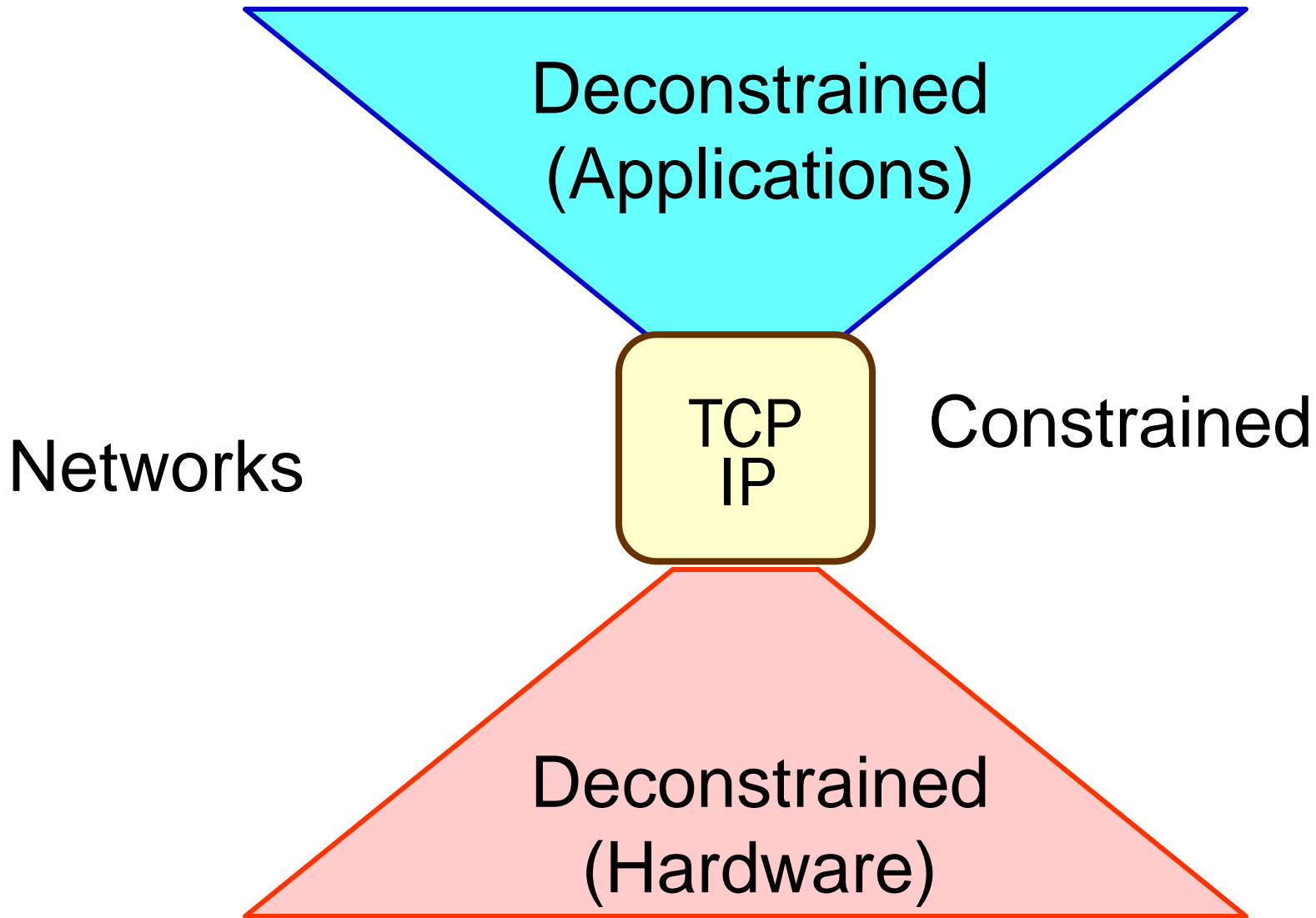


Too clever?

Diverse applications



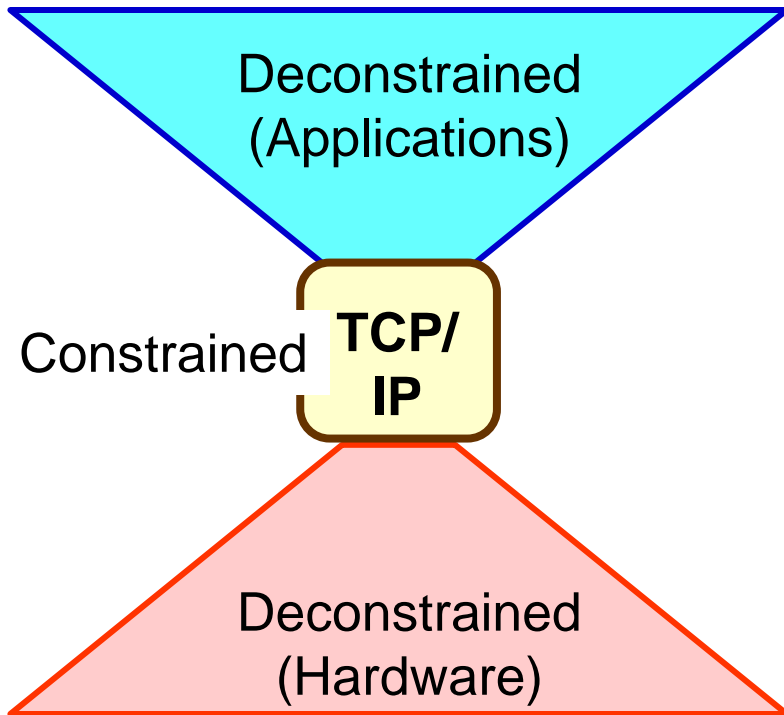
Layered architectures



“constraints that deconstrain” (Gerhart and Kirschner)

Networked OS

- OS better starting point than phone/comms systems
- Extreme robustness confers surprising evolvability
- Creative engineers
- Rode hardware evolution



Facilitated wild evolution

Created

- whole new ecosystem
- completely opposite

Why?

Architecture

Layered architectures

Essentials

Deconstrained
(Applications)

Few global variables

Don't cross layers

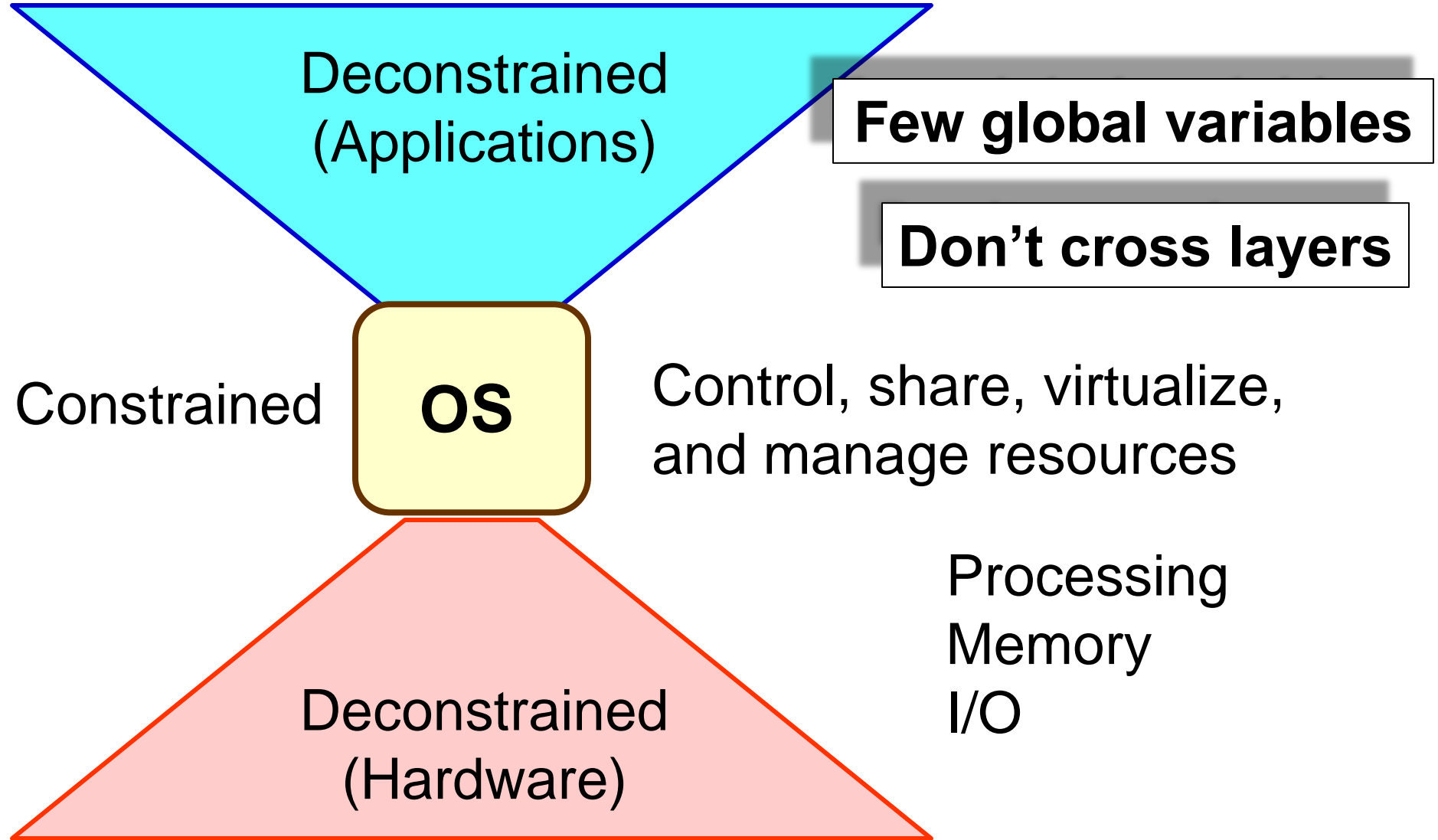
Constrained

OS

Control, share, virtualize,
and manage resources

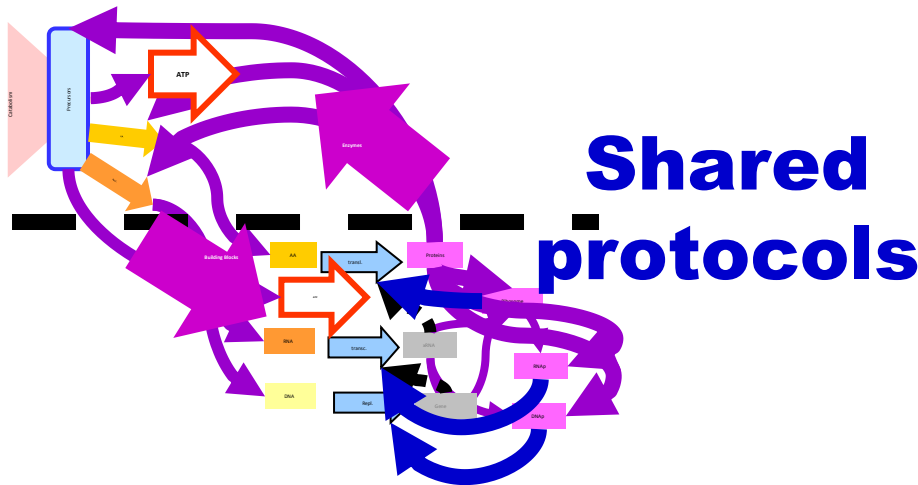
Processing
Memory
I/O

Deconstrained
(Hardware)



Layered architectures

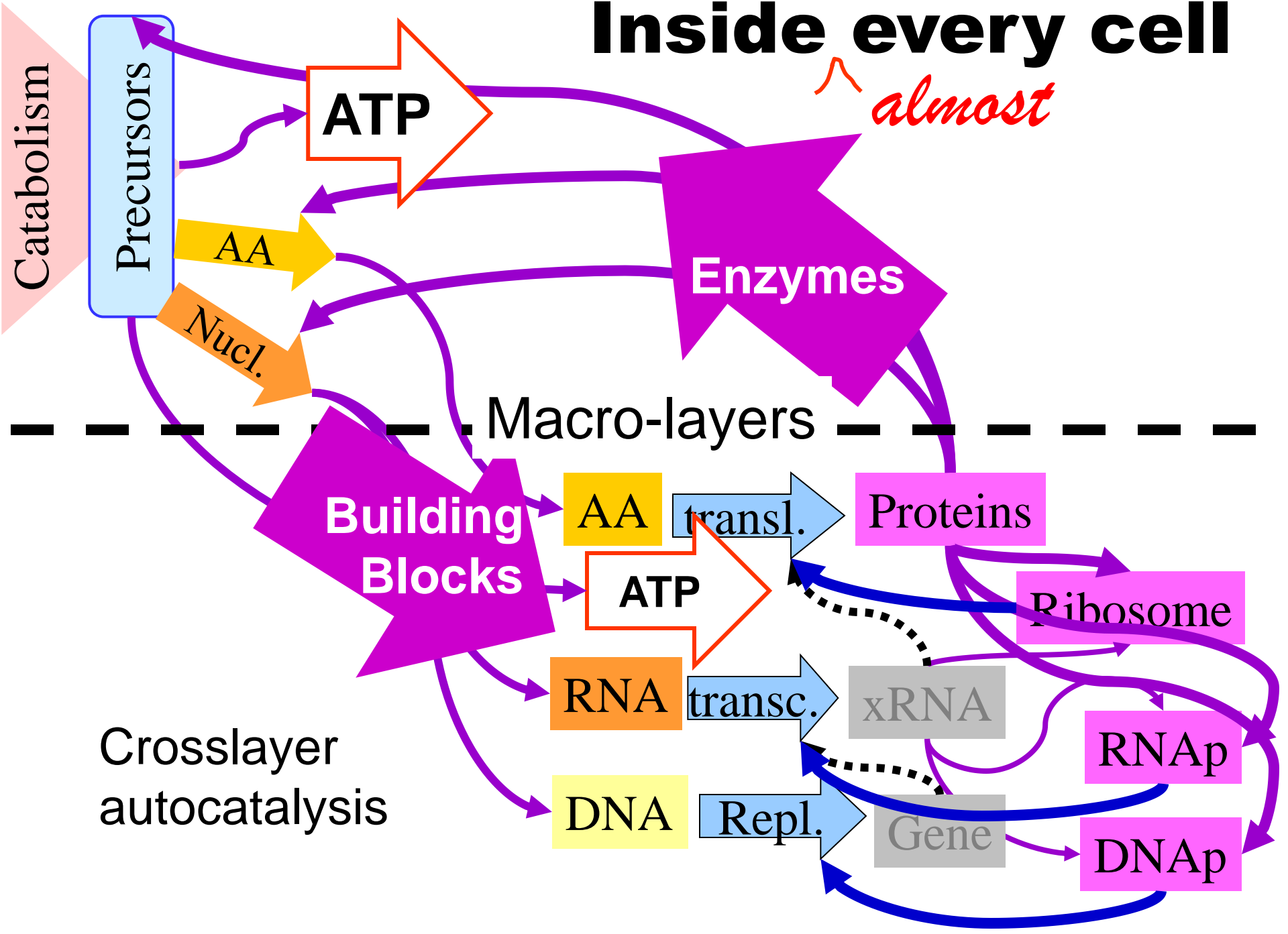
Deconstrained
(diverse)
Environments



Bacterial biosphere

Architecture
=
Constraints
that
Deconstrain

Inside every cell



What makes the bacterial biosphere so adaptable?

Deconstrained phenotype

Environment

Action

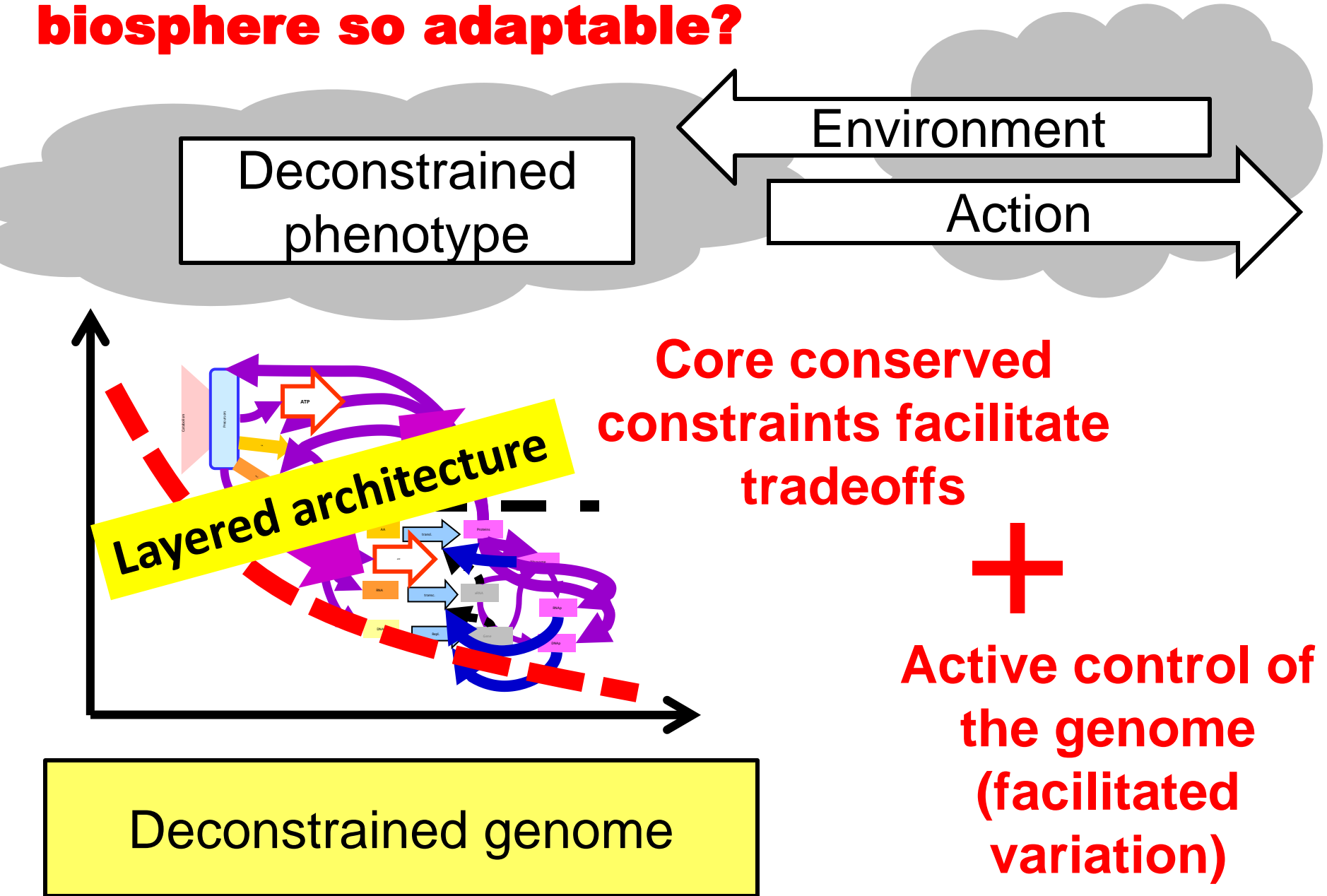
Core conserved constraints facilitate tradeoffs

+

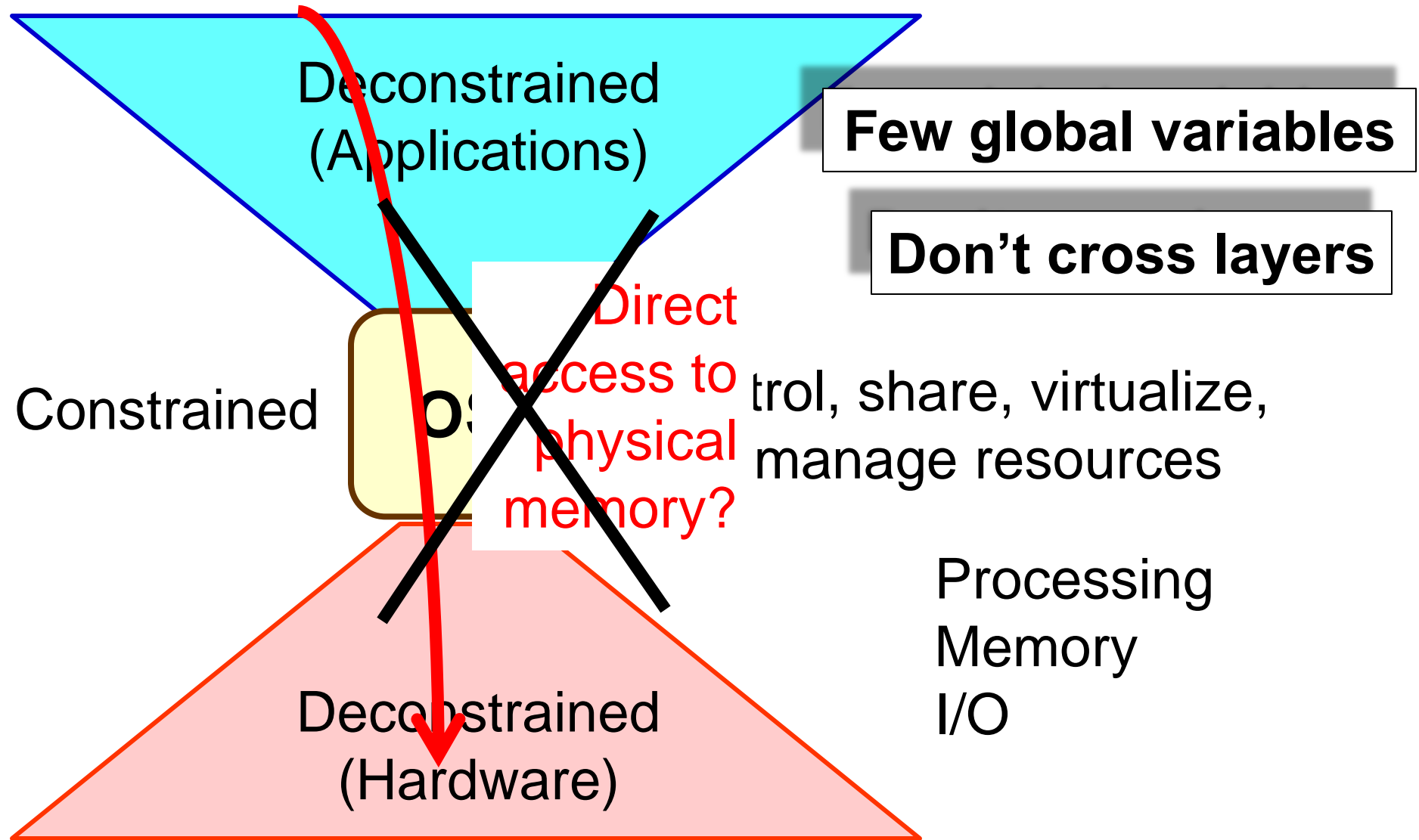
Active control of the genome (facilitated variation)

Layered architecture

Deconstrained genome



Layered architectures



Bacterial biosphere

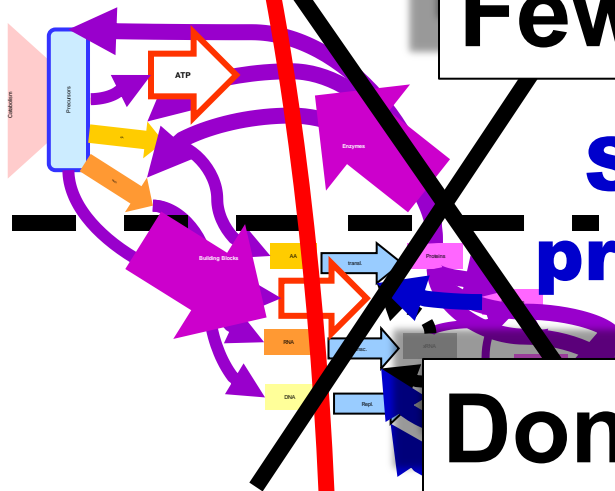
Deconstrained
(diverse)
Environments

Few global variables

Shared
protocols

Don't cross layers

Deconstrained (diverse)
Genomes



Problems with *leaky* layering

Modularity benefits are lost

- Global variables? @\$%*&!^% @&
- Poor portability of applications
- Insecurity of physical address space
- Fragile to application crashes
- No scalability of virtual/real addressing
- Limits optimization/control by duality?

Fragilities of layering/virtualization

“Universal” fragilities that must be avoided

- Hijacking, parasitism, predation
 - Universals are vulnerable
 - Universals are valuable
- Cryptic, hidden
 - breakdowns/failures
 - unintended consequences
- Hyper-evolvable but with frozen core

Layered architectures

Deconstrained
(Applications)

Few global variables?

Don't cross layers?

**TCP/
IP**

Control, share, virtualize,
and manage resources

I/O
Comms
Latency?
Storage?
Processing?

Deconstrained
(Hardware)

Constrained

IPC

App

App

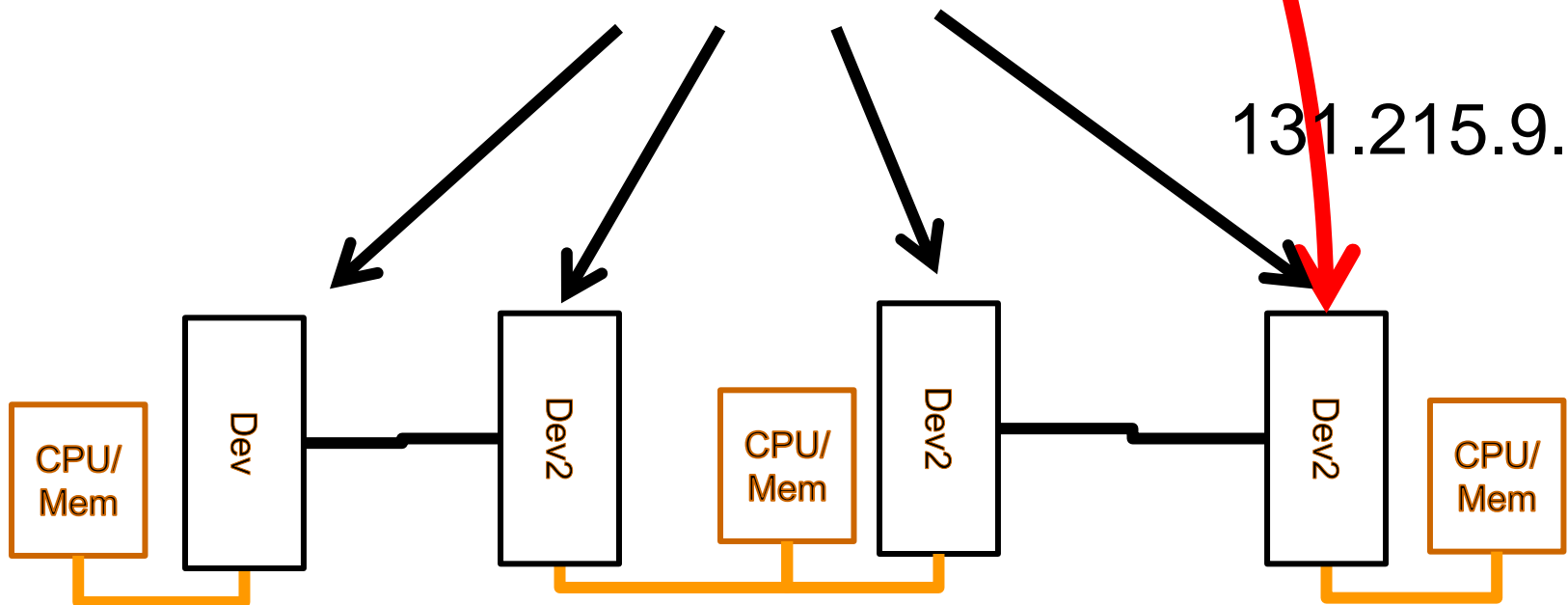
caltech.edu?

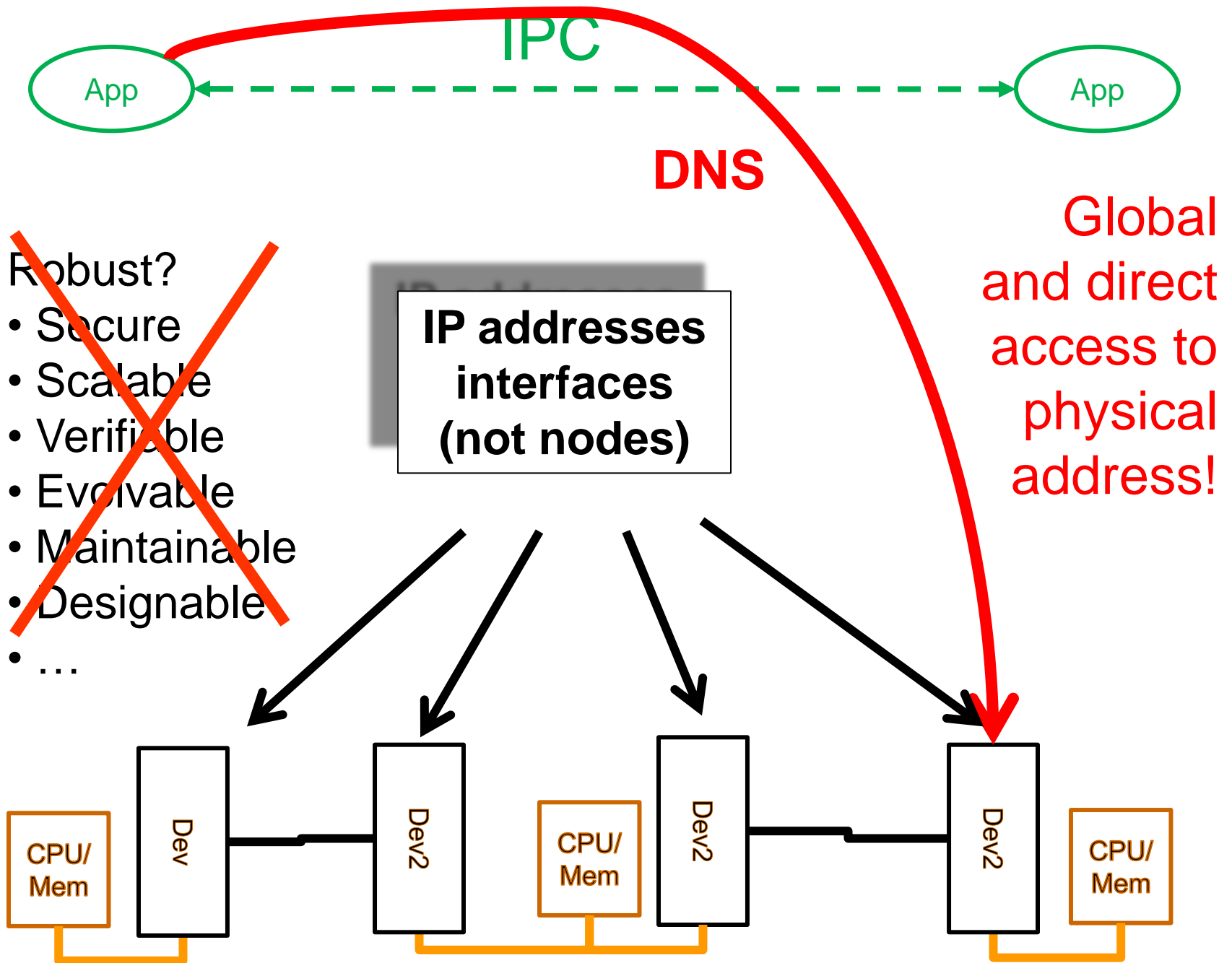
DNS

IP addresses
interfaces
(not nodes)

Global
and direct
access to
physical
address!

131.215.9.49



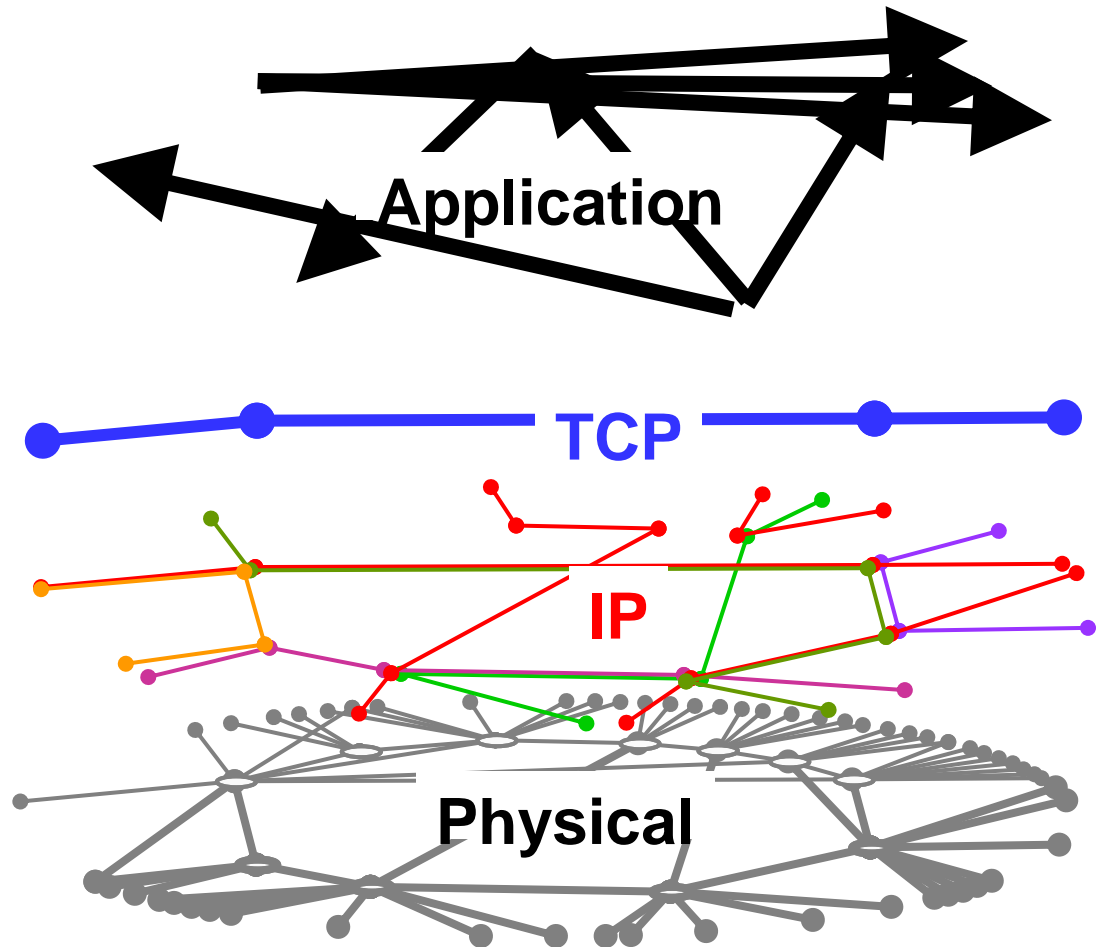


Naming and addressing need to be

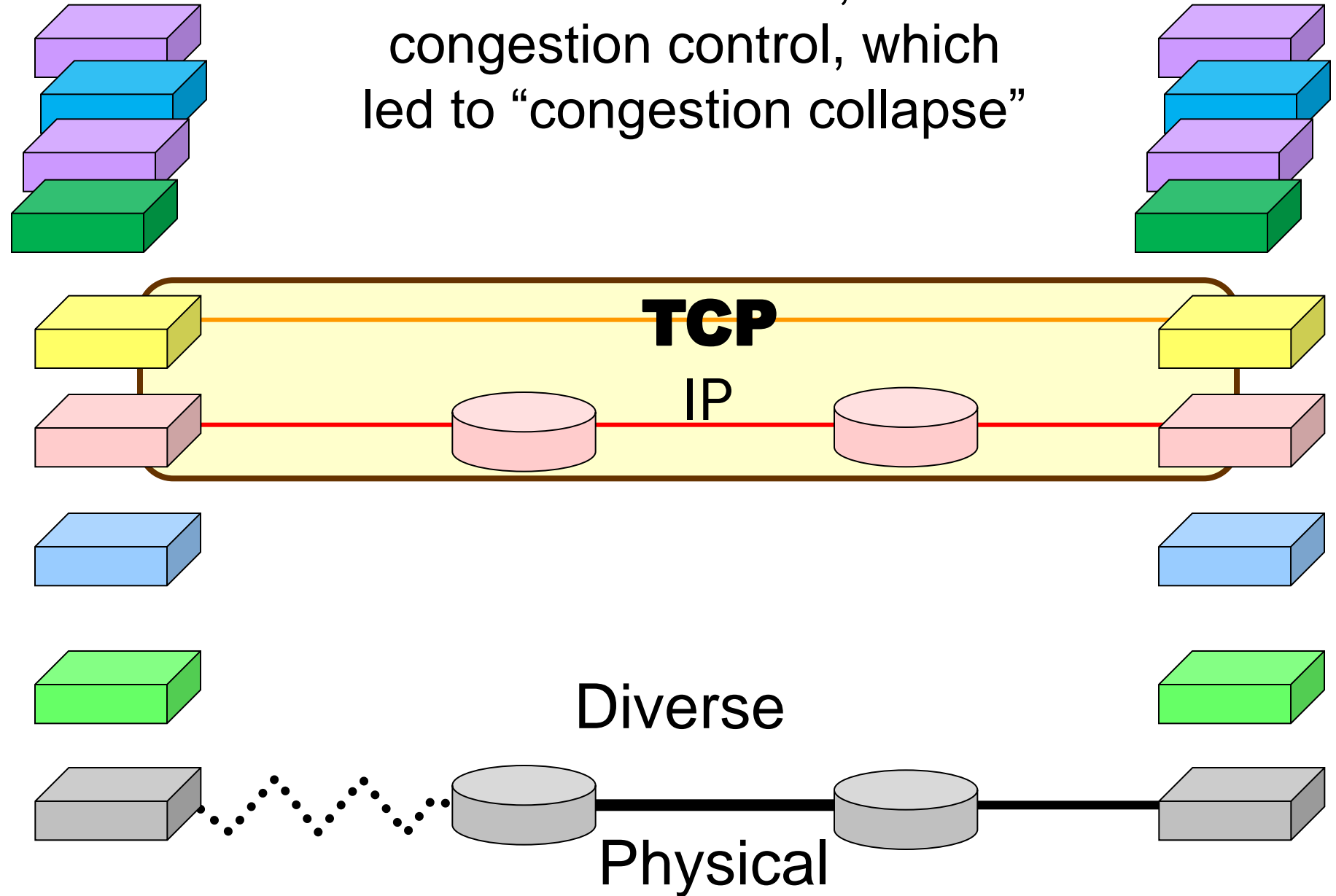
- resolved within layer
- translated between layers
- not exposed outside of layer

Related “issues”

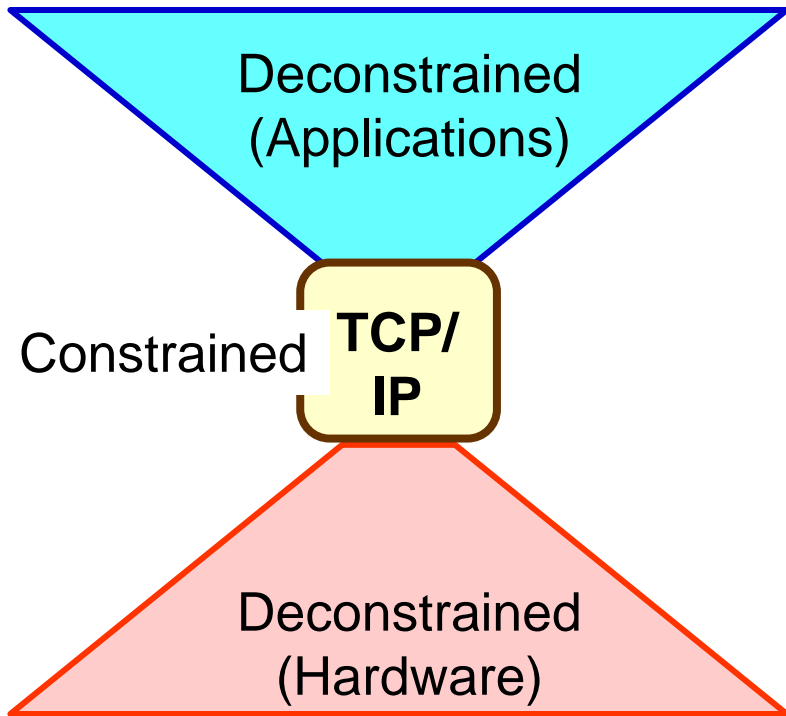
- VPNs
- NATS
- Firewalls
- Multihoming
- Mobility
- Routing table size
- Overlays
- ...



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



Original design challenge?



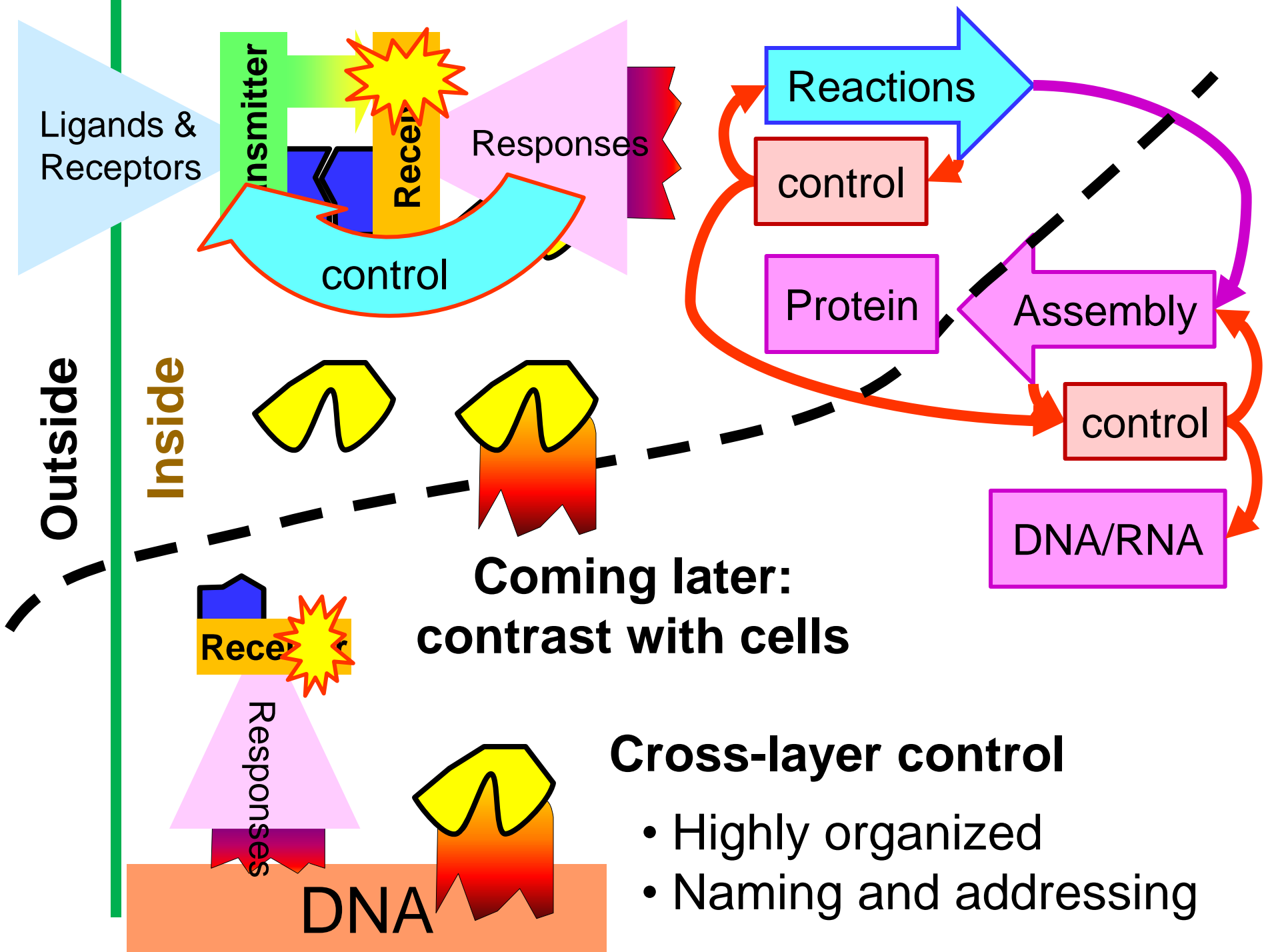
Networked OS

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

Facilitated wild evolution

Created

- whole new ecosystem
- completely opposite



Next layered architectures

Deconstrained
(Applications)

Few global variables

Don't cross layers

?

Control, share, virtualize,
and manage resources

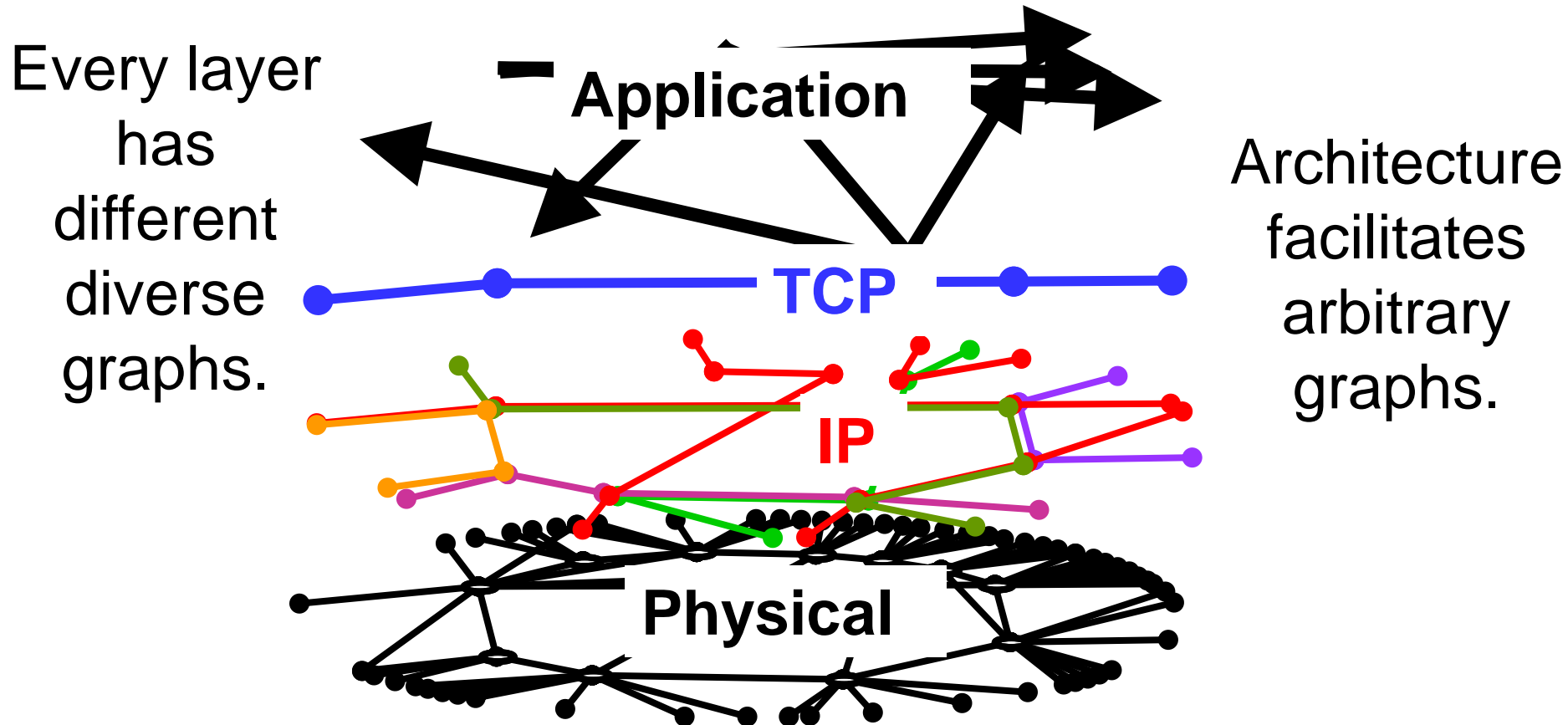
Deconstrained
(Hardware)

Comms
Memory, storage
Latency
Processing
Cyber-physical

Constrained

**Persistent errors
and confusion
("network science")**

Architecture is *least*
graph topology.



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

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

