Universal laws and architecture:

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

Accident or necessity?

Human complexity

Robust	Yet Fragile
☺ Metabolism	☹ Obesity, diabetes
☺ Regeneration & repair	☹ Cancer
☺ Immune/inflammation	☹ AutoImmune/Inflame
☺ Microbe symbionts	☹ Parasites, infection
☺	…,…
	…%$#
Risk "management"	Obfuscate, amplify,…

☹ Fat accumulation
☹ Insulin resistance
☹ Proliferation
☹ Inflammation

Accident or necessity?

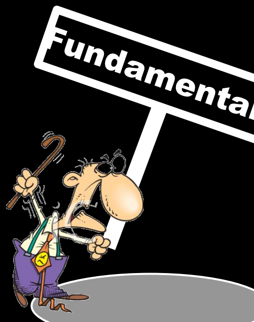
Robust	Fragile
☺ Metabolism	☹ Obesity, diabetes
☺ Regenerati	
☺ Healing wo	une/Inflame

☹ Fat accumulation
☹ Insulin resistance
☹ Proliferation
☹ Inflammation

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

Both

Accident or necessity?

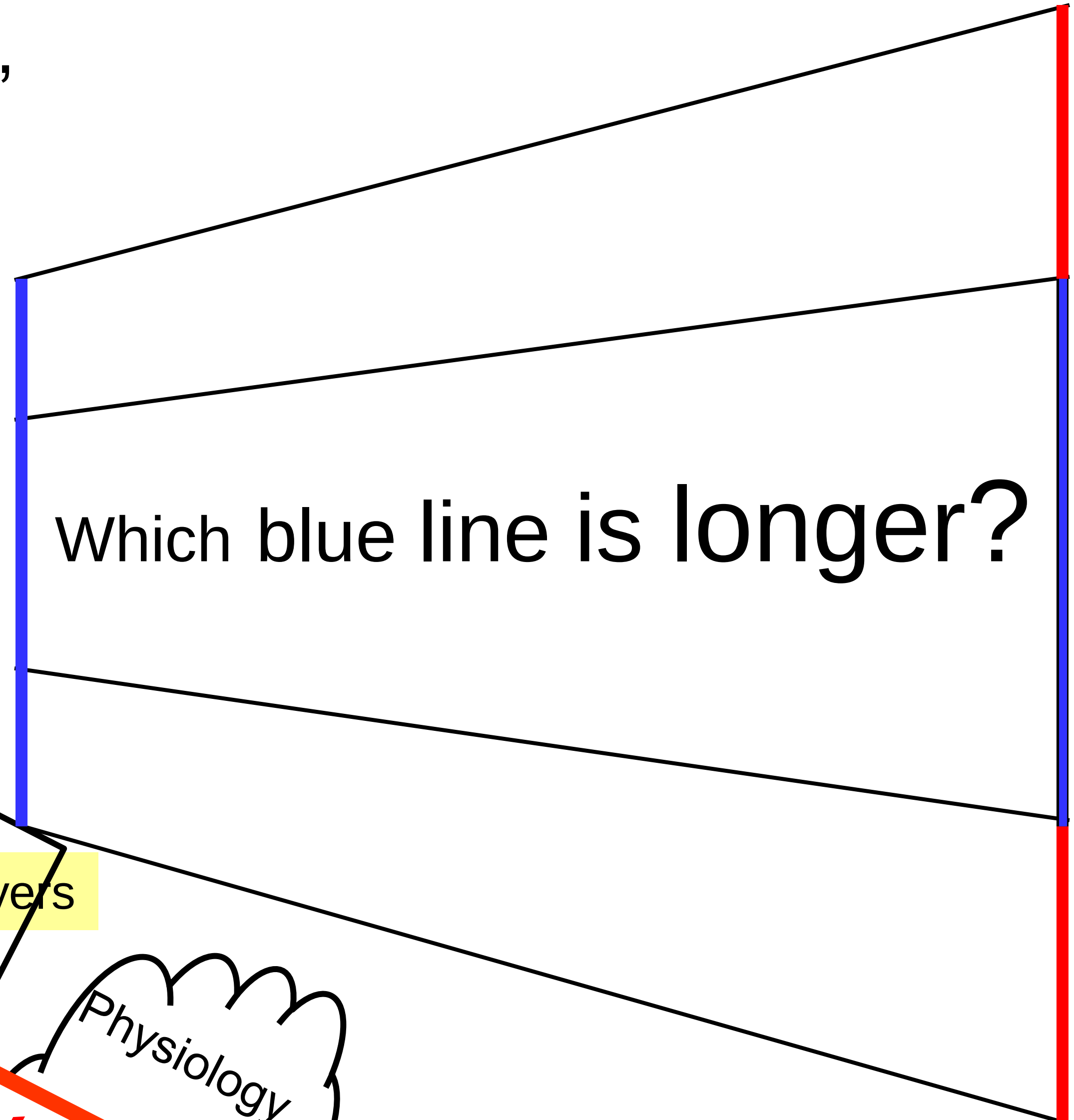


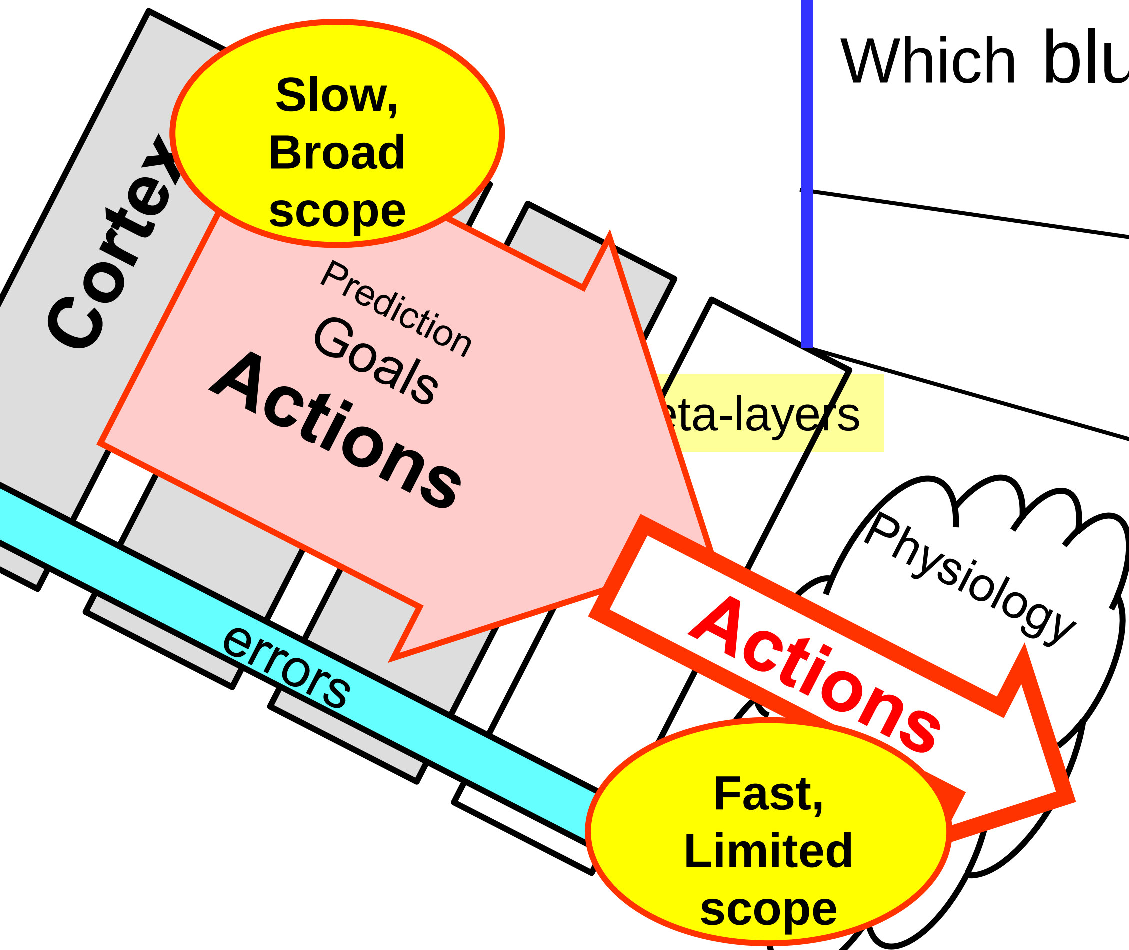
Robust		Fragile
Modular	*and*	Distributed
Simple	~~***xor***~~	Complex
Plastic		Frozen
Evolvable		Frozen

tradeoffs

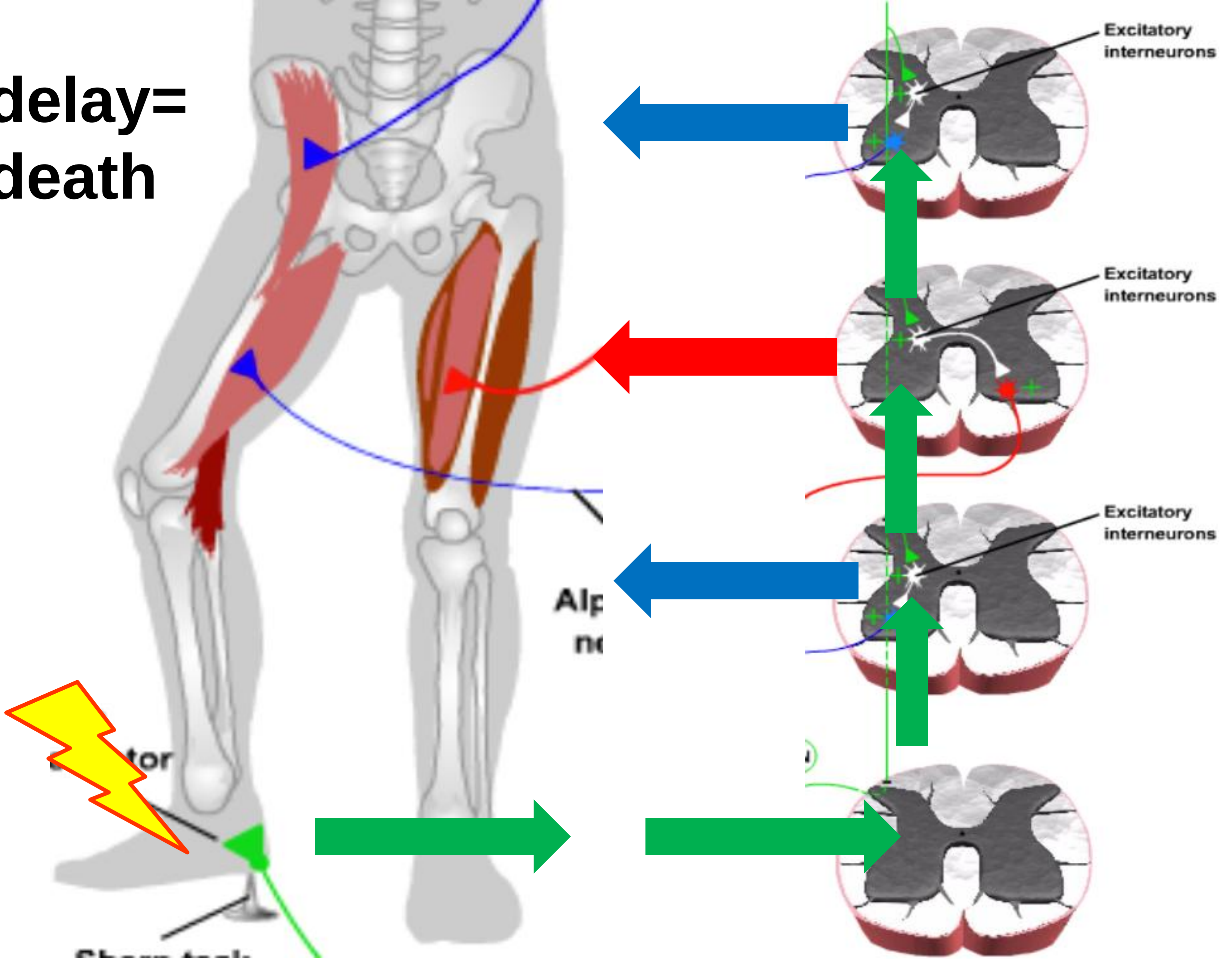
"Seeing is dreaming?"

"Seeing is believing?"

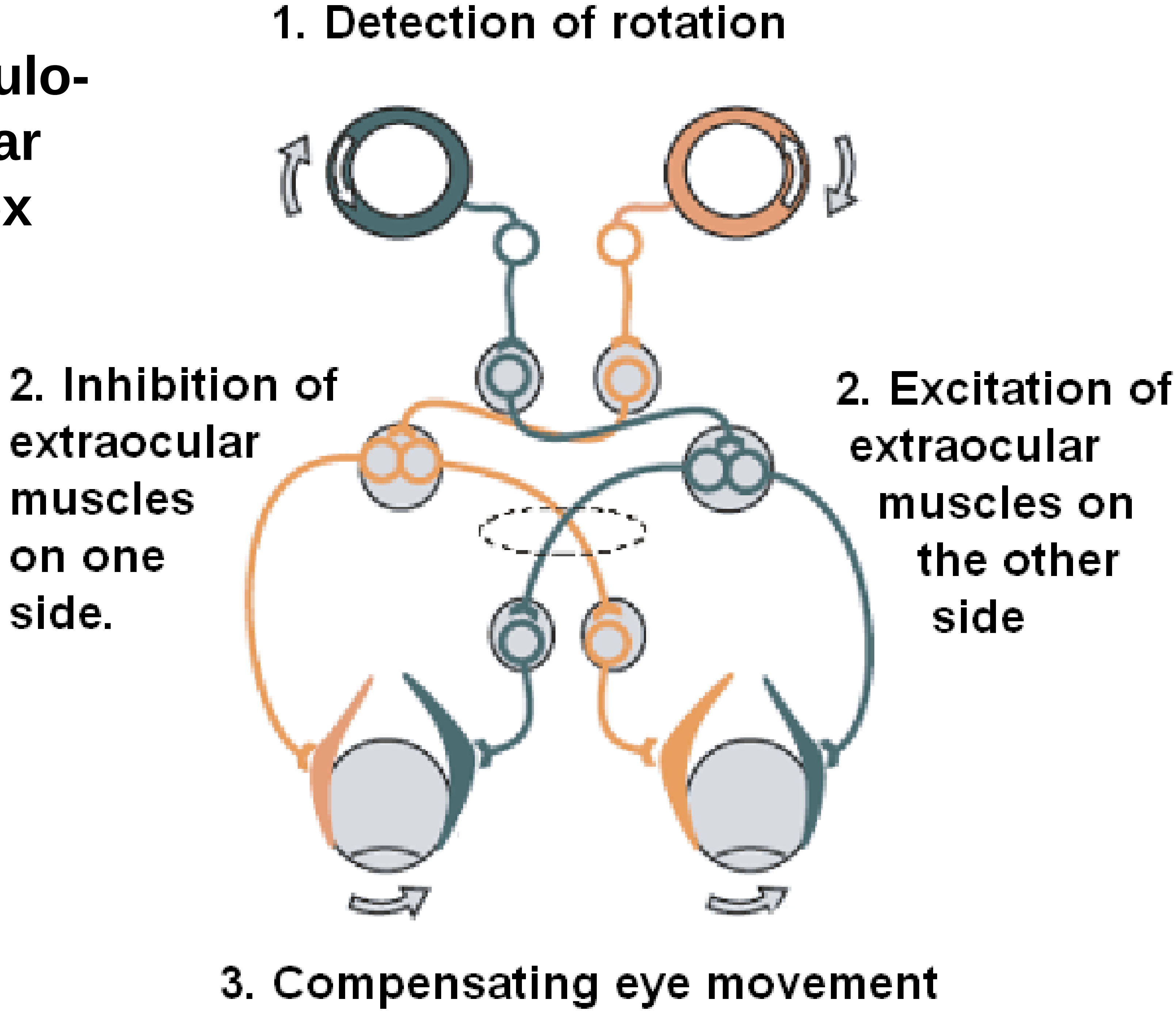


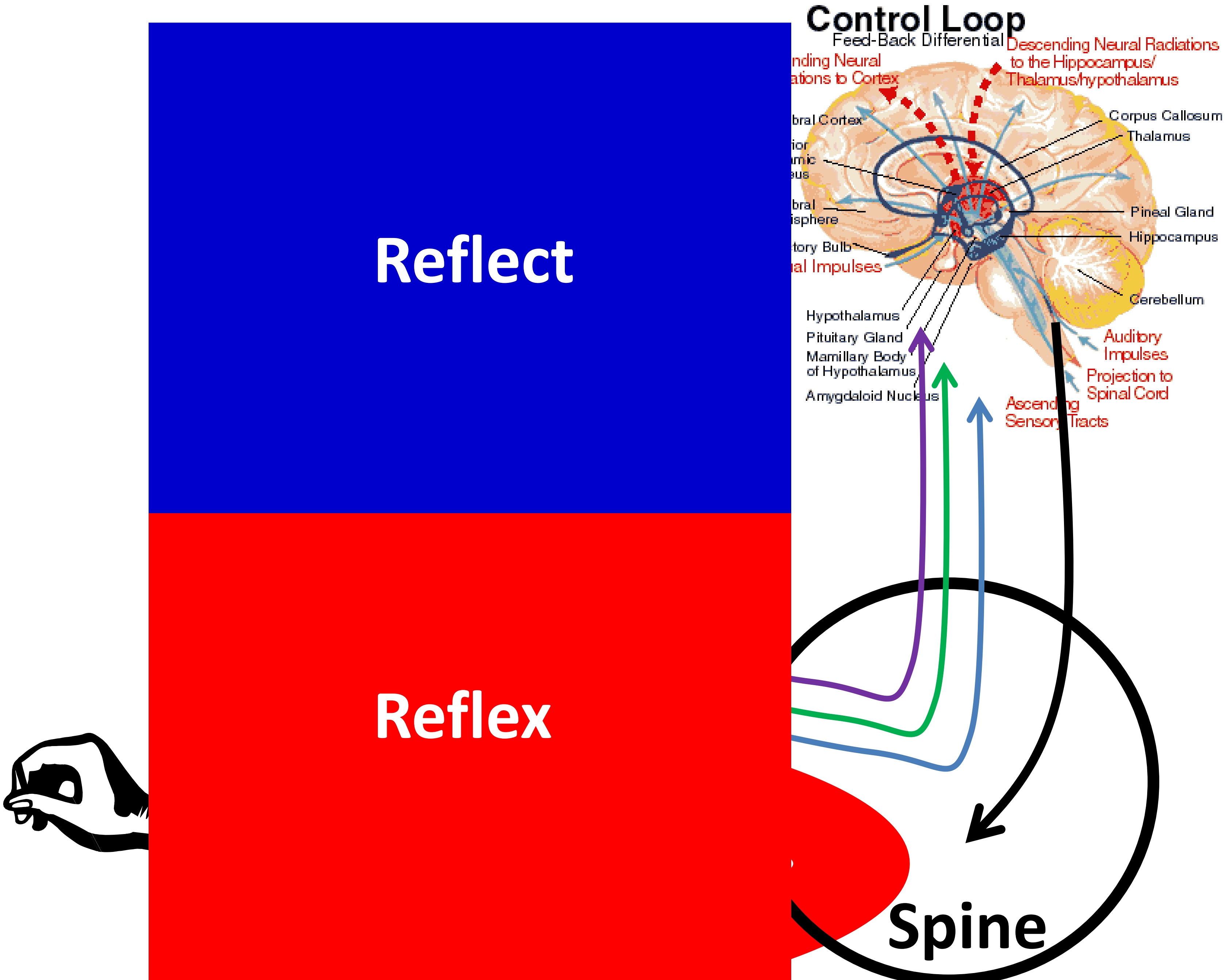


delay=
death


Excitatory interneurons
Excitatory interneurons
Excitatory interneurons

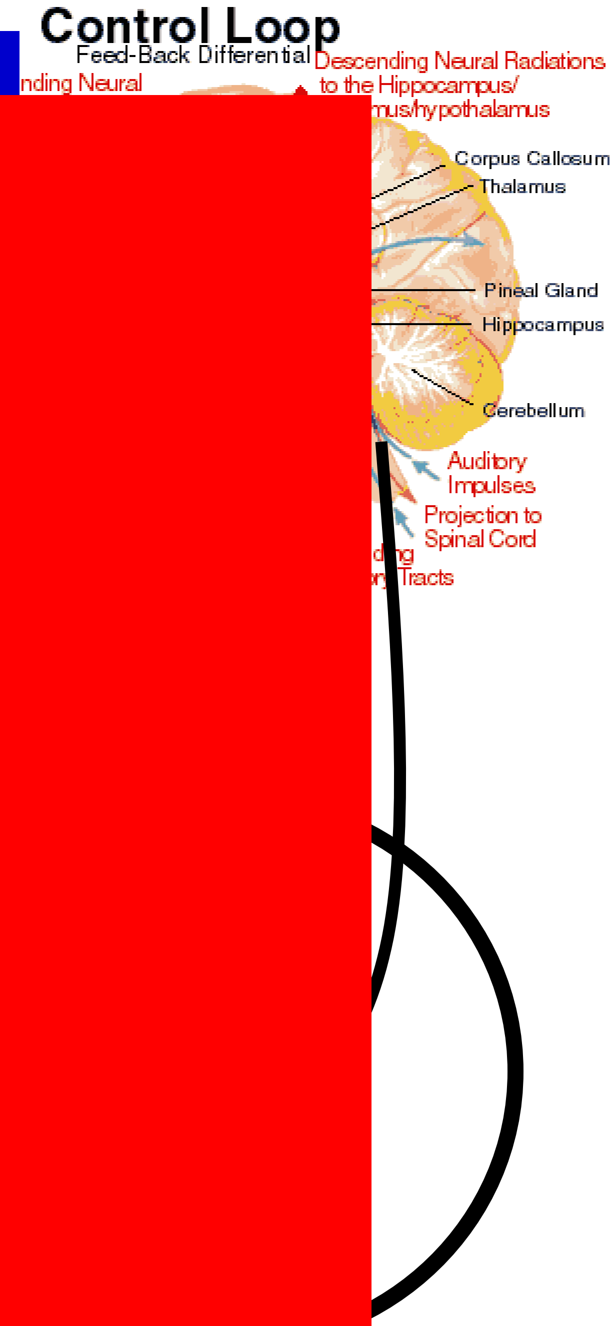
Vestibulo-ocular reflex



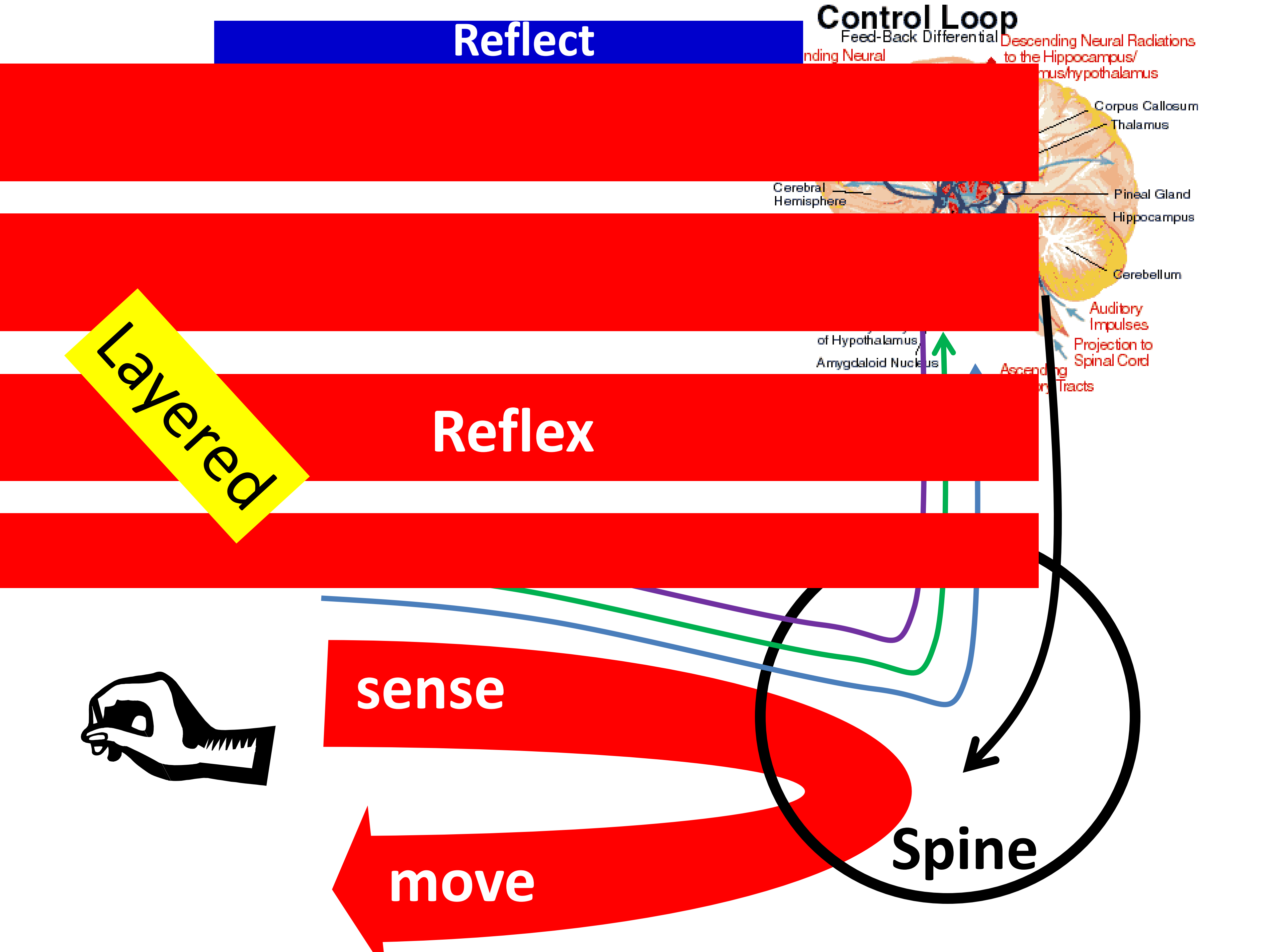


Reflect
Reflex
Control Loop
Feed-Back Differential
Descending Neural Radiations to the Hippocampus/ Thalamus/hypothalamus
Corpus Callosum
Thalamus
Pineal Gland
Hippocampus
Cerebellum
Hypothalamus
Pituitary Gland
Mamillary Body of Hypothalamus
Amygdaloid Nucleus
Auditory Impulses
Projection to Spinal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

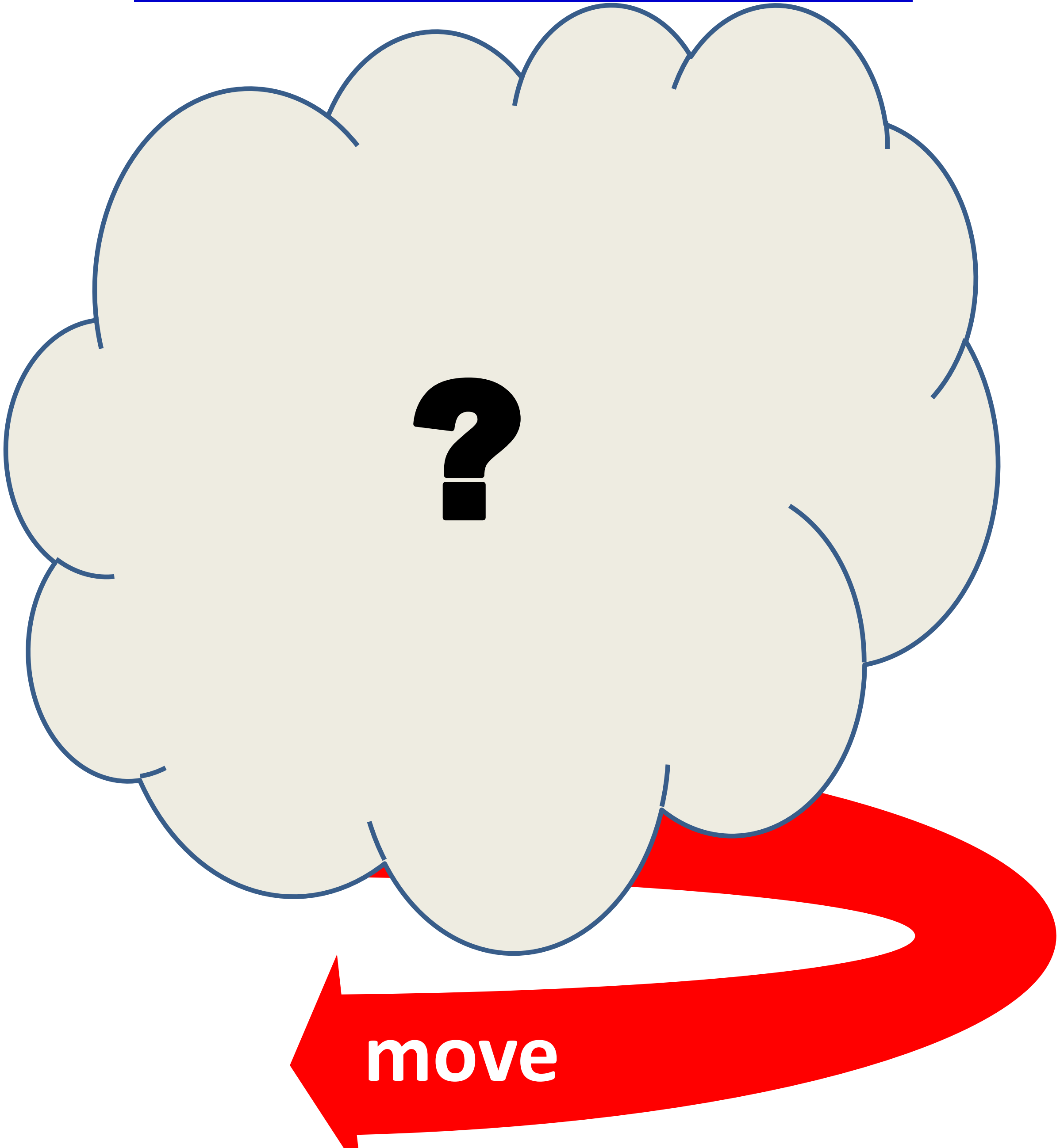
Reflect



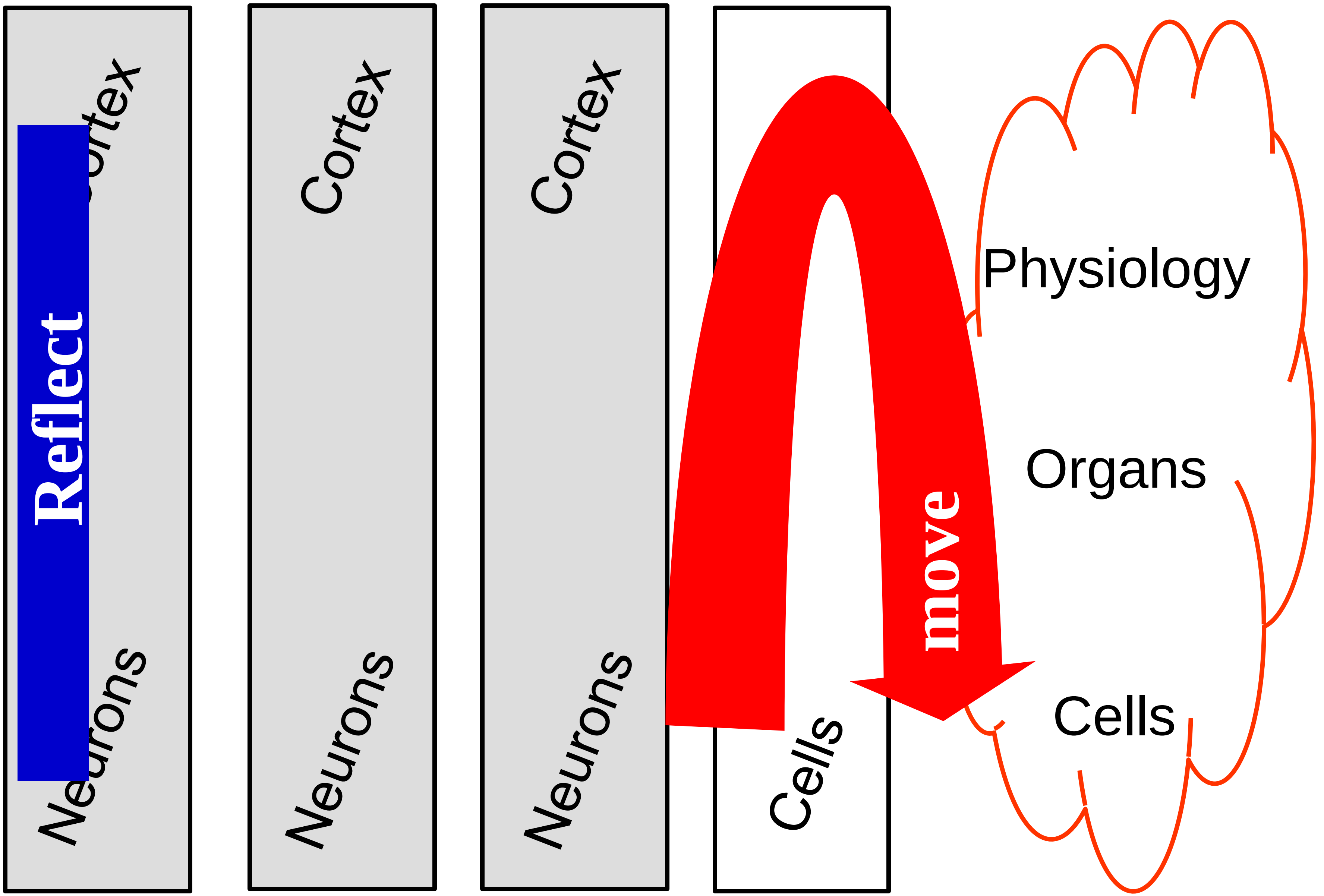
Reflex

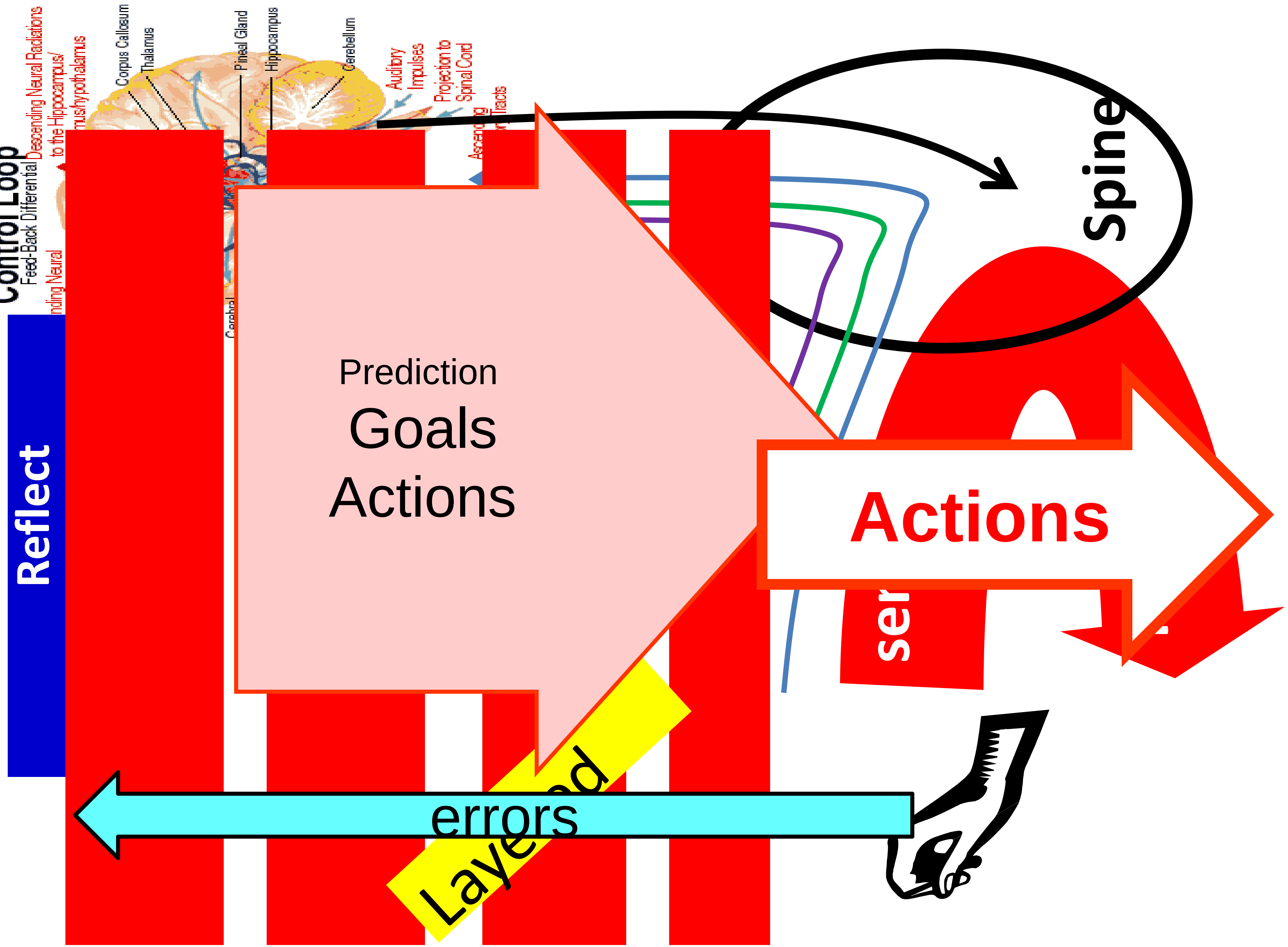

Reflect
Control Loop
Feed-Back Differential
Descending Neural Radiations
to the Hippocampus/
Corpus Callosum
Thalamus
Cerebral
Hemisphere
Pineal Gland
Hippocampus
Cerebellum
Auditory
Impulses
Projection to
Spinal Cord
of Hypothalamus
Amygdaloid Nucleus
Layered
Reflex
sense
move
Spine

Reflect

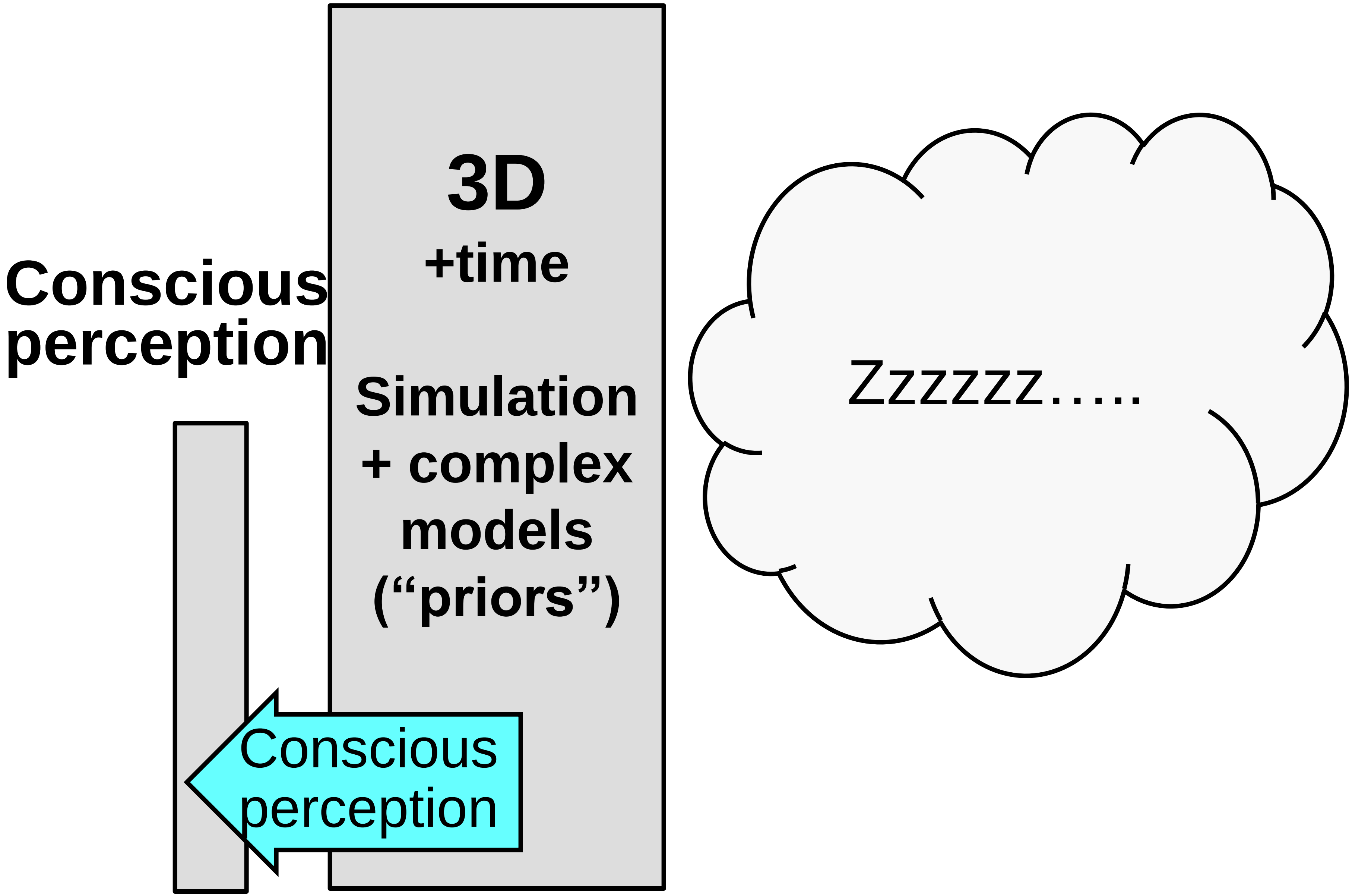


Layered architectures



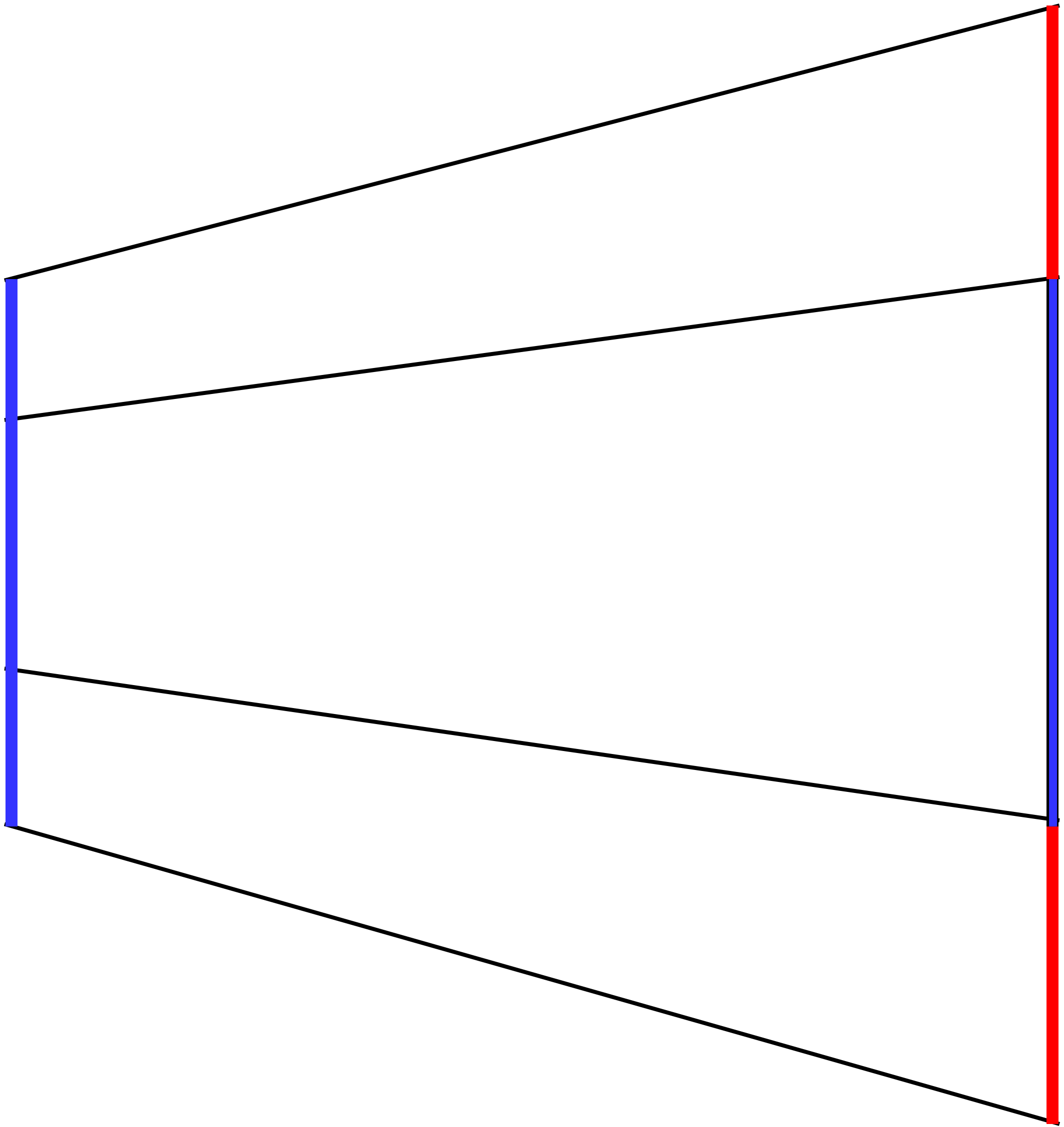

Prediction
Goals
Actions
Actions
Spine
Reflect
errors
Layered
Control Loop
Feed-Back Differential
Descending Neural Radiations to the Hippocampus/
Corpus Callosum
Thalamus
Pineal Gland
Hippocampus
Cerebellum
Auditory Impulses
Projection to Spinal Cord

Seeing is ***dreaming***

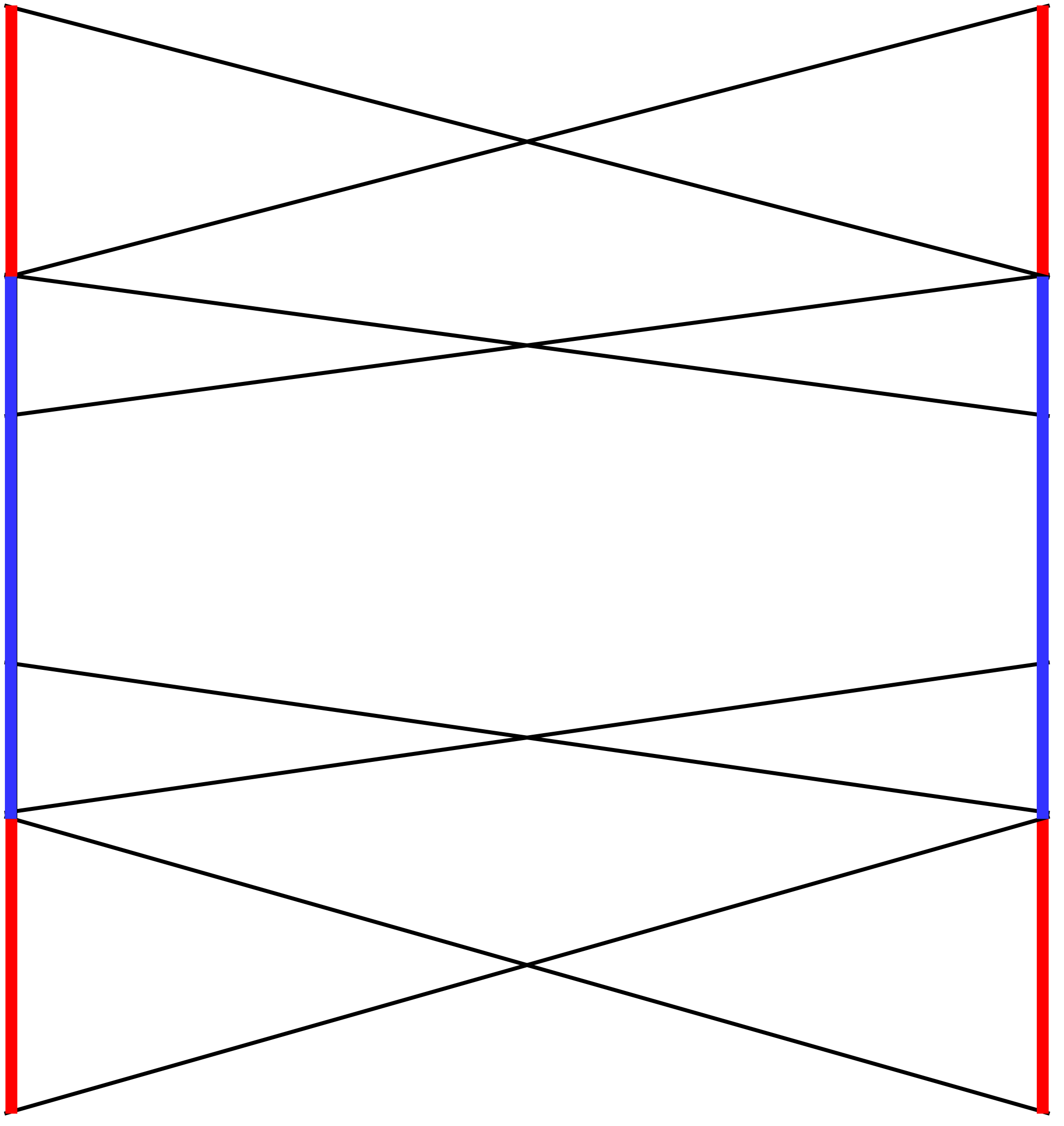


Which blue line is longer?

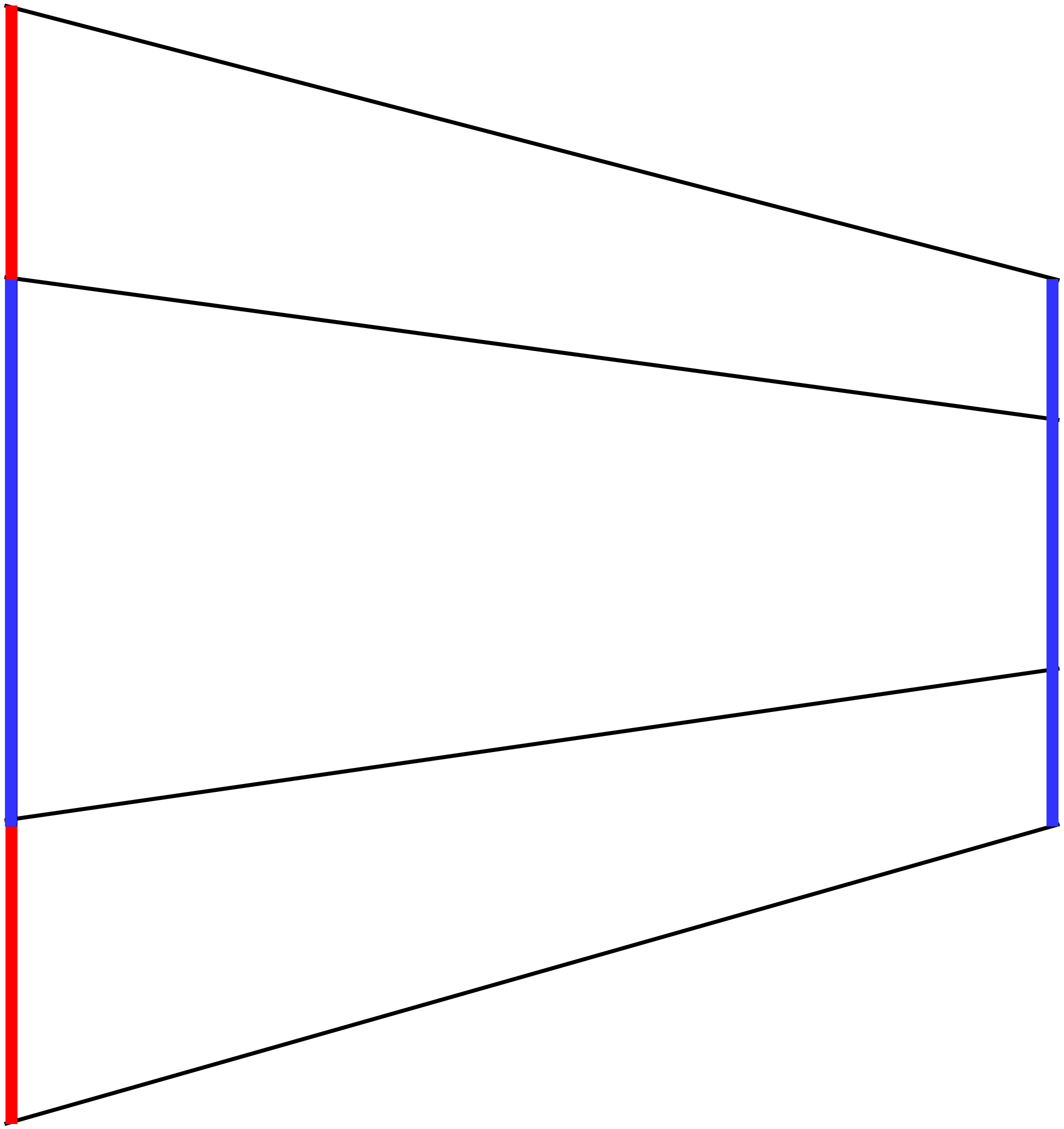
Which blue line is longer?



Which blue line is longer?



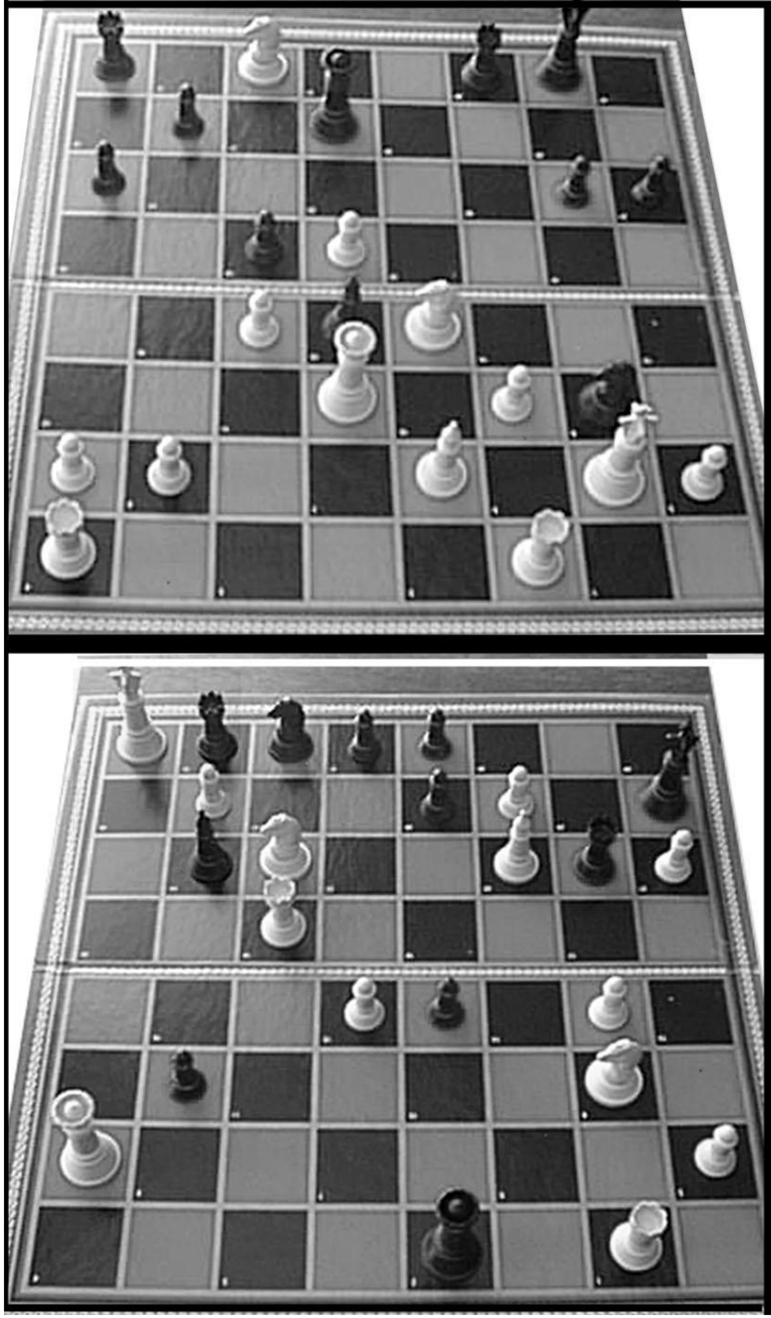
Which blue line is longer?



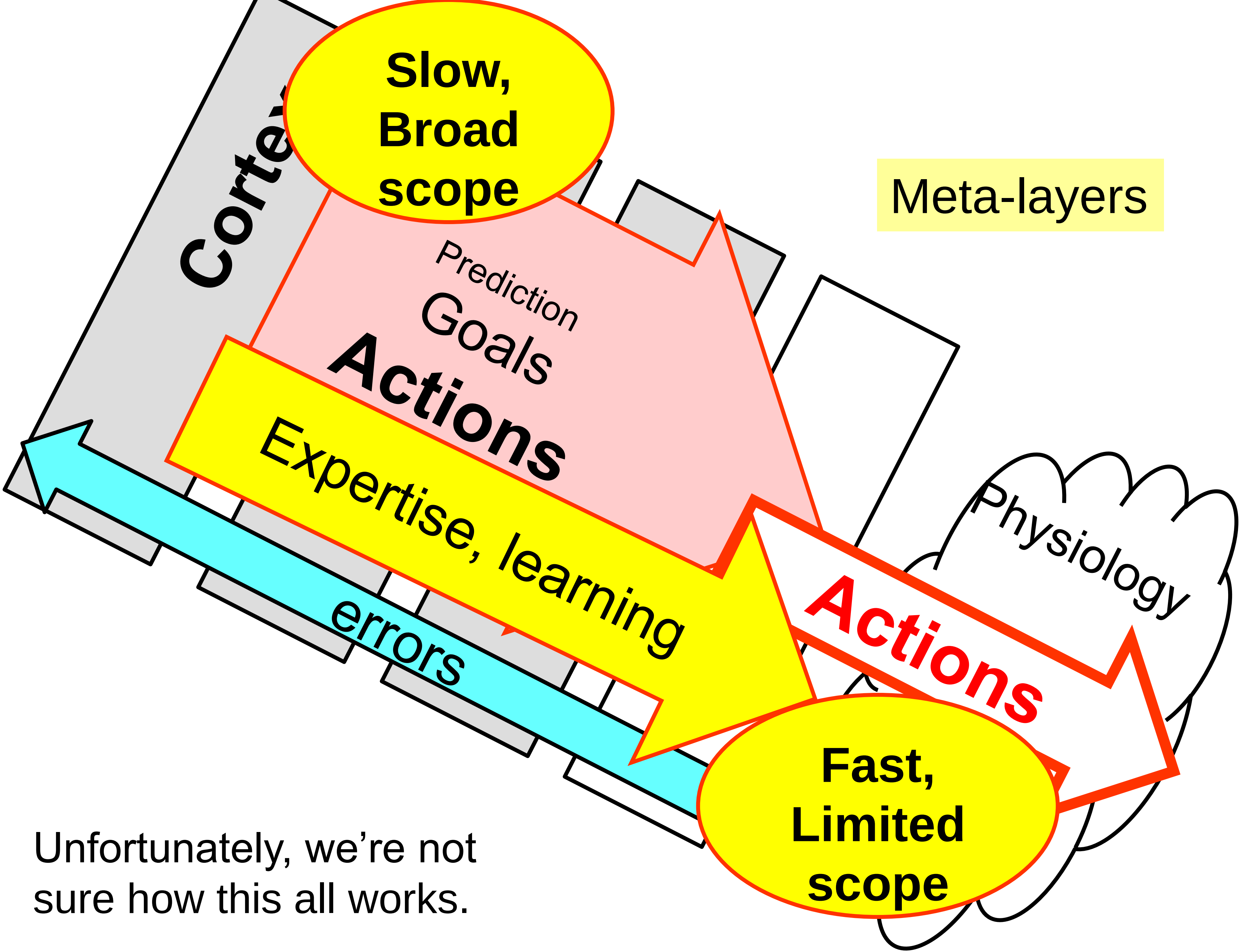

Chess experts

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

(Simon and Gilmartin, de Groot)

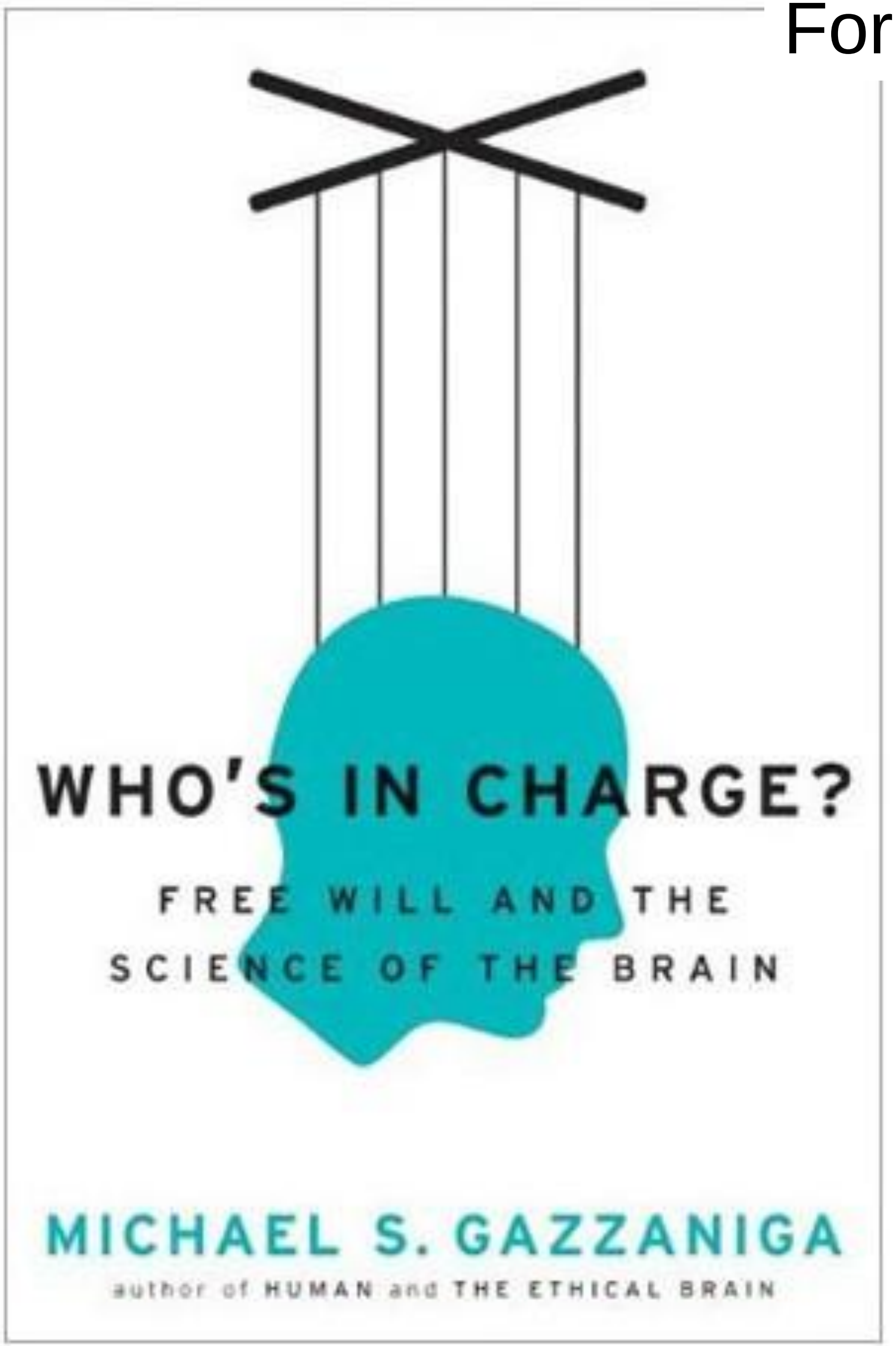


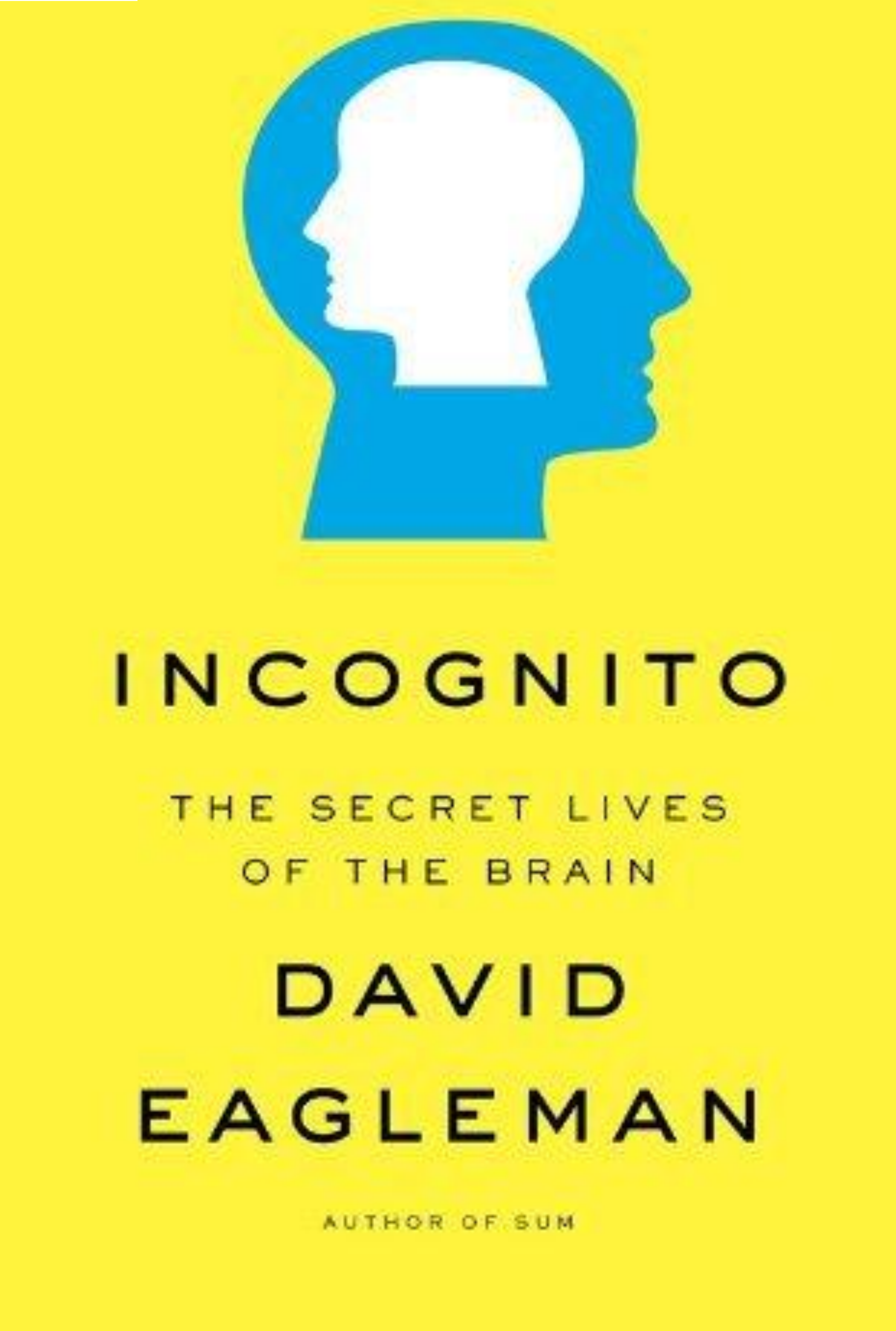
www.psywww.com/intropsych/ch07_cognition/expertise_and_domain_specific_knowledge.html



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

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

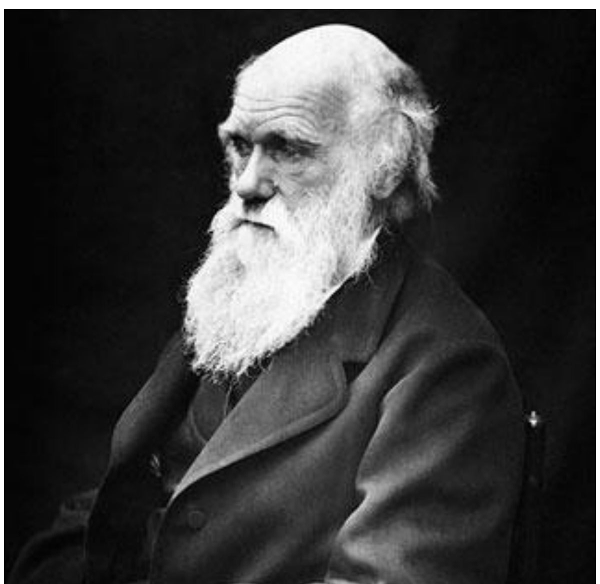
Kirschner and Gerhart

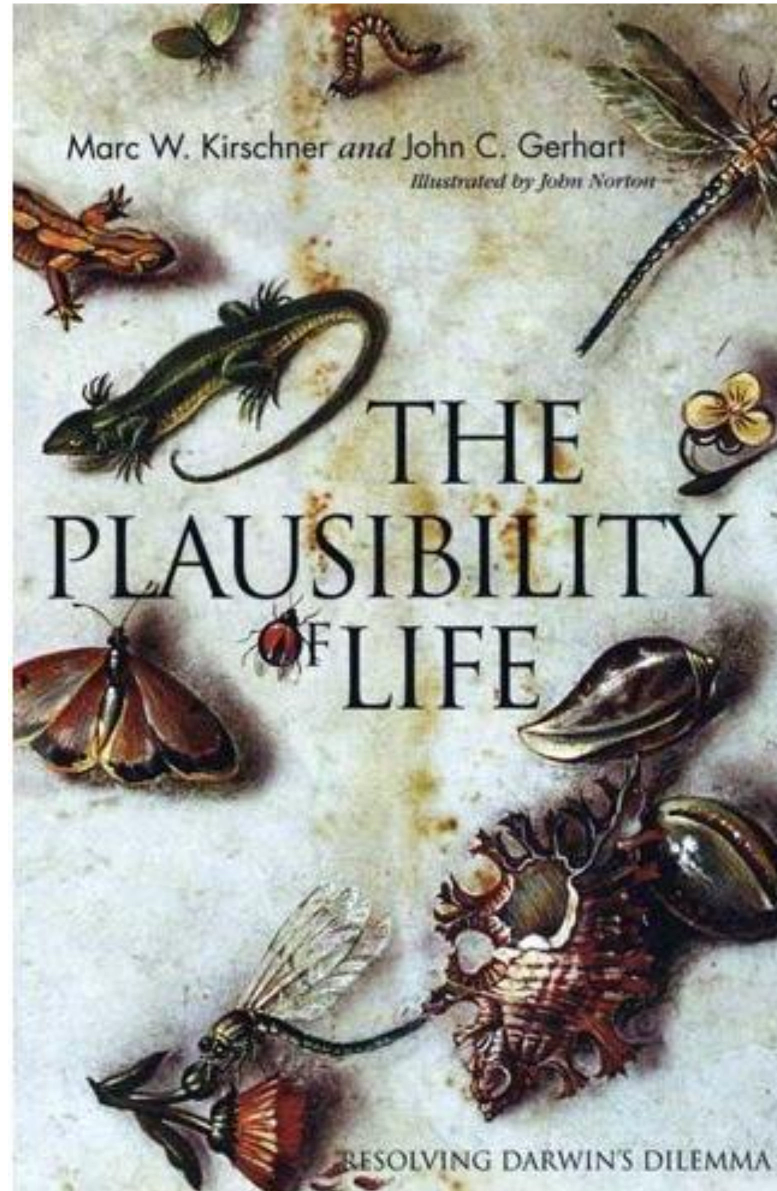
Facilitated variation

Architecture =

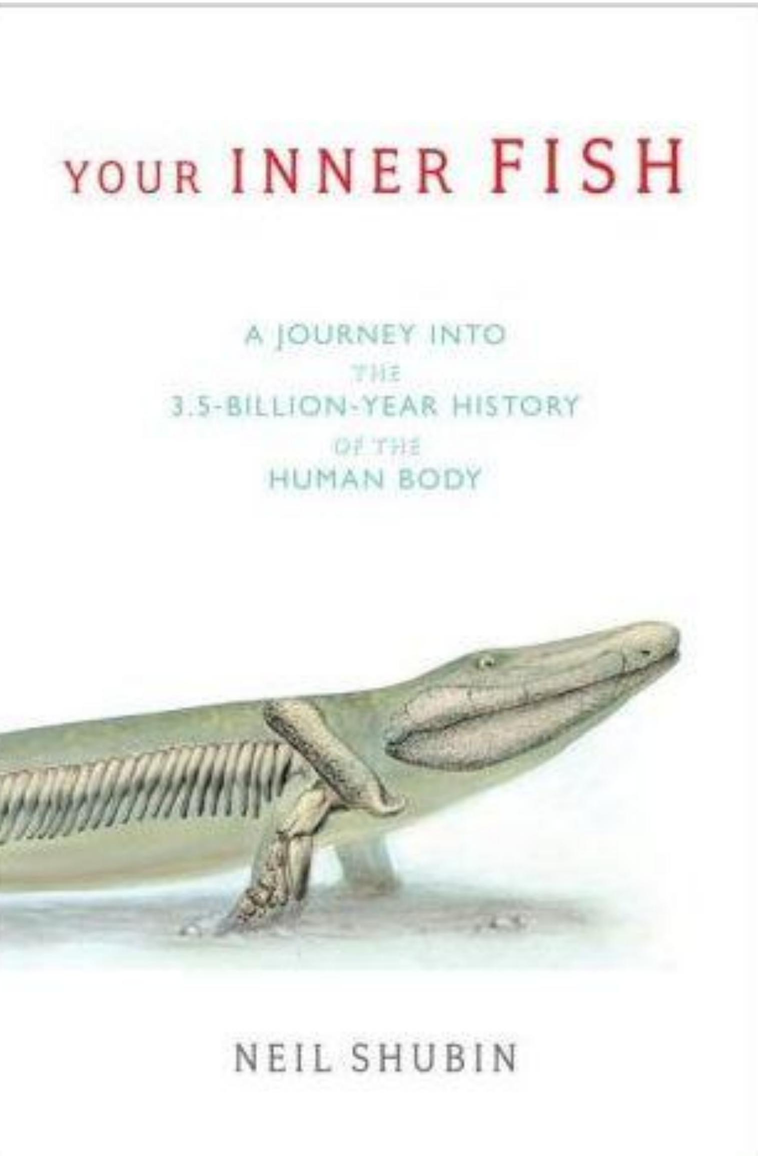
Constraints that deconstrain

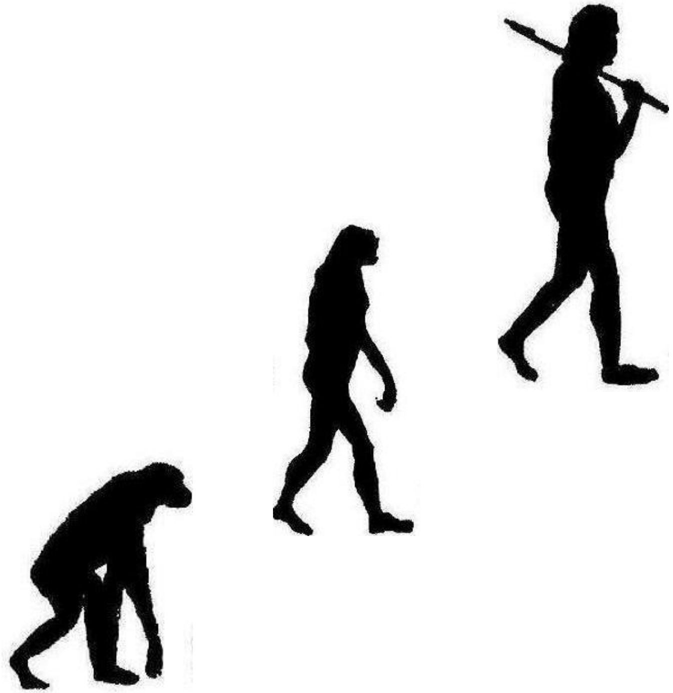
- Weak linkage
- Exploratory mechanisms
- Compartmentalization



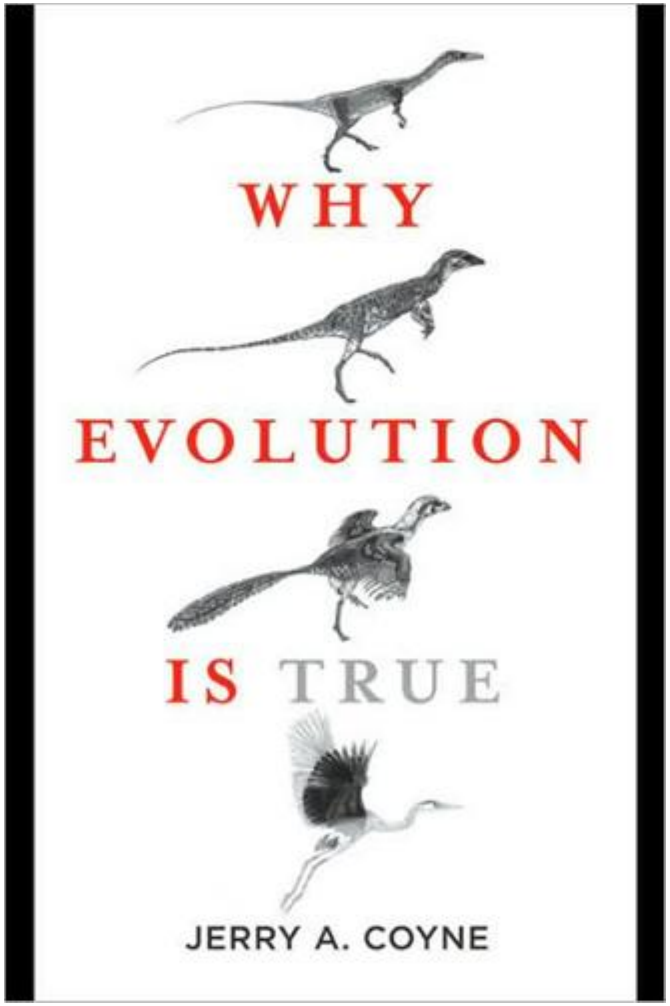


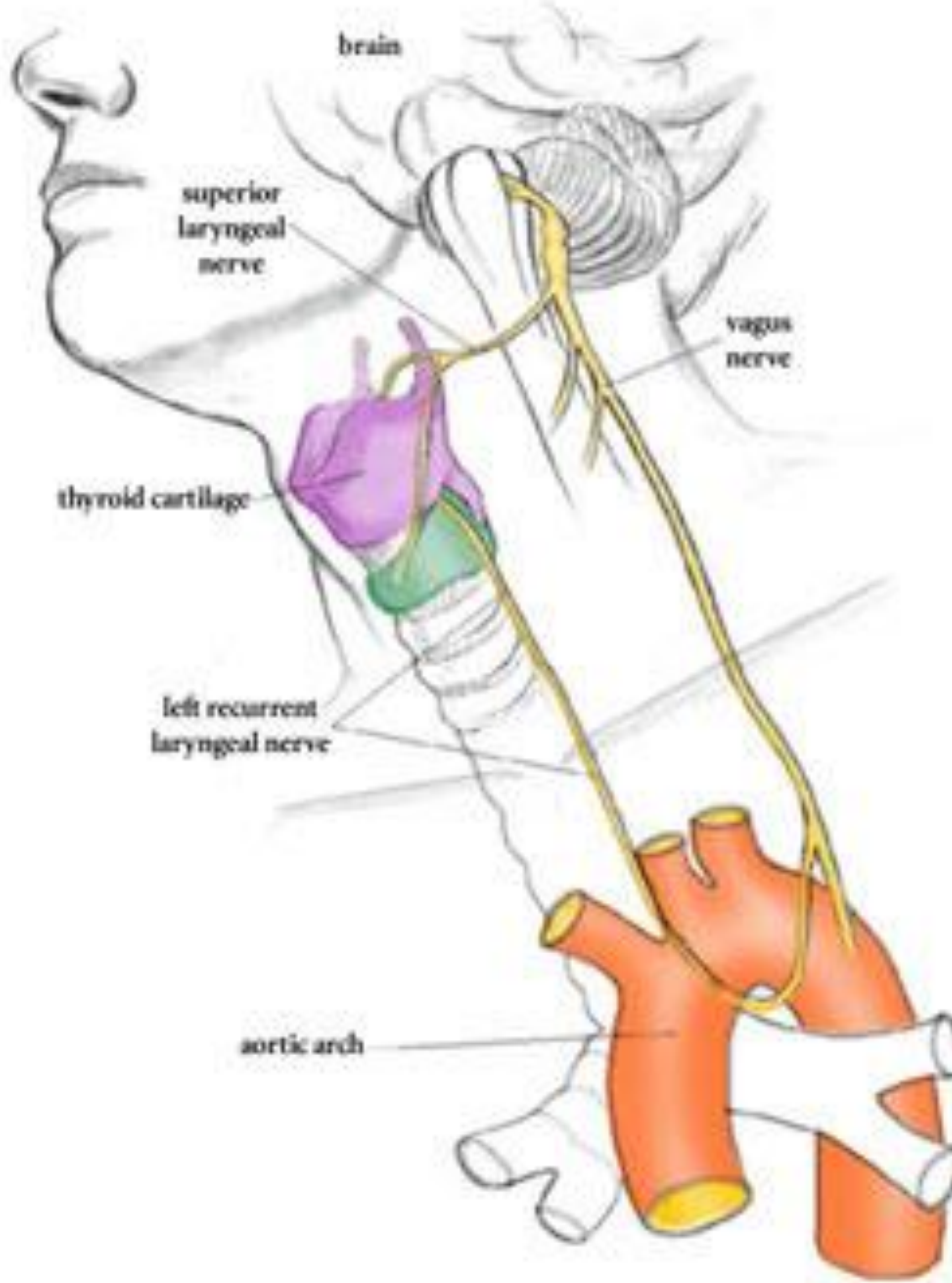
Unfortunately, not intelligent design





Ouch.


WHY
EVOLUTION
IS TRUE
JERRY A. COYNE


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

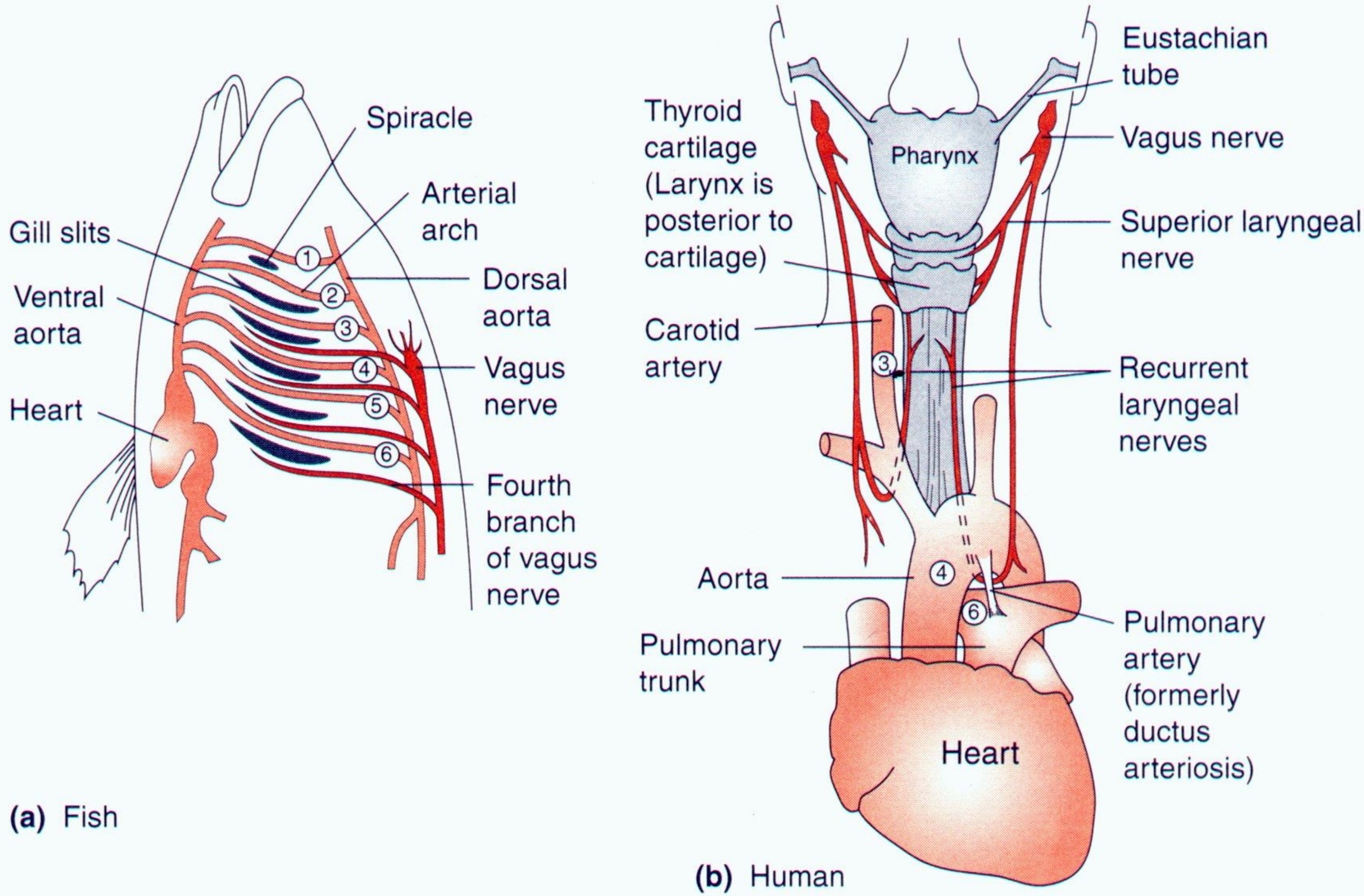
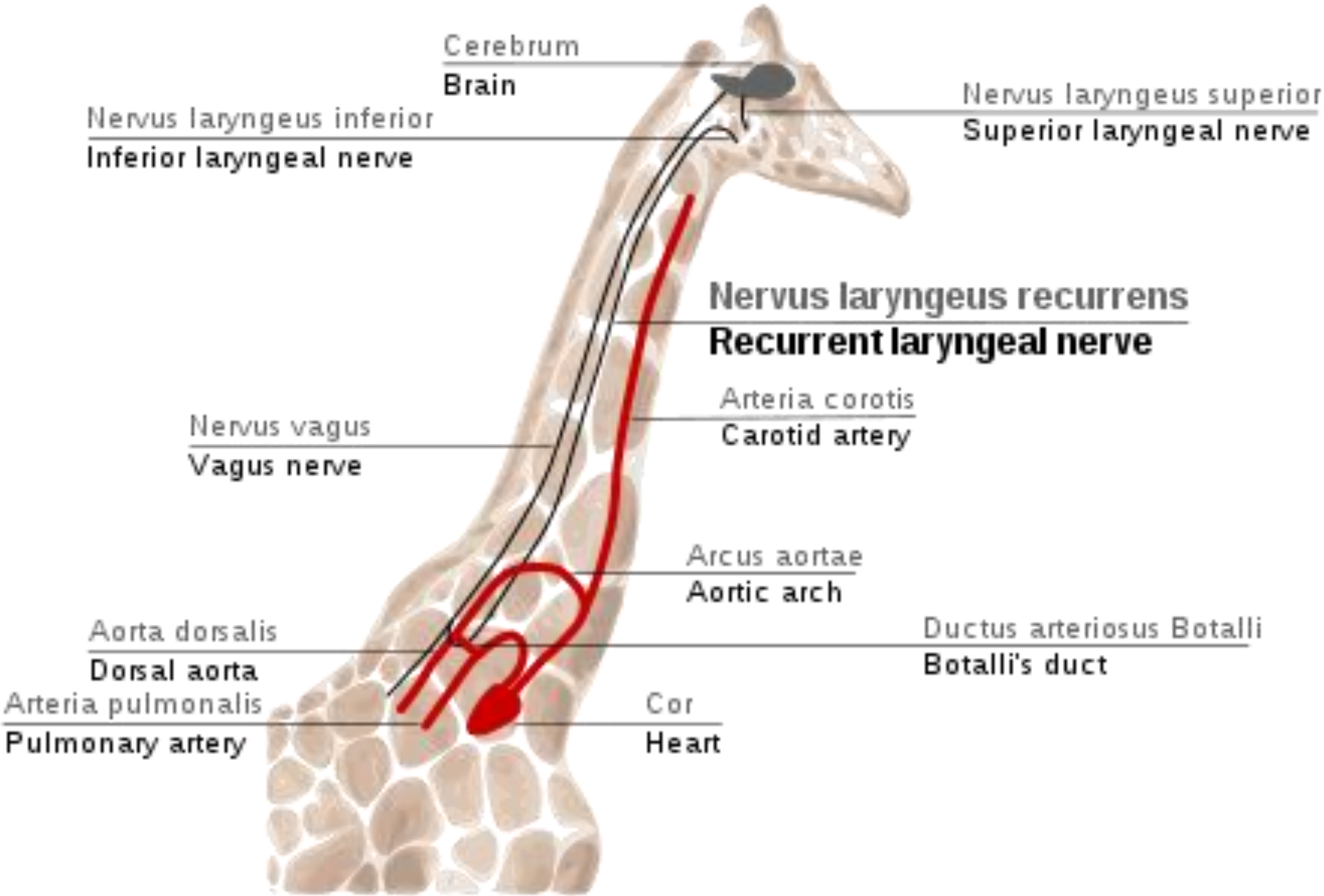
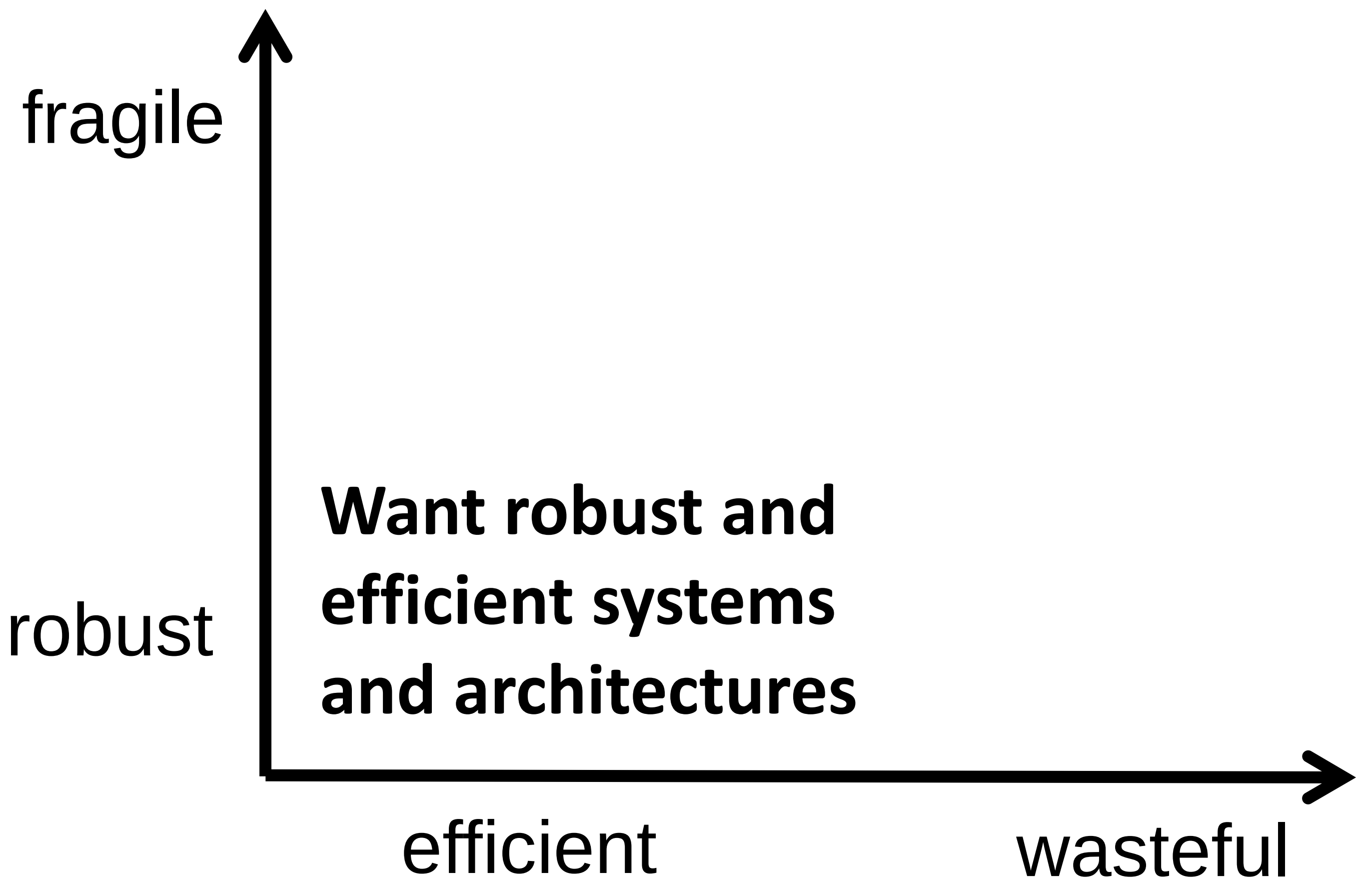


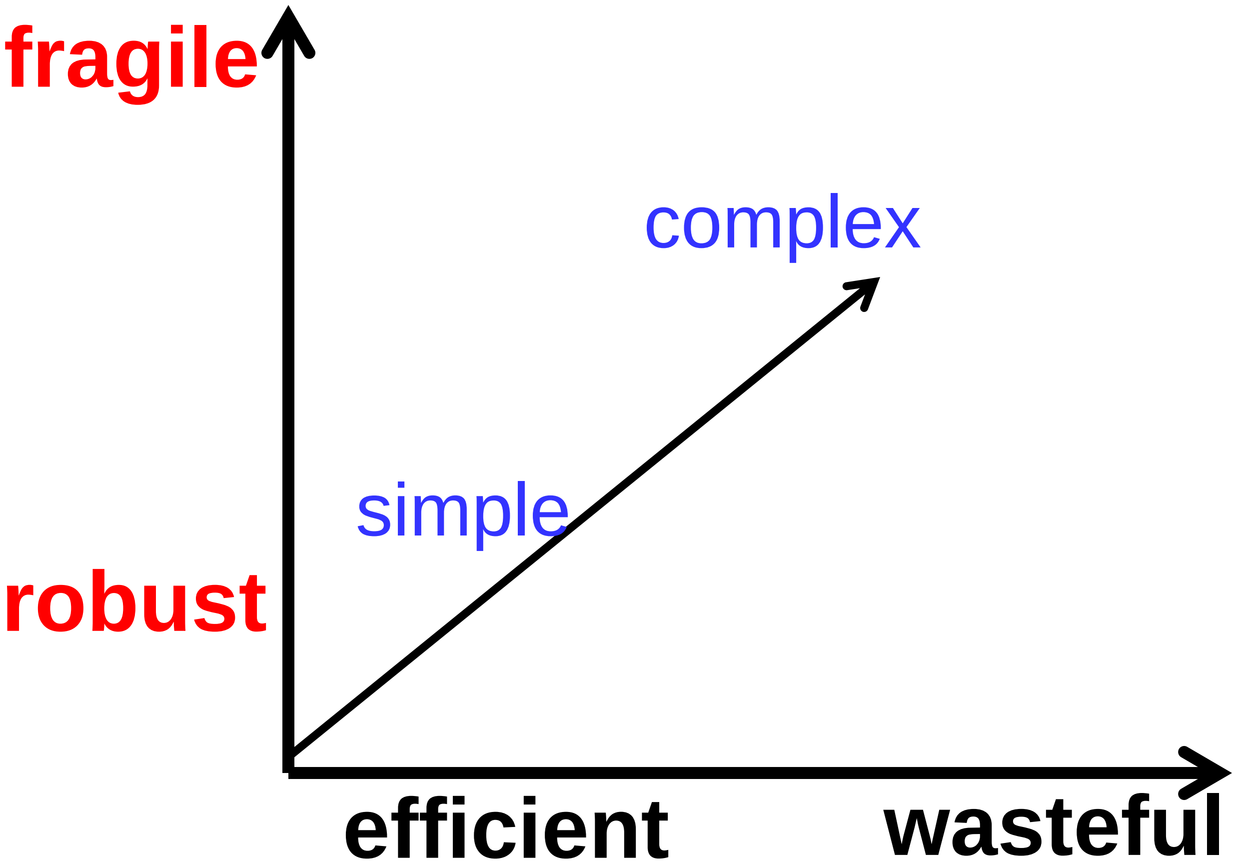
FIGURE 3–11 Schematic diagram showing the relationship between the vagus cranial nerve and the arterial arches in fish (*a*) and human (*b*). Only the third, fourth, and part of the sixth arterial arches remain in placental mammals, the sixth acting only during fetal development to carry blood to the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


Cerebrum
Brain
Nervus laryngeus inferior
Inferior laryngeal nerve
Nervus laryngeus superior
Superior laryngeal nerve
Nervus laryngeus recurrens
Recurrent laryngeal nerve
Arteria corotis
Carotid artery
Nervus vagus
Vagus nerve
Arcus aortae
Aortic arch
Aorta dorsalis
Dorsal aorta
Ductus arteriosus Botalli
Botalli's duct
Arteria pulmonalis
Pulmonary artery
Cor
Heart

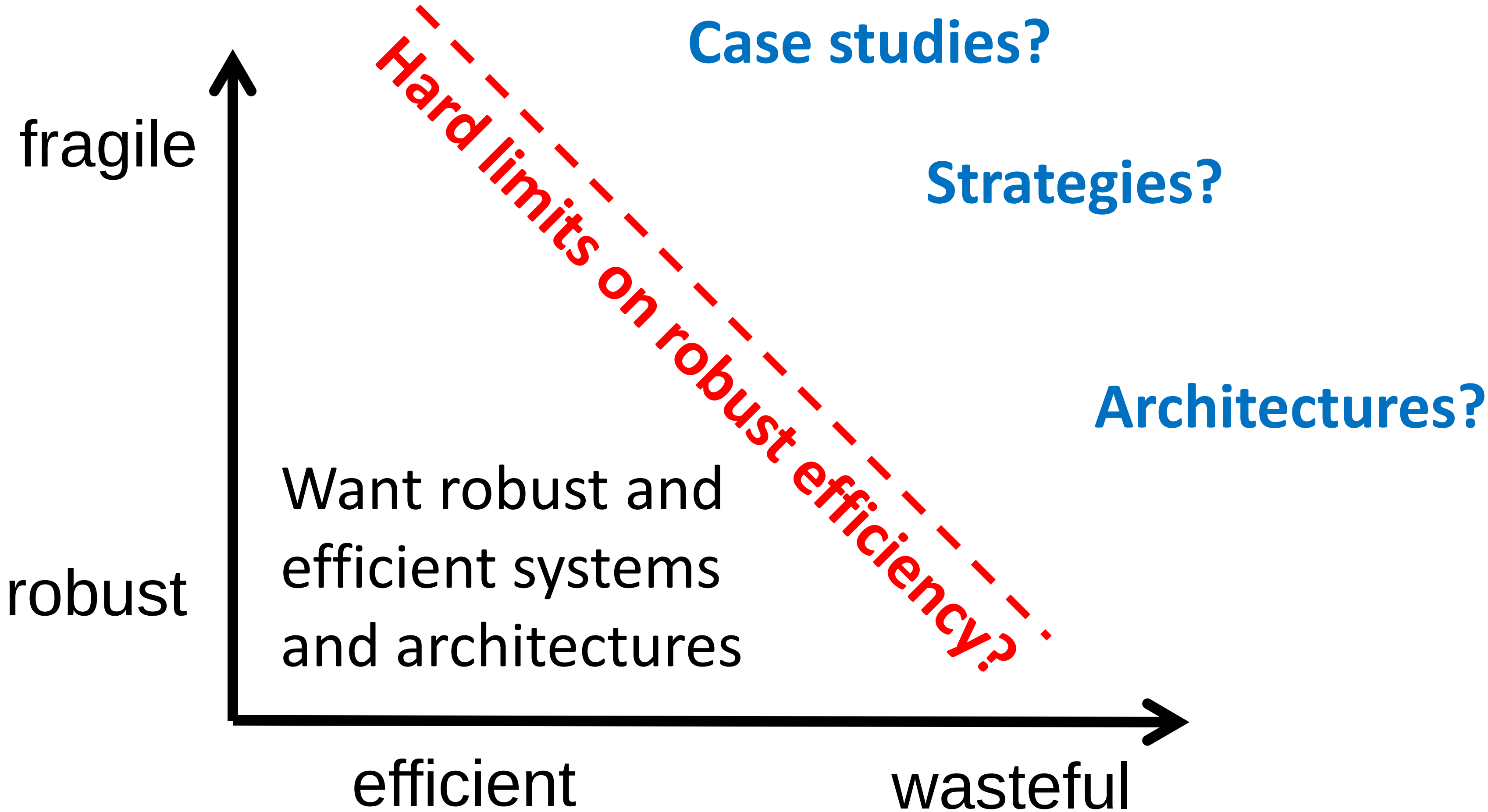
Want to understand the space of systems/architectures



Requirements on systems and architectures



Want to understand the space of systems/architectures



Control, OR

Kalman

Comms

Pontryagin

Bode

Shannon

Nash

Theory?

Deep, but fragmented,
incoherent, incomplete

Von
Neumann

Carnot

Turing

Boltzmann

Godel

Heisenberg

Compute

Einstein

Physics

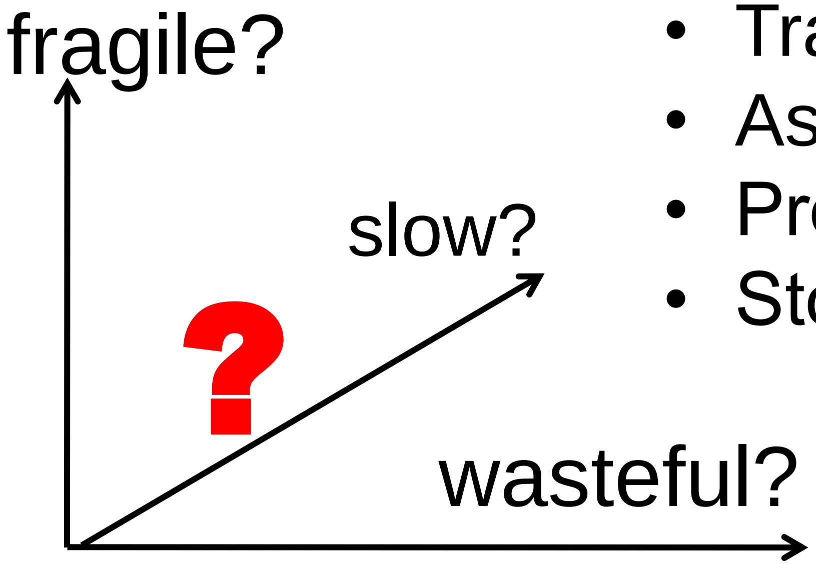
Control

Bode

Comms

Shannon

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



Carnot

Turing

Boltzmann

Godel

Heisenberg

Compute

Physics

Einstein

UG biochem, math, control theory

Glycolytic Oscillations and Limits on Robust Efficiency

Fiona A. Chandra,[1]* Gentian Buzi,[2] John C. Doyle[2]

Both engineering and evolution are constrained by trade-offs between efficiency and robustness, but theory that formalizes this fact is limited. For a simple two-state model of glycolysis, we explicitly derive analytic equations for hard trade-offs between robustness and efficiency with oscillations as an inevitable side effect. The model describes how the trade-offs arise from individual parameters, including the interplay of feedback control with autocatalysis of network products necessary to power and catalyze intermediate reactions. We then use control theory to prove that the essential features of these hard trade-off "laws" are universal and fundamental, in that they depend minimally on the details of this system and generalize to the robust efficiency of any autocatalytic network. The theory also suggests worst-case conditions that are consistent with initial experiments.

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

Chandra, Buzi, and Doyle

Most important paper so far.

Science AAAS

www.sciencemag.org SCIENCE VOL 333 8 JULY 2011

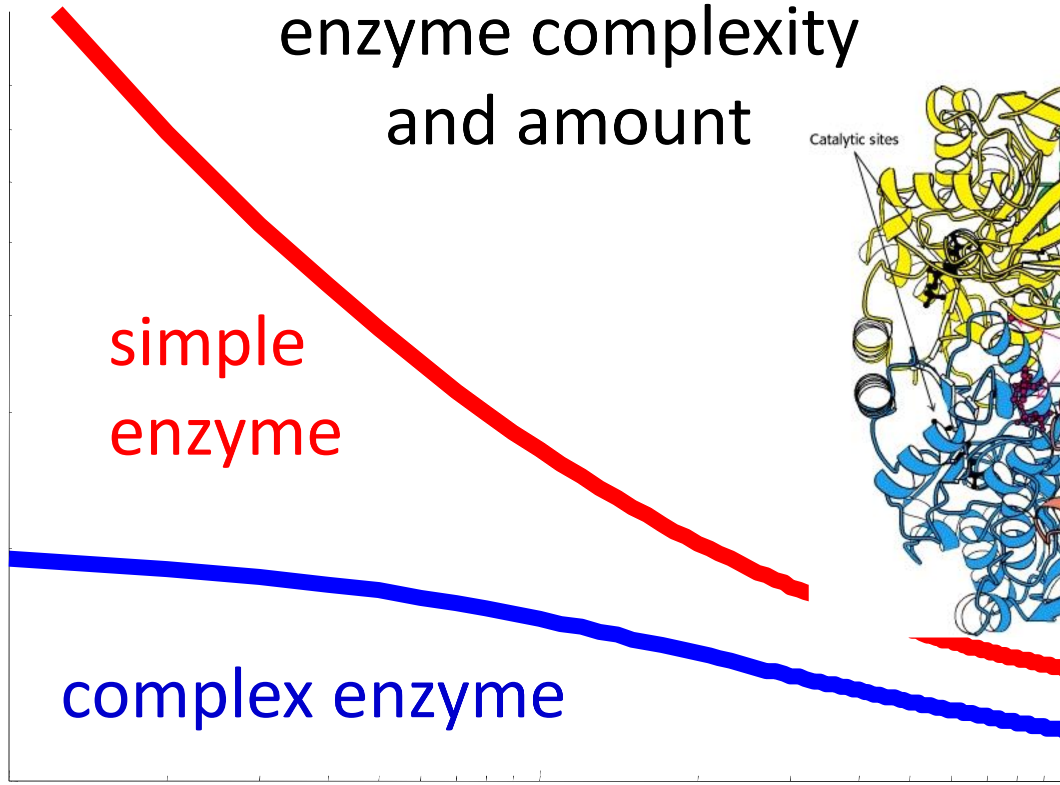
Theorem!

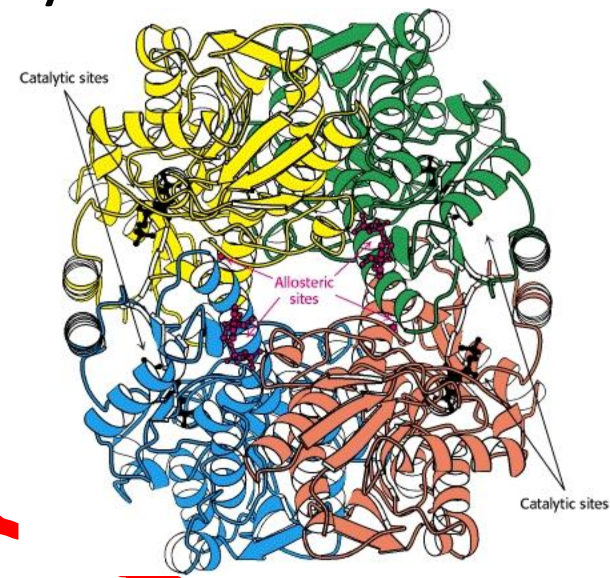
$$\frac{1}{\pi}\int_0^\infty \ln\left|S(j\omega)\right|\left(\frac{z}{z^2+\omega^2}\right)d\omega \geq \ln\left|\frac{z+p}{z-p}\right|$$

z and *p* functions of enzyme complexity and amount

Fragility

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

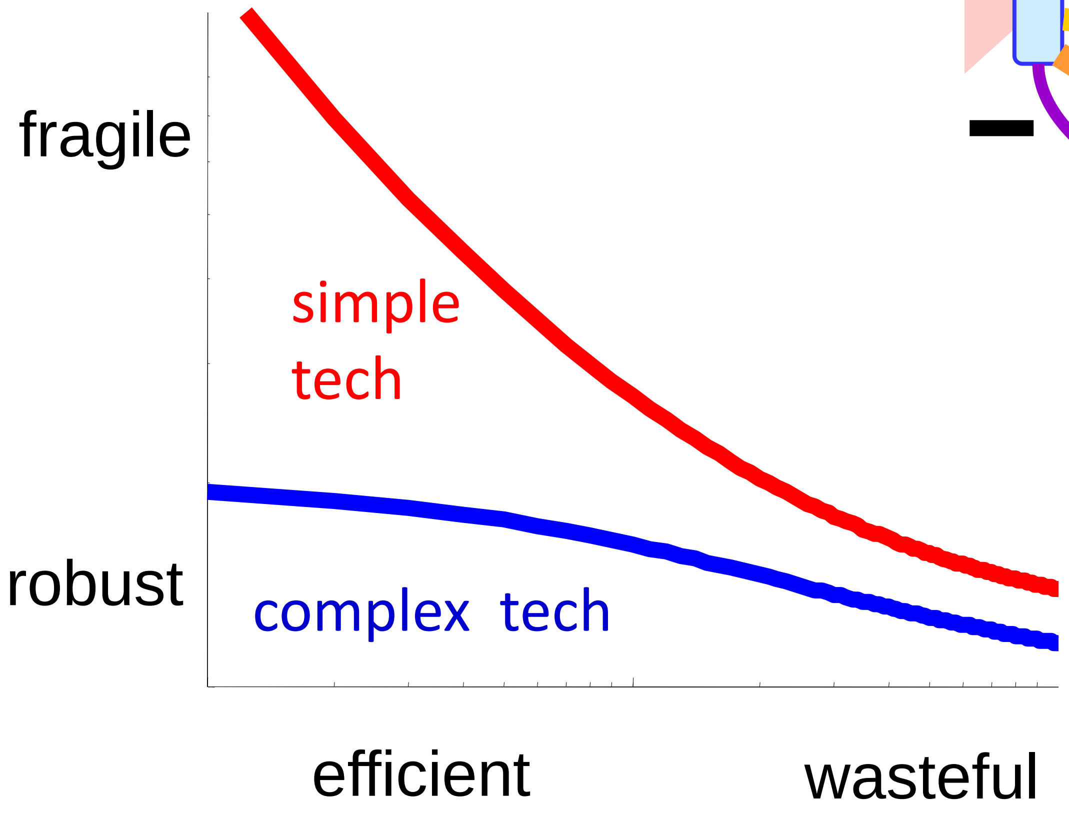


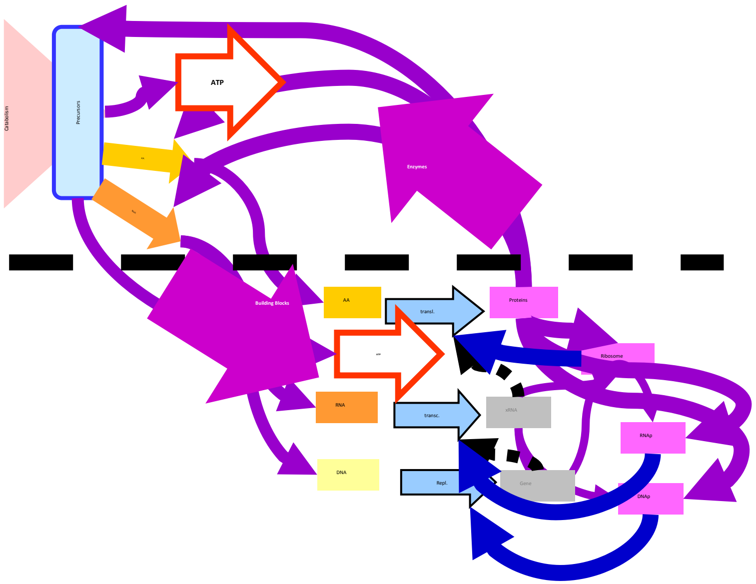


Enzyme amount

Savageaumics

How general is this picture?
Very! Constraints!
i.e. hard limits and architecture





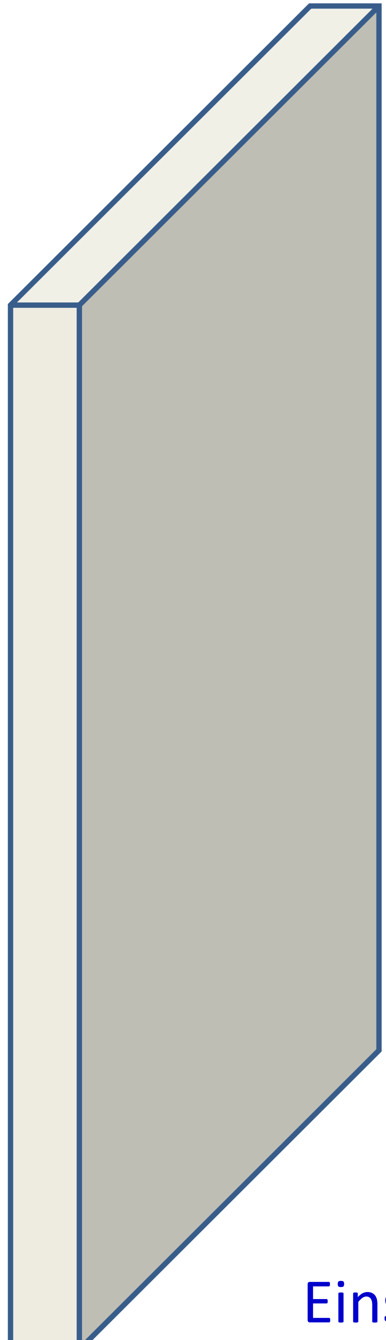
Control, OR

Bode

Delay is *most* important

Turing

Compute



Communications

Shannon

Delay is *least* important

Carnot

Boltzmann

Heisenberg

Physics

Einstein

Control, OR **Communications**

Bode Shannon

Delay is *most* important → **Delay is ~~*least*~~ important**

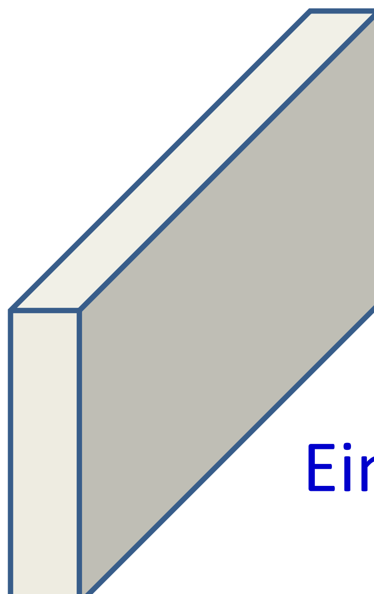
Carnot

Boltzmann

Turing

Heisenberg

Einstein



Compute **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)

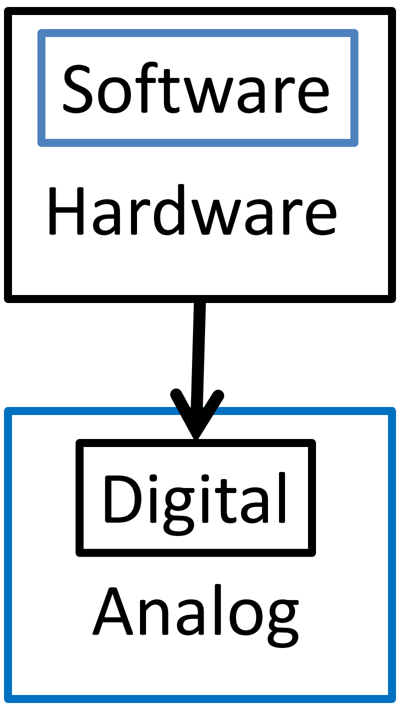
Compute

*Also world-class runner.

Turing as "new" starting point?

Essentials:

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

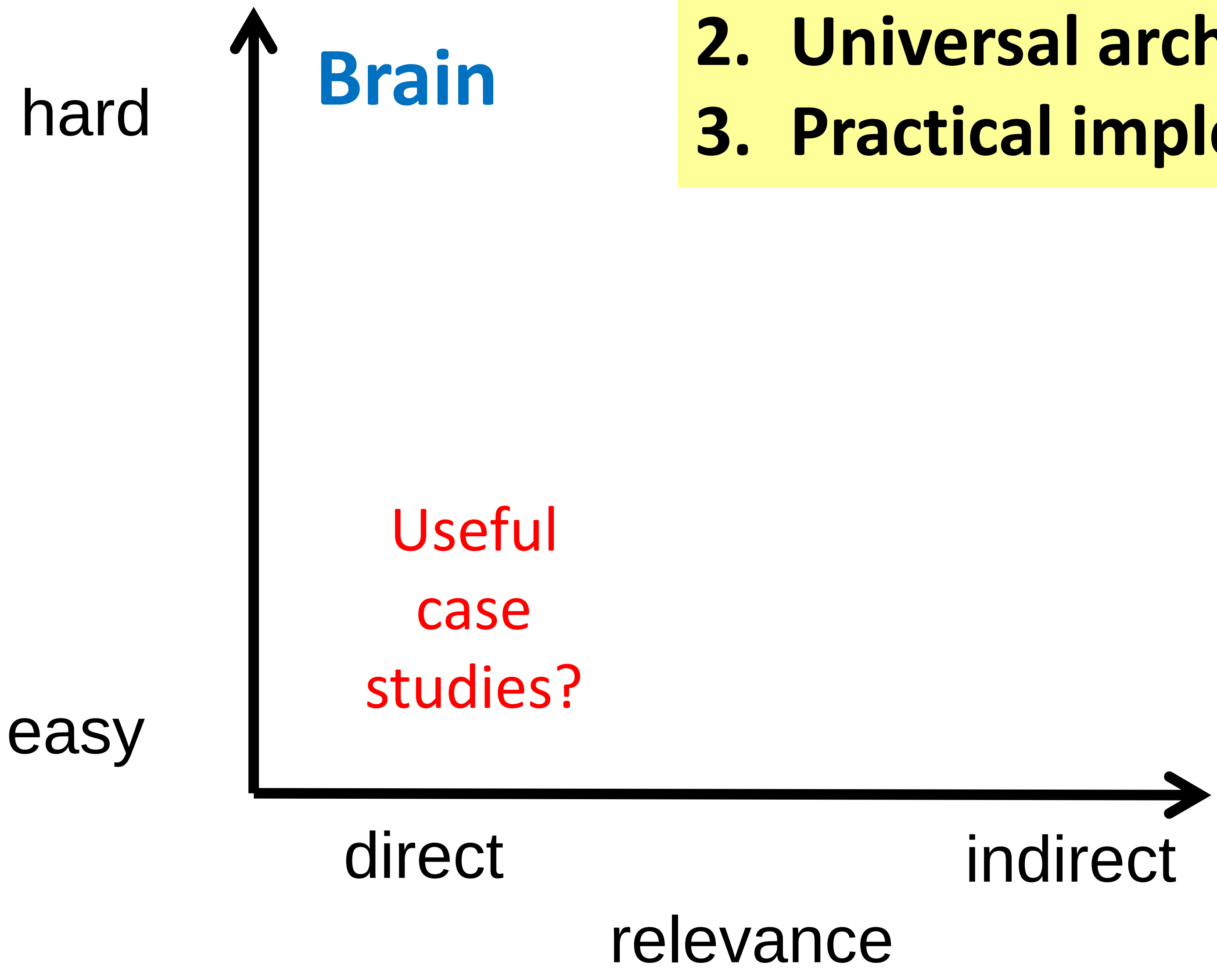


Turing's 3 step research:

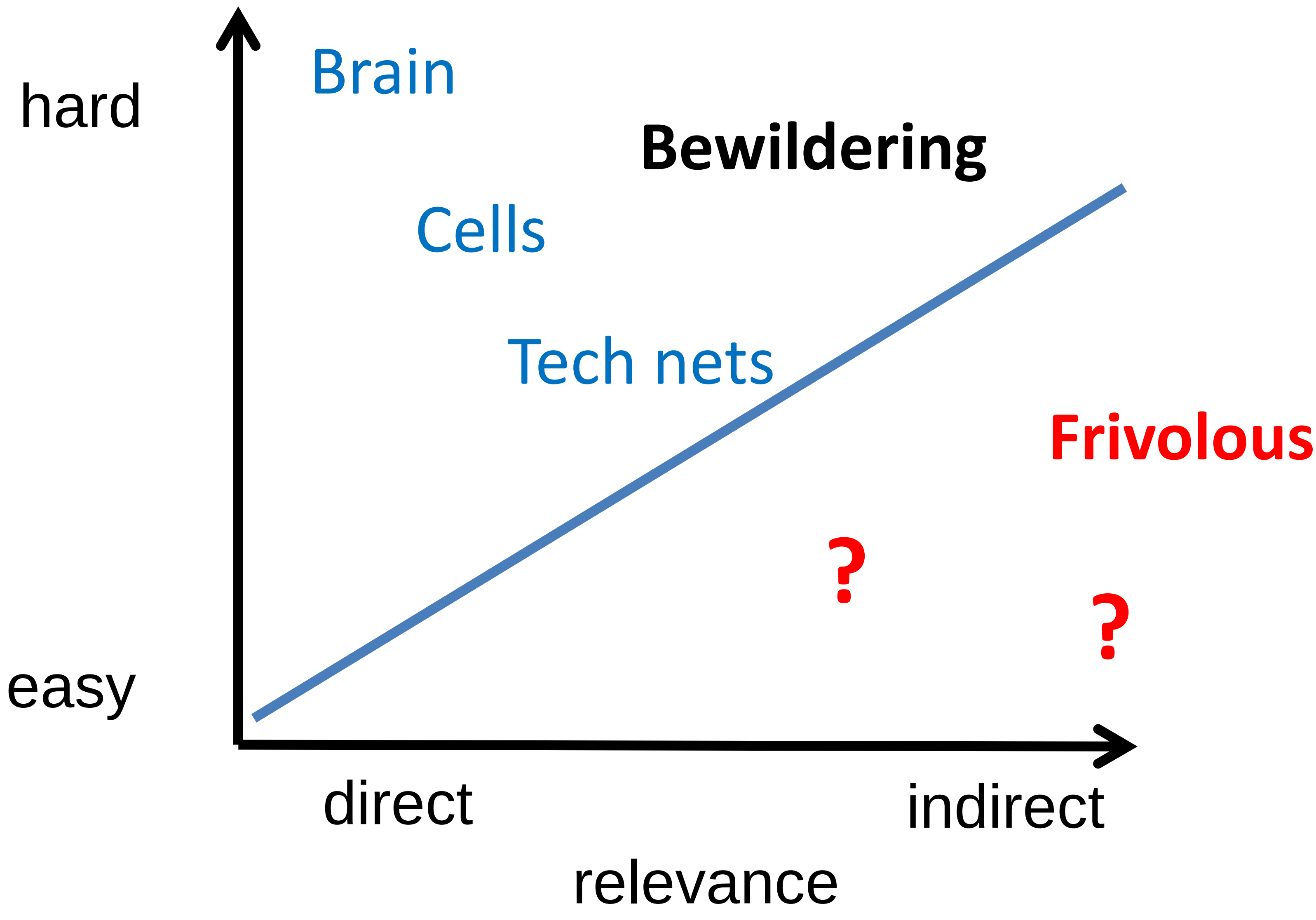
0. Virtual (TM) machines
1. hard limits, (un)decidability using standard model (TM)
2. Universal architecture achieving hard limits (UTM)
3. Practical implementation in digital electronics (biology?)

Essentials:

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



3. **Universal architecture**
4. **Practical implementation**

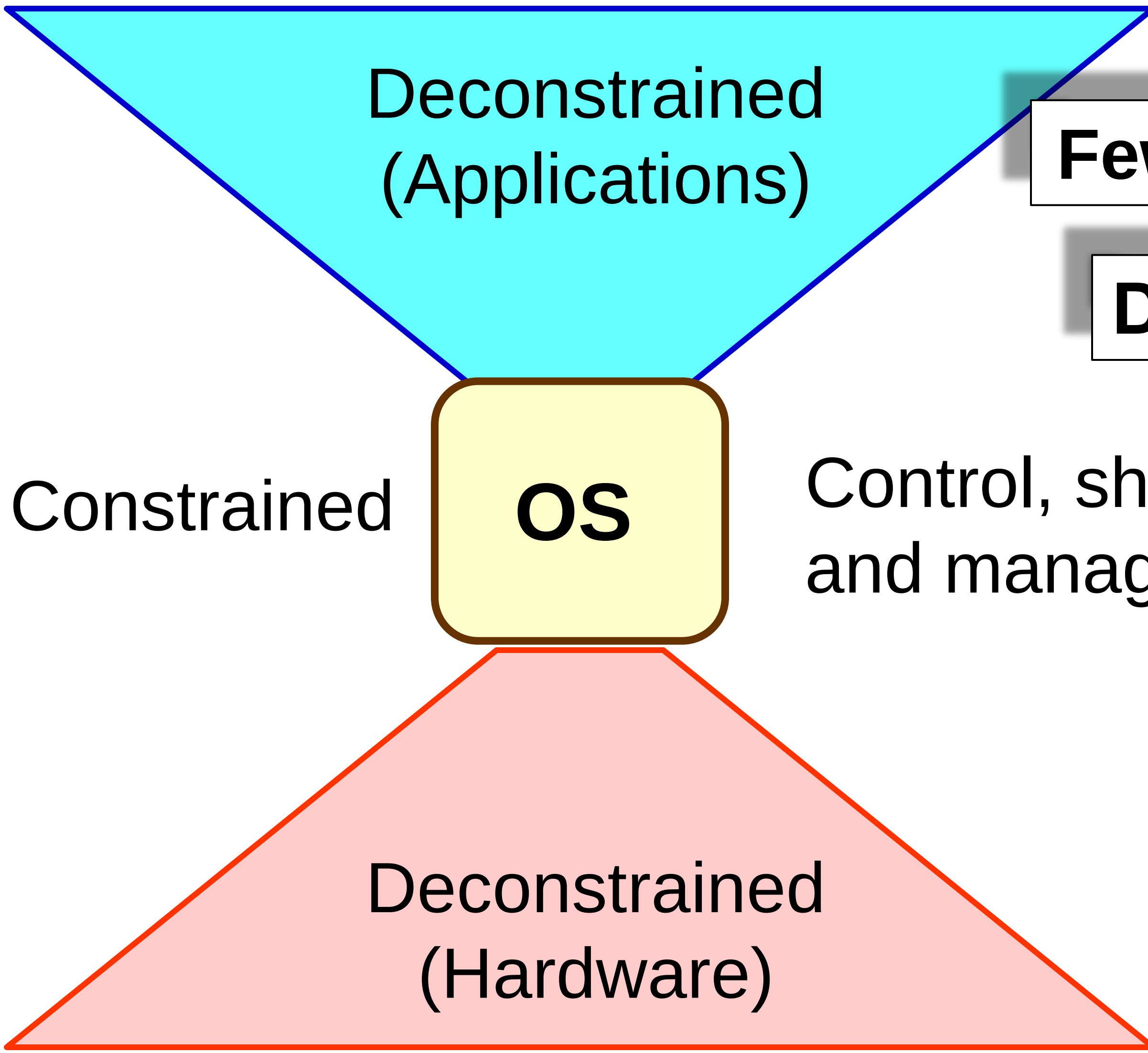


Layered architectures

Essentials

Few global variables

Don’t cross layers



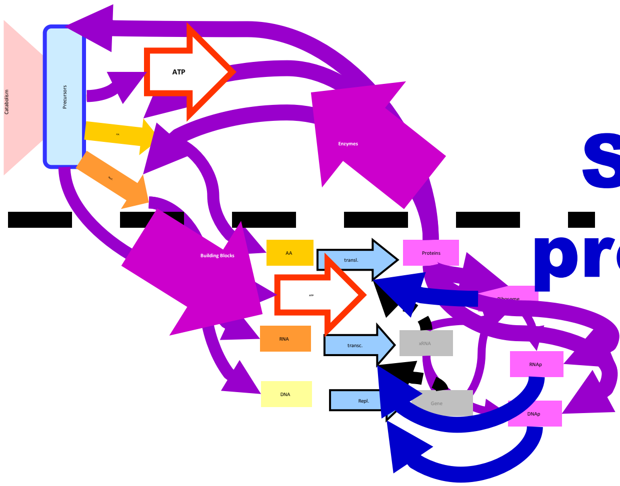
Control, share, virtualize, and manage resources

Processing
Memory
I/O

Layered architectures

Bacterial biosphere

Deconstrained
(diverse)
Environments

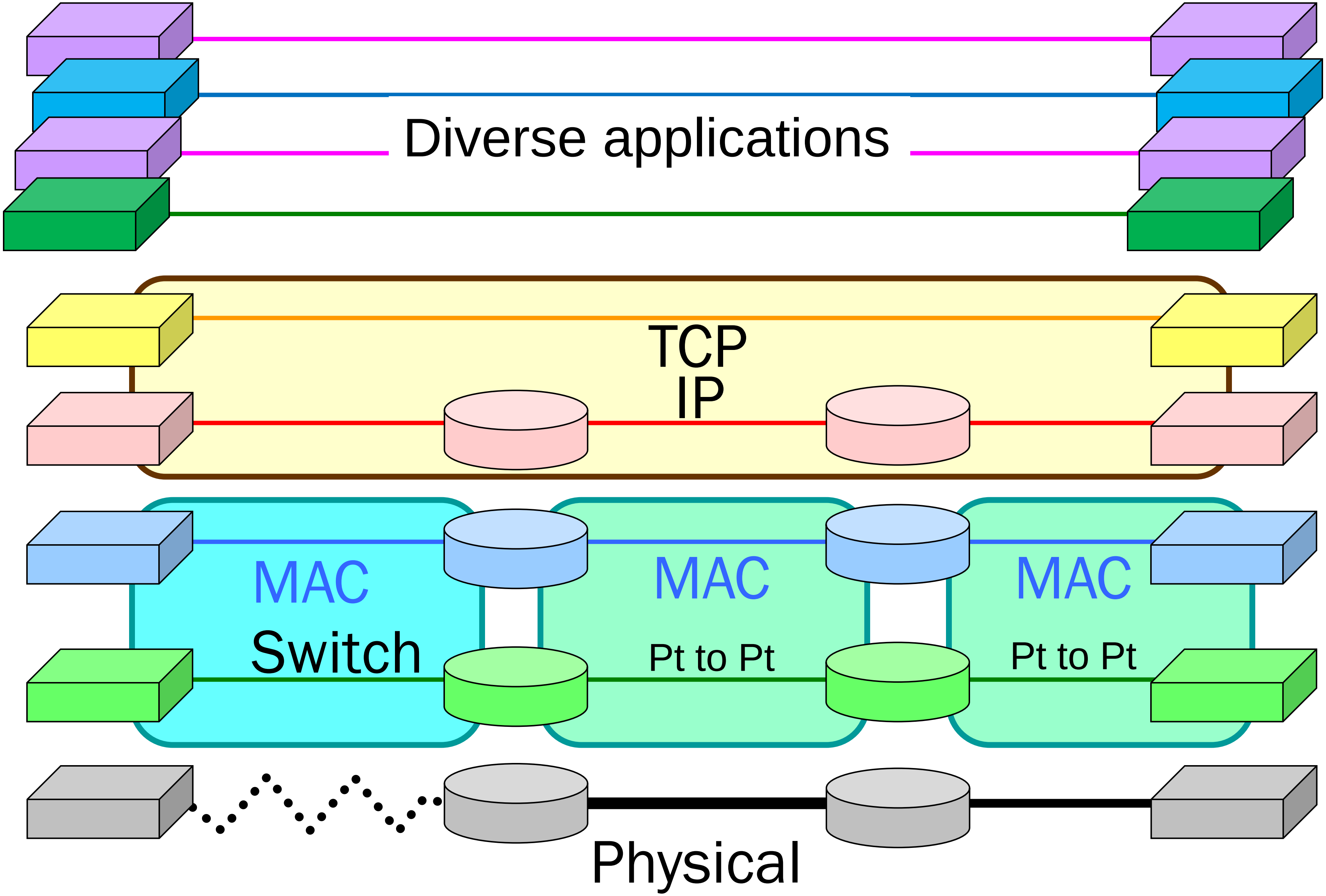


Shared protocols

Deconstrained (diverse)
Genomes

Architecture
=
Constraints
that
Deconstrain

Layered architectures



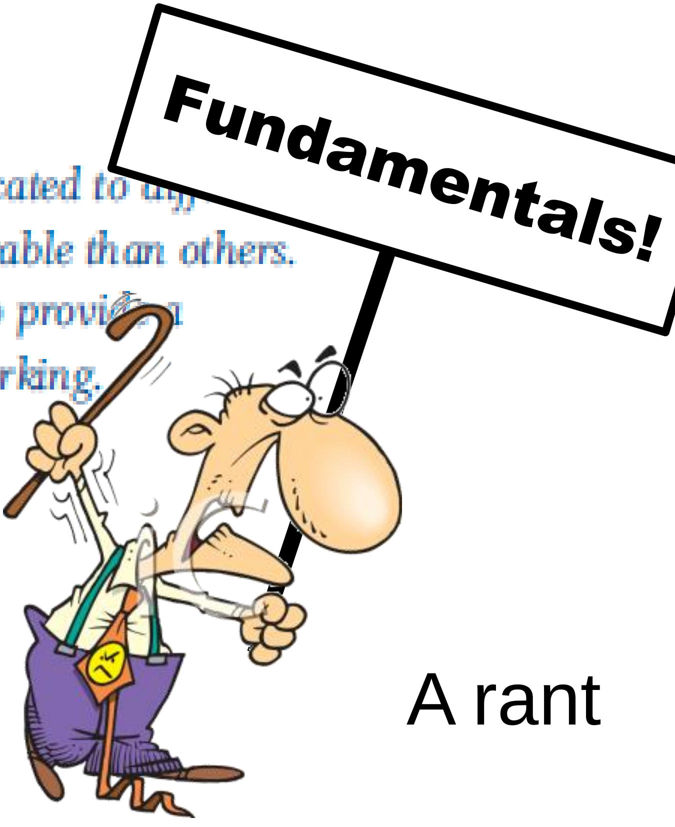
Proceedings of the IEEE, Jan 2007

OR optimization

Layering as Optimization Decomposition: A Mathematical Theory of Network Architectures

There are various ways that network functionalities can be allocated to 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.

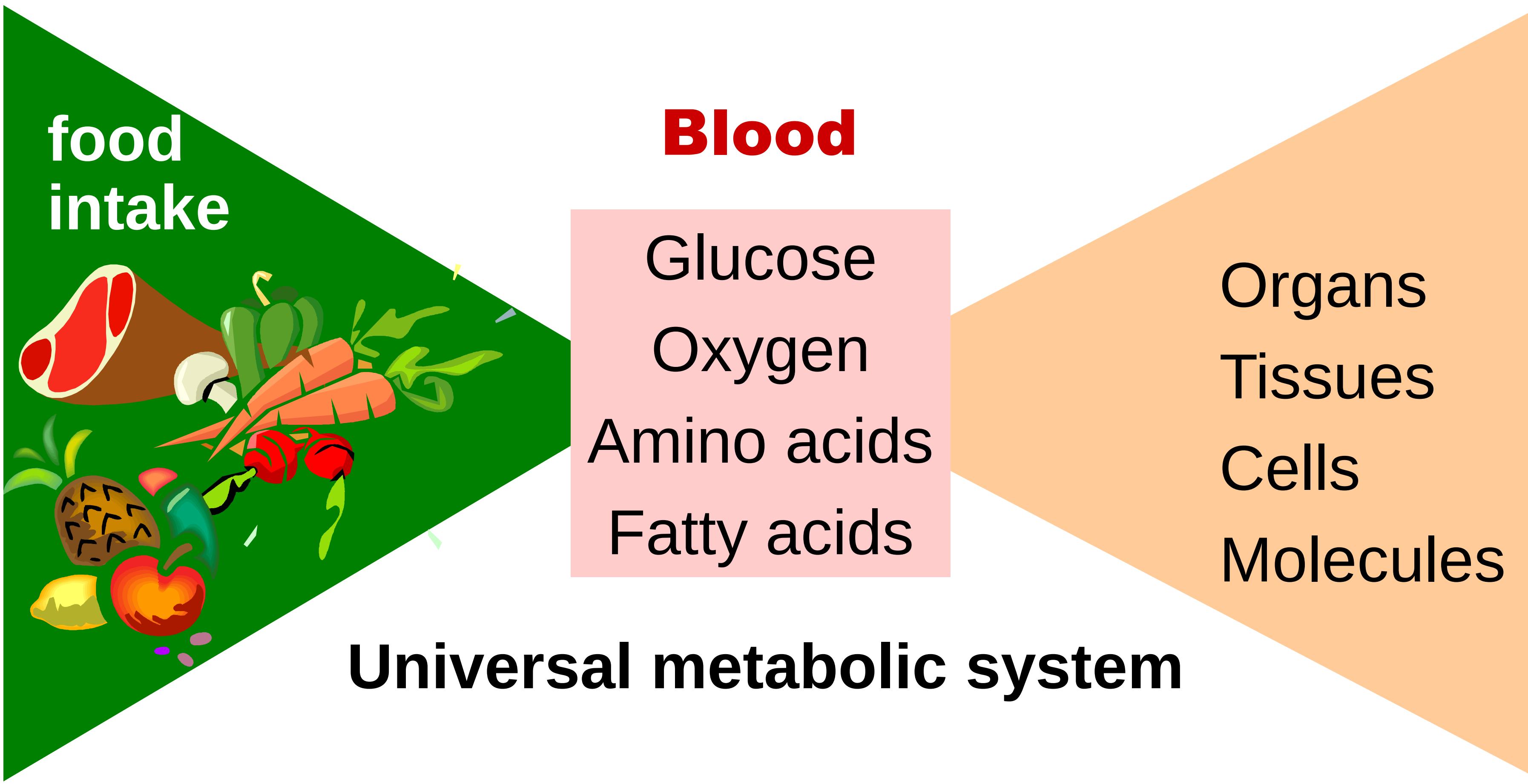
By Mung Chiang, *Member IEEE*, Steven H. Low, *Senior Member IEEE*,
A. Robert Calderbank, *Fellow IEEE*, and John C. Doyle



Chang, Low, Calderbank, Doyle

A rant

Peter Sterling and Allostasis

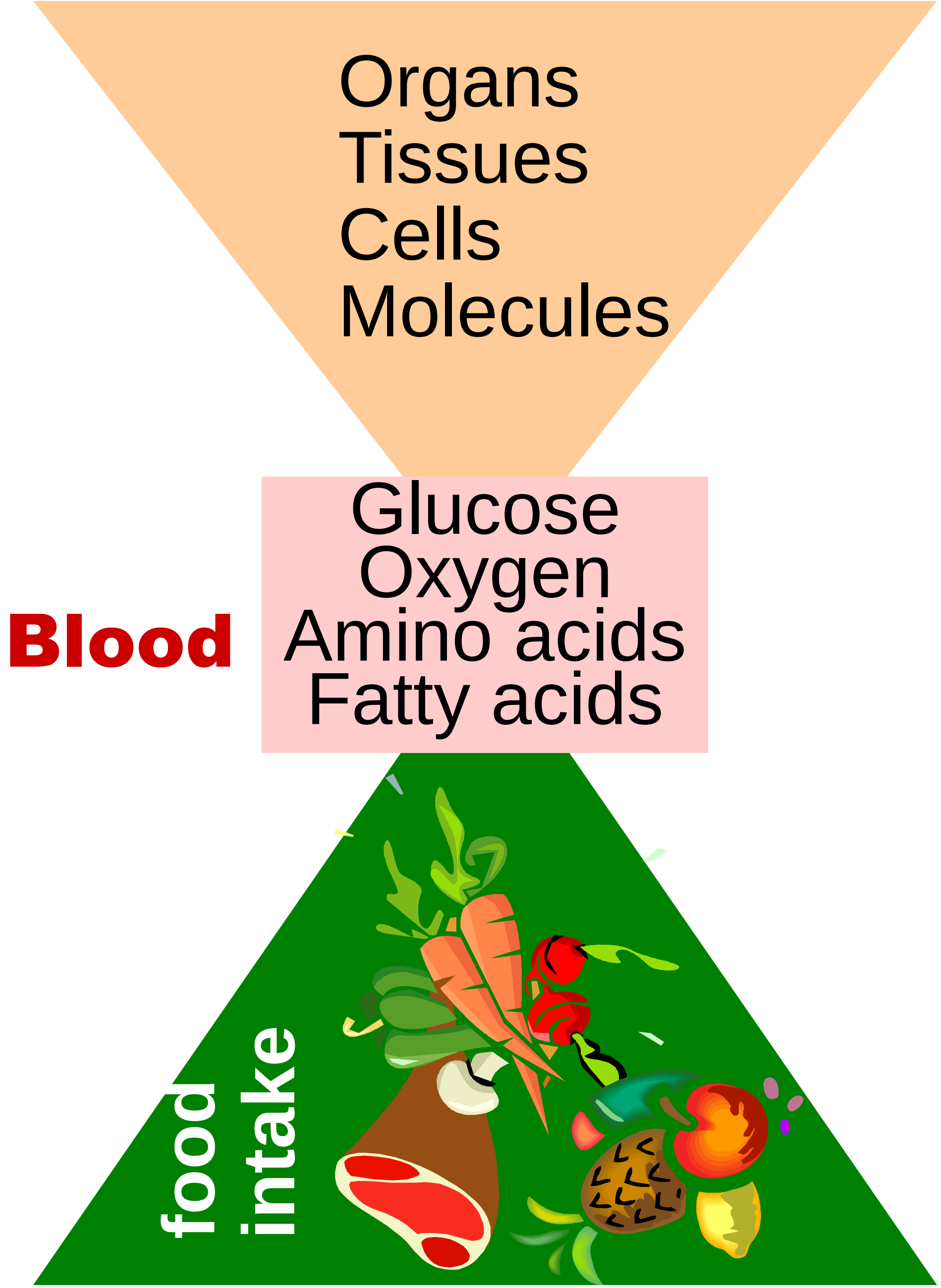


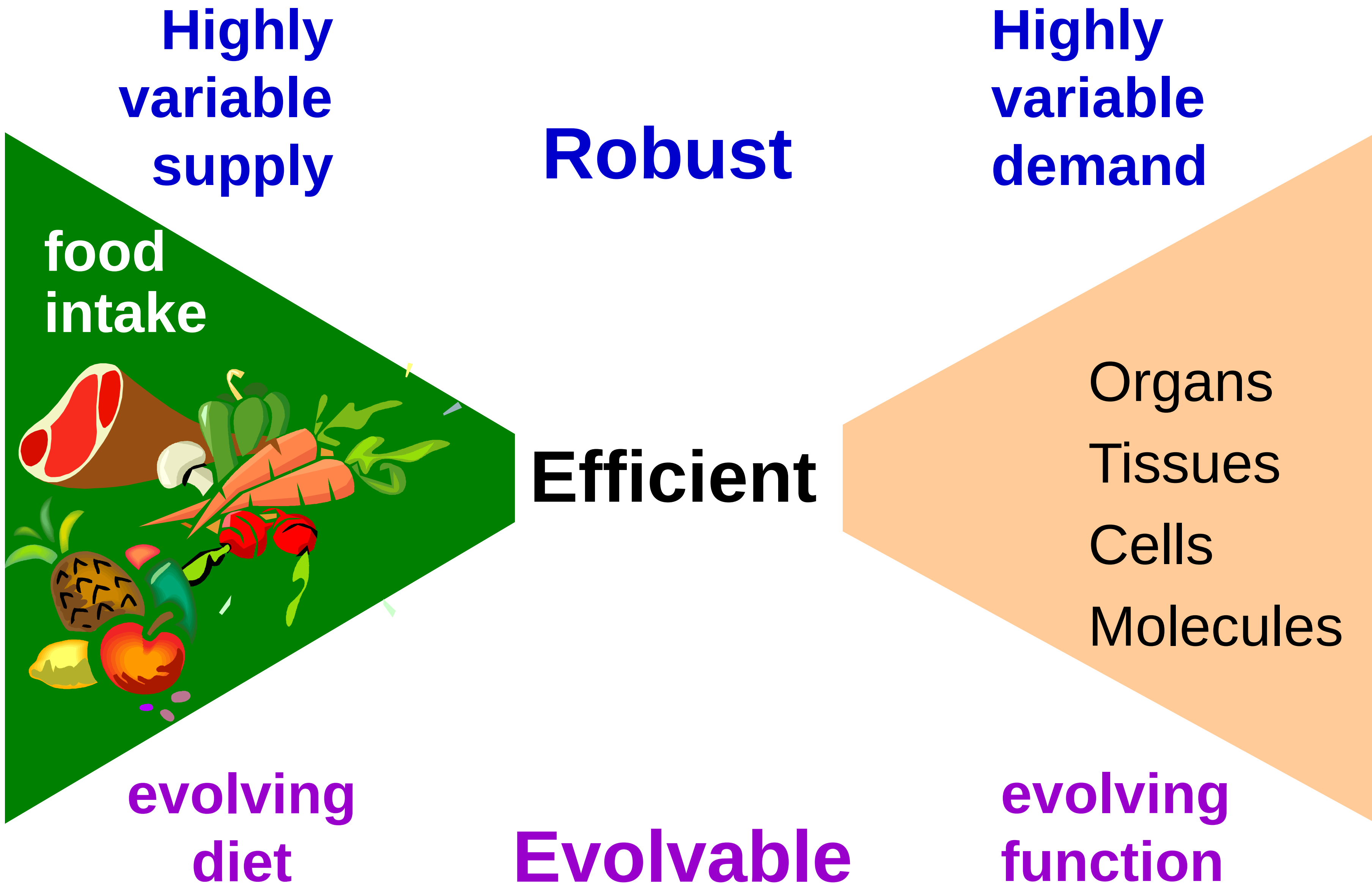
food intake

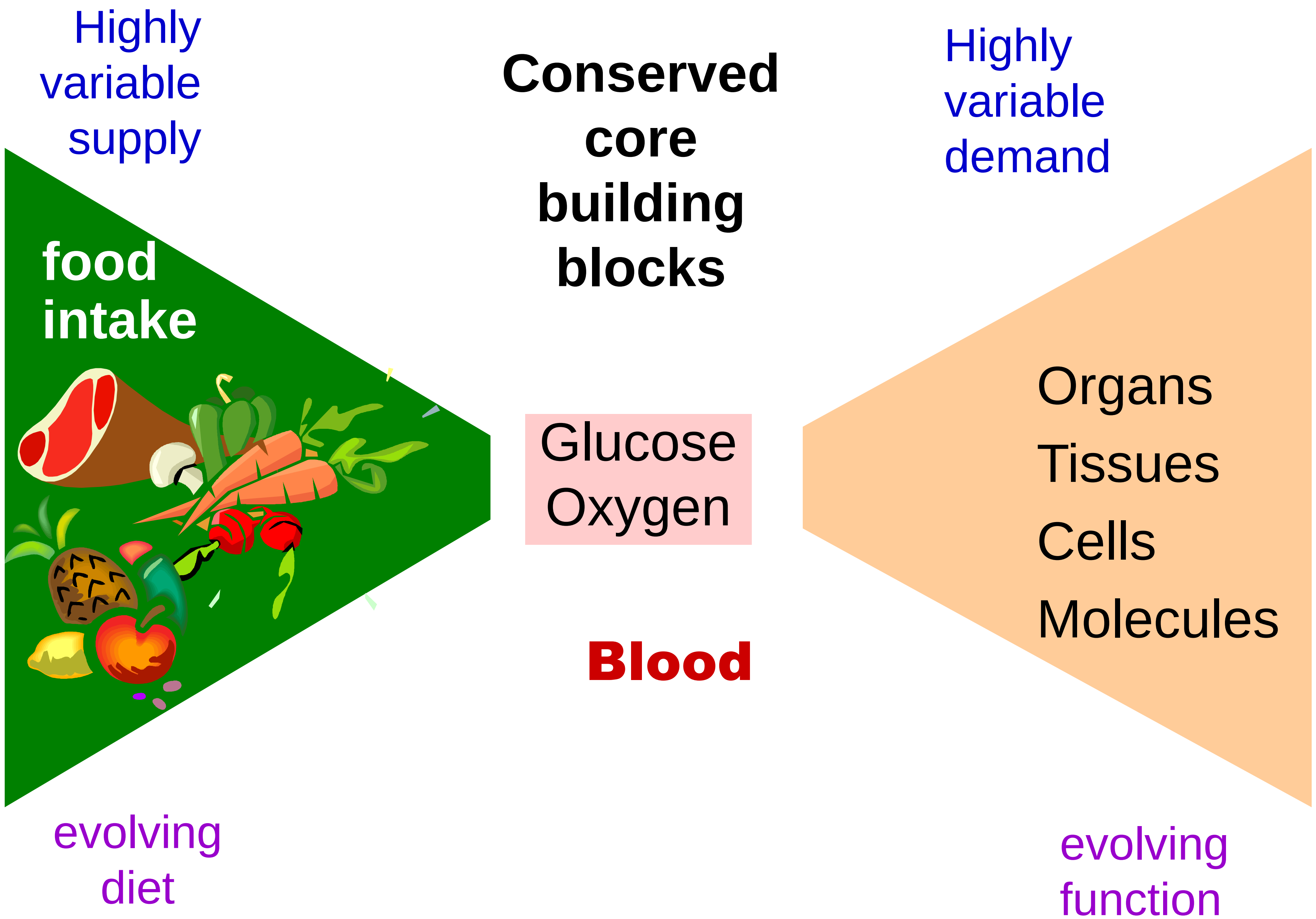
Blood

Glucose
Oxygen
Amino acids
Fatty acids

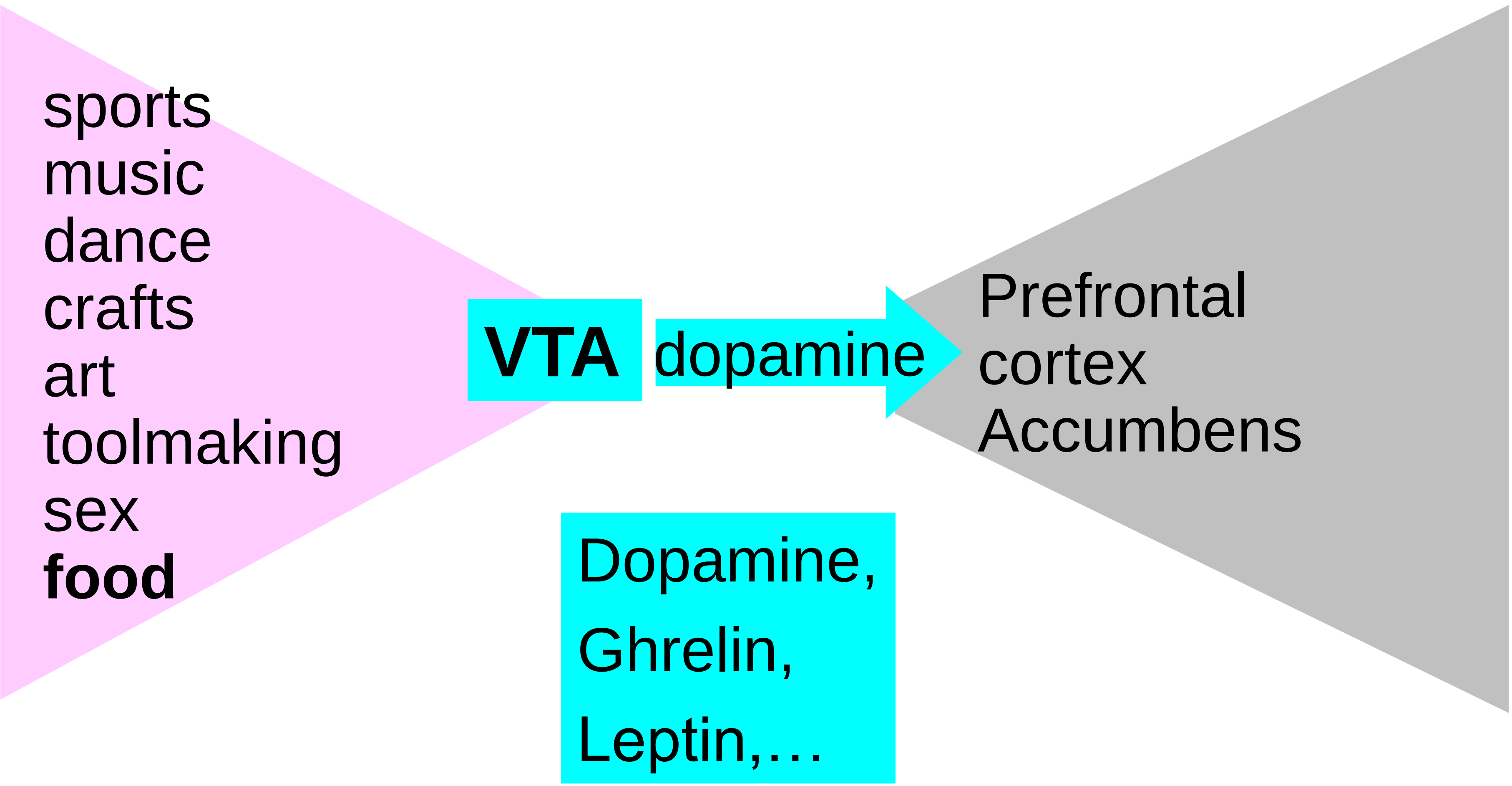
Organs
Tissues
Cells
Molecules


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
Evolvable
evolving function

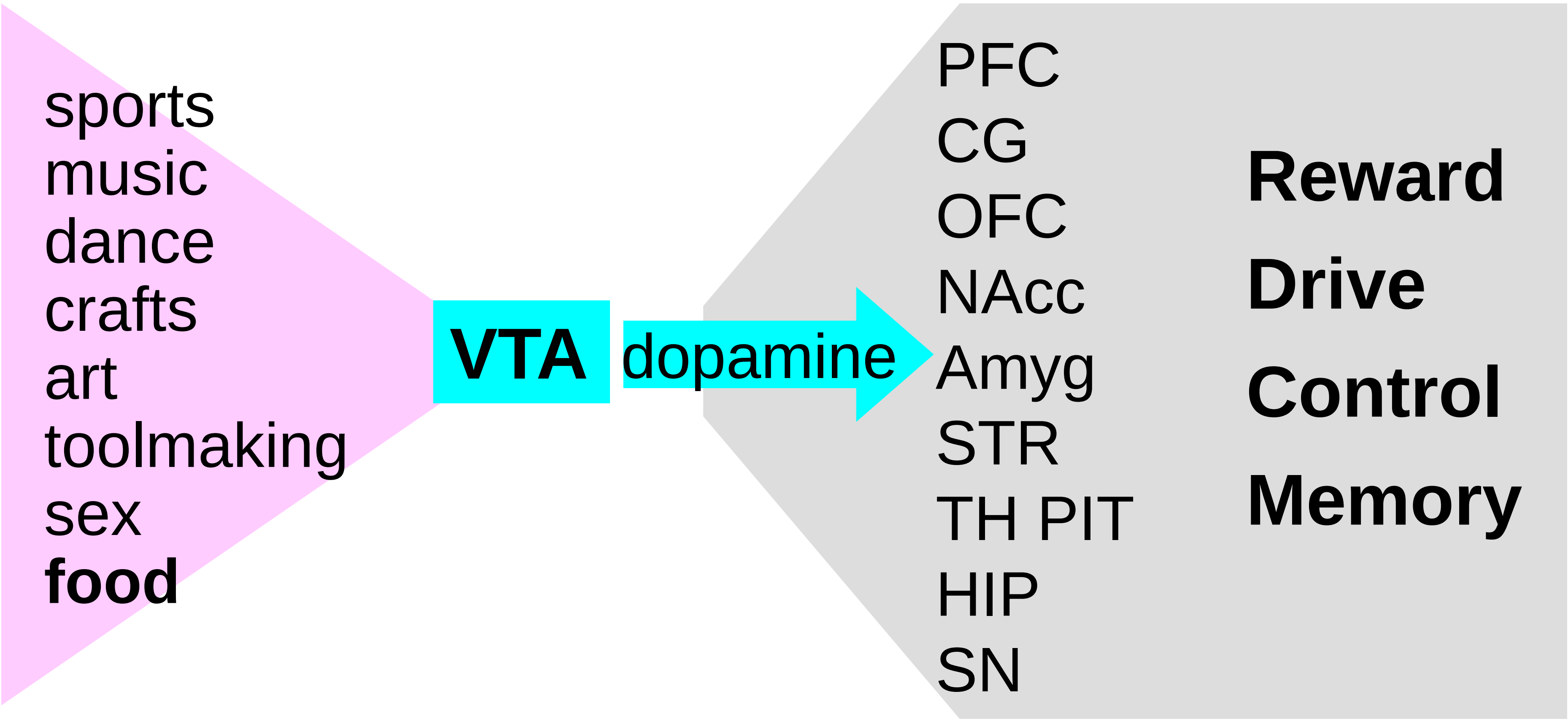

Highly variable supply
Conserved core building blocks
Highly variable demand
food intake
Glucose
Oxygen
Organs
Tissues
Cells
Molecules
Blood
evolving diet
evolving function

Universal reward systems

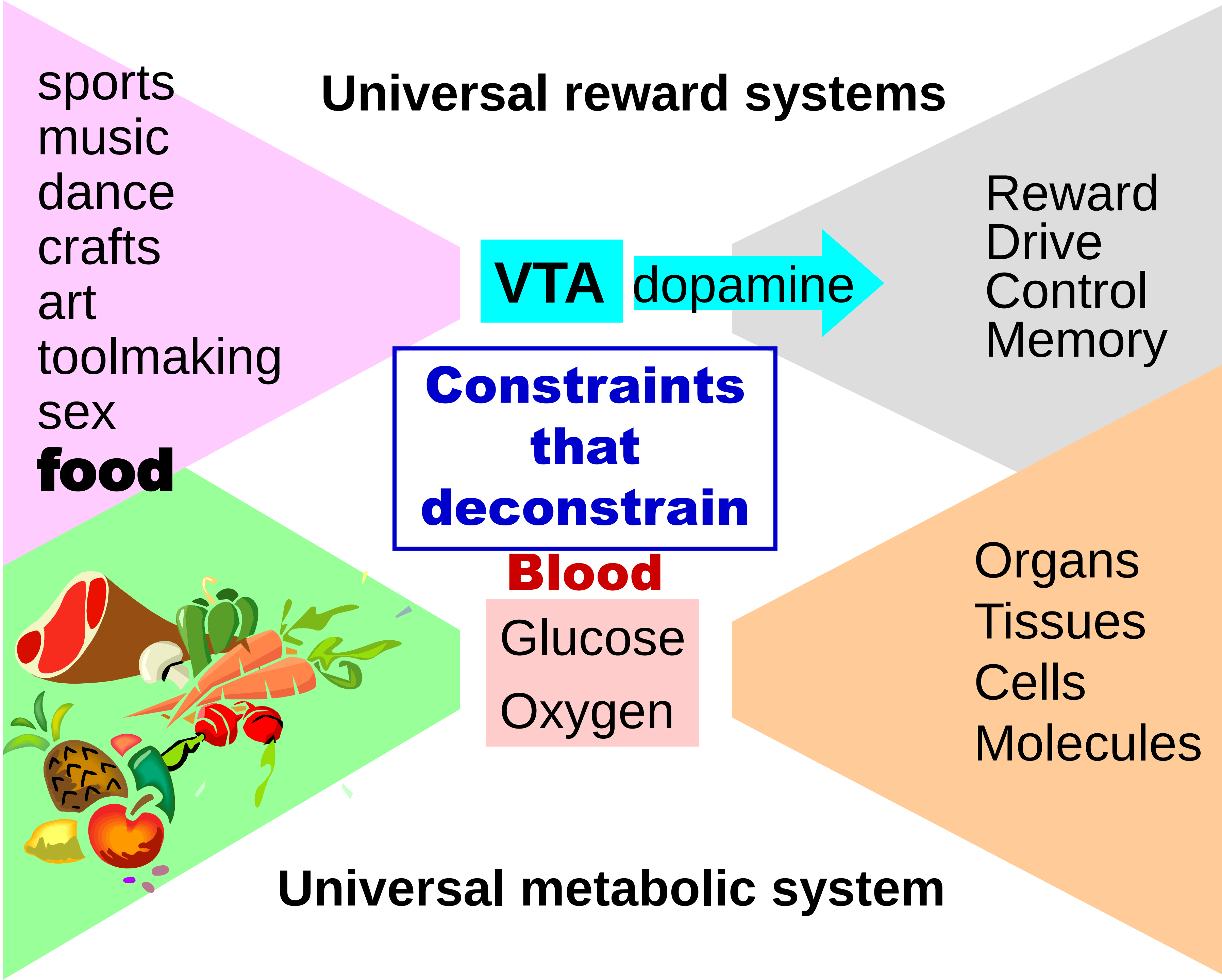


Ridiculous oversimplification

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

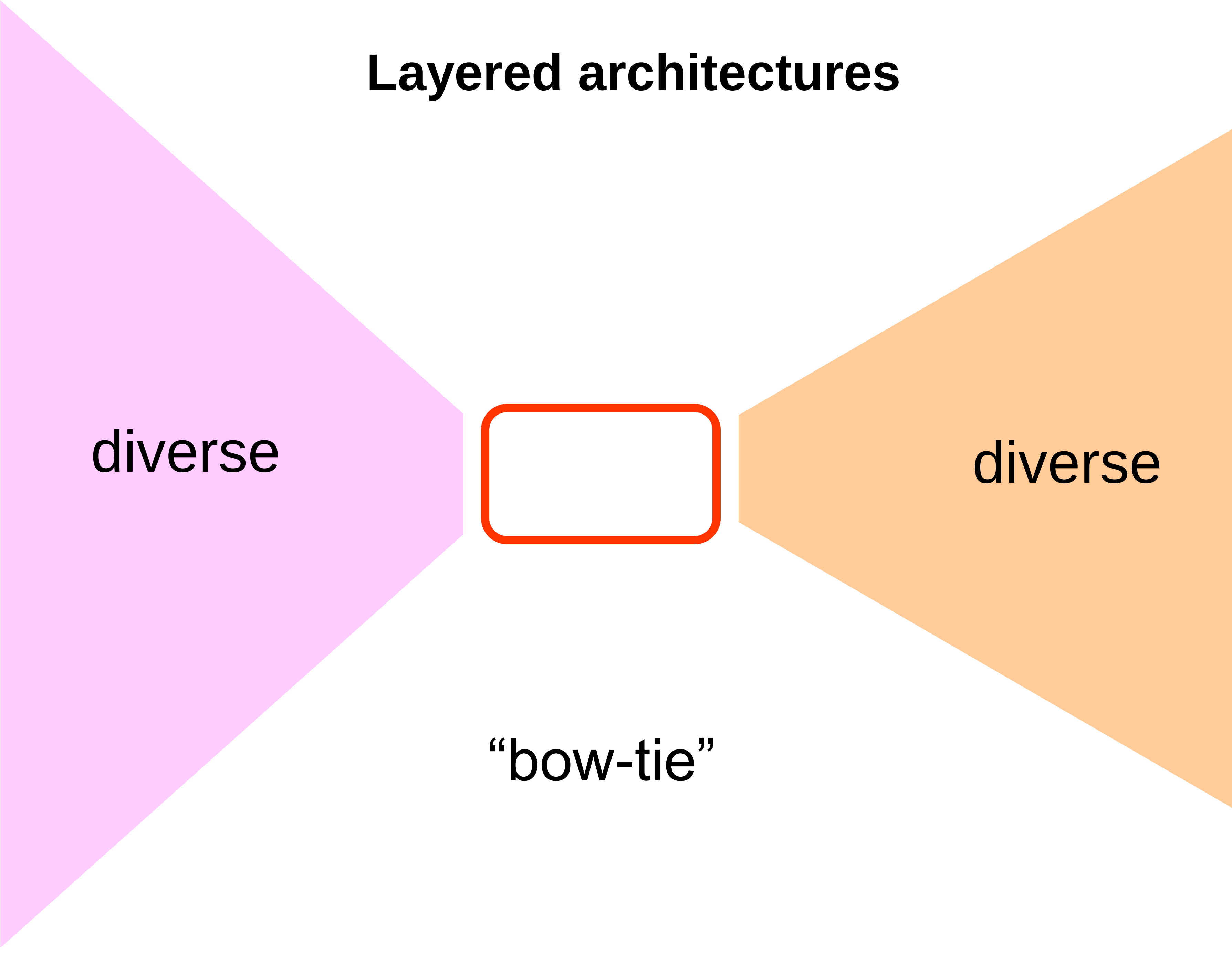
sports
music
dance
crafts
art
toolmaking
sex
food

that deconstrain

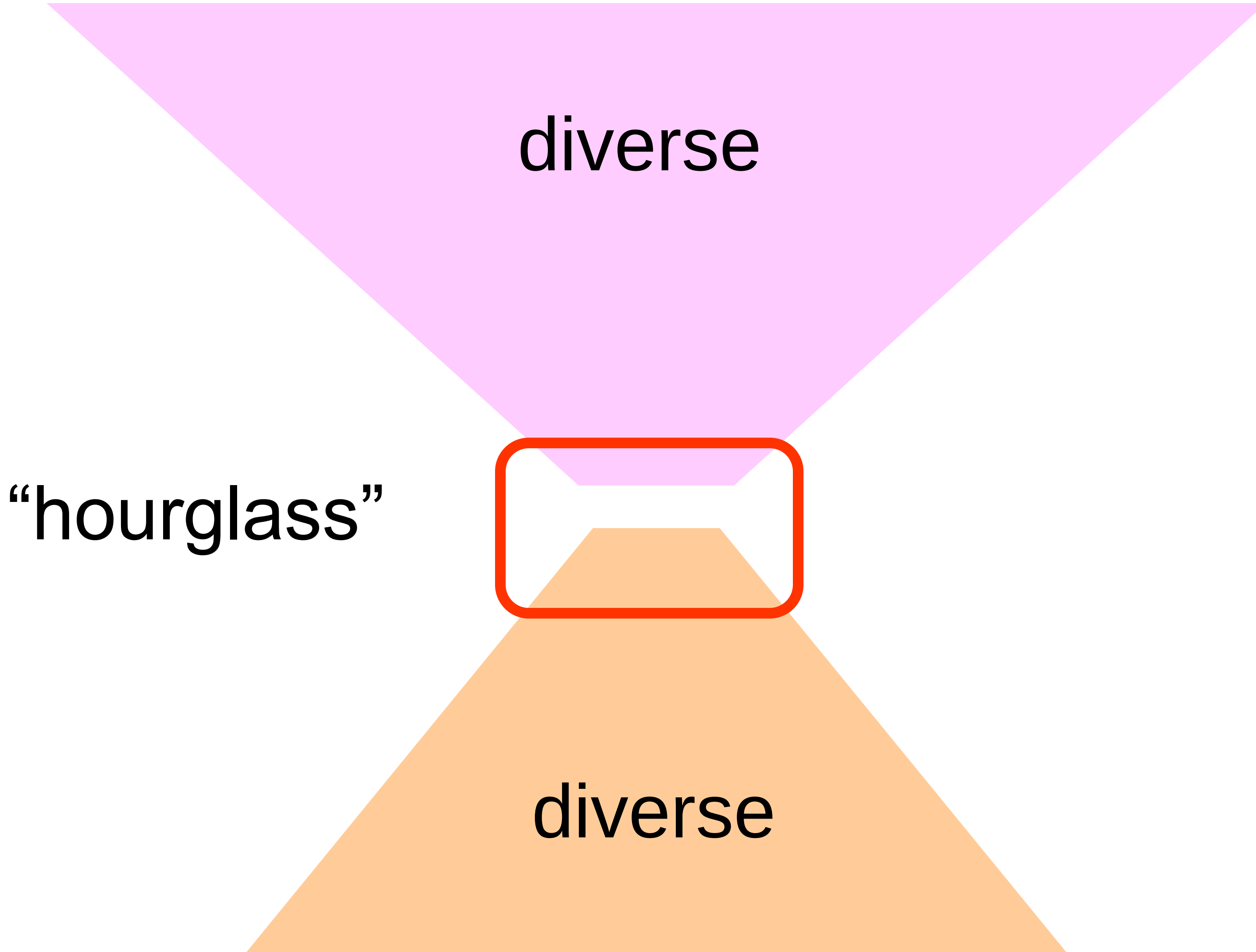
Reward
Drive
Control
Memory

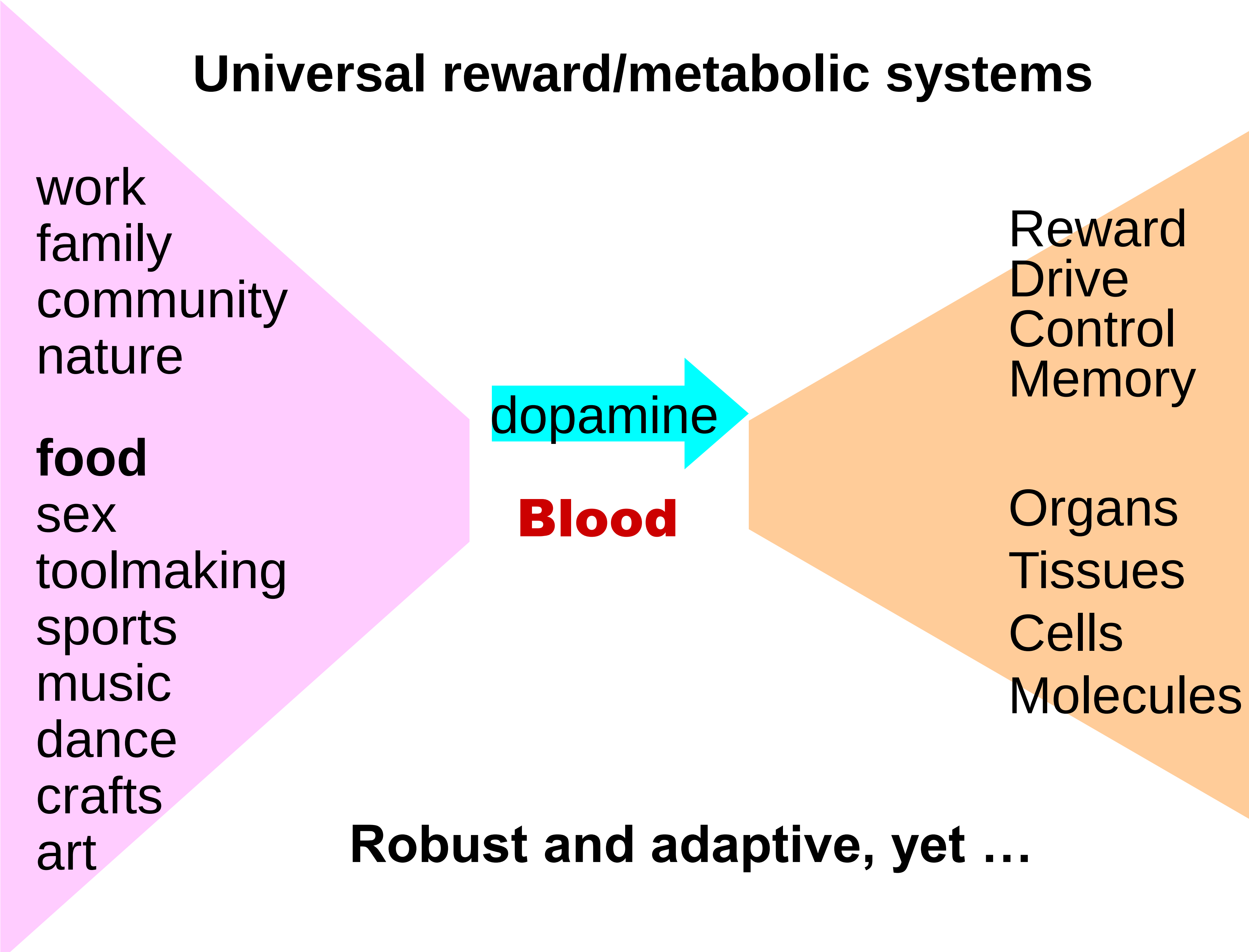
Organs
Tissues
Cells
Molecules

Layered architectures



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”

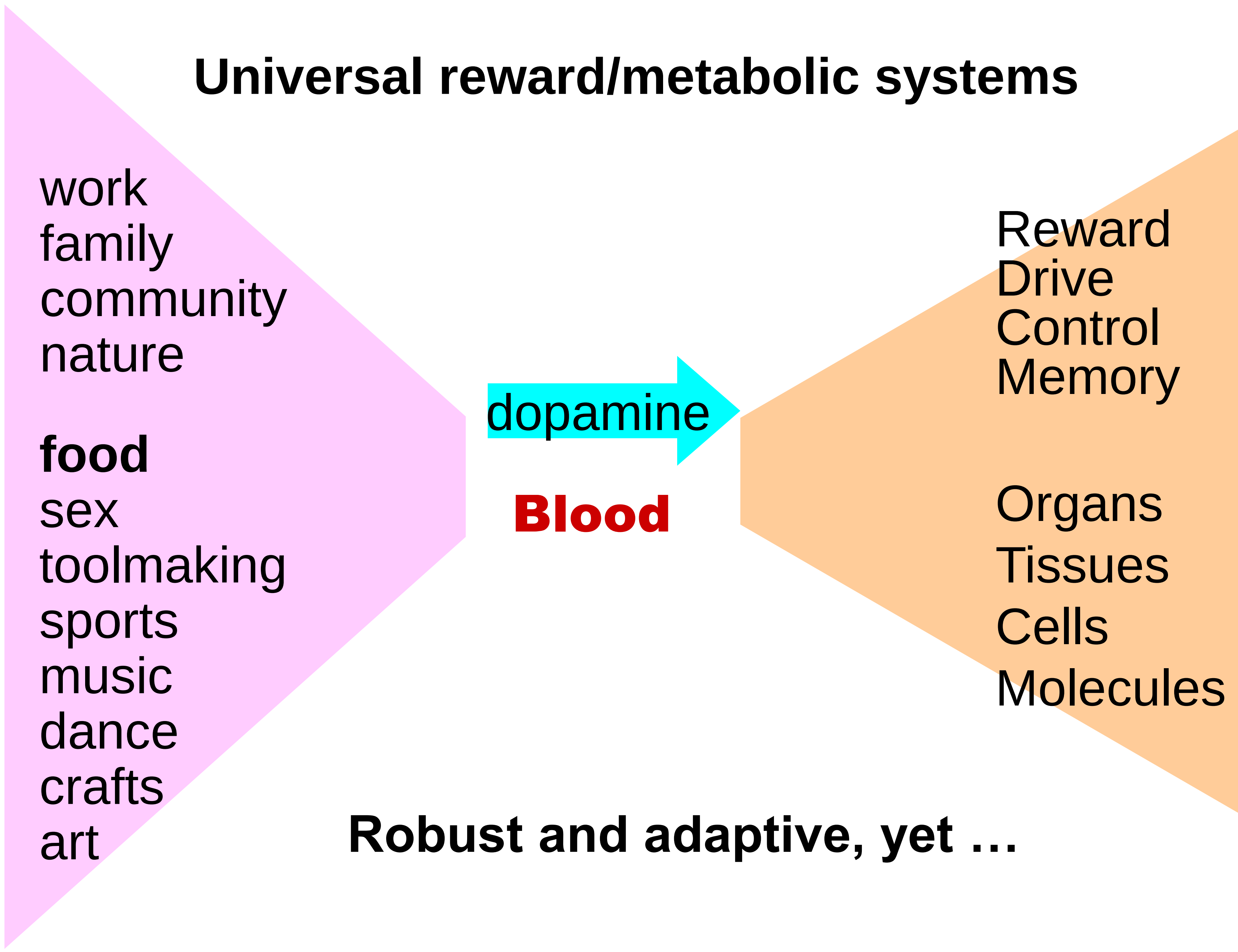
Modularity 2.0

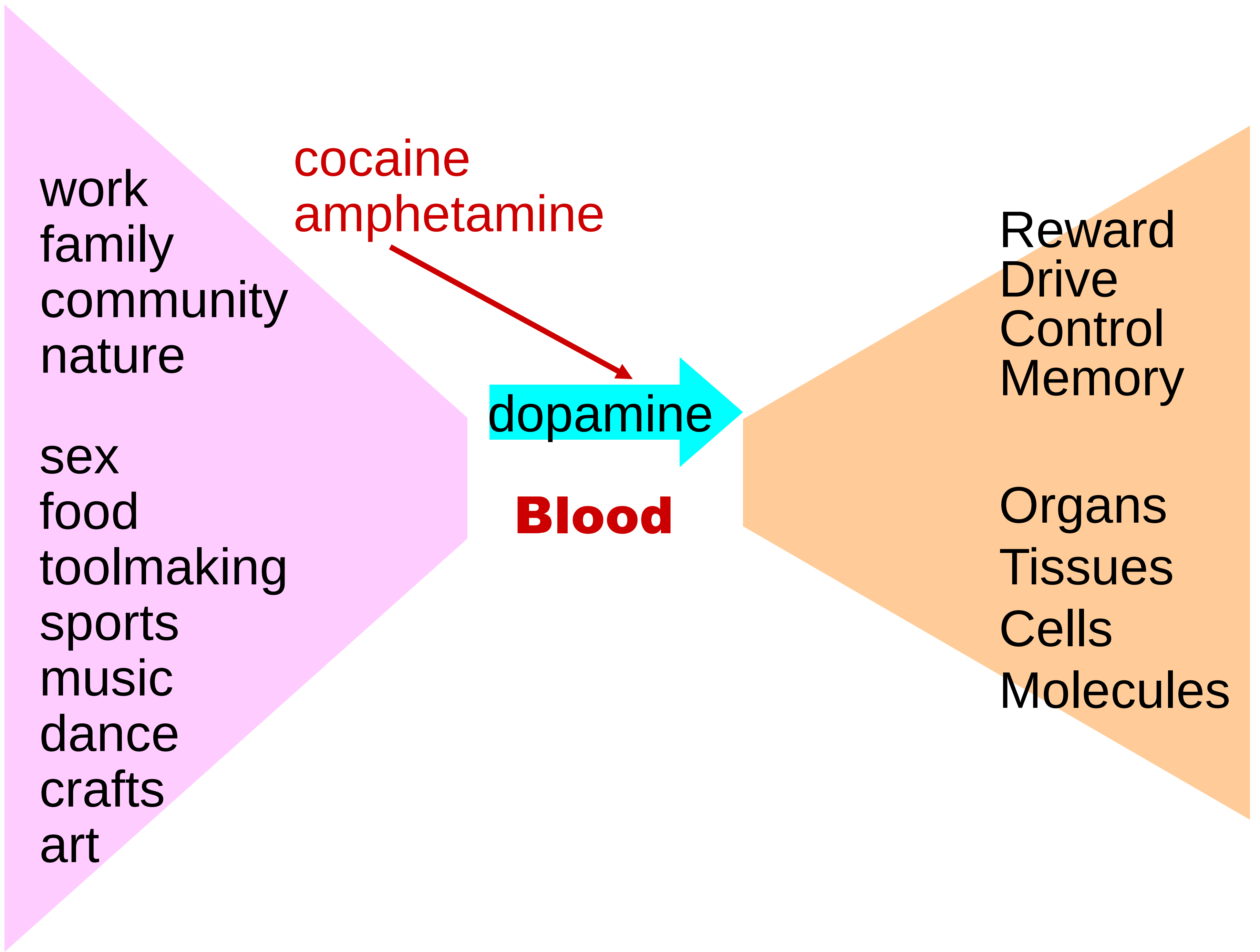
Most important “modules”

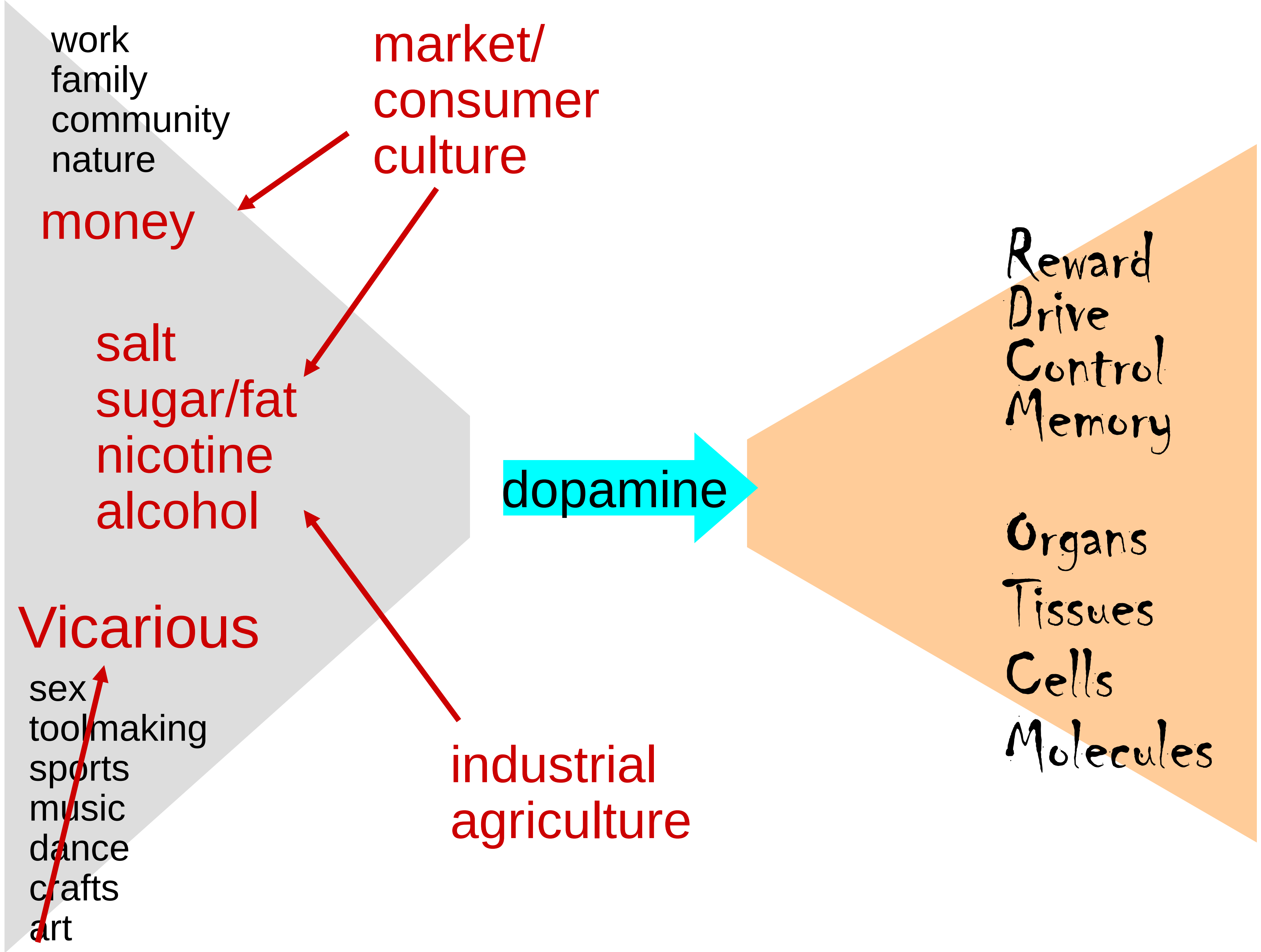
dopamine

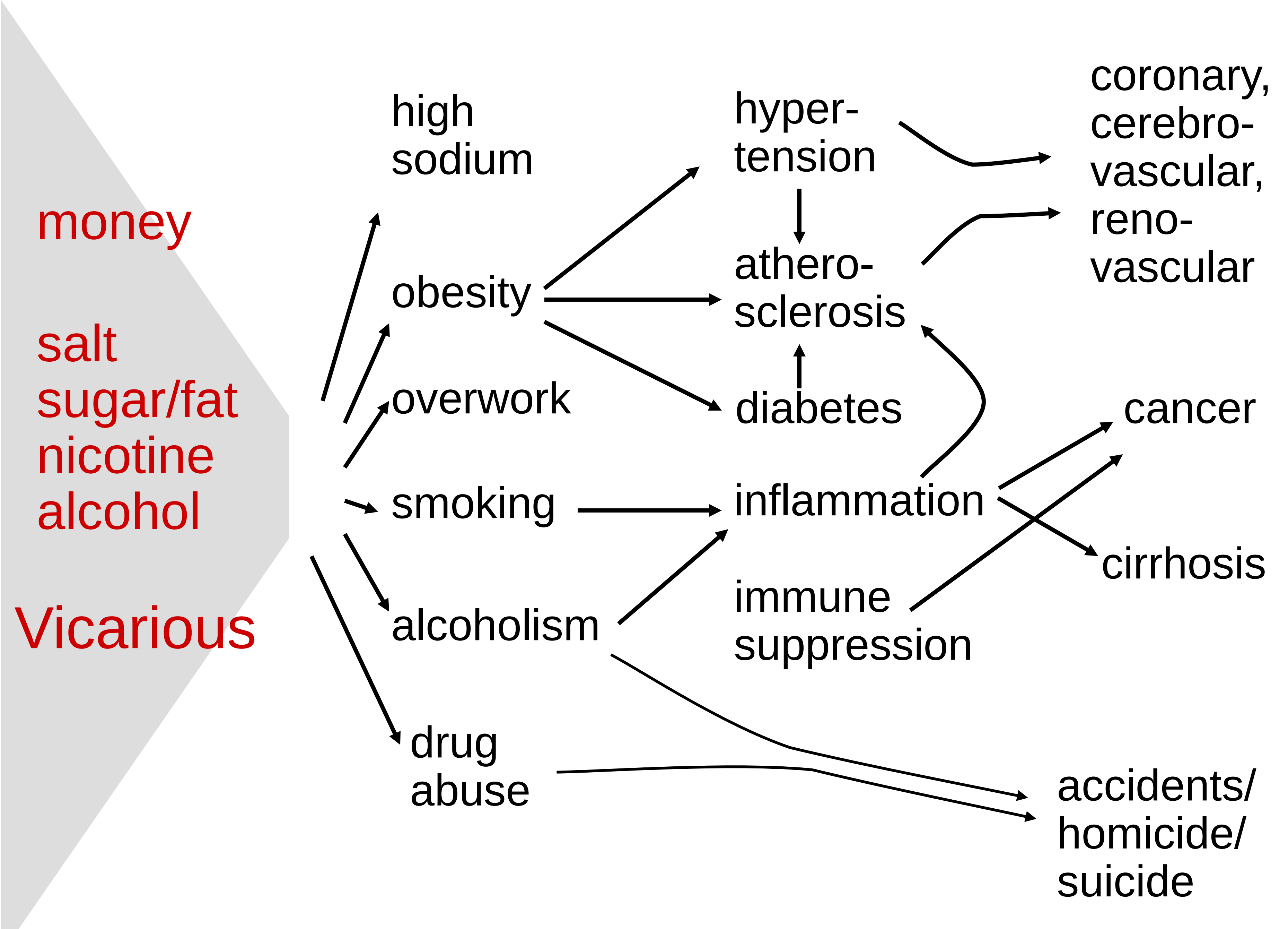
Blood

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

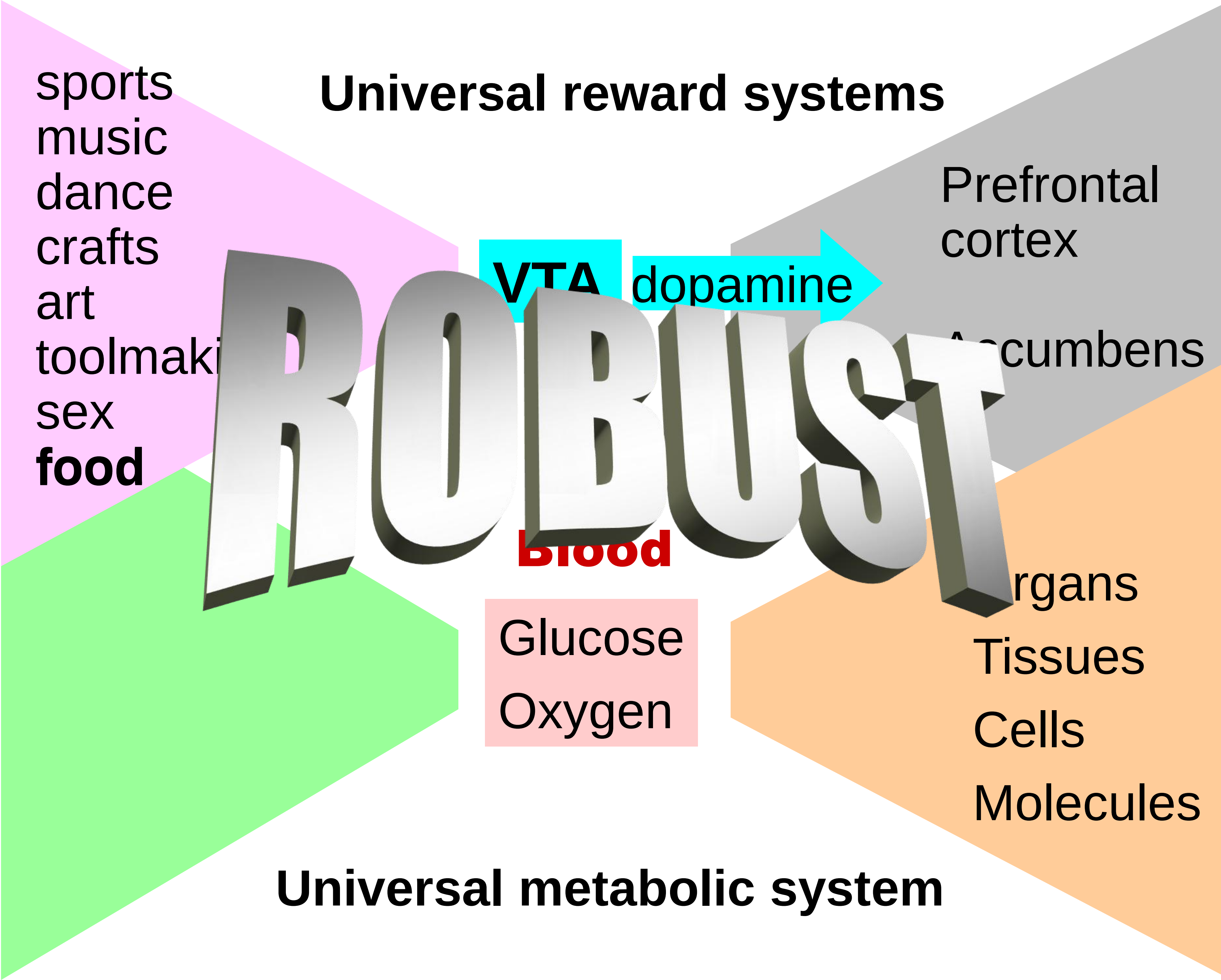

Universal reward/metabolic systems
work
family
community
nature
food
sex
toolmaking
sports
music
dance
crafts
art
dopamine
Blood
Reward
Drive
Control
Memory
Organs
Tissues
Cells
Molecules
Robust and adaptive, yet …

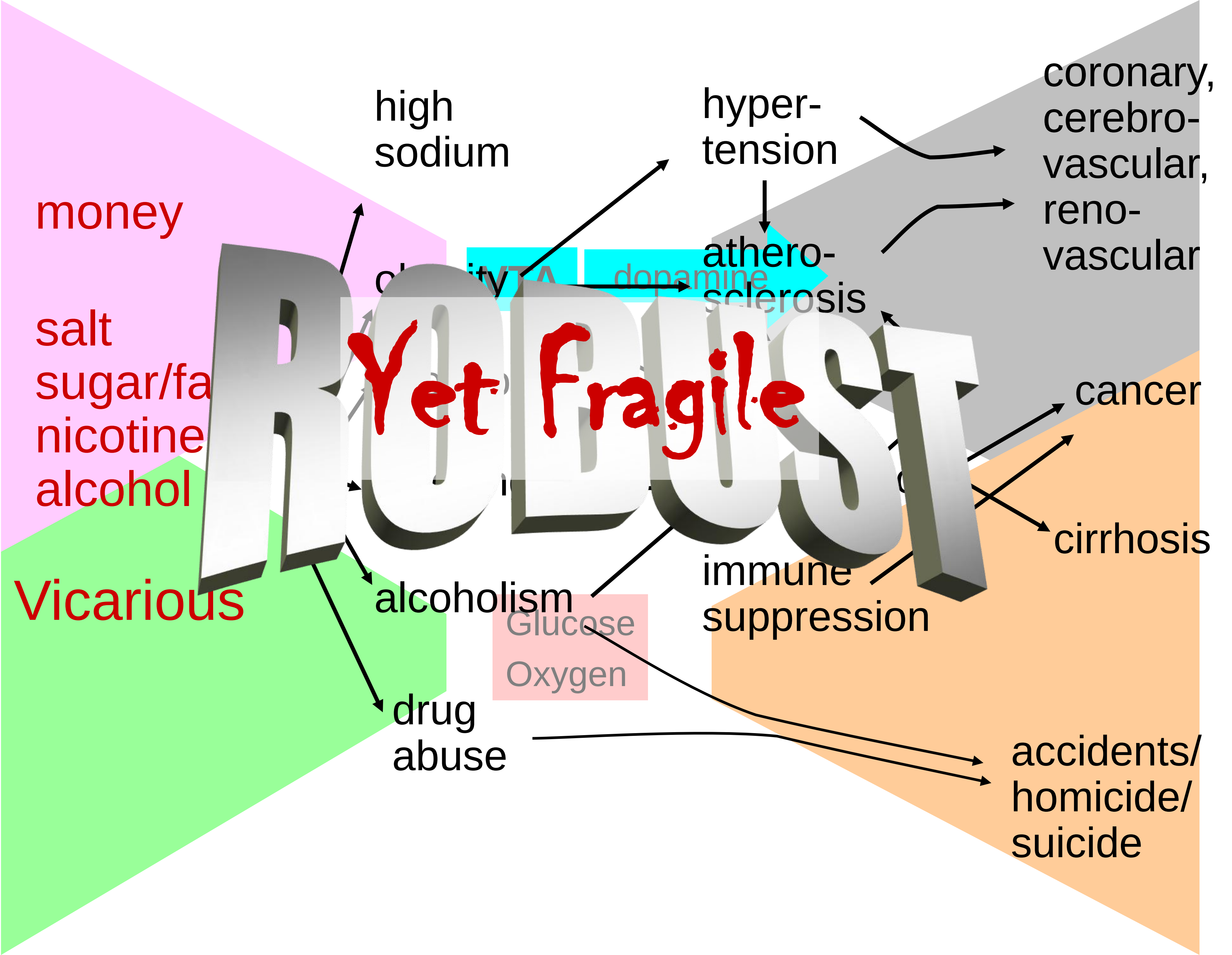

cocaine
amphetamine
work
family
community
nature
sex
food
toolmaking
sports
music
dance
crafts
art
dopamine
Blood
Reward
Drive
Control
Memory
Organs
Tissues
Cells
Molecules


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



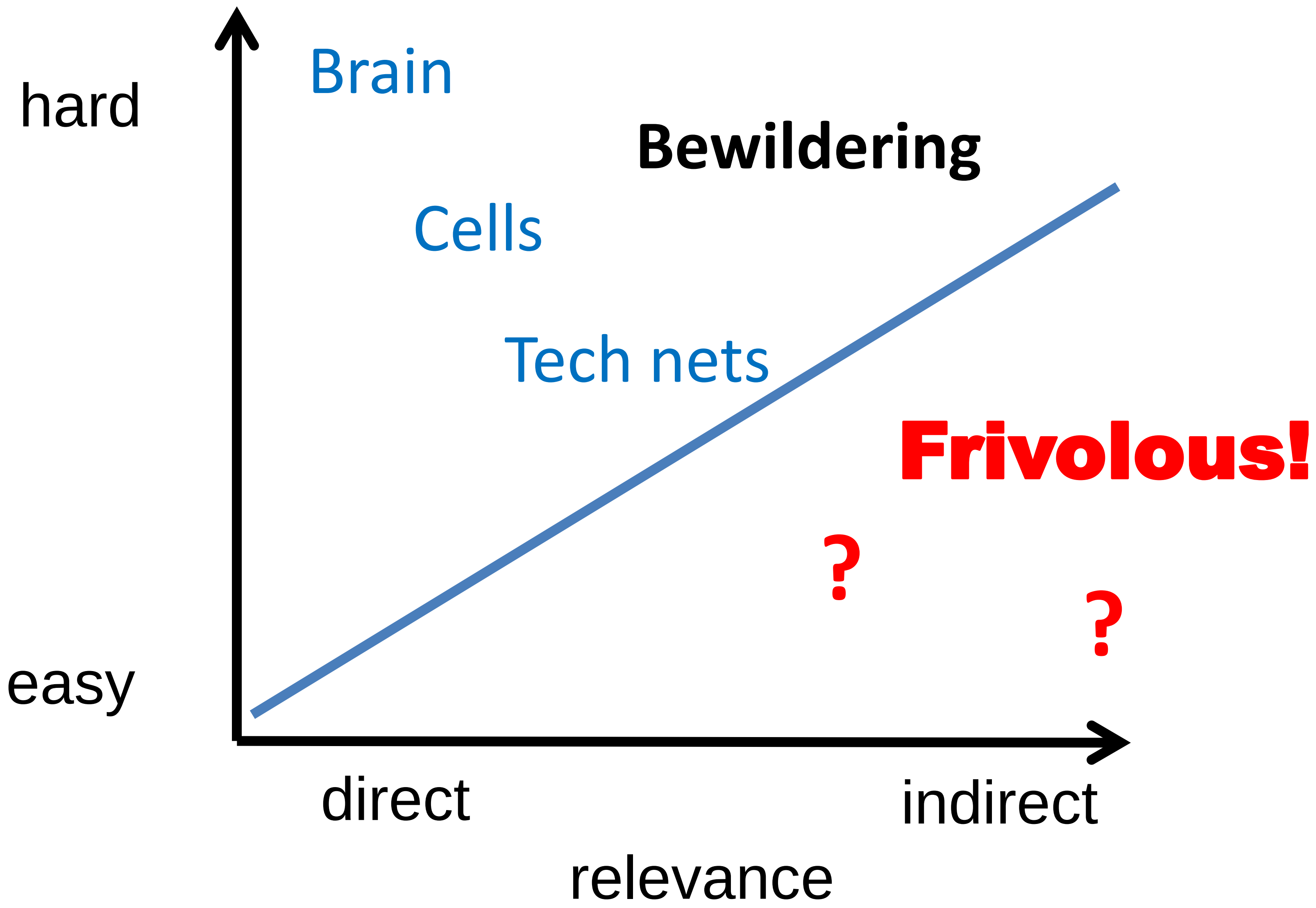
From Sterling


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



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

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

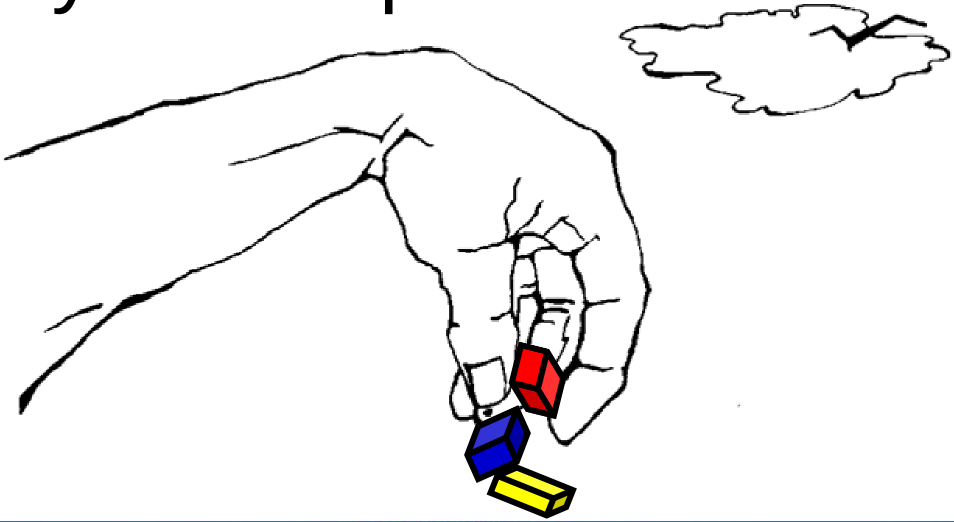
- 9 letters: adeginorz
- 9!= 362,880 sequences of 9 letters
- Only “organized” is a word

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

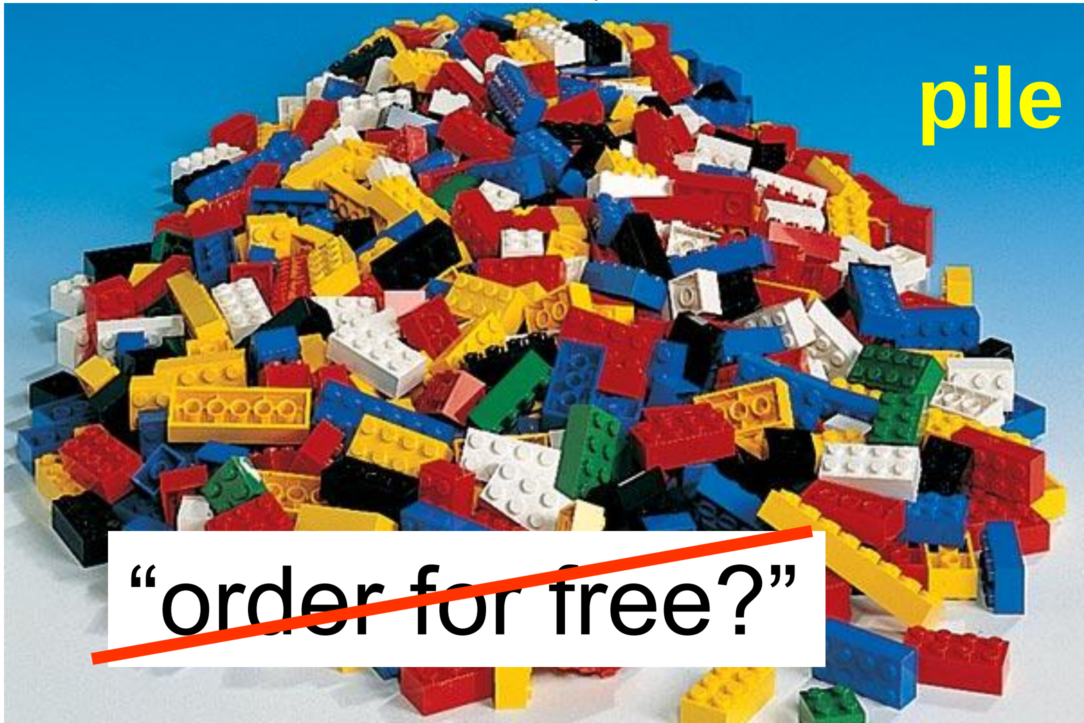
large **thin**

large **thin**

1 << # toys << # piles

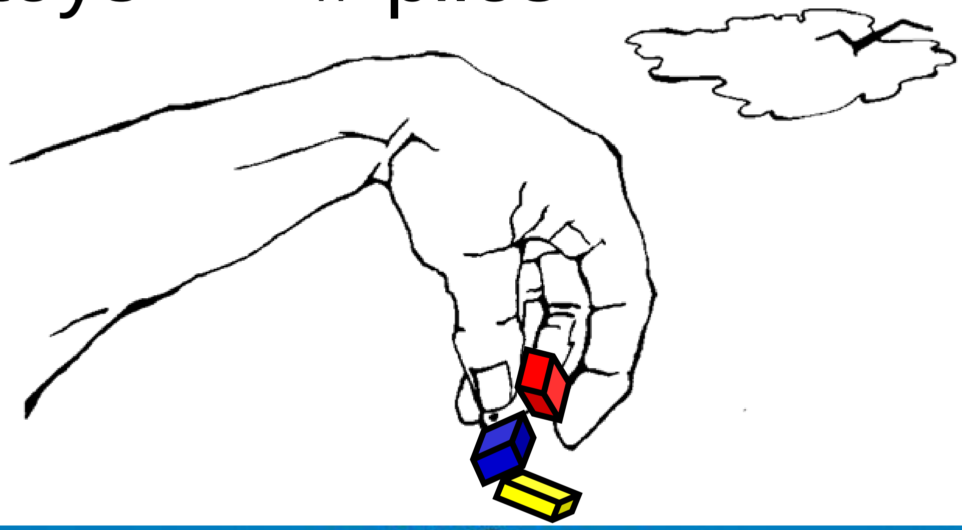


toys



~~large thin~~

~~1 << # toys << # piles~~



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

statistical physics
random ensembles
minimally tuned
phase transitions
bifurcations

REVIEW

Reverse Engineering of Biological Complexity

Marie E. Csete[1] 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

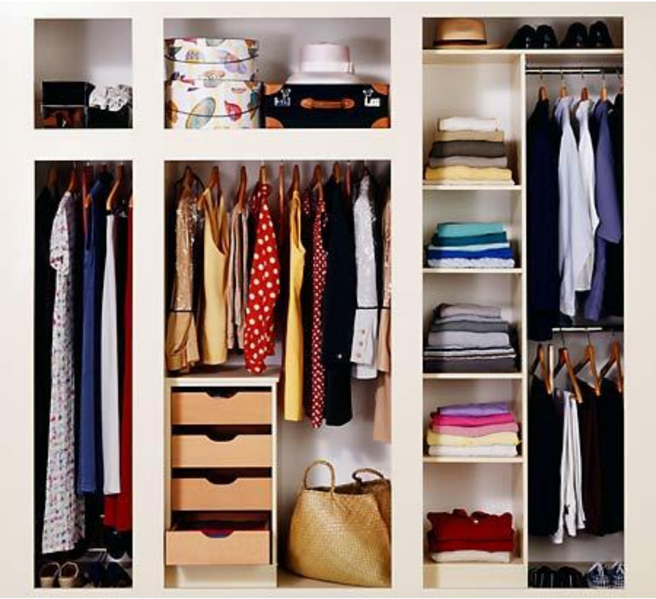
Biologists and biophy
ing complex networks oft
a biological network's
(*15*). They find that "per
homeostatic regulation are
networks (*16*, *17*), despite
anisms" that can seem g
(*18*–*20*). Some even concl
anisms and their resulting
in engineering (*20*, *21*). H
is in the nature of their rob
ity that biology and adva

Science
AAAS

Csete and Doyle

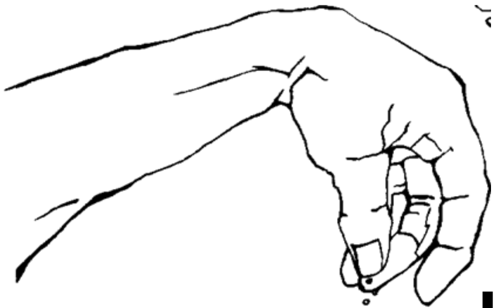
1 MARCH 2002 VOL 295 SCIENCE www.sciencemag.org

wardrobe



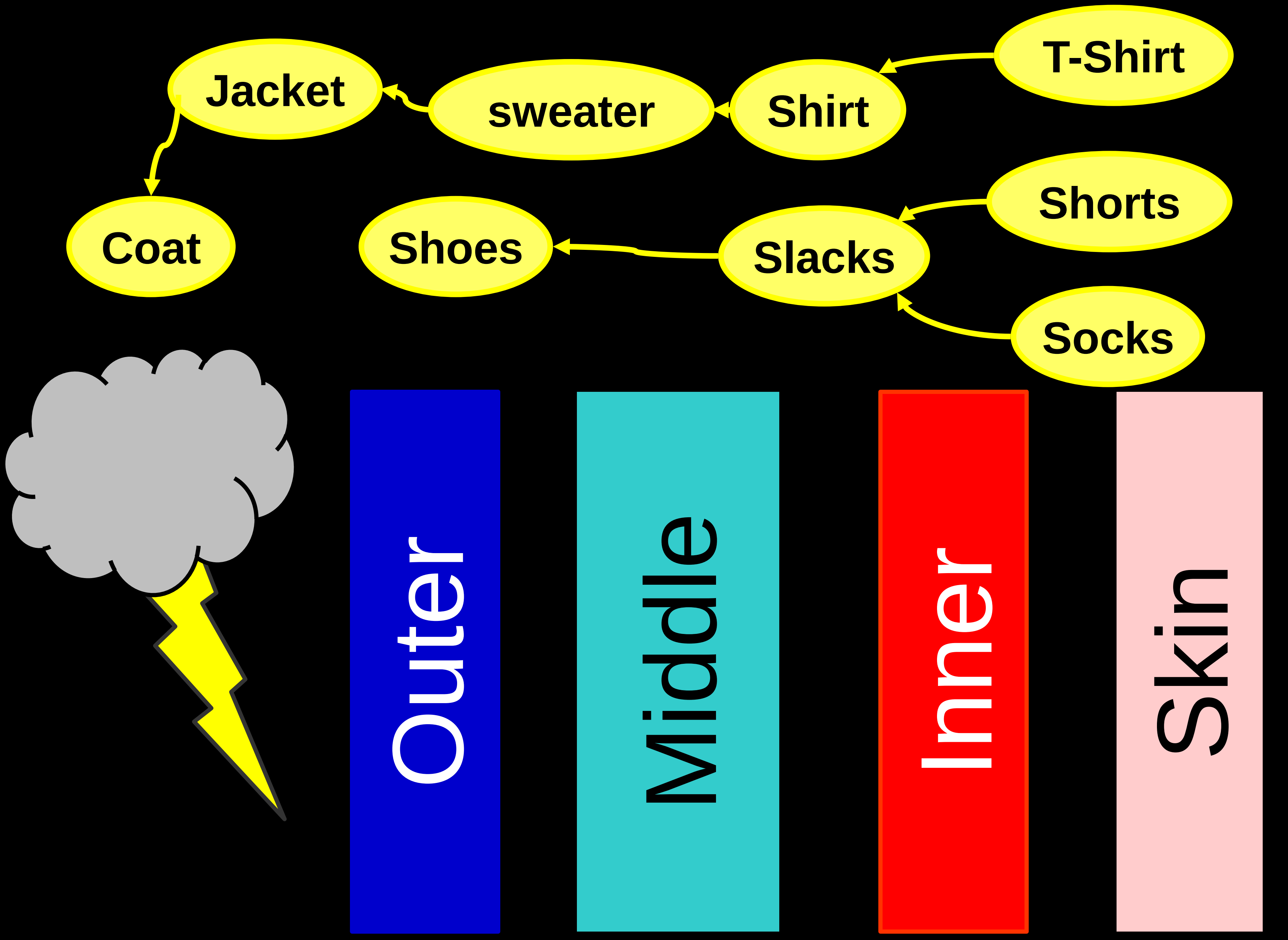
large **thin**

1 << # outfits << # heaps



heap


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.
Cool
1
Wicking Base Layer
+
3
Weatherproof Shell
Frigid
1
Wicking Base Layer
+
2
Insulating Thermal Layer
+
3
Weatherproof Shell
Extreme
1
Wicking Base Layer
+
2
Insulating Thermal Layer
+
2
Extra Insulating Layer
+
3
Weatherproof Shell
Layering
Tradeoffs

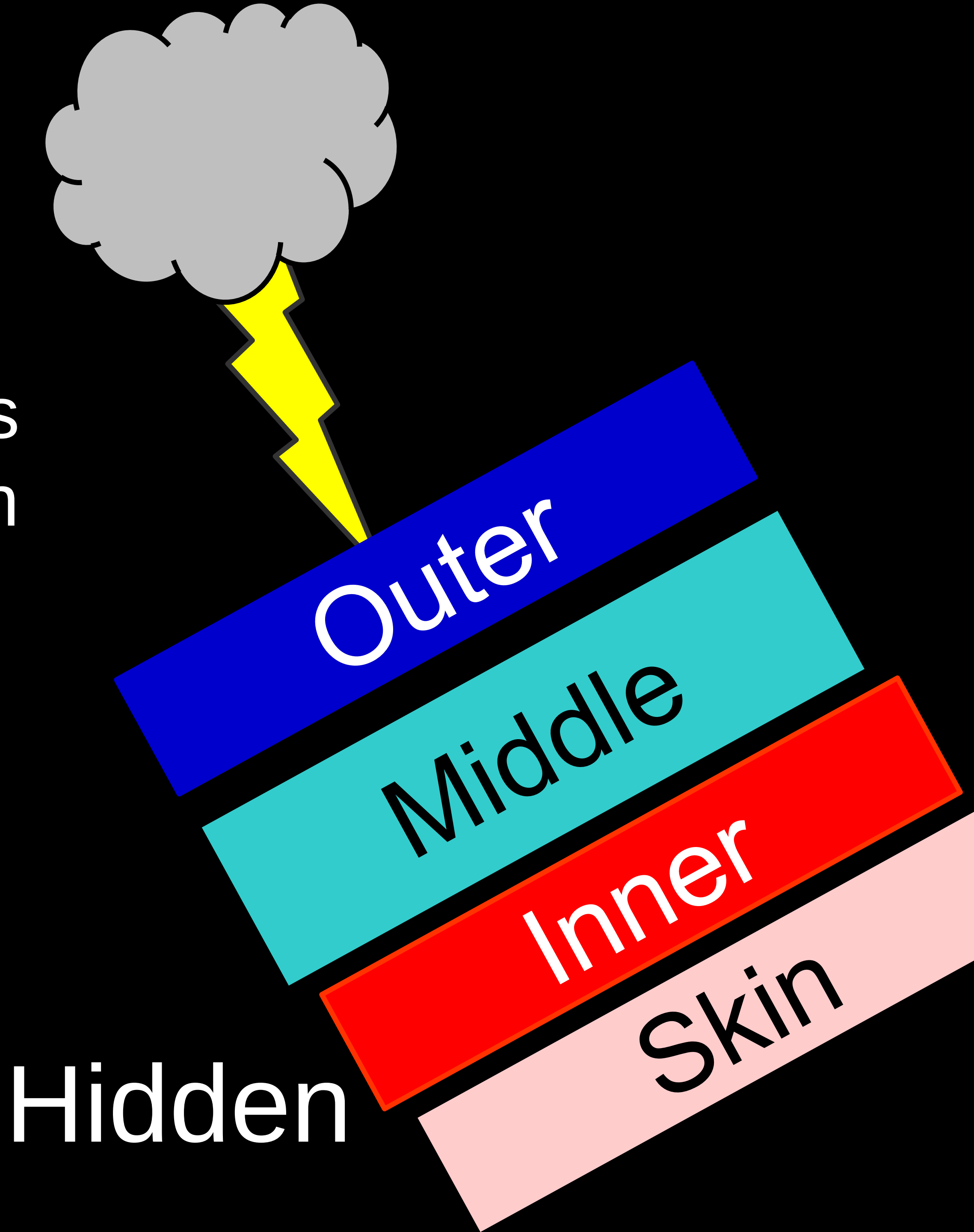


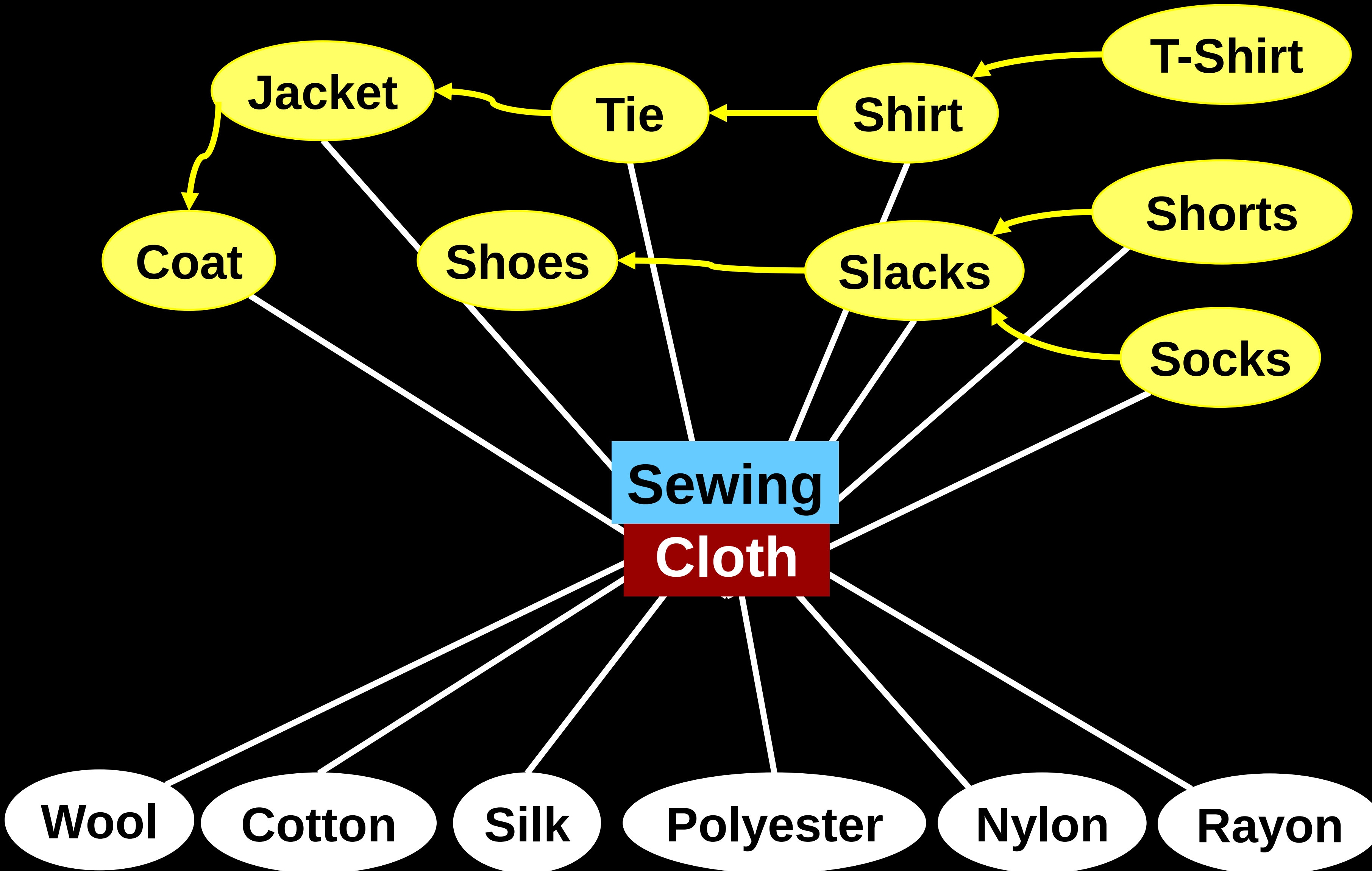
Jacket
sweater
Shirt
T-Shirt
Coat
Shoes
Slacks
Shorts
Socks
Outer
Middle
Inner
Skin

System constraints

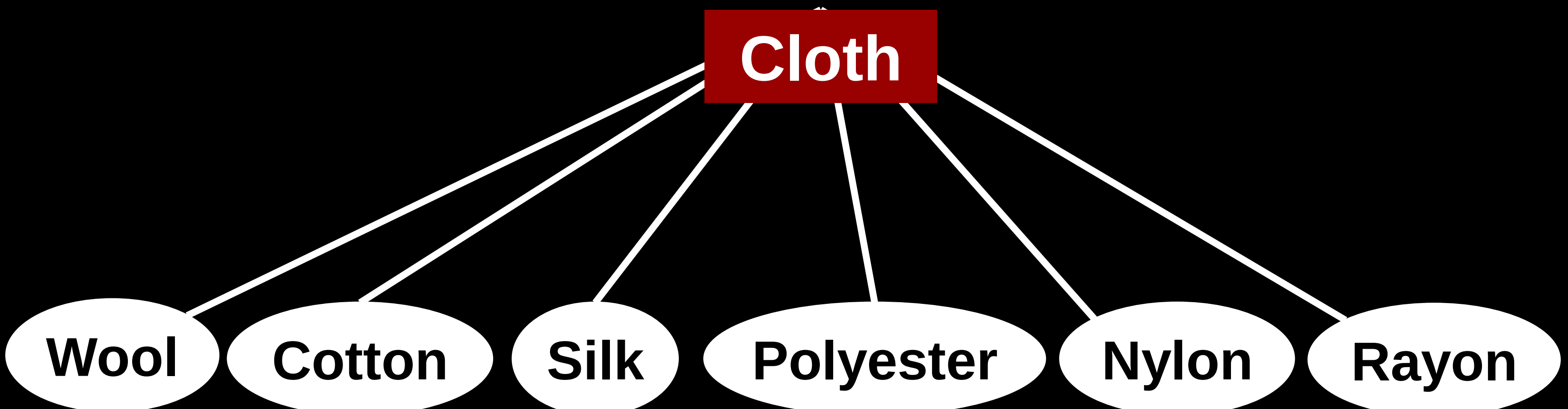
Robust to variations and requirements in

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

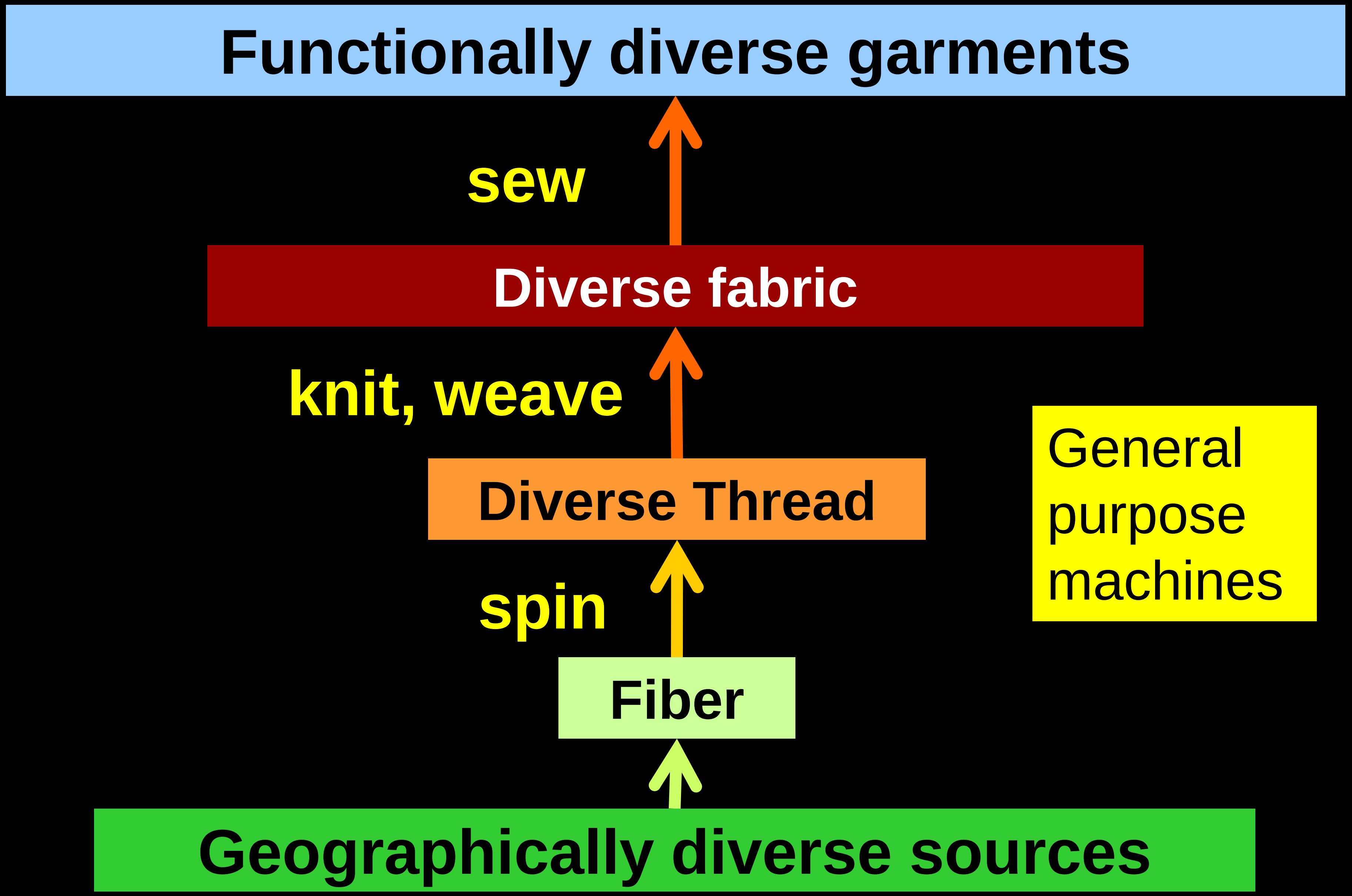




T-Shirt
Jacket
Tie
Shirt
Shorts
Coat
Shoes
Slacks
Socks
Sewing
Cloth
Wool
Cotton
Silk
Polyester
Nylon
Rayon

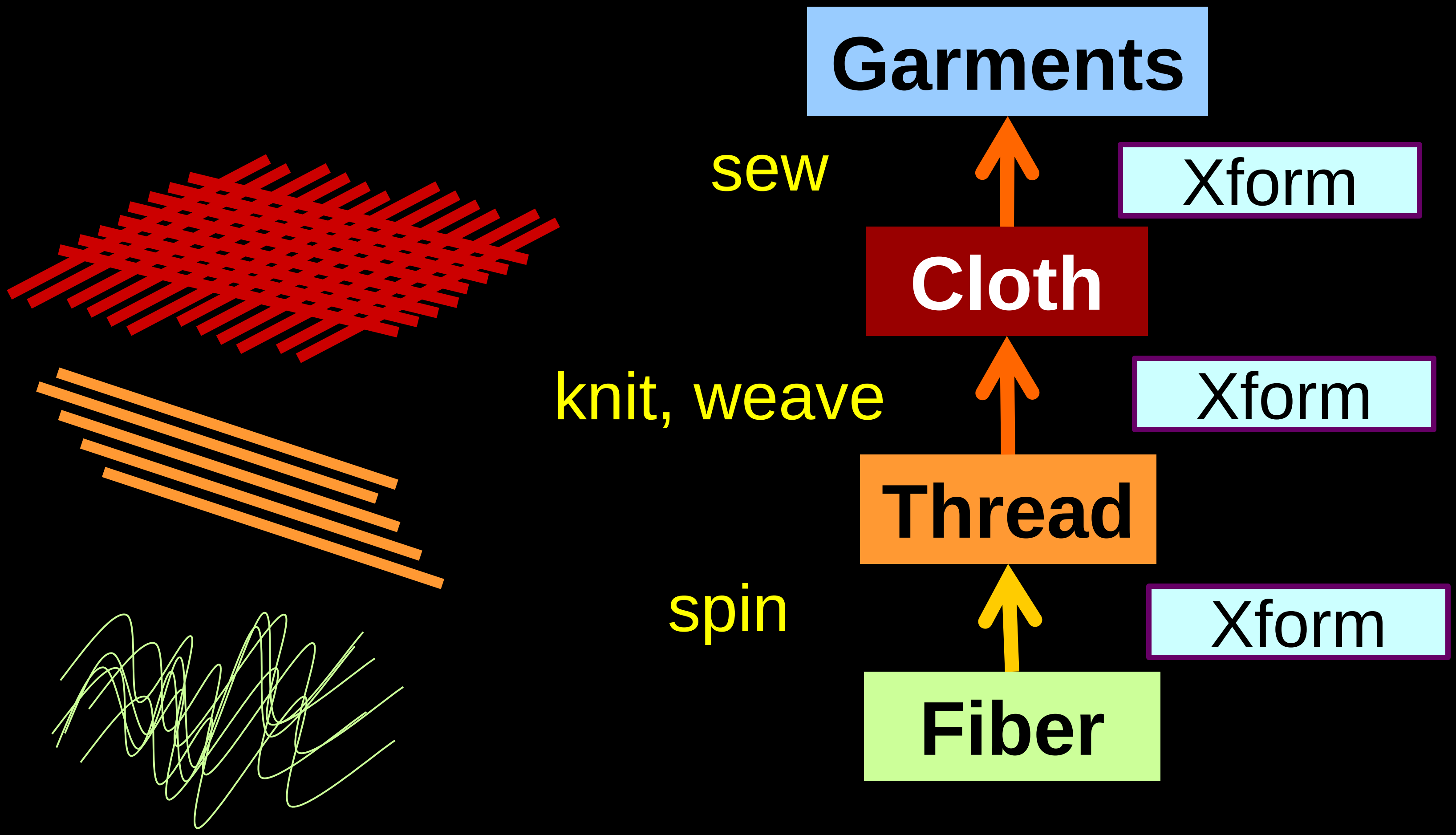


Component constraints



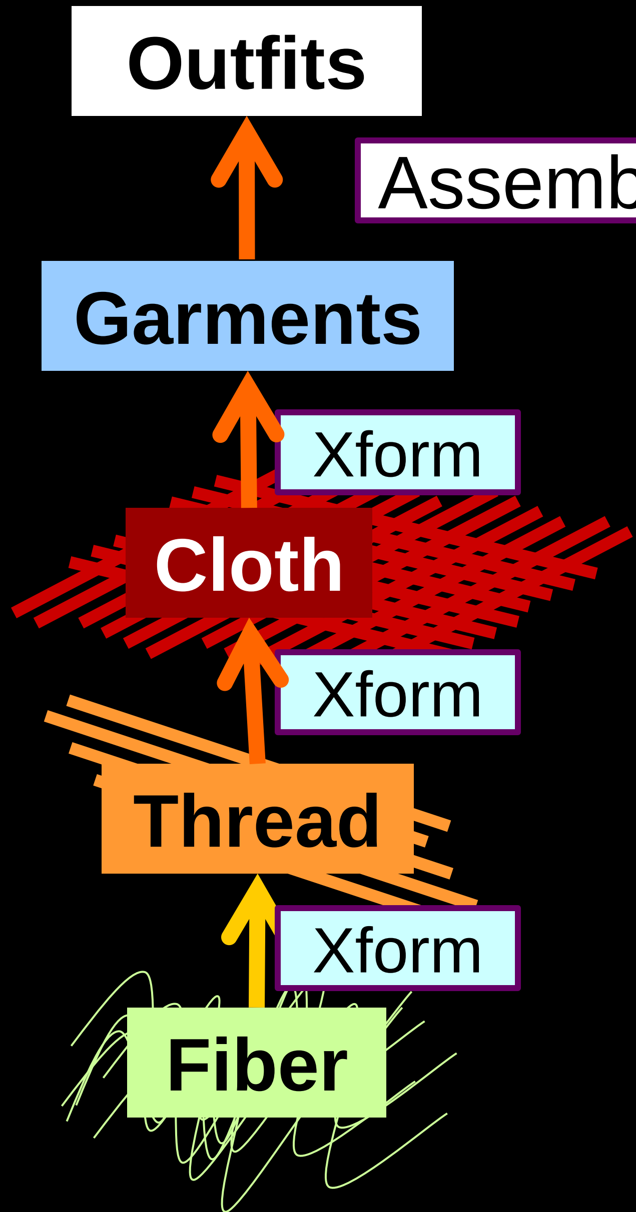
Functionally diverse garments
sew
Diverse fabric
knit, weave
Diverse Thread
spin
Fiber
Geographically diverse sources
General purpose machines

Architecture and Modularity 2.0



Prevents unraveling of lower layers

Hidden, large, thin, nonconvex

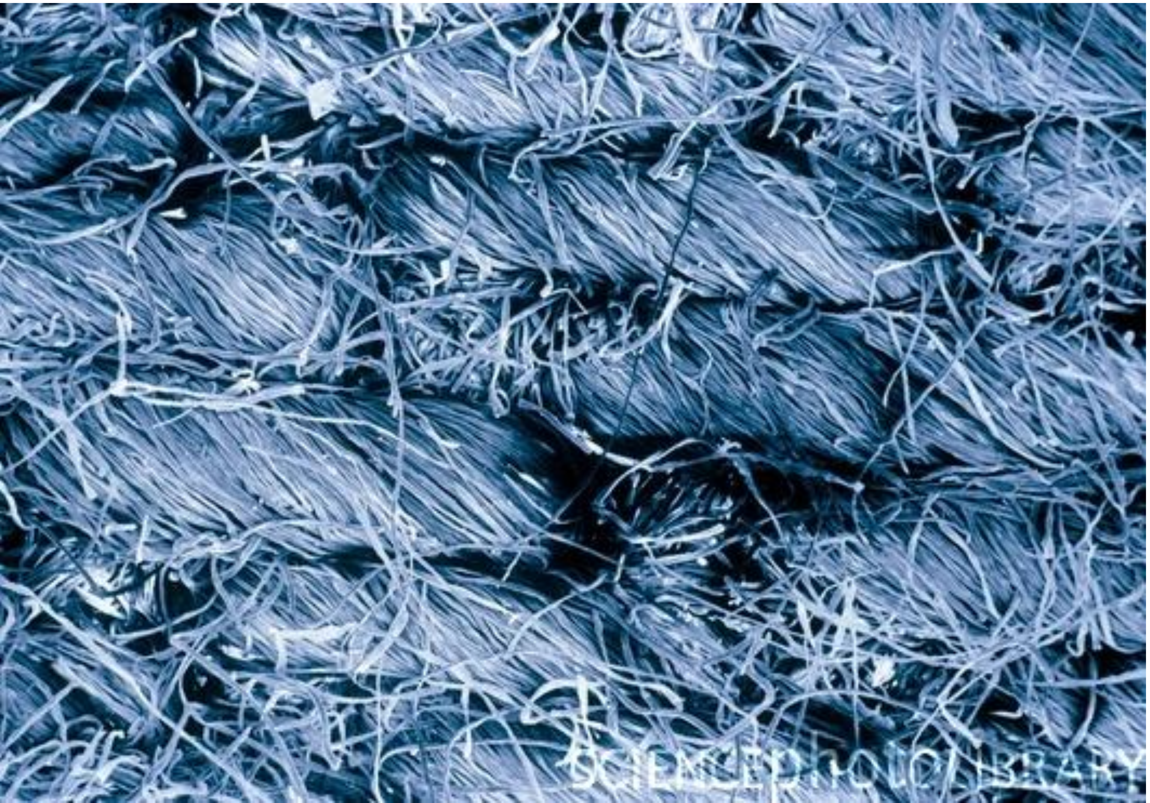


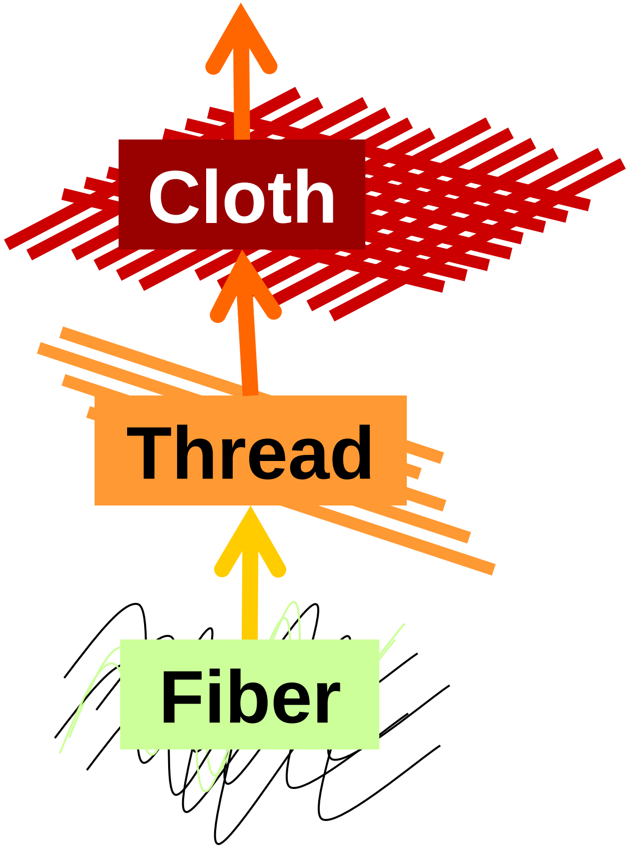
are *necessary*

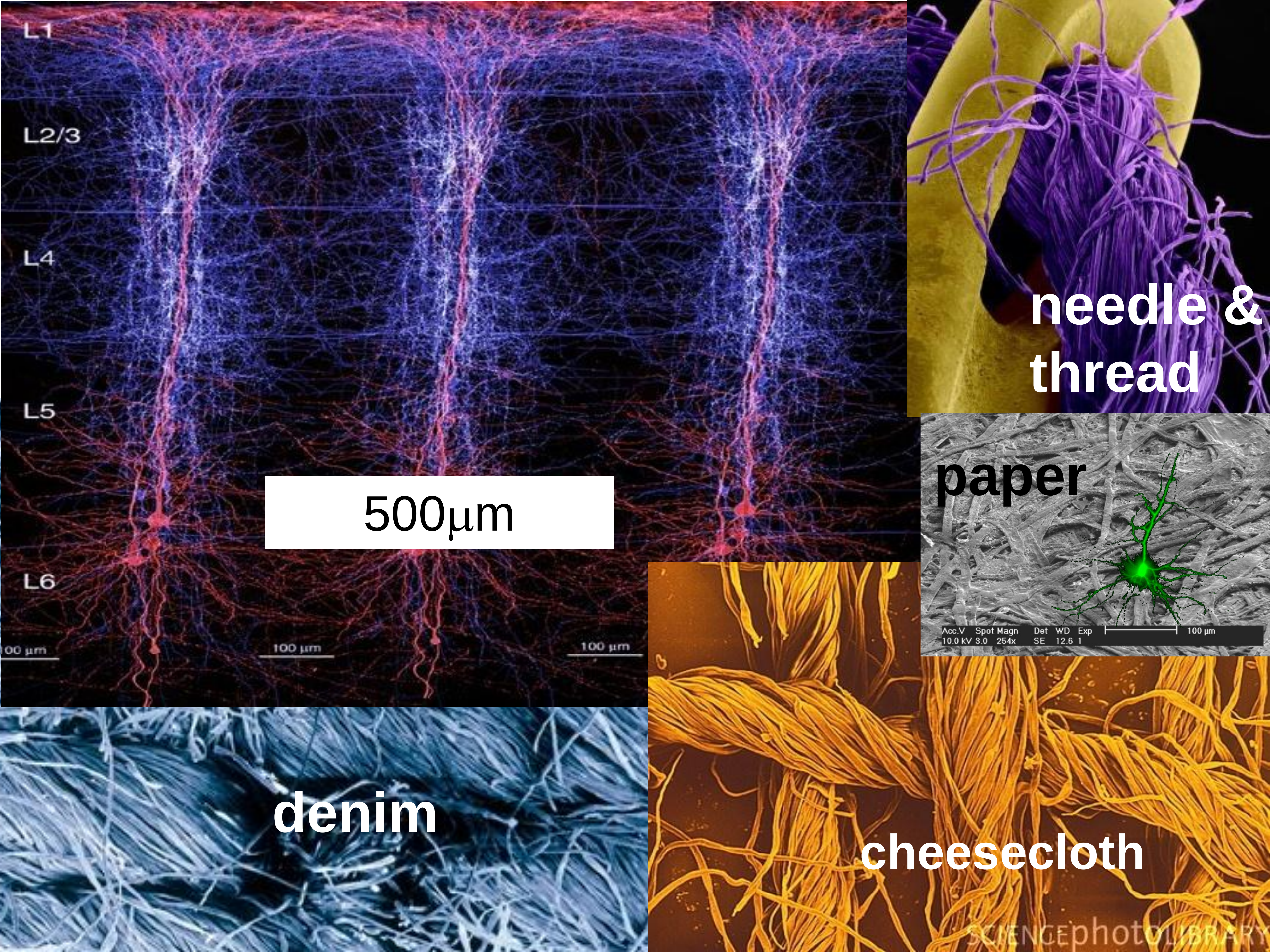
500μm

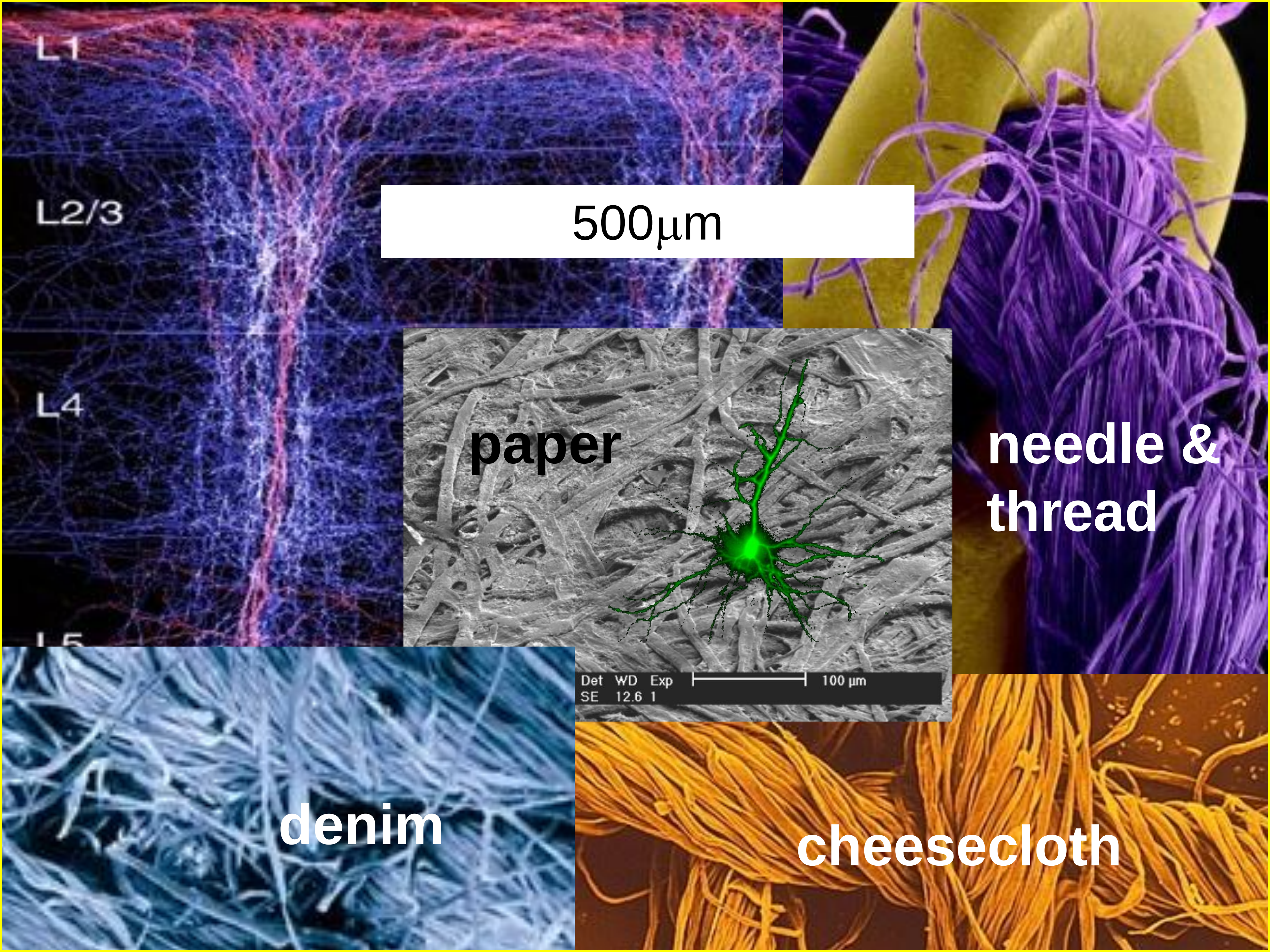
.5mm

denim





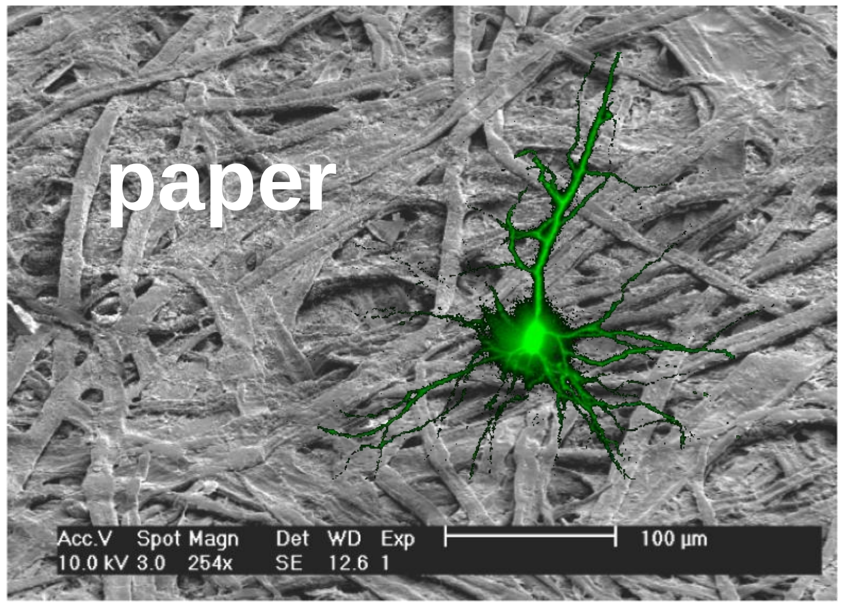

L1
L2/3
L4
L5
L6
100 µm
100 µm
100 µm
500µm
needle &
thread
paper
Acc.V Spot Magn Det WD Exp
10.0 kV 3.0 254x SE 12.6 1
100 µm
denim
cheesecloth
SCIENCEphotoLIBRARY

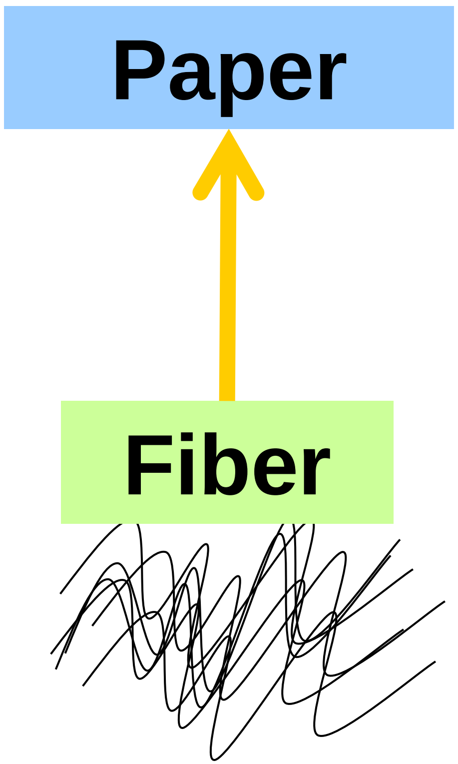


L1
L2/3
L4
L5
500μm
paper
Det WD Exp
SE 12.6 1
100 μm
needle &
thread
denim
cheesecloth

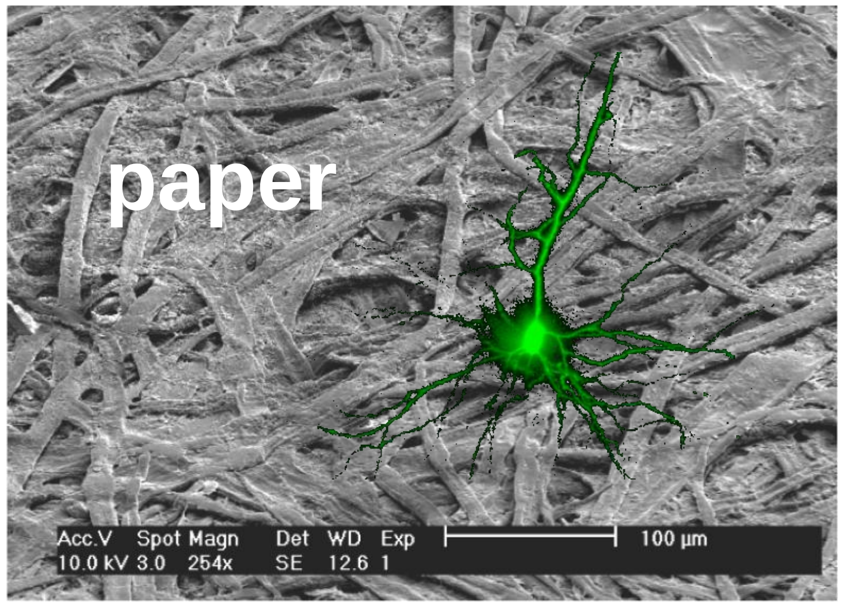
.5mm x .35 mm cotton paper

500μm

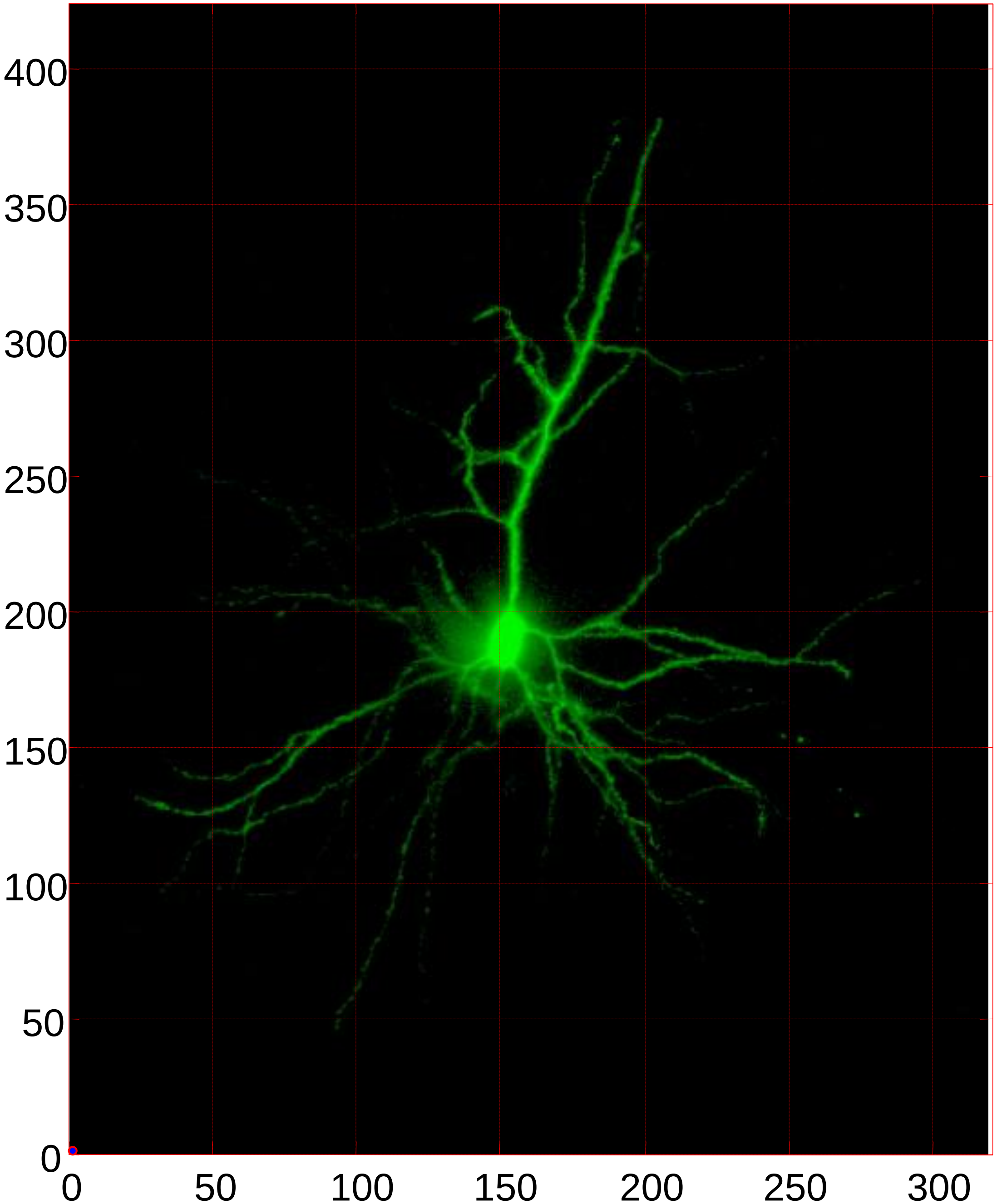




500µm



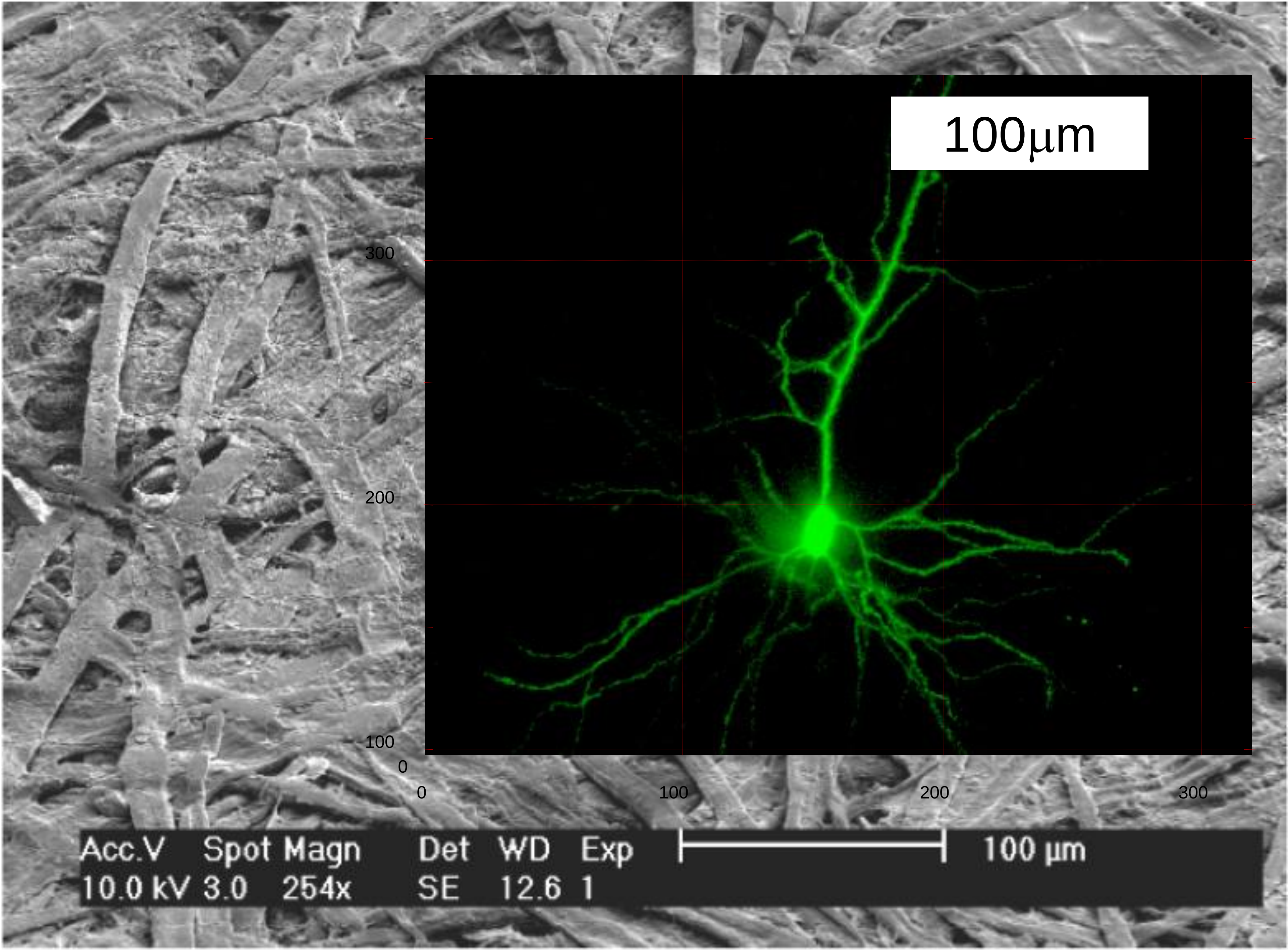
Minimal architecture



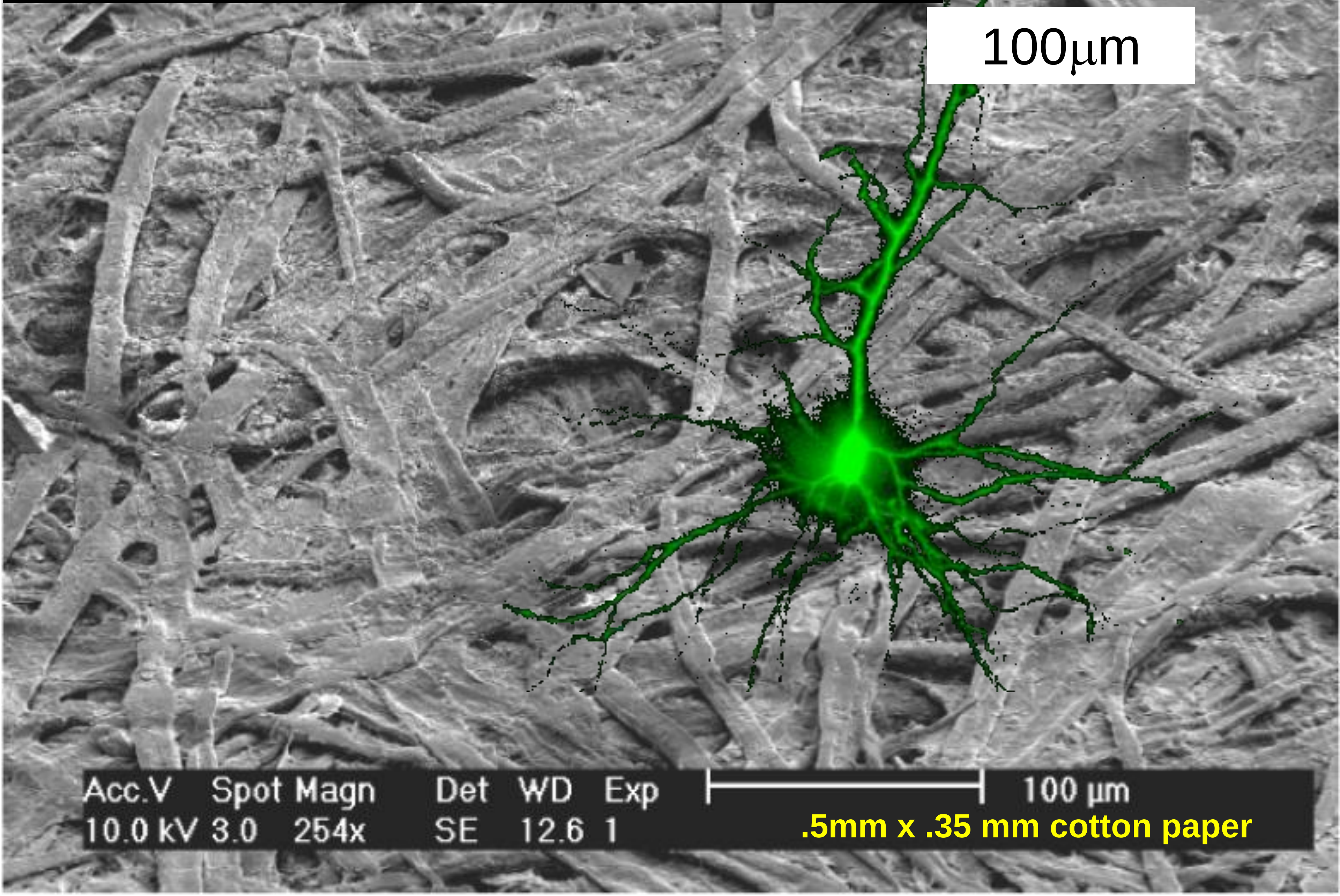
100μm

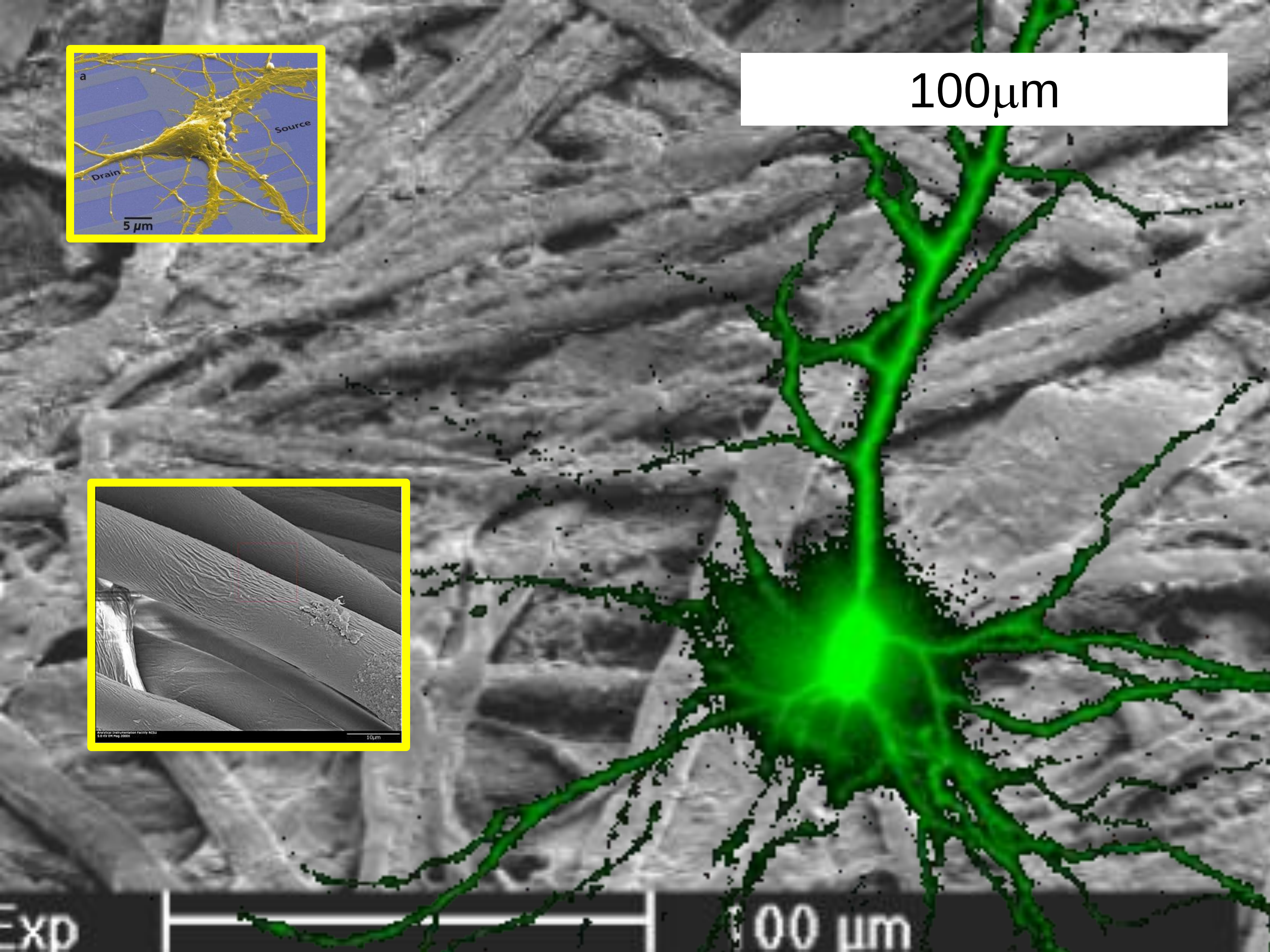
A neonatal rat pyramidal neuron

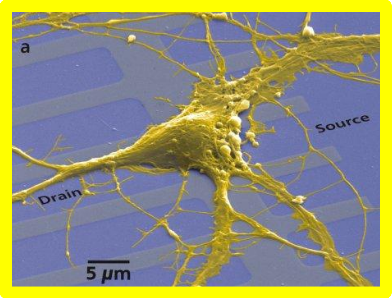
filled with Lucifer Yellow imaged on the BioRad MRC600 confocal microscope using a 20X oil objective, NA=0.8. Image size is 320 x 425 x 120 μm.


100μm
300
200
100
0
0
100
200
300
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



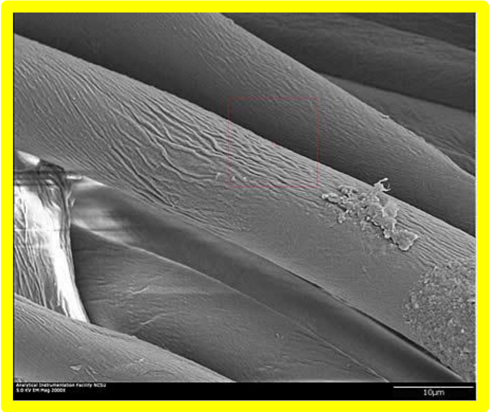

100μm
a
Source
Drain
5 μm
Exp
00 μm



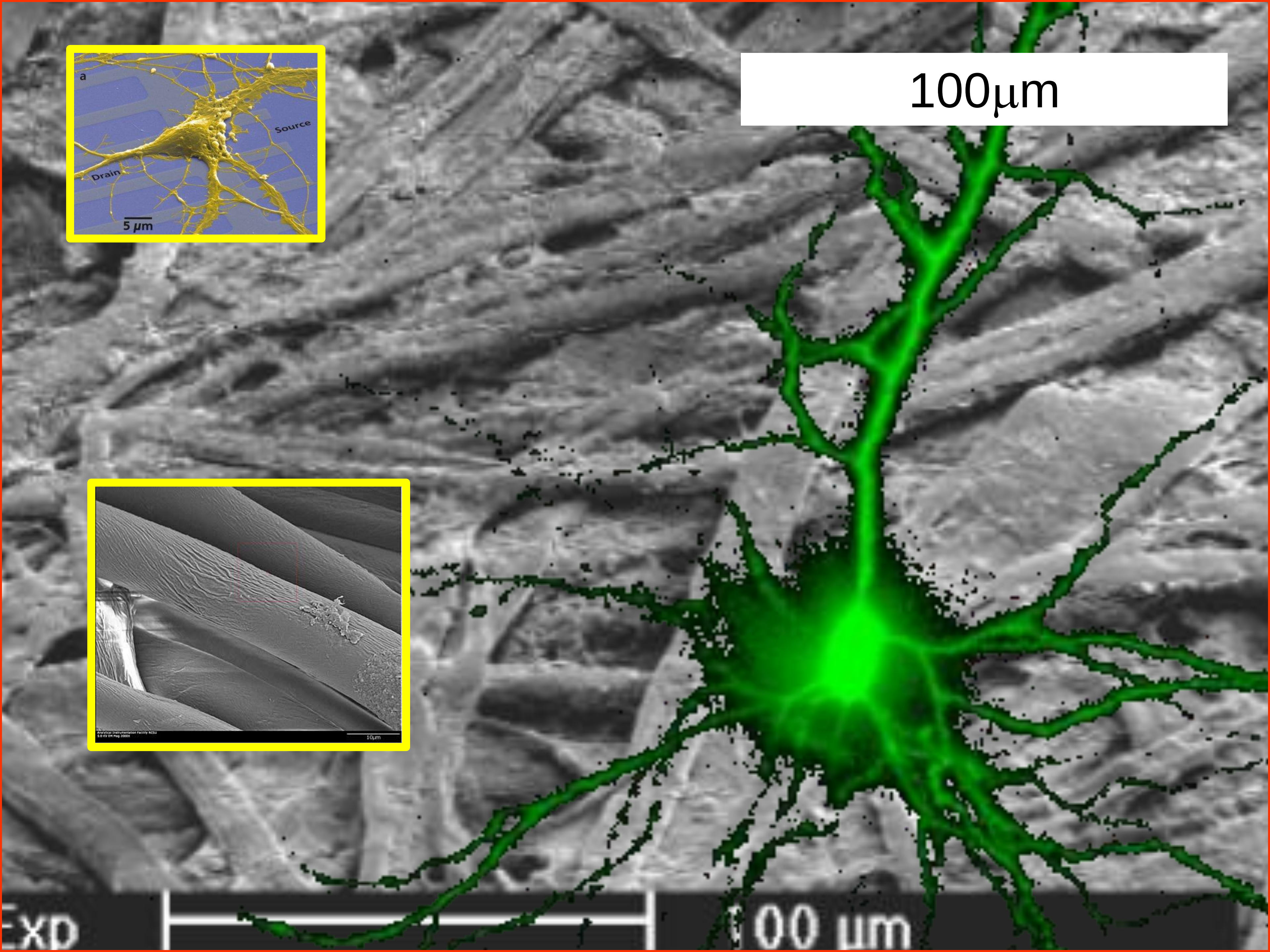
47x35 micron

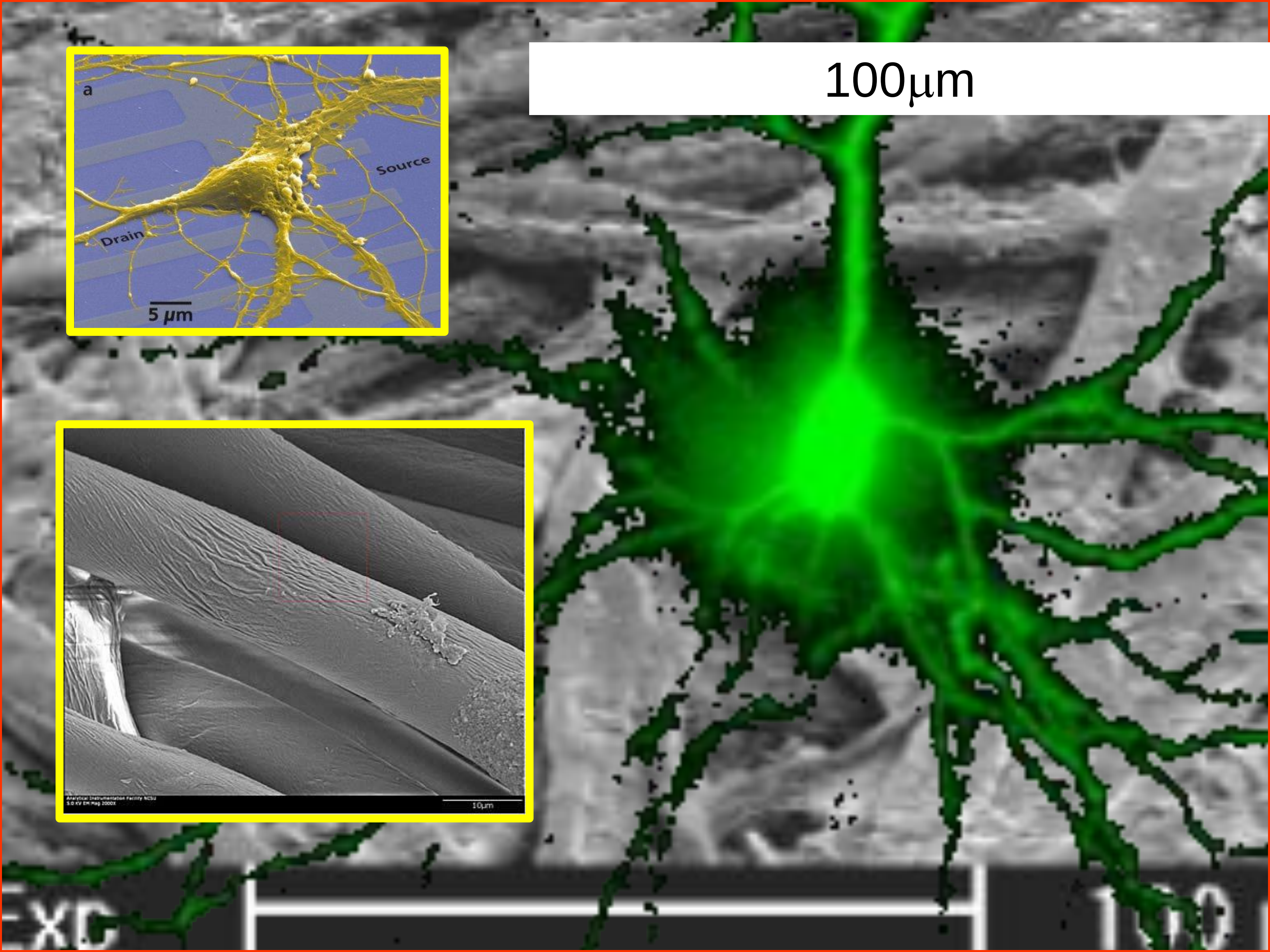
100μm

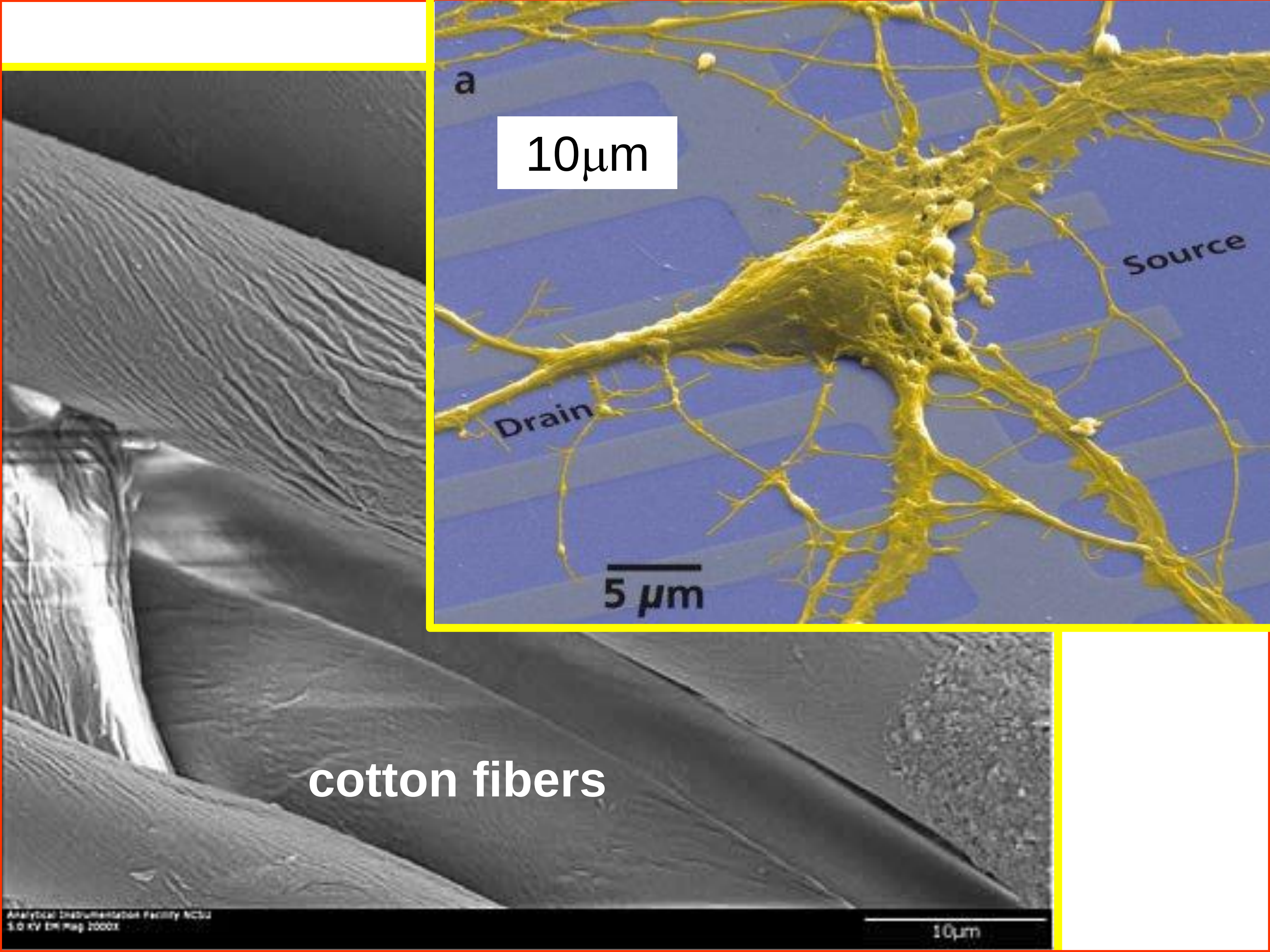
cotton fibers

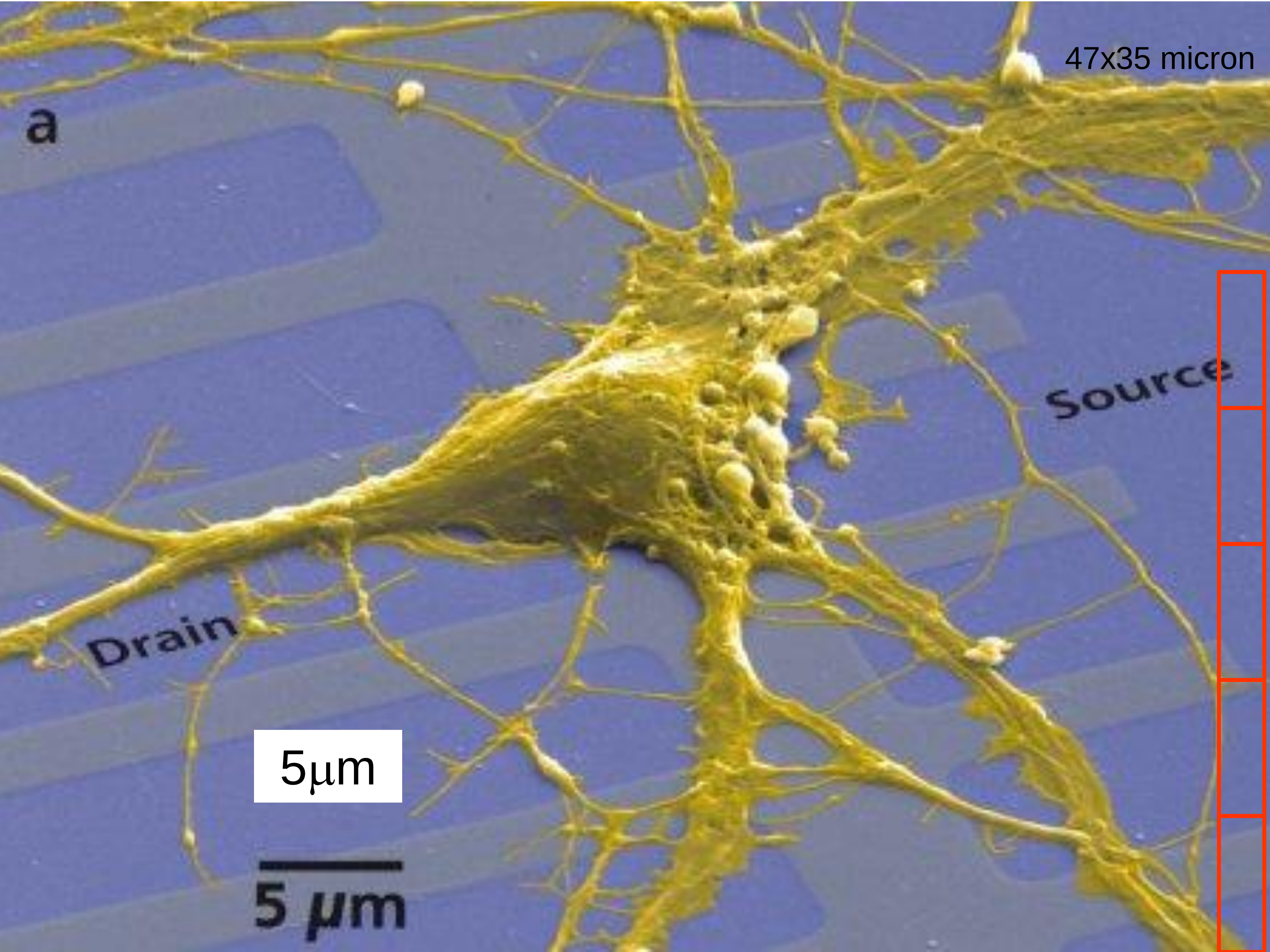


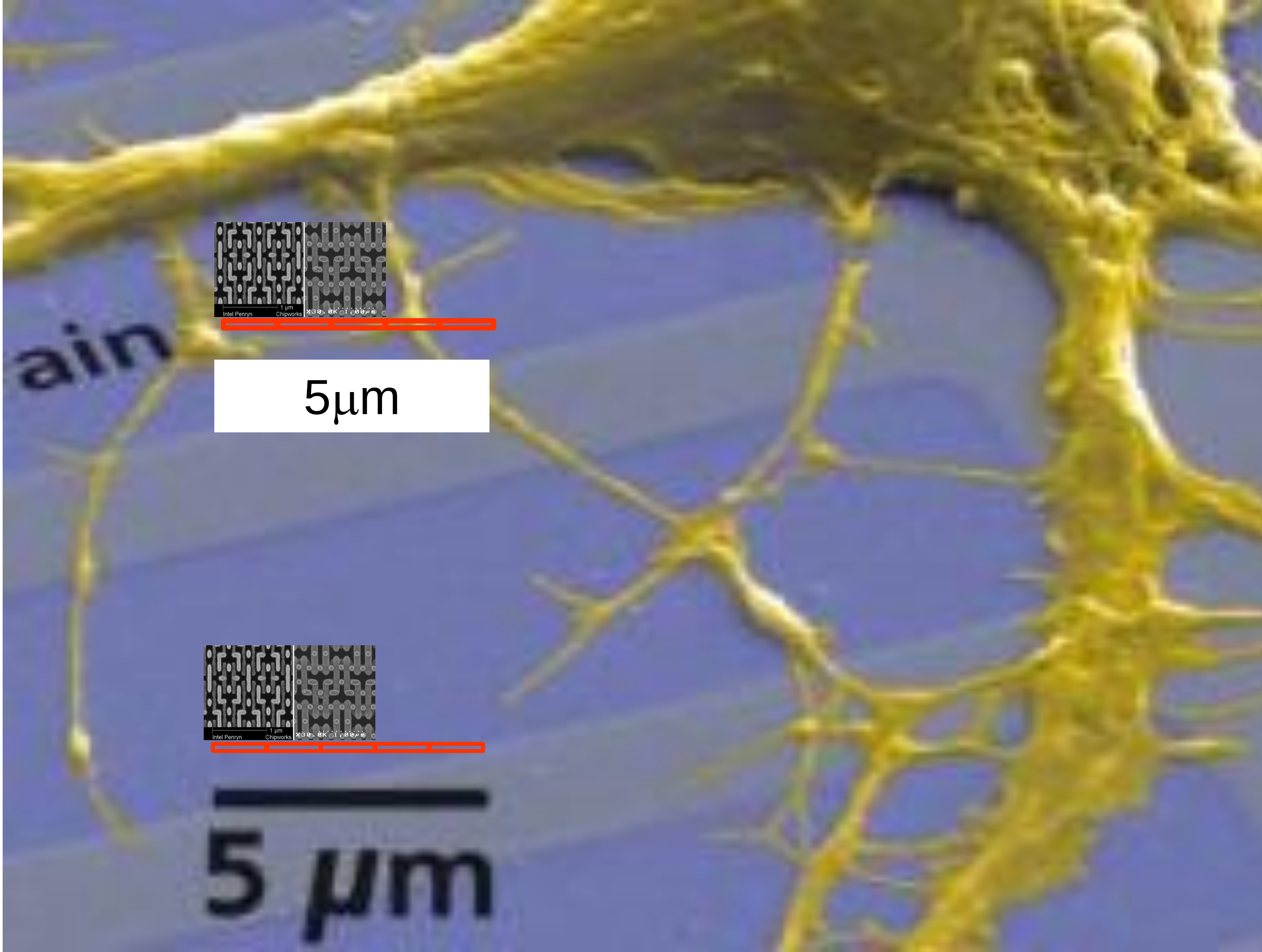
60x50 microns


100μm
a
Source
Drain
5 μm
Exp
00 μm

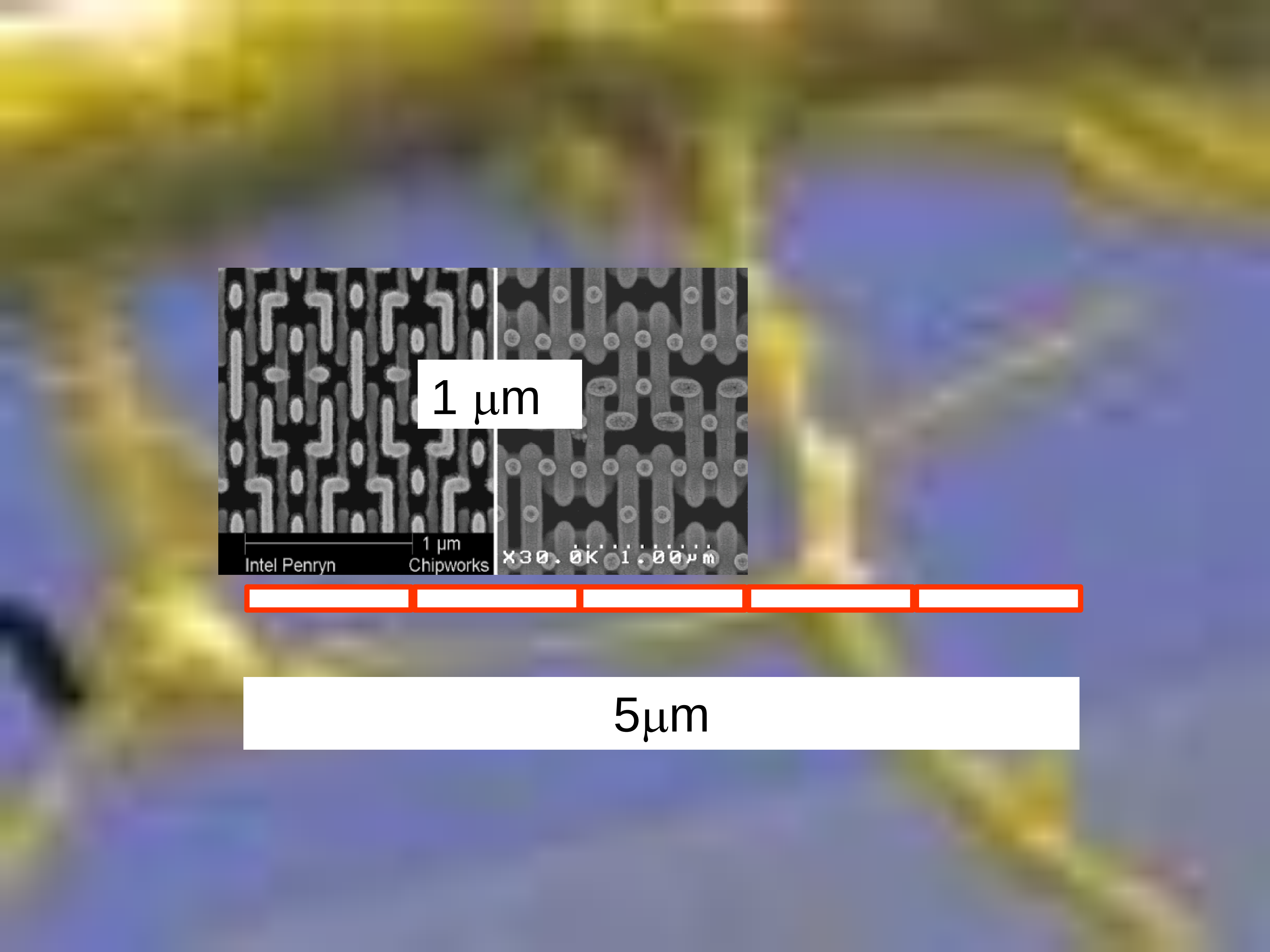

100µm
a
Source
Drain
5 µm
10µm


a
10μm
Source
Drain
5 μm
cotton fibers
10µm

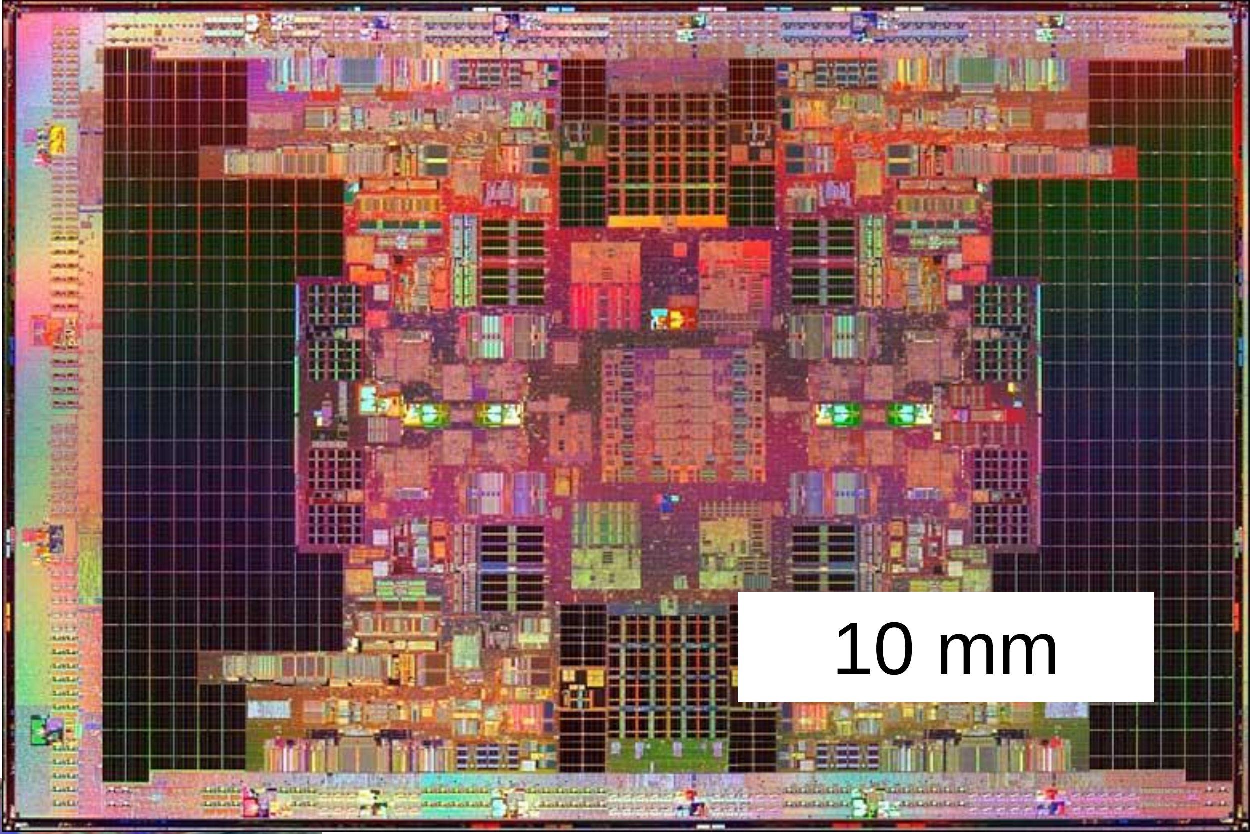

47x35 micron
a
Source
Drain
5μm
5 μm

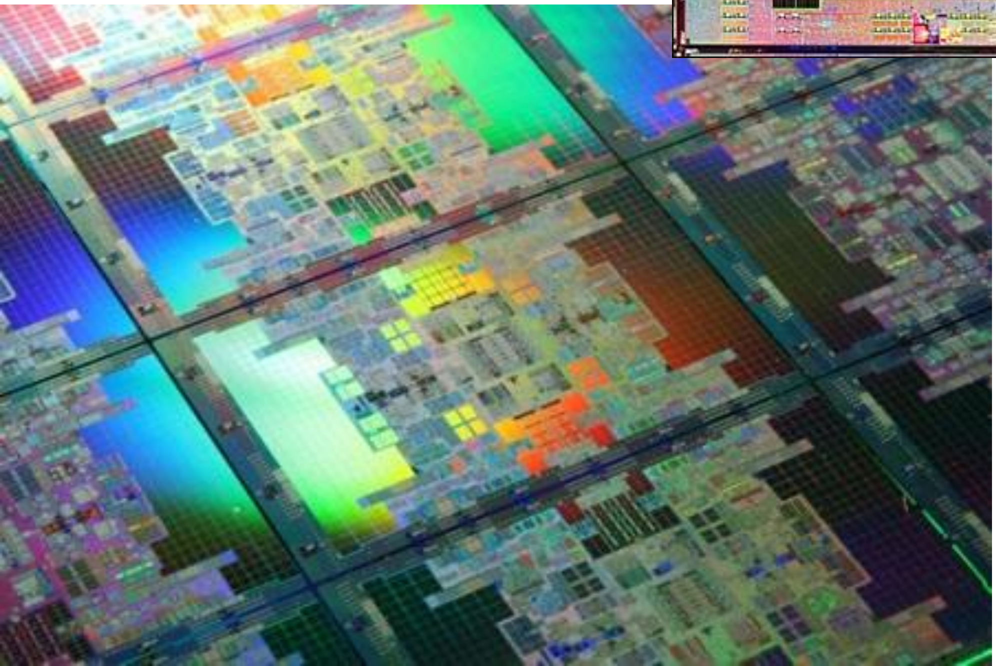


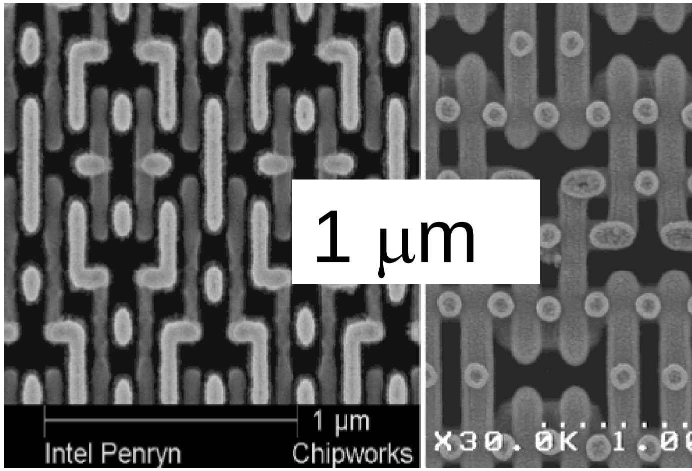
Intel Penryn
1 µm
Chipworks
5µm
Intel Penryn
1 µm
Chipworks
5 µm

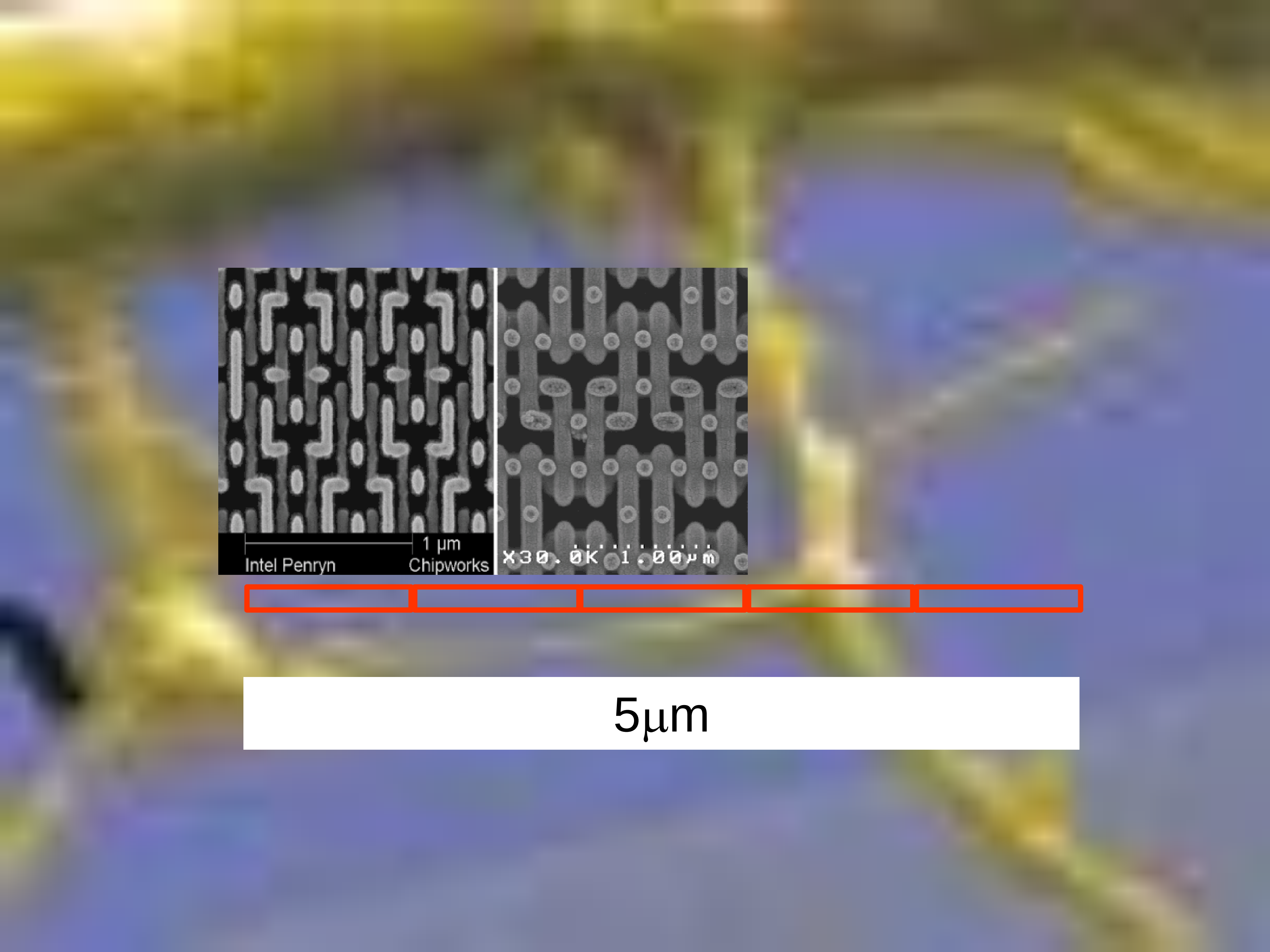

1 µm
Intel Penryn
Chipworks
X30.0K 1.00µm
1 µm
5µm

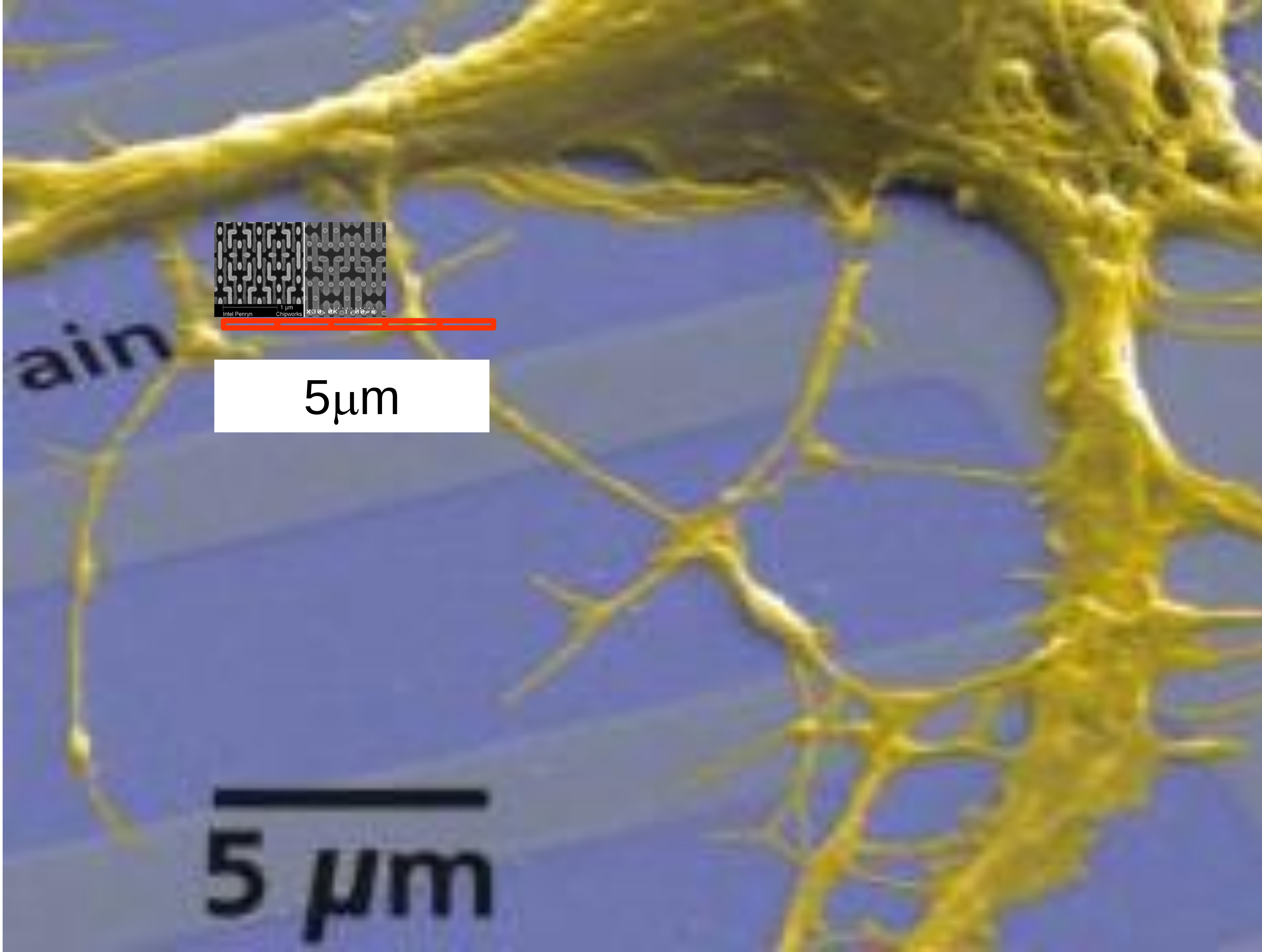
Intel Tukwila quad core chip with more than 2 billion transistors



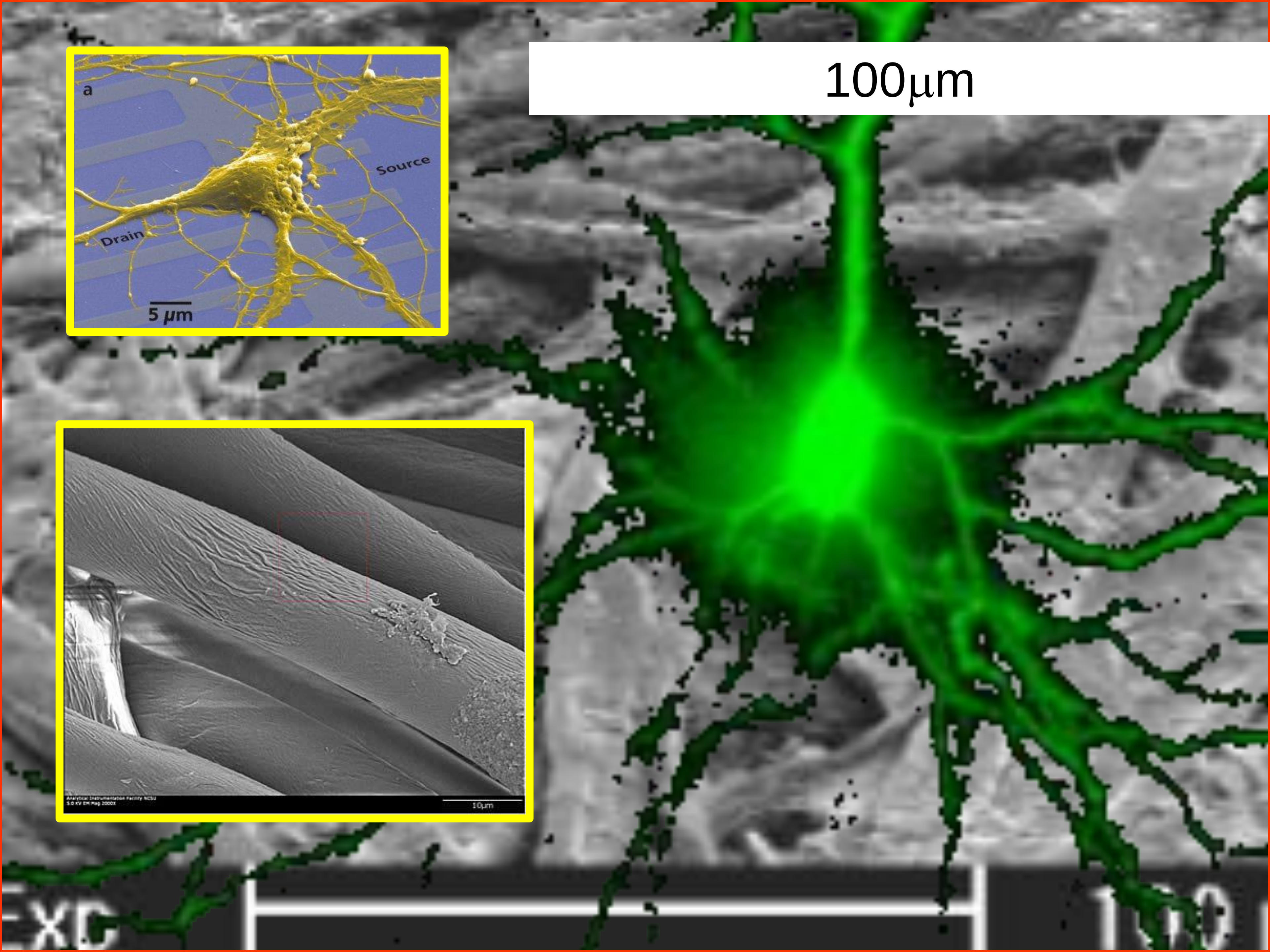




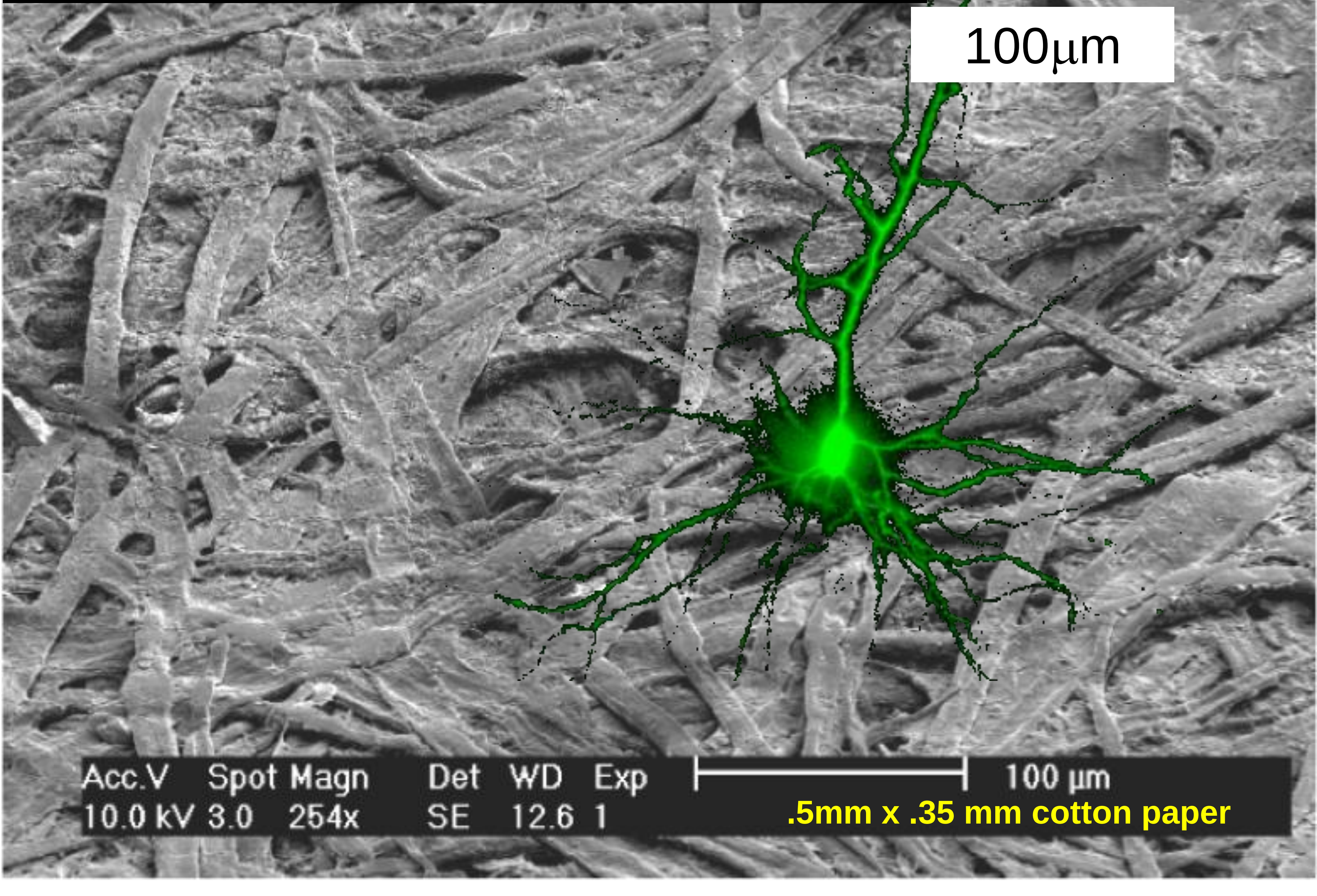

1 µm
Intel Penryn
Chipworks
X30.0K 1.00µm
5µm



ain
Intel Penryn
1 µm
Chipworks
5µm
5 µm

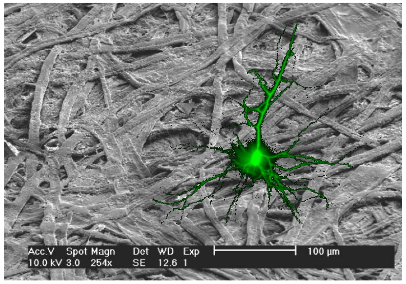

100μm
a
Source
Drain
5 μm
10μm

.5mm x .35 mm cotton paper



500μm

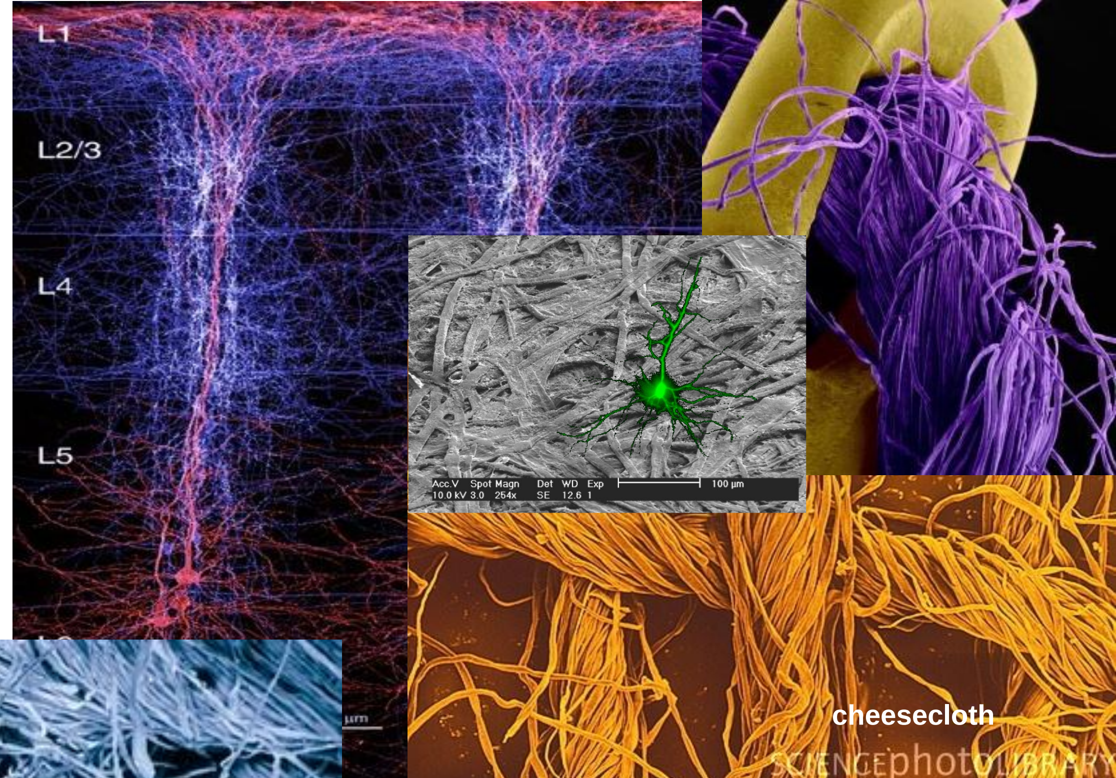
.5mm

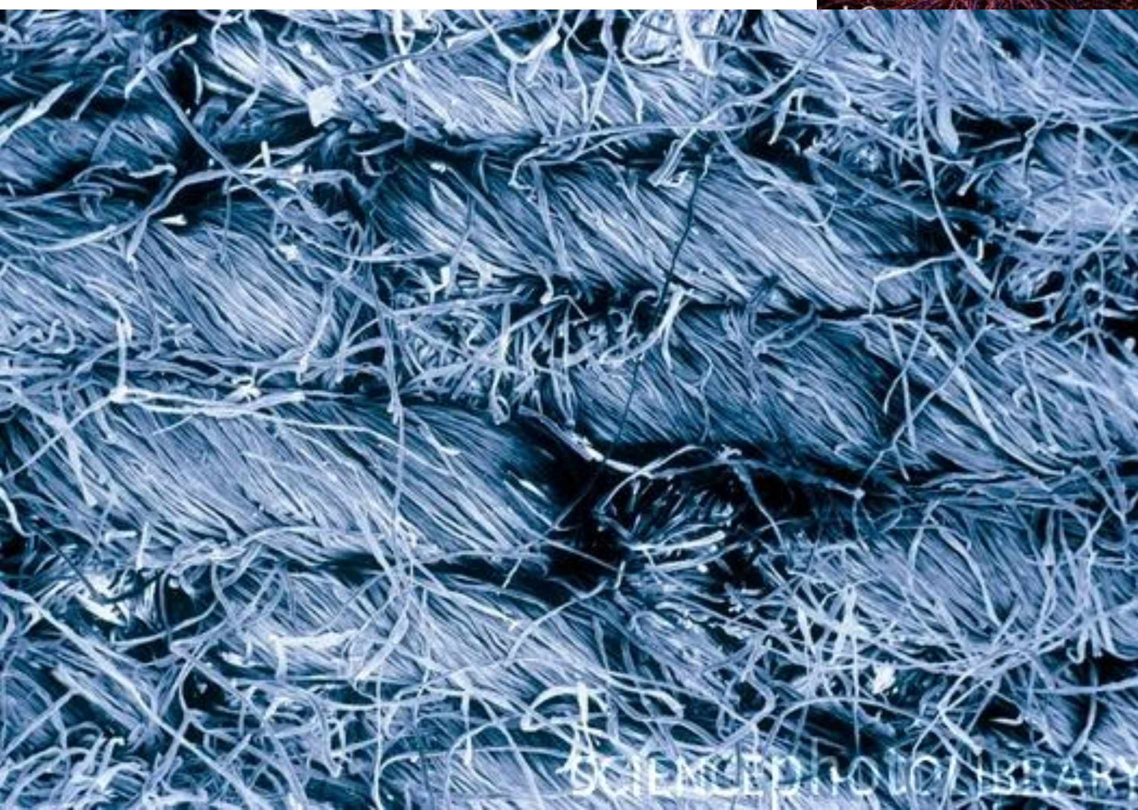


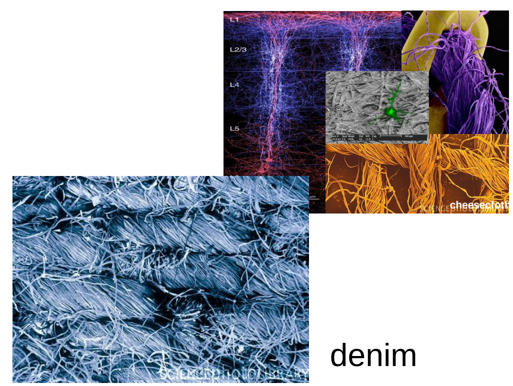
500µm

.5mm

denim



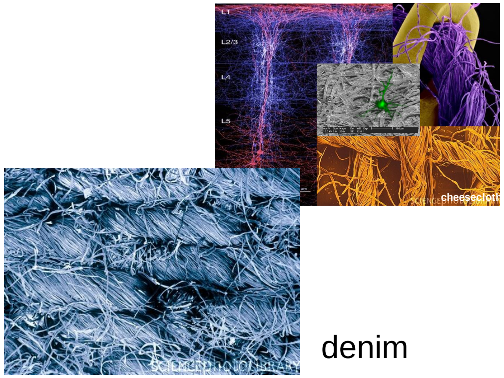




denim

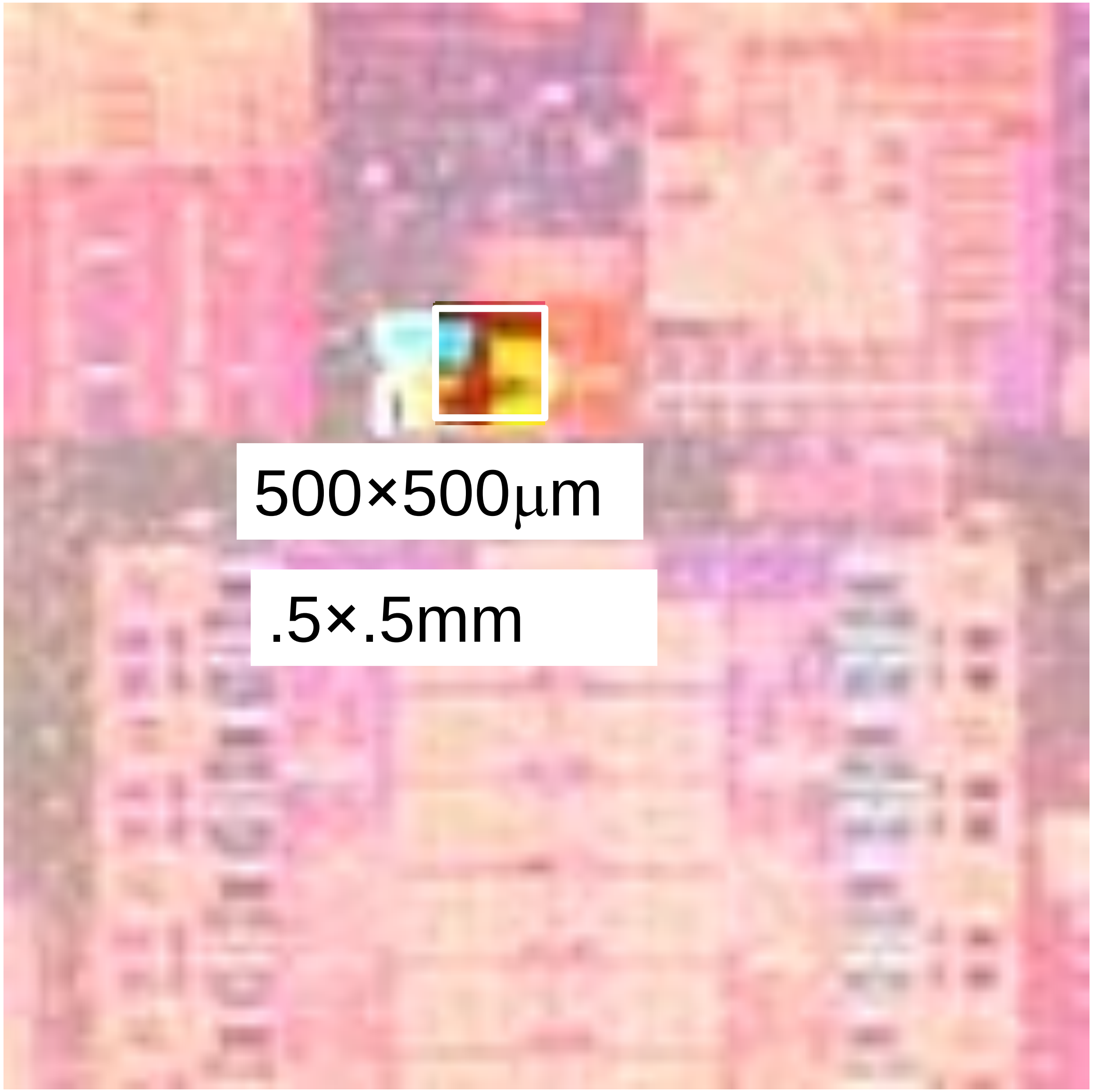
500×500μm

.5×.5mm

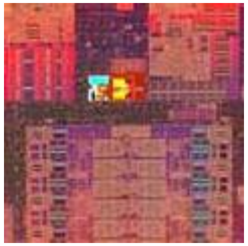


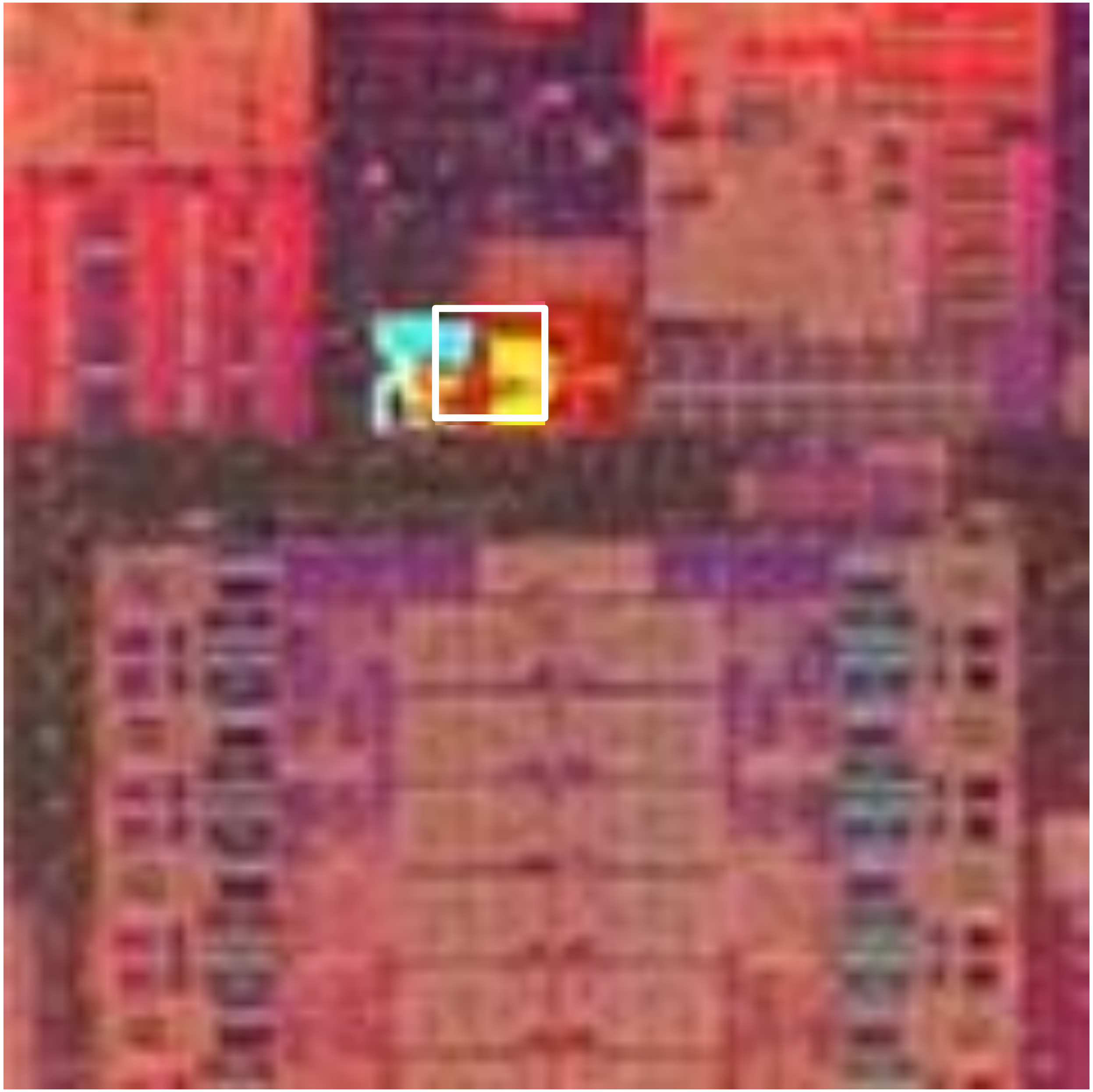
denim

5×5 mm

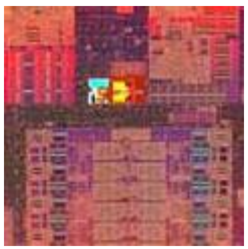


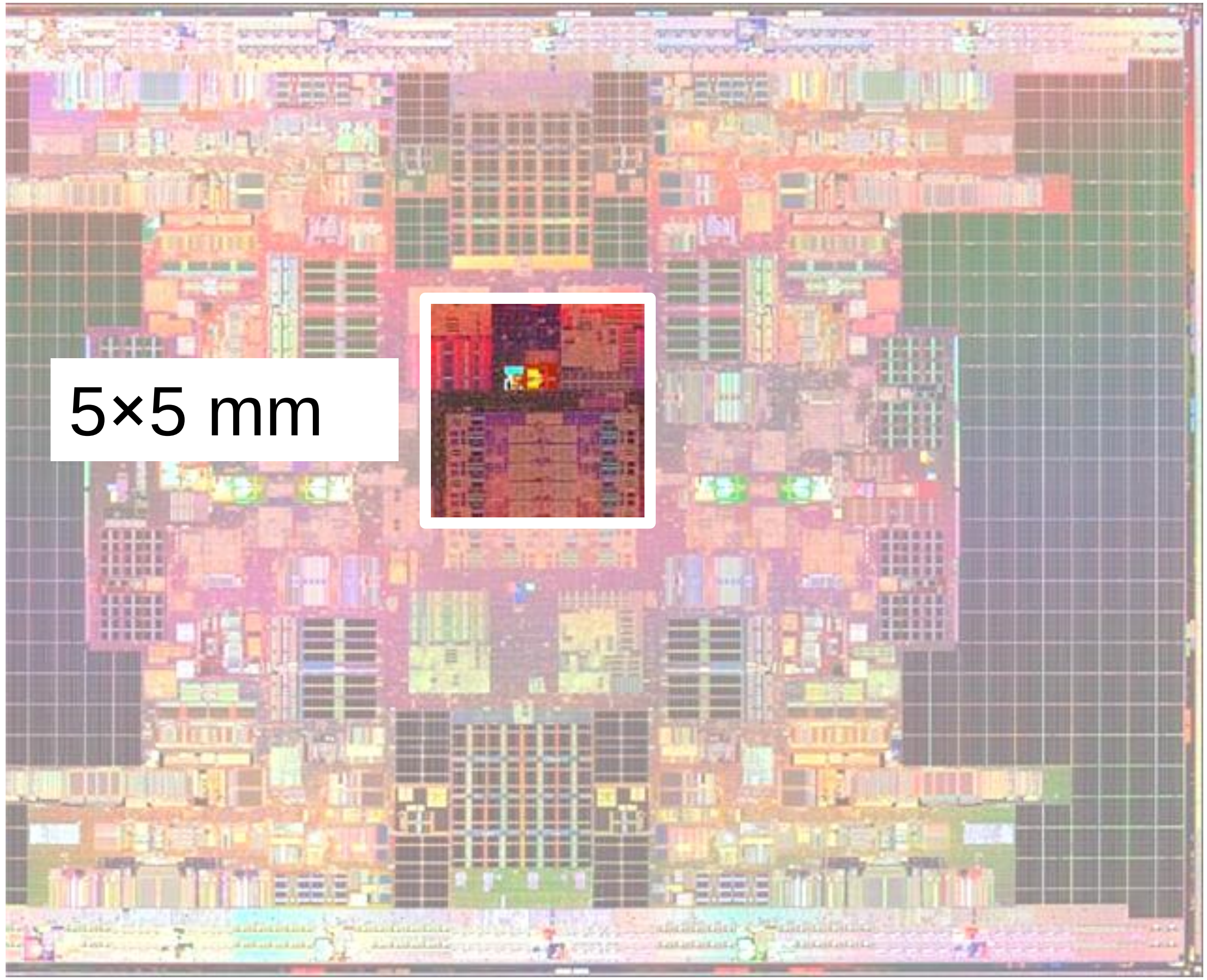
5×5 mm

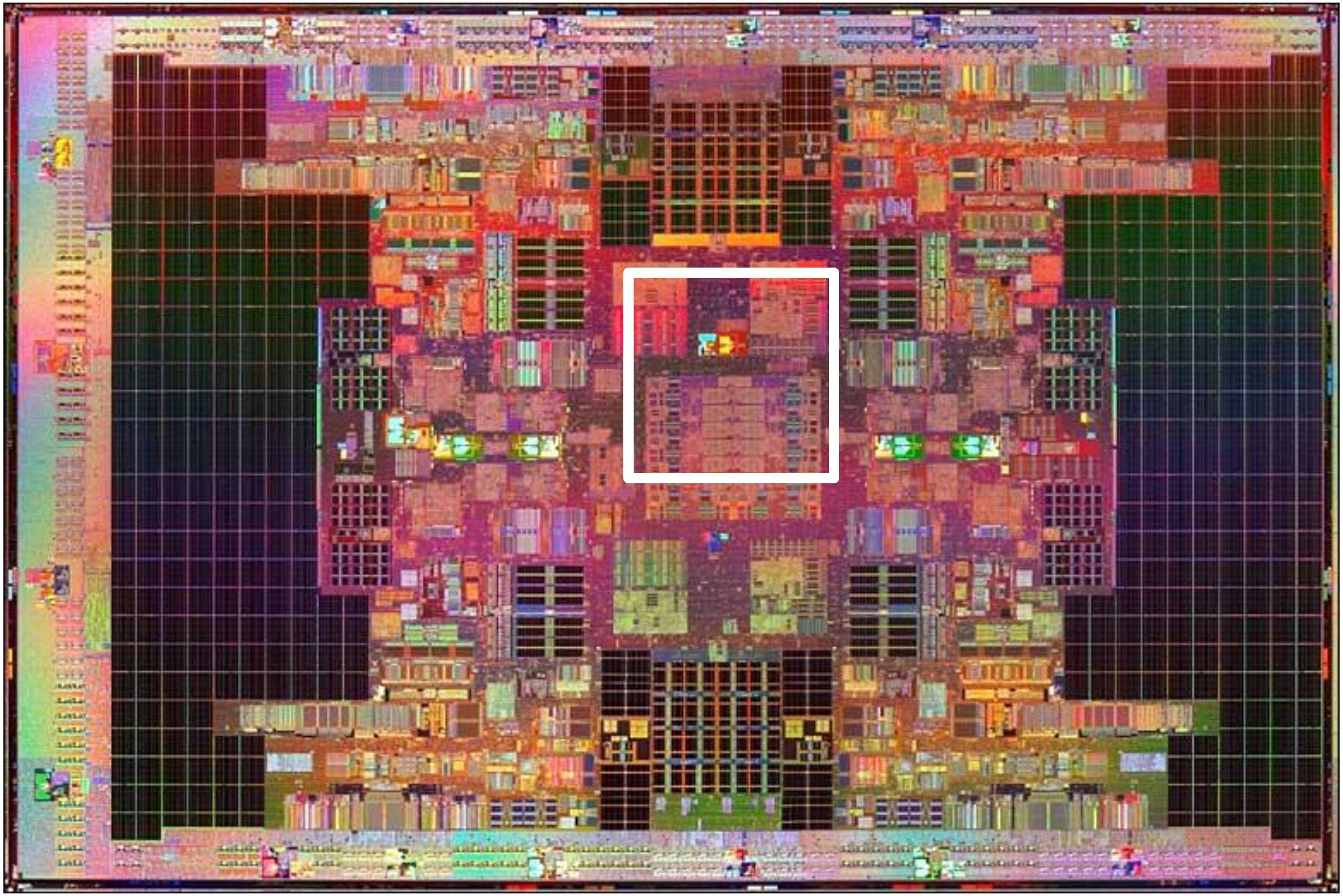


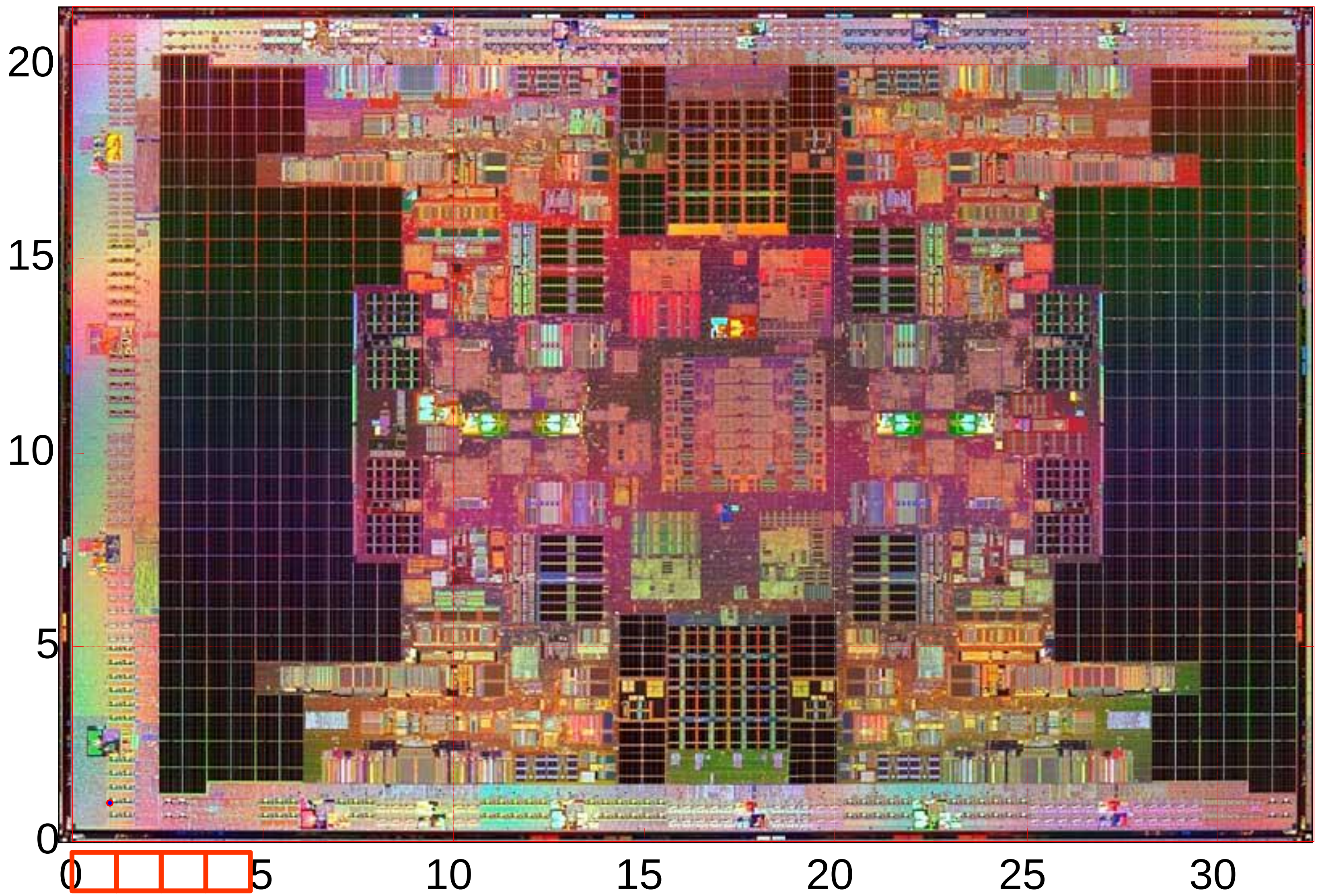


5×5 mm

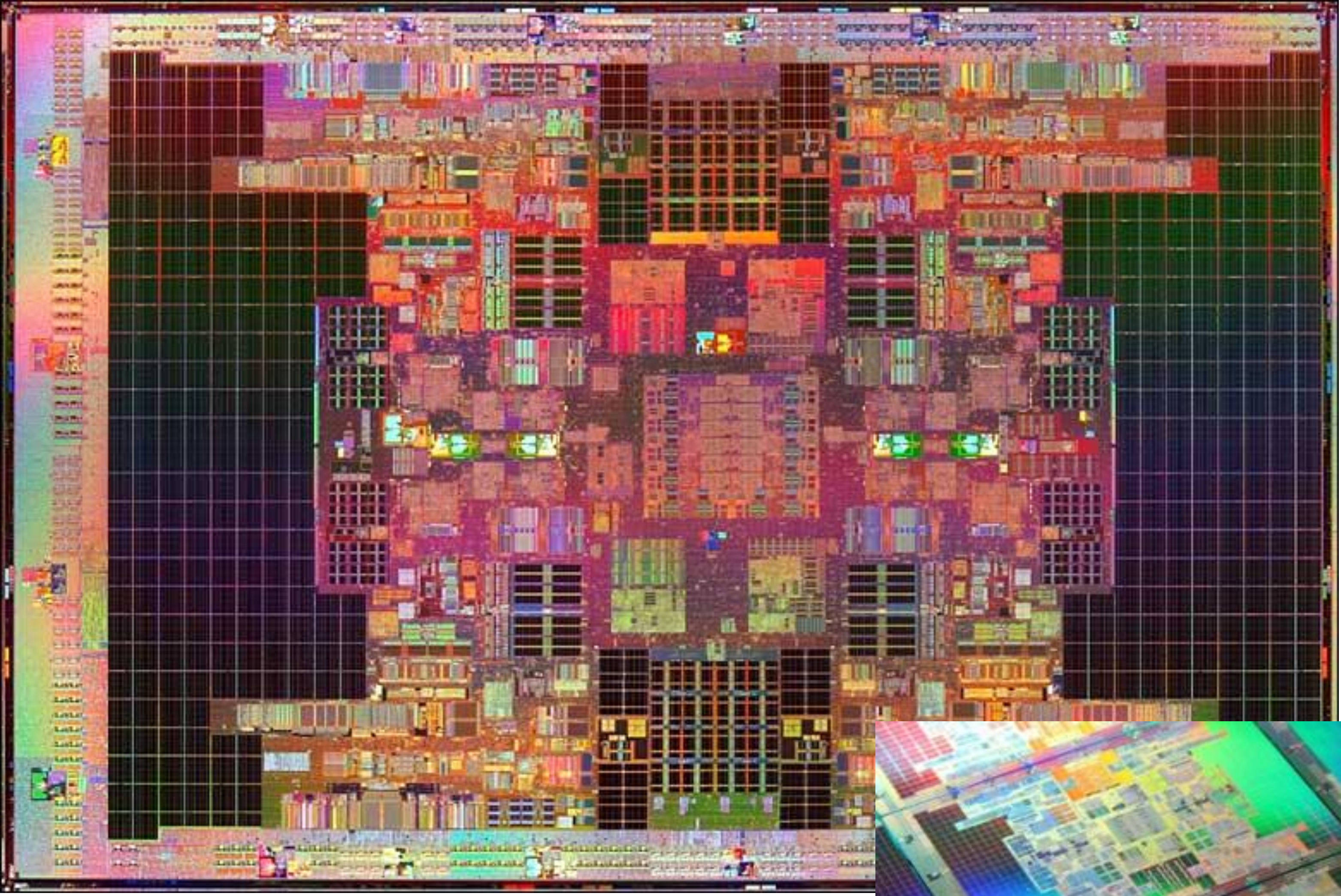


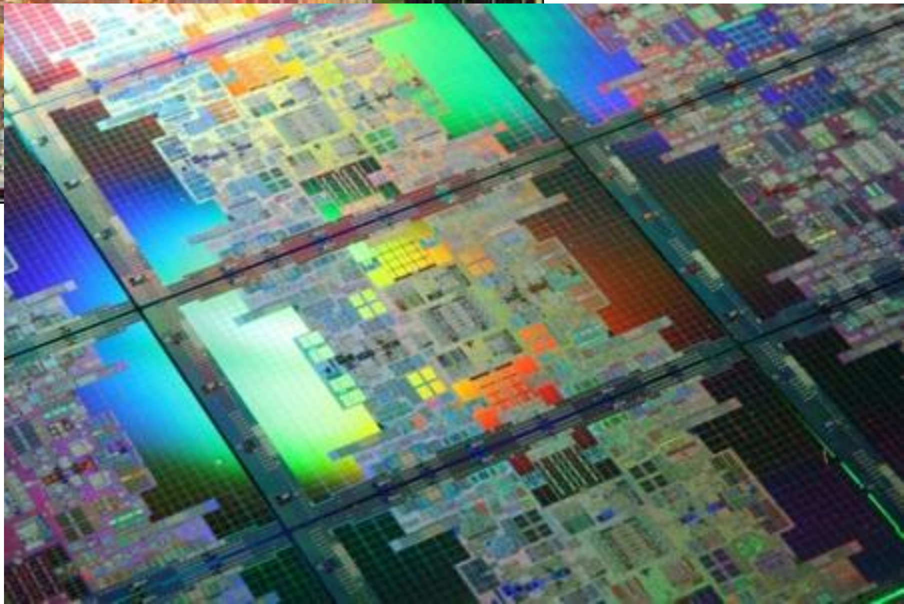






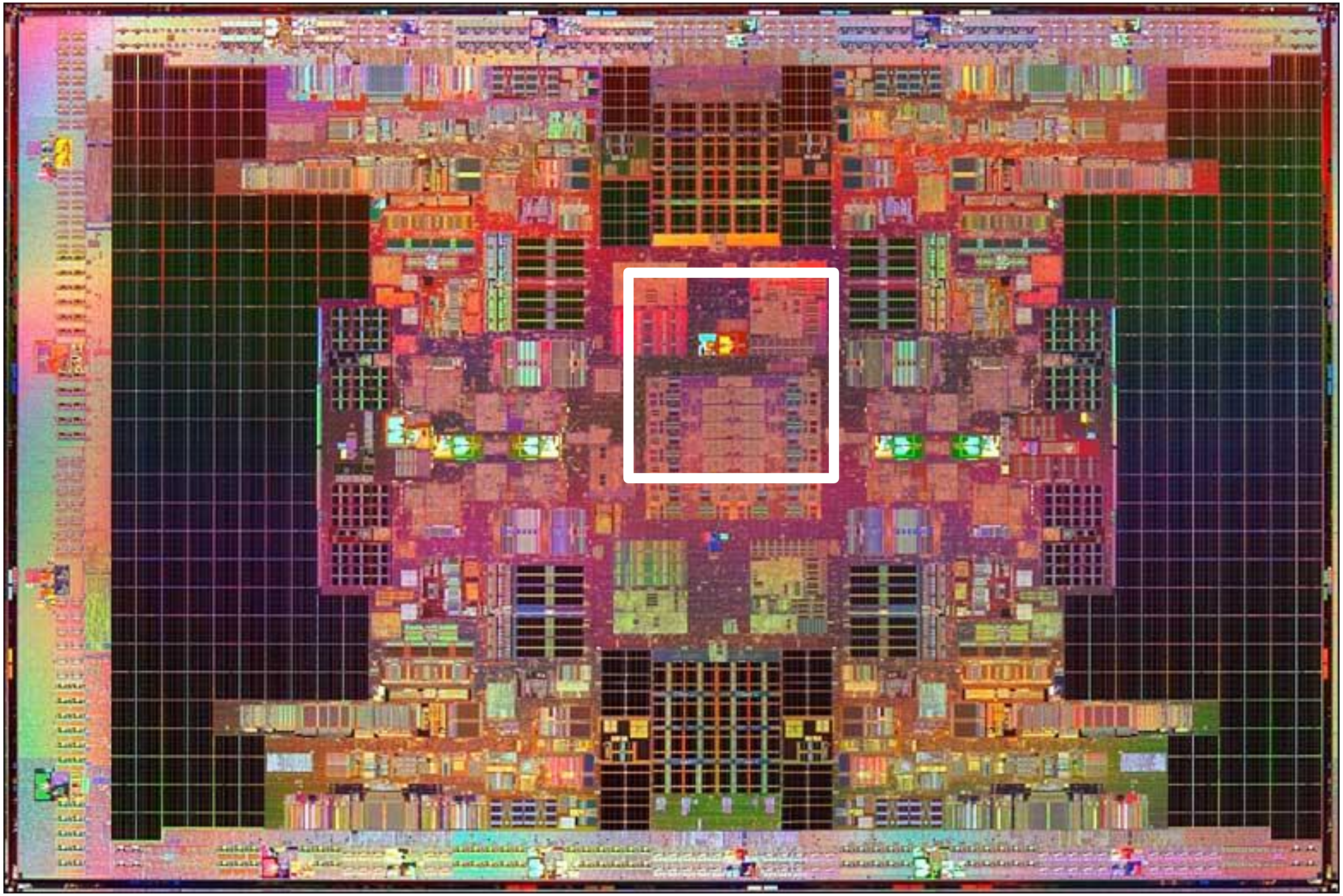
21.5×32.5 mm



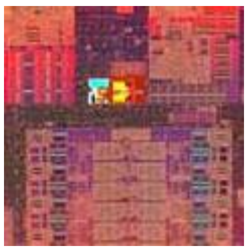


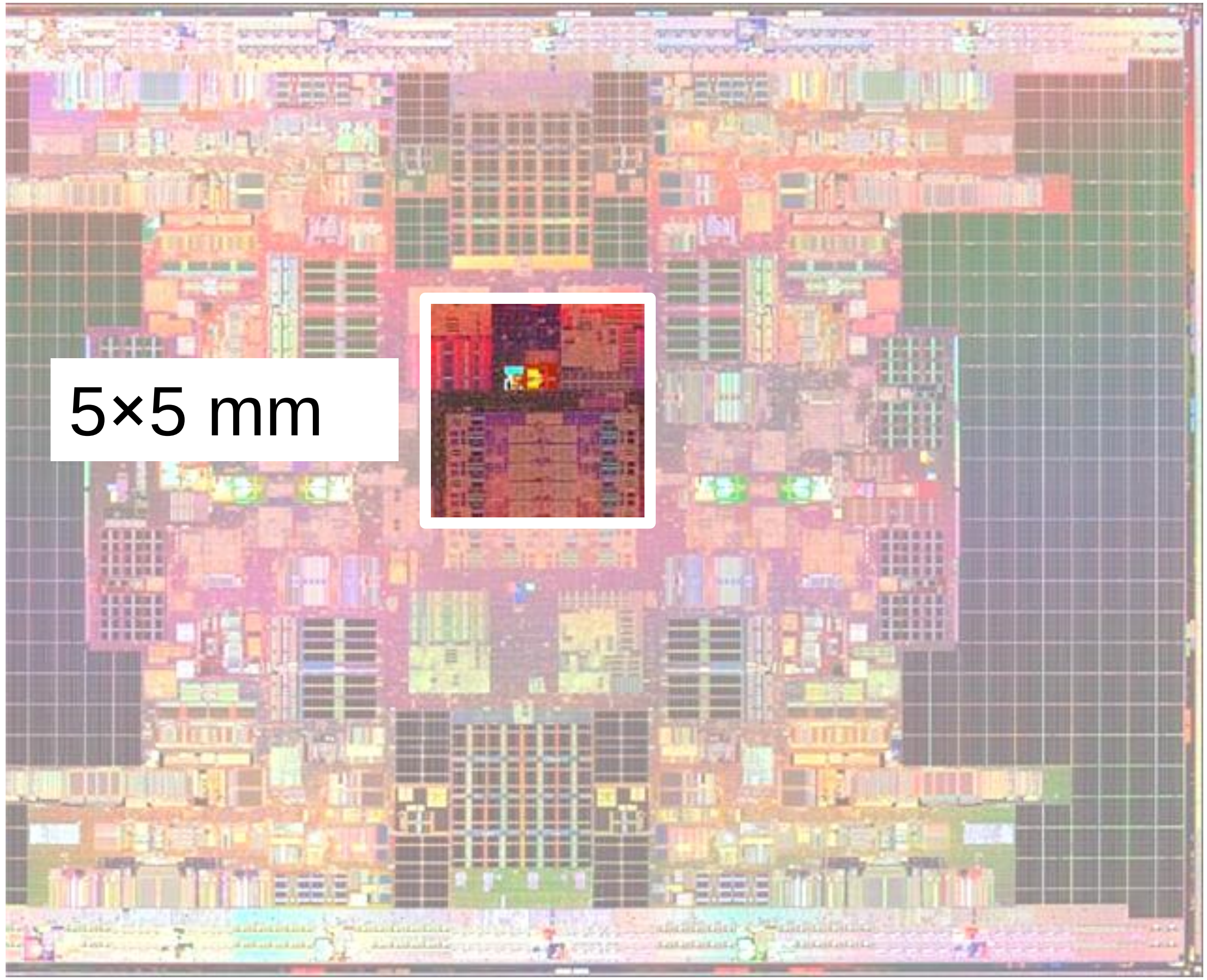
Intel Tukwila quad core chip with more than 2 billion transistors

21.5×32.5 mm

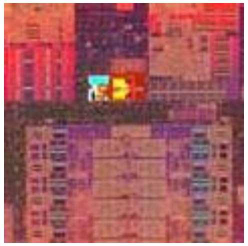


5×5 mm

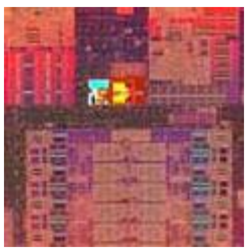


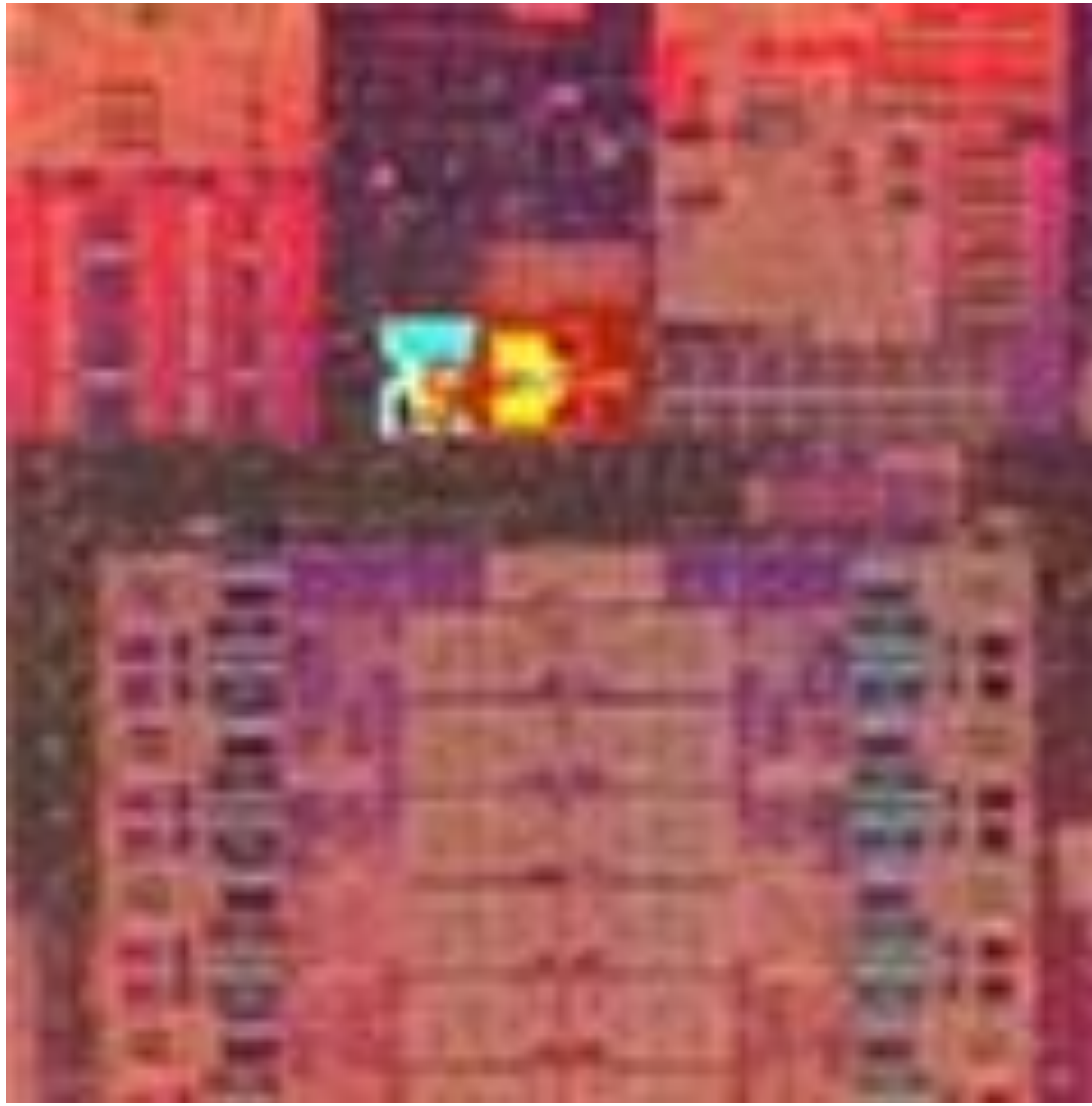


5×5 mm

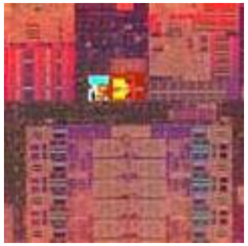


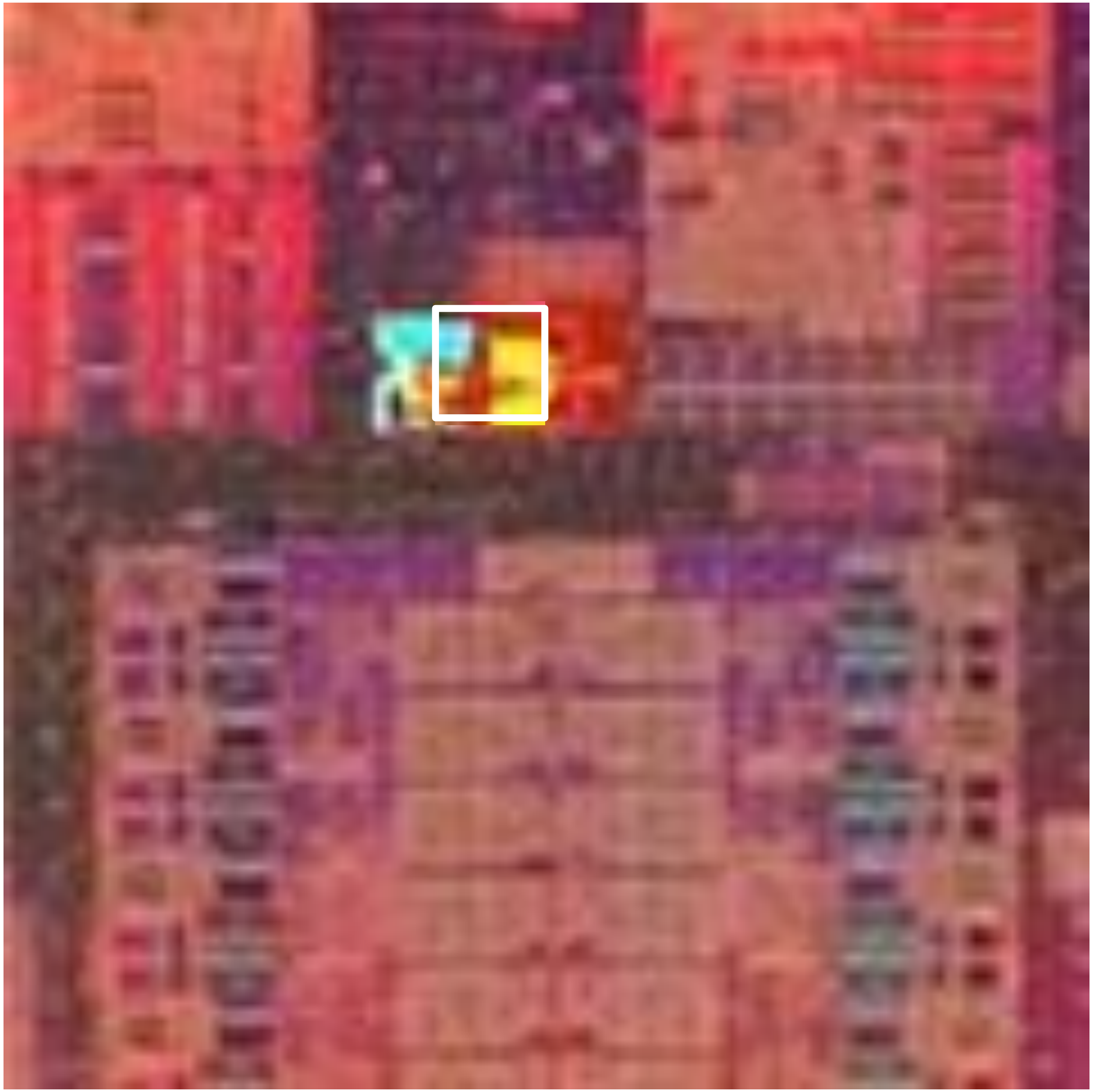
5×5 mm



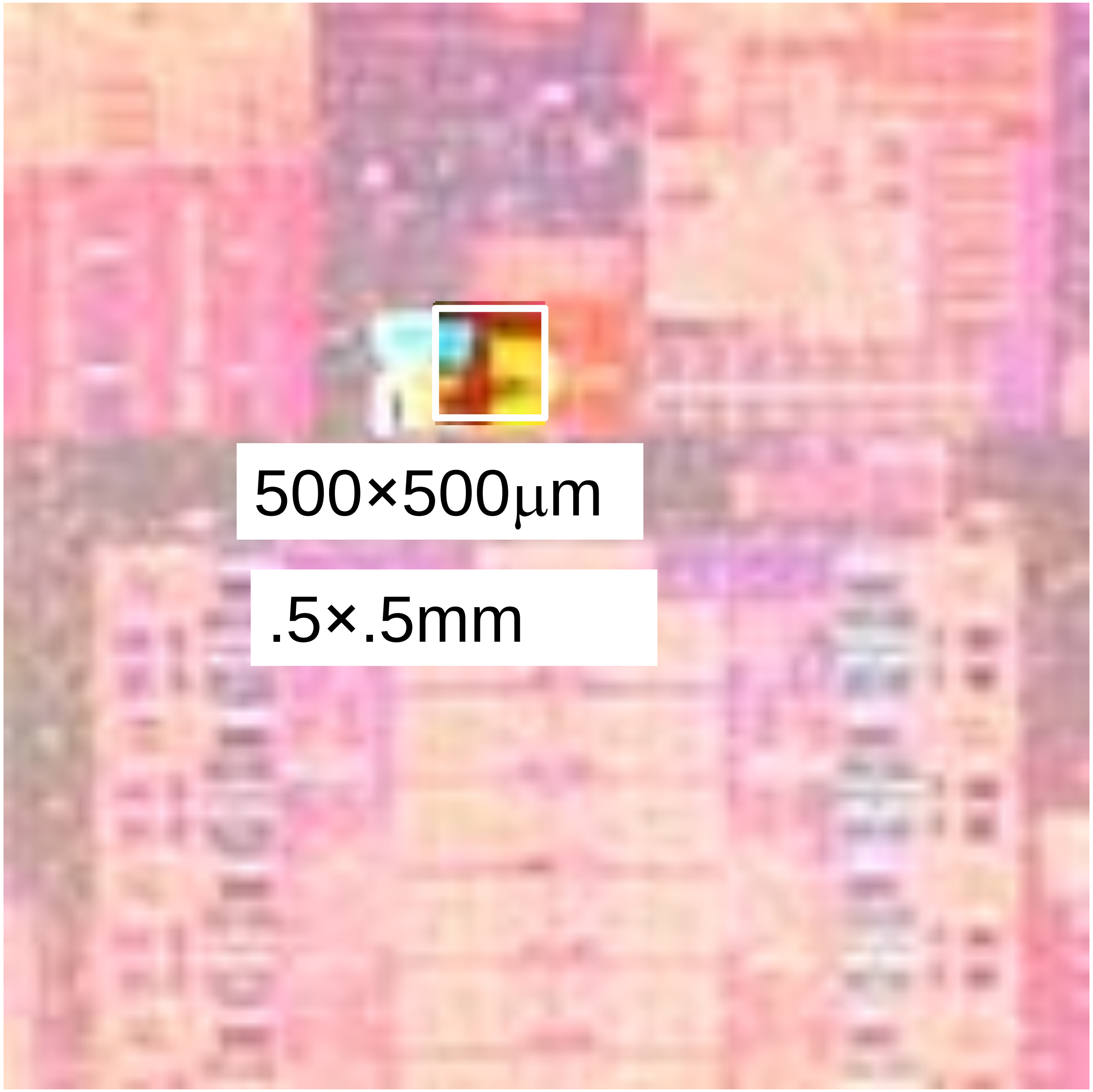


5×5 mm



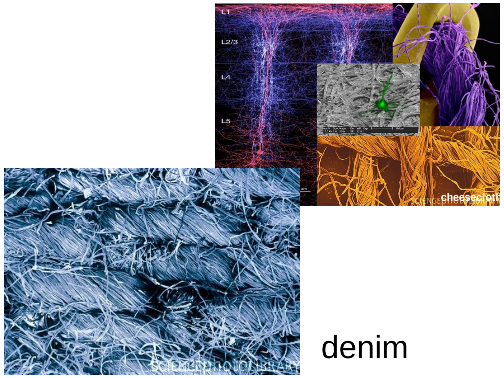


5×5 mm



500×500μm

.5×.5mm

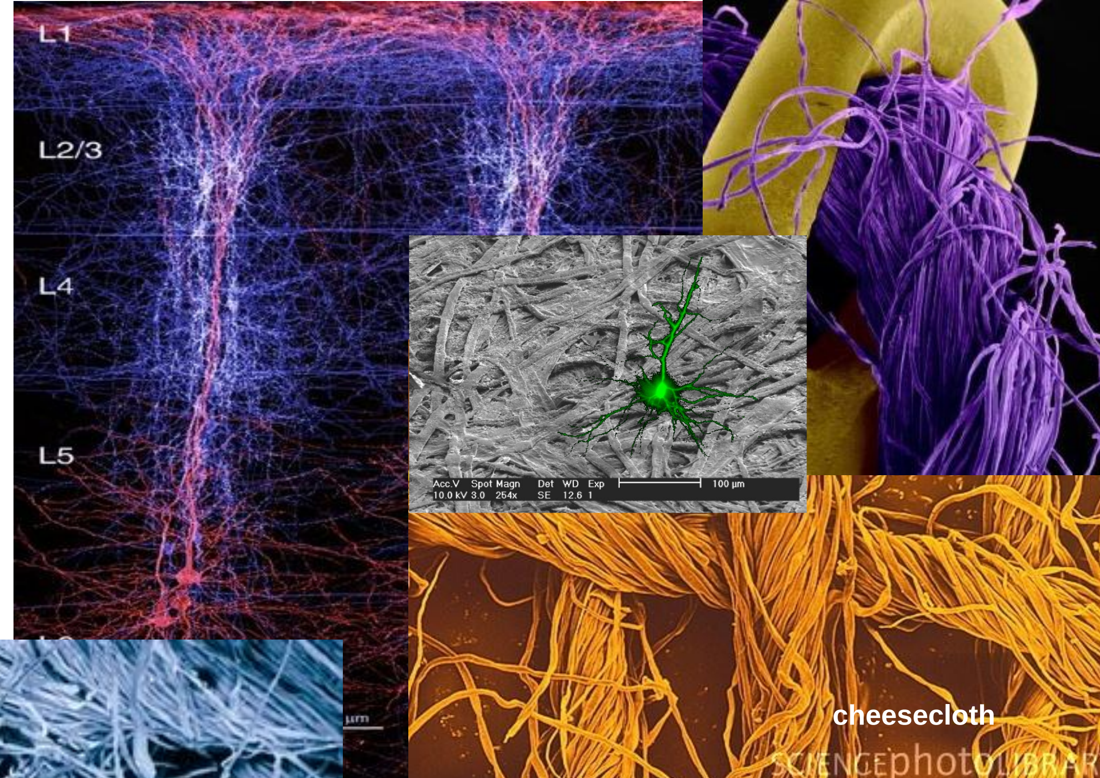


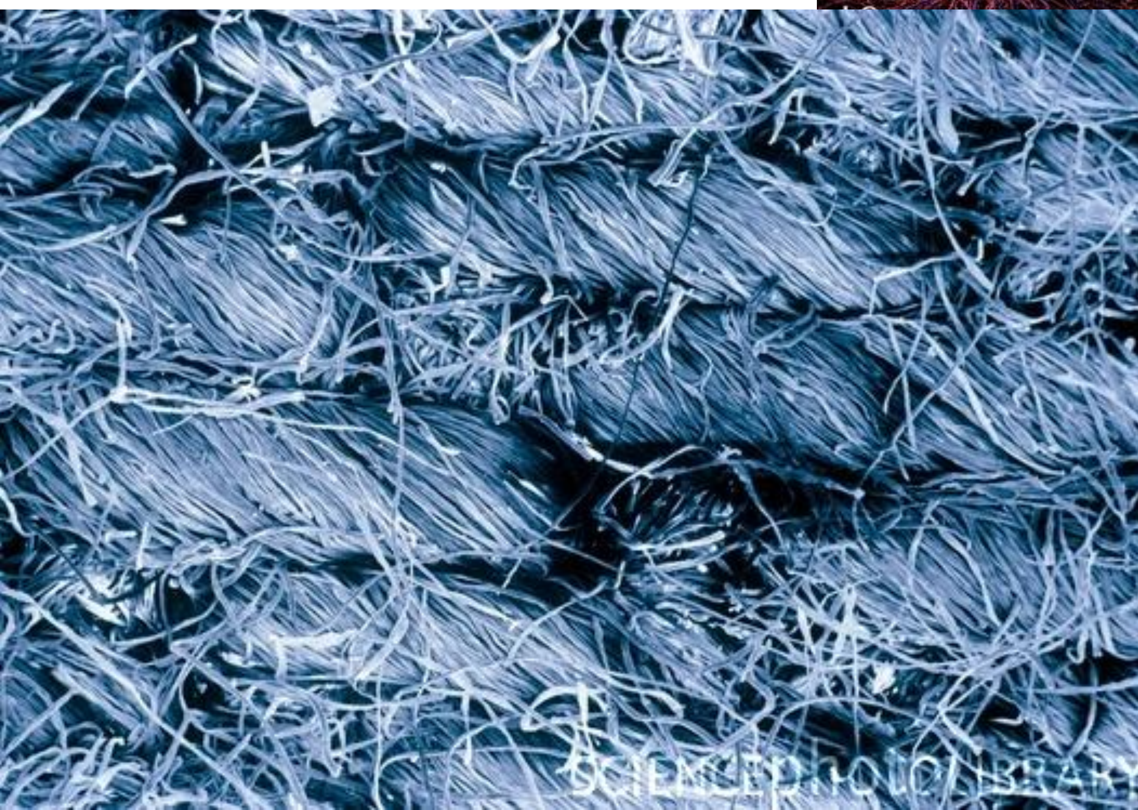
denim

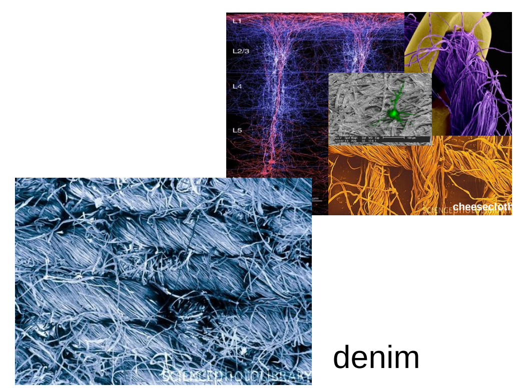
500μm

.5mm

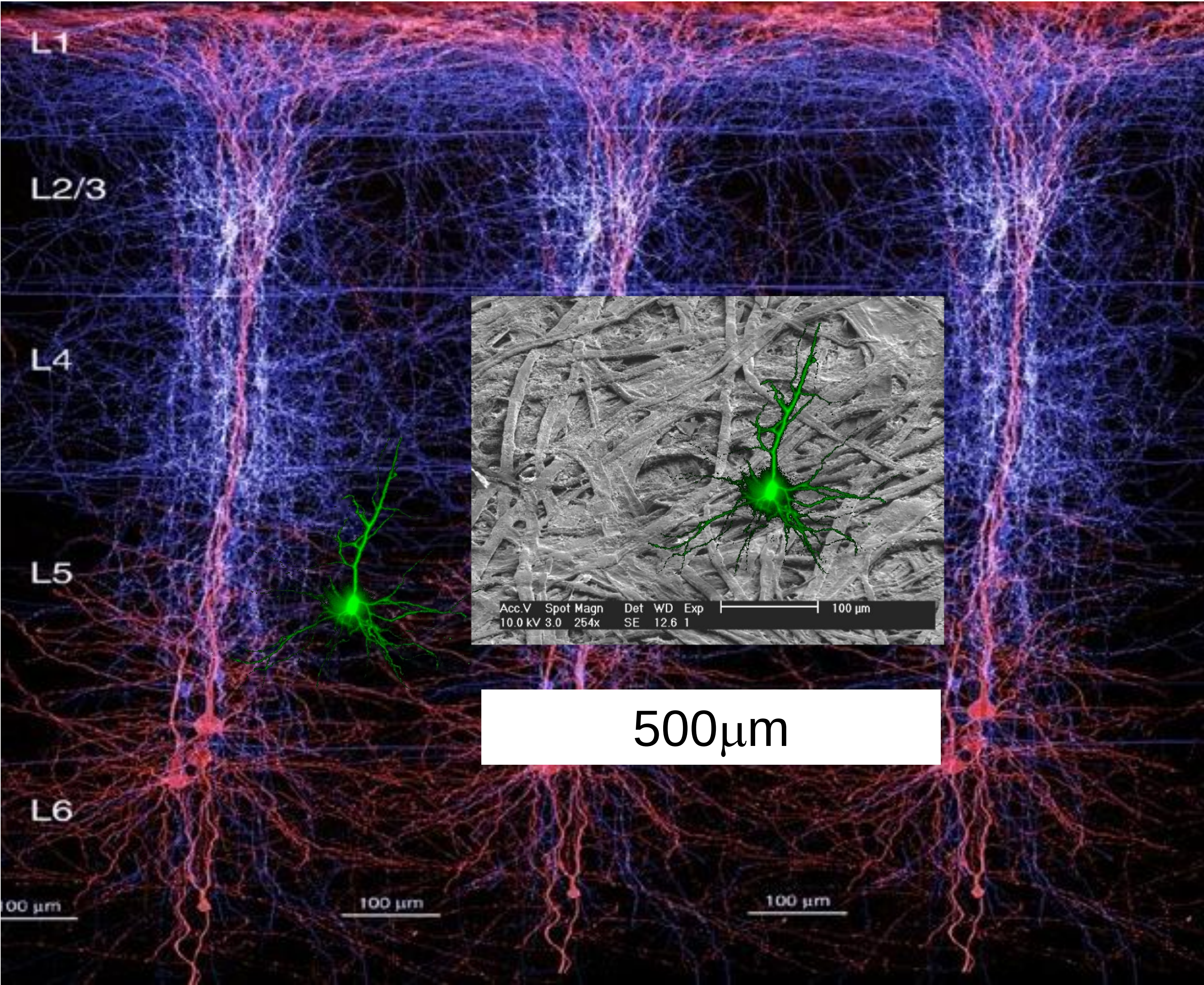
denim

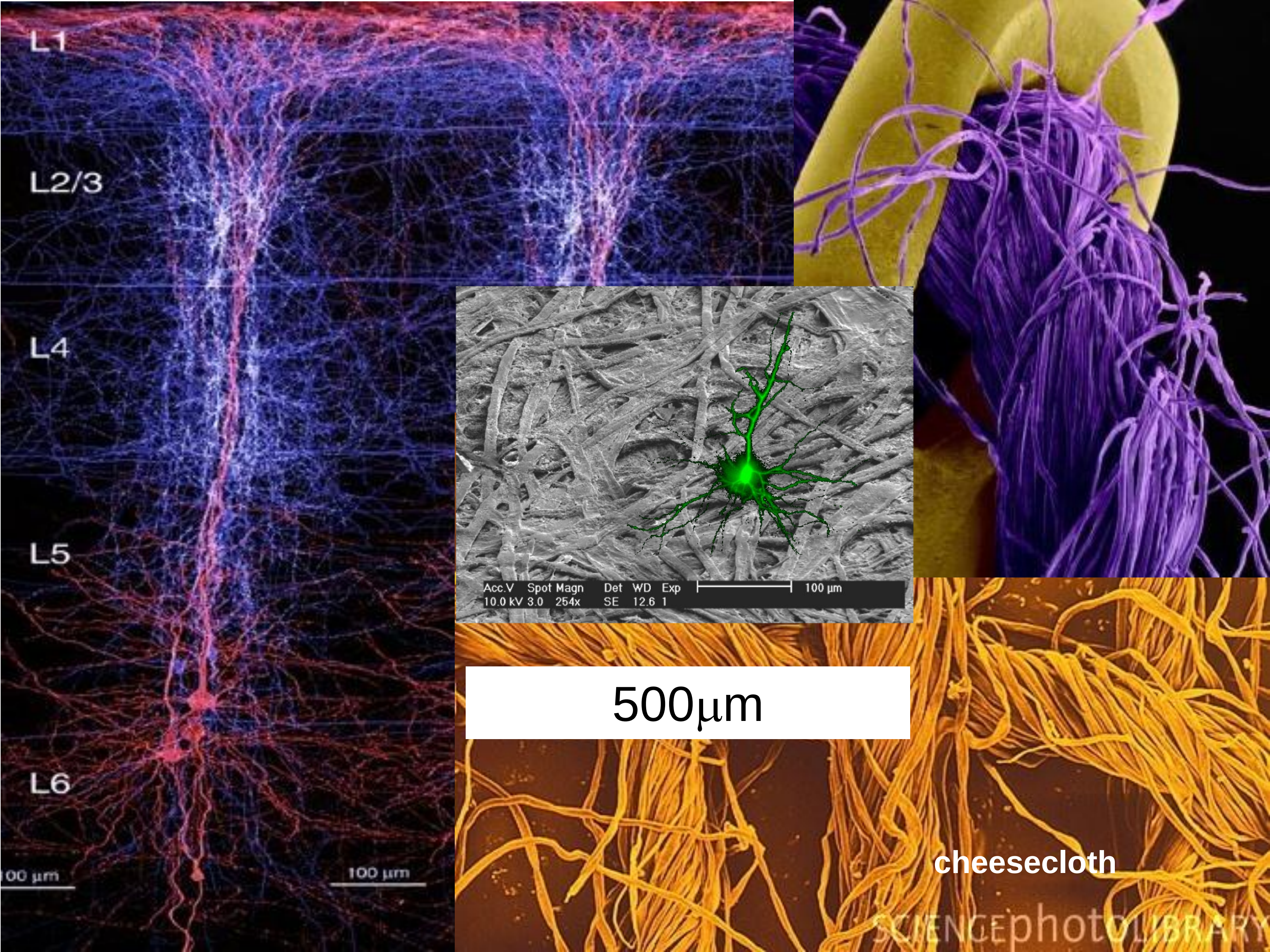




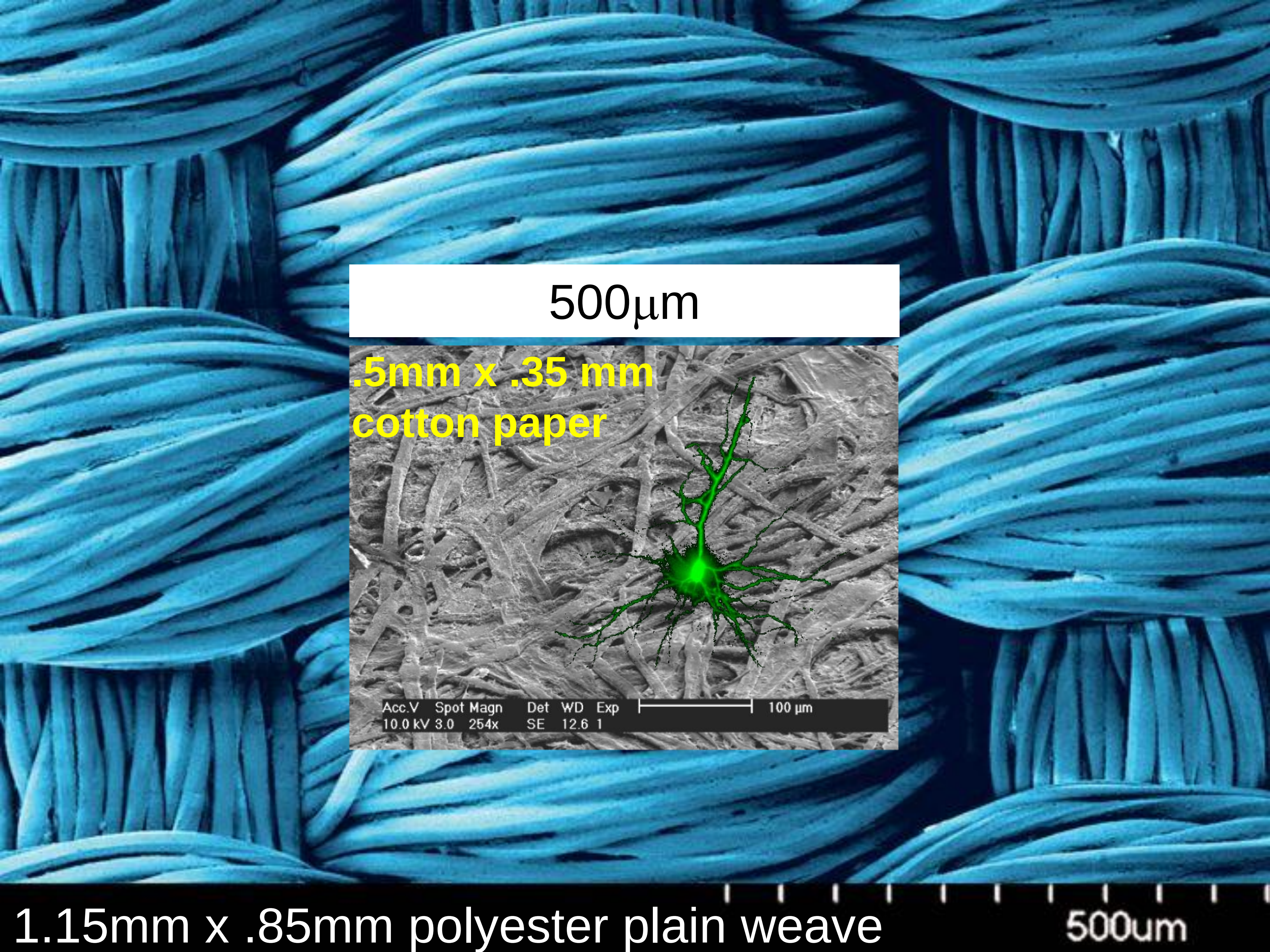


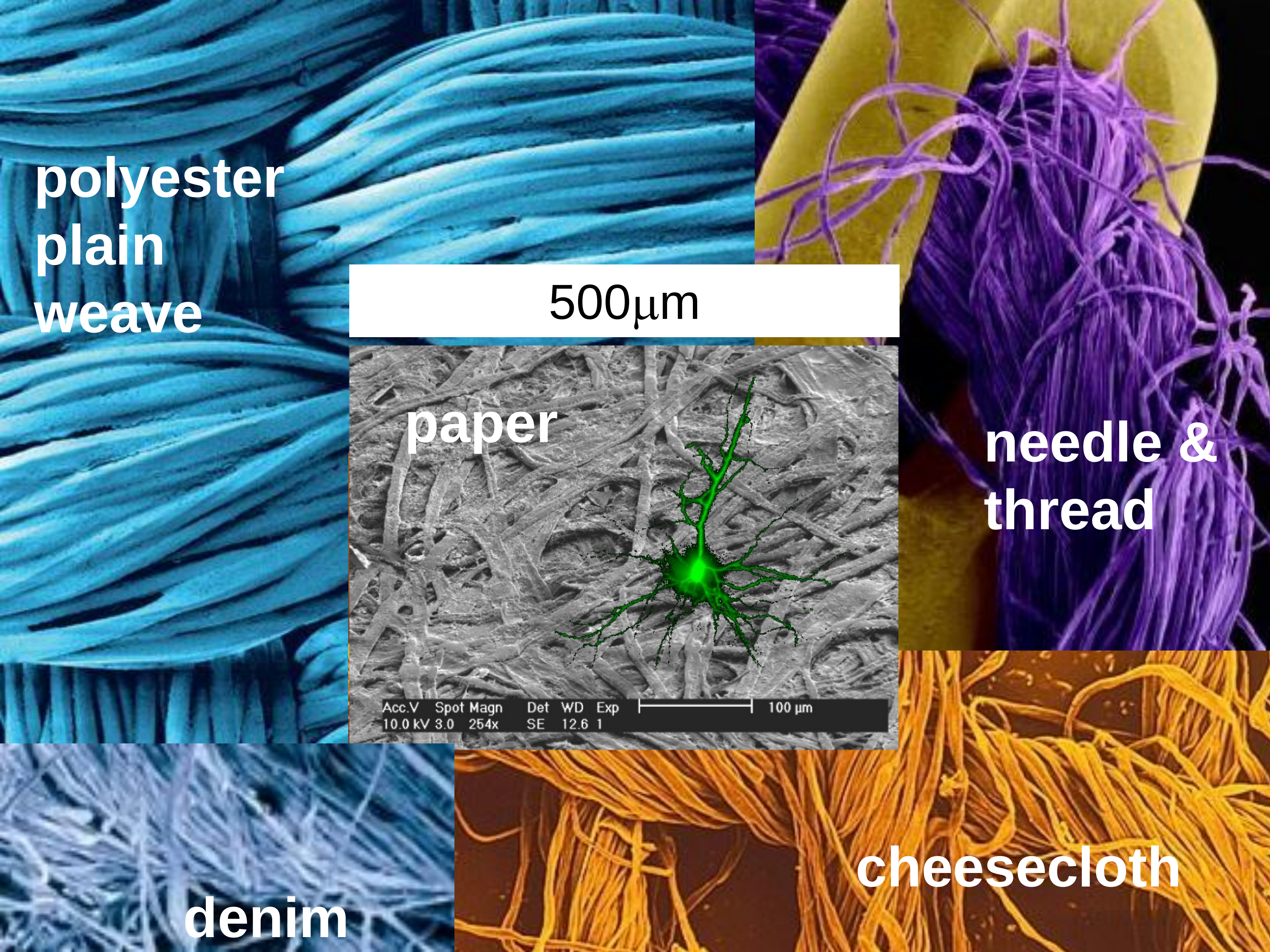
denim

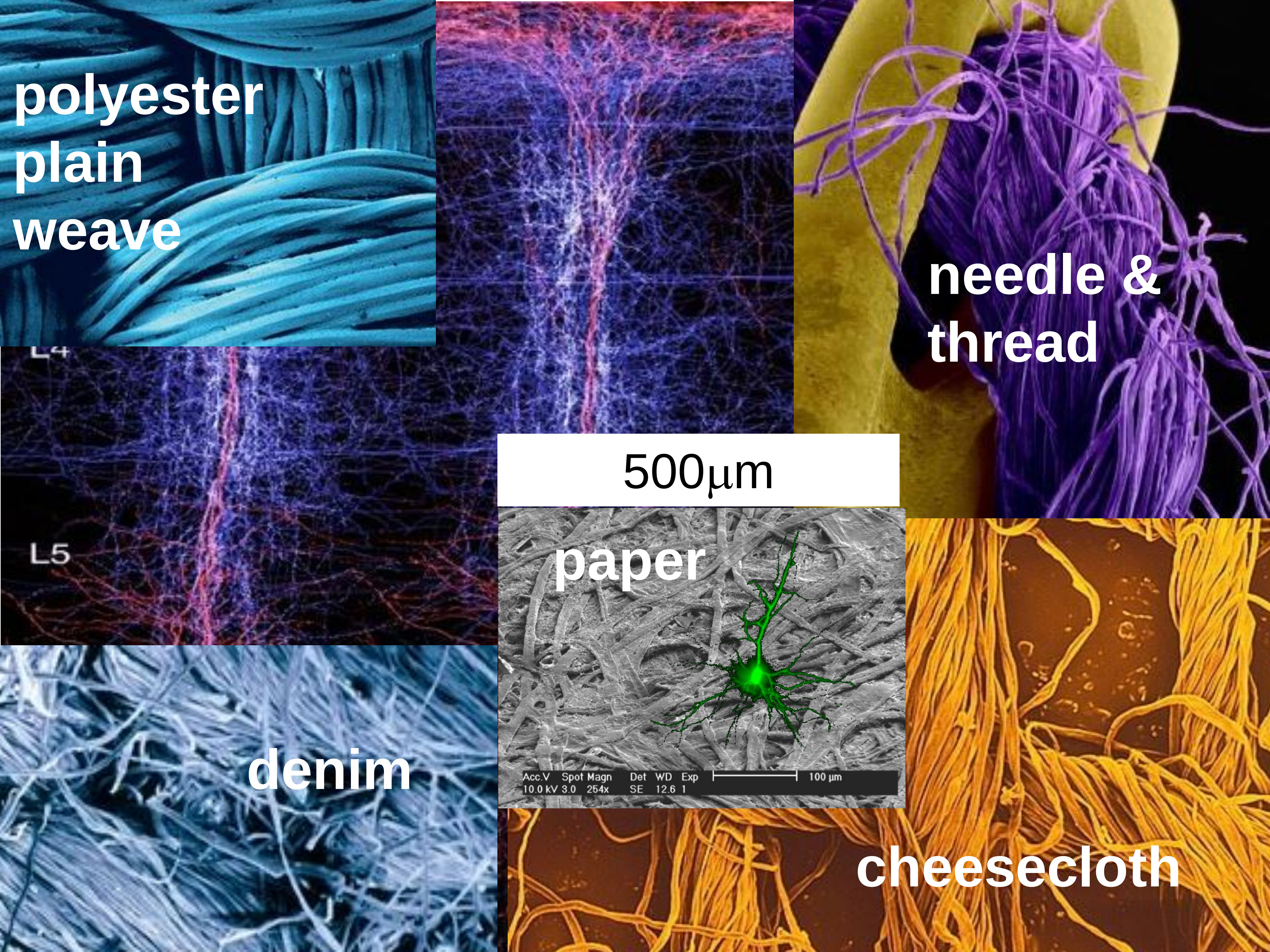

L1
L2/3
L4
L5
L6
Acc.V Spot Magn Det WD Exp
10.0 kV 3.0 254x SE 12.6 1
100 µm
500µm
100 µm
100 µm



L1
L2/3
L4
L5
L6
100 µm
Acc.V Spot Magn Det WD Exp 100 µm
10.0 kV 3.0 254x SE 12.6 1
500µm
cheesecloth
SCIENCEphotoLIBRARY

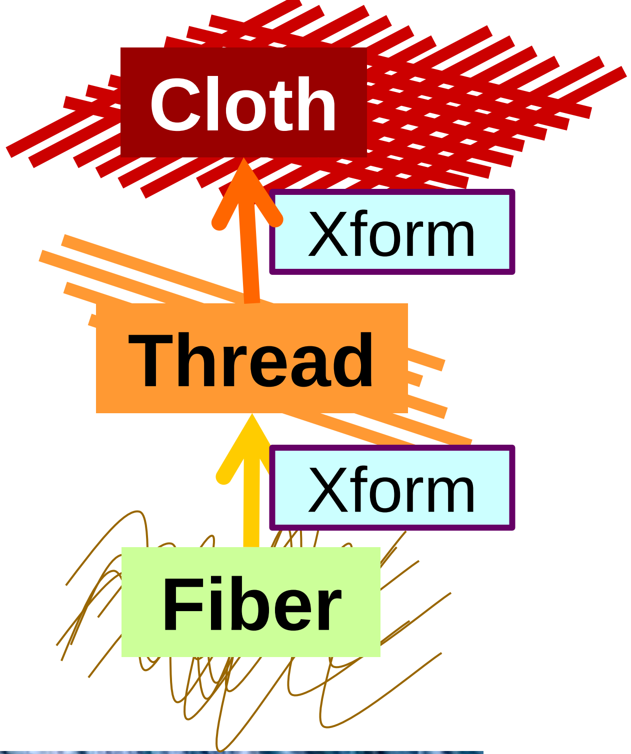

500µm
.5mm x .35 mm
cotton paper
Acc.V Spot Magn Det WD Exp
10.0 kV 3.0 254x SE 12.6 1
100 µm
1.15mm x .85mm polyester plain weave
500um

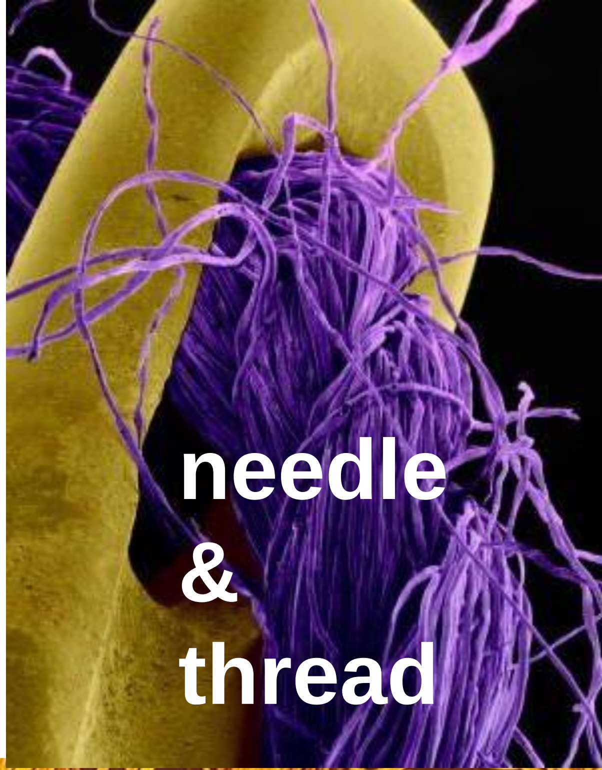

polyester plain weave
500μm
paper
Acc.V Spot Magn Det WD Exp 100 μm
10.0 kV 3.0 254x SE 12.6 1
needle & thread
denim
cheesecloth


polyester
plain
weave
L4
L5
needle &
thread
500μm
paper
Acc.V Spot Magn Det WD Exp 100 μm
10.0 kV 3.0 254x SE 12.6 1
denim
cheesecloth

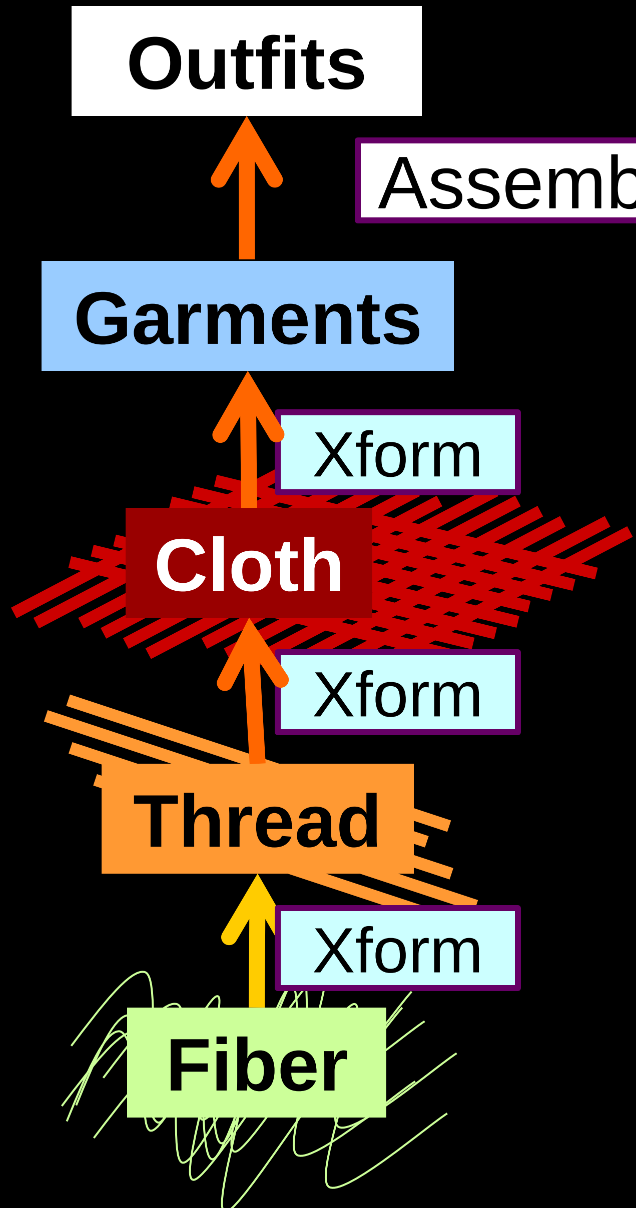
Hidden, large, thin, nonconvex

are *necessary*





Hidden, large, thin, nonconvex

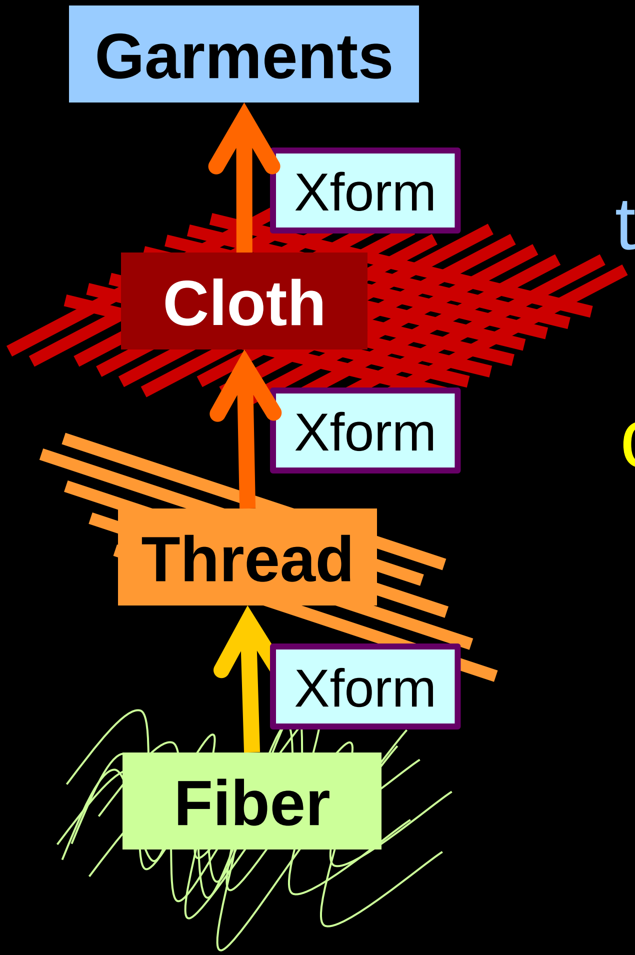


are *necessary*

Universal strategies?

Even though garments seem analog/continuous

Garments have limited access to threads and fibers



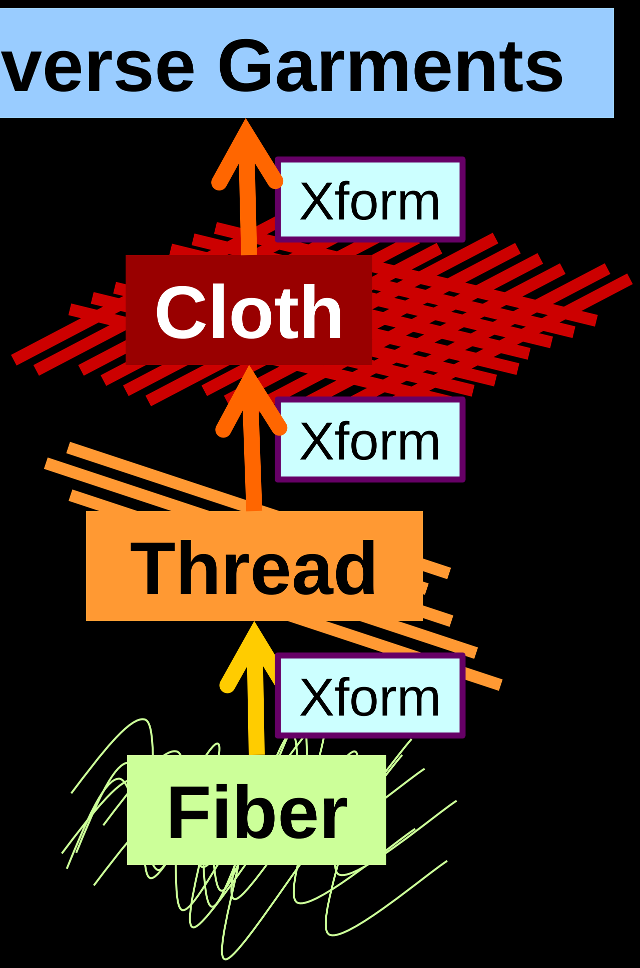
quantization for robustness

constraints on cross-layer interactions

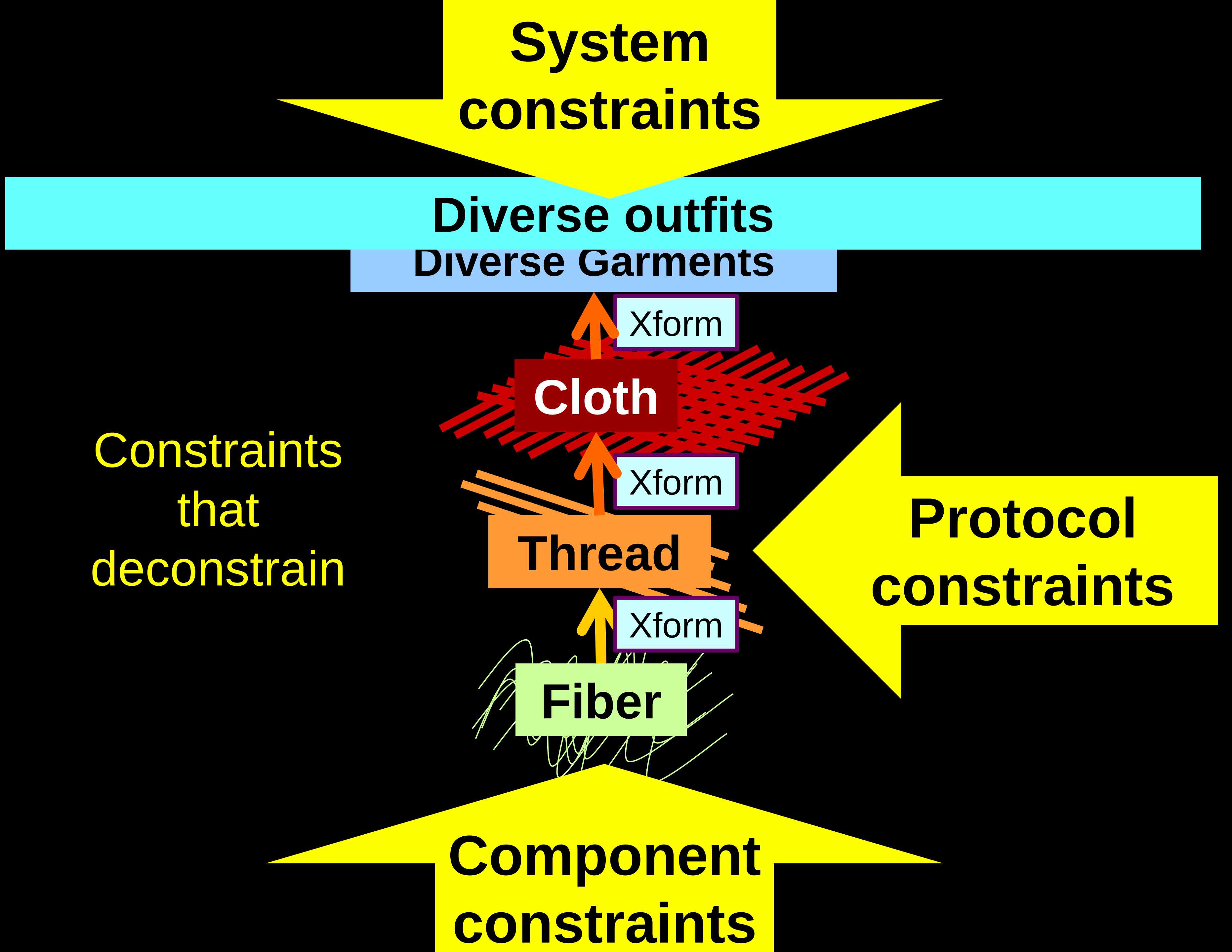
Prevents unraveling of lower layers

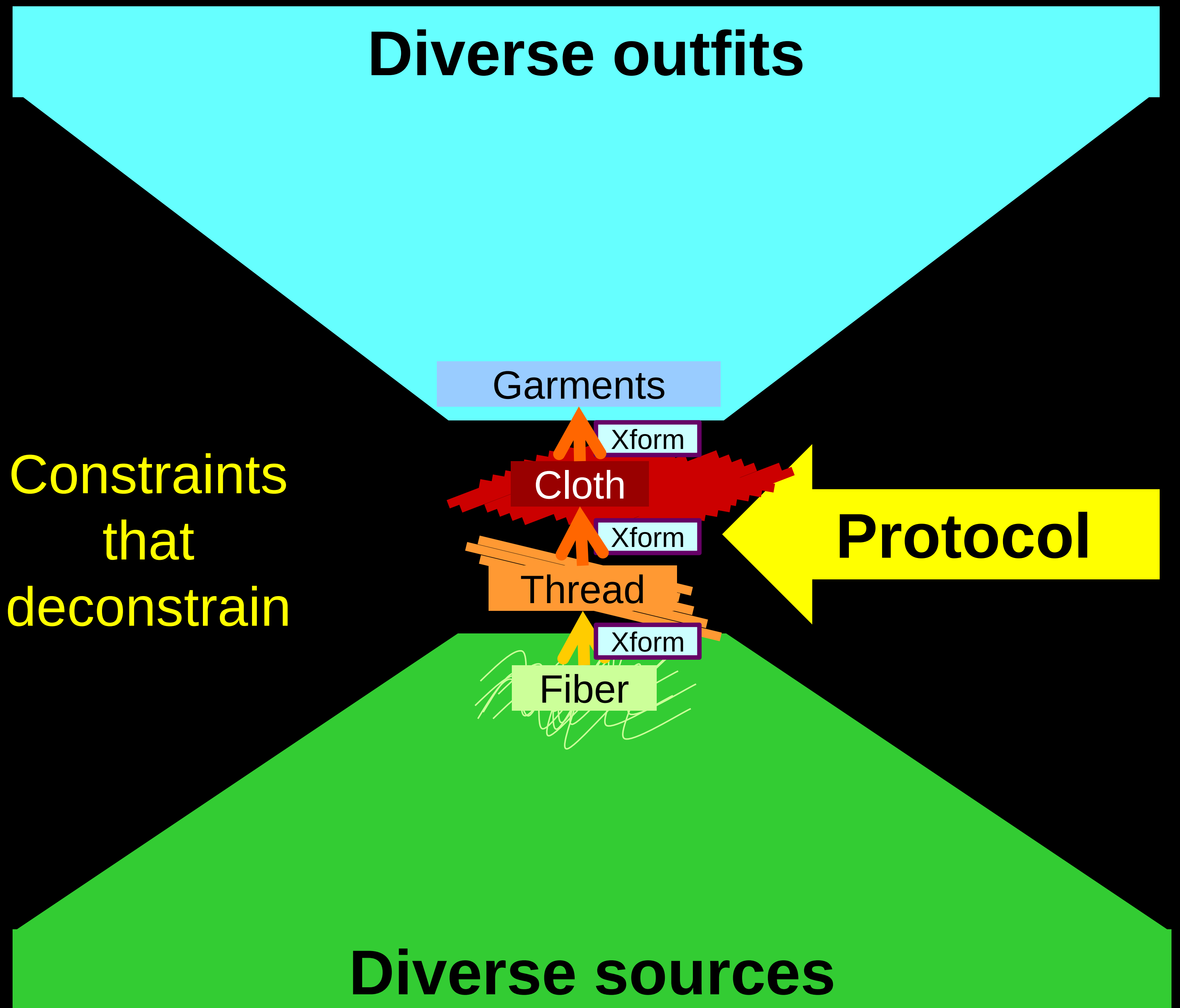
Diverse outfits

Constraints that deconstrain



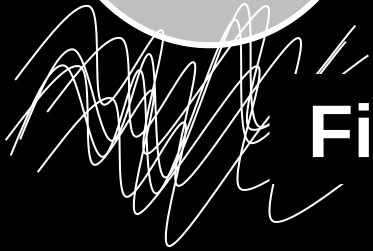
Geographically diverse sources


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
Constraints that deconstrain
Protocol
Diverse sources

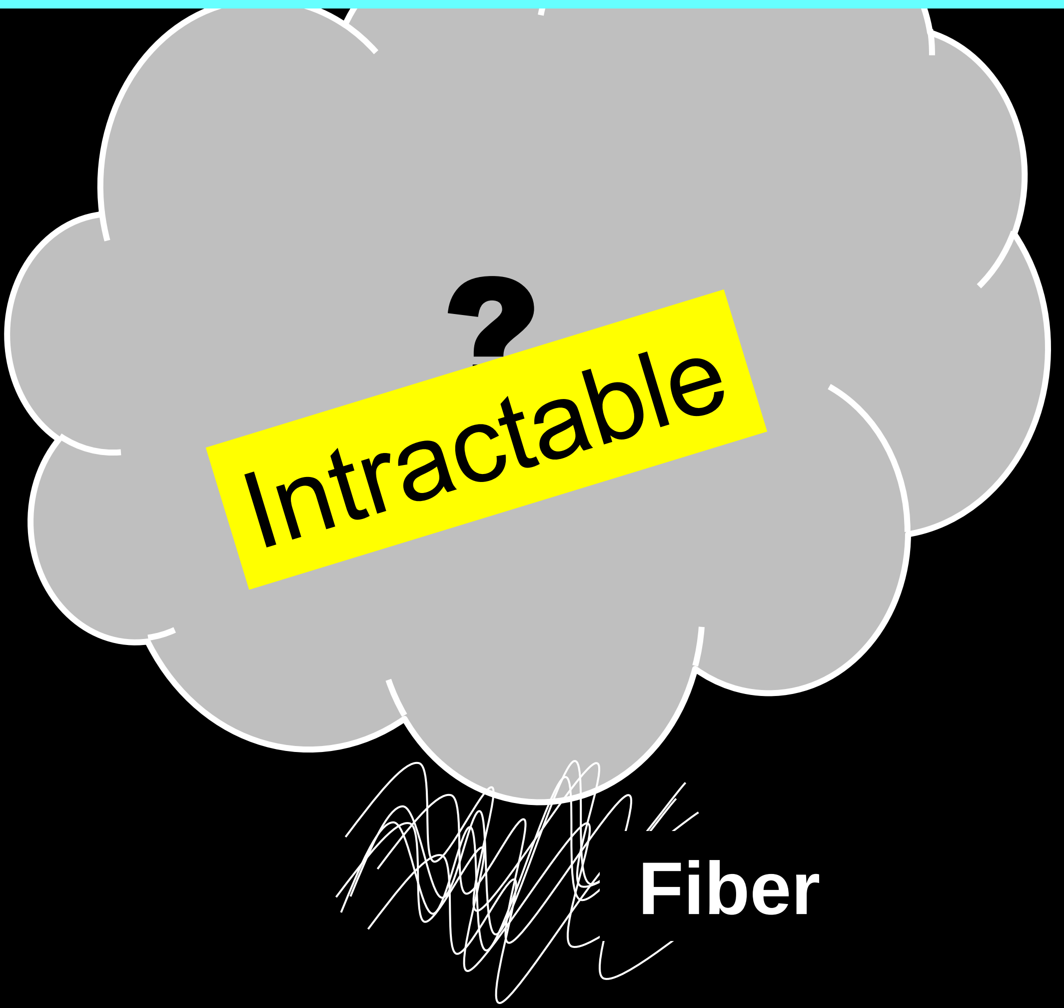
Diverse outfits

?



Fiber

Diverse outfits



SOC/EOC?

Self-Organized Clothing

Edge of Couture

Scale-Free Fashion

Standard error

Diverse outfits

Small gap

No architecture

Self-Organized Clothing

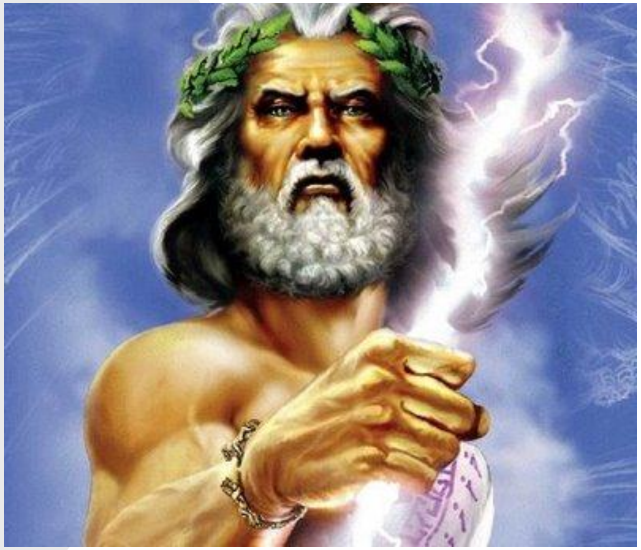
Edge of Couture

Scale-Free Fashion

Standard error

Diverse outfits

Huge gap
No architecture
Supernatural

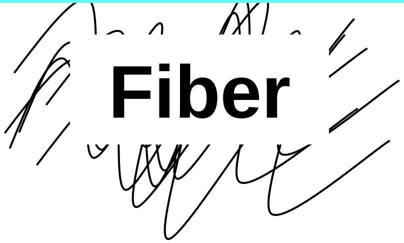


Fiber

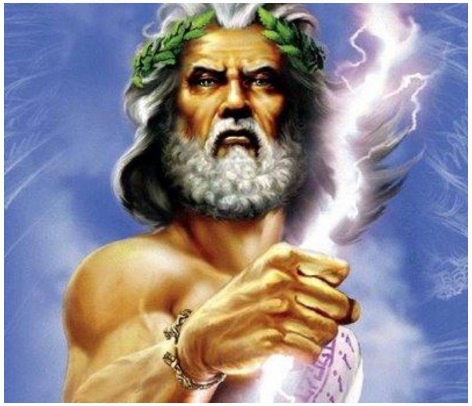
Mysteries in the gaps
No architecture

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

Diverse outfits



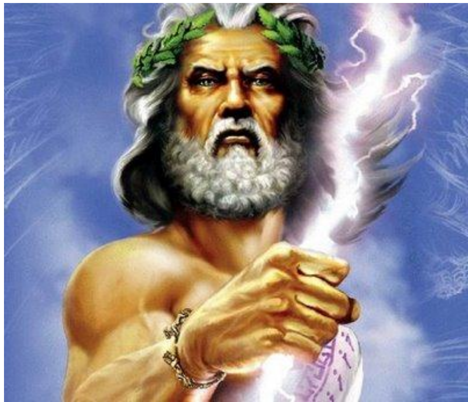
Diverse outfits



Huge gap
Supernatural

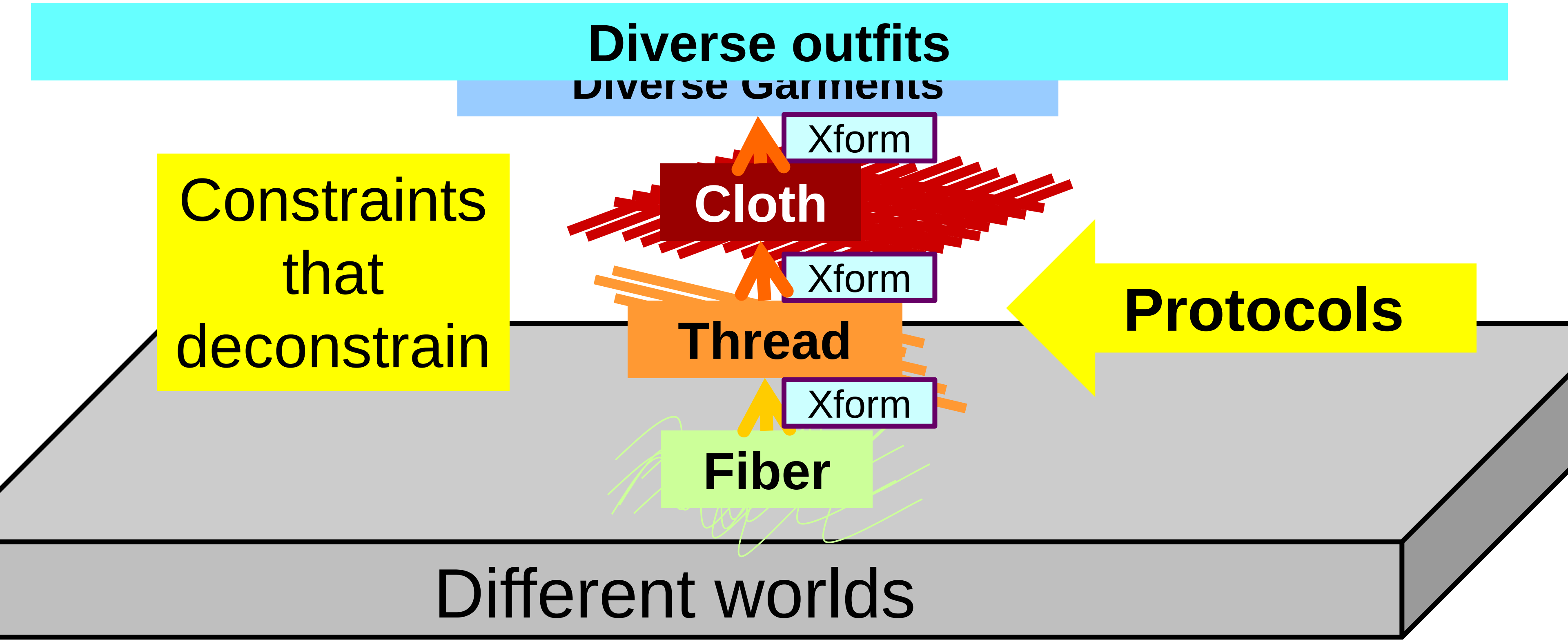
Mysteries in the gaps
No architecture

Huge gap
Supernatural



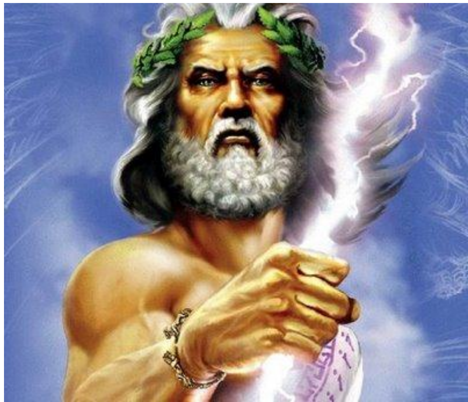
Mainstream

Small gap
Emergent



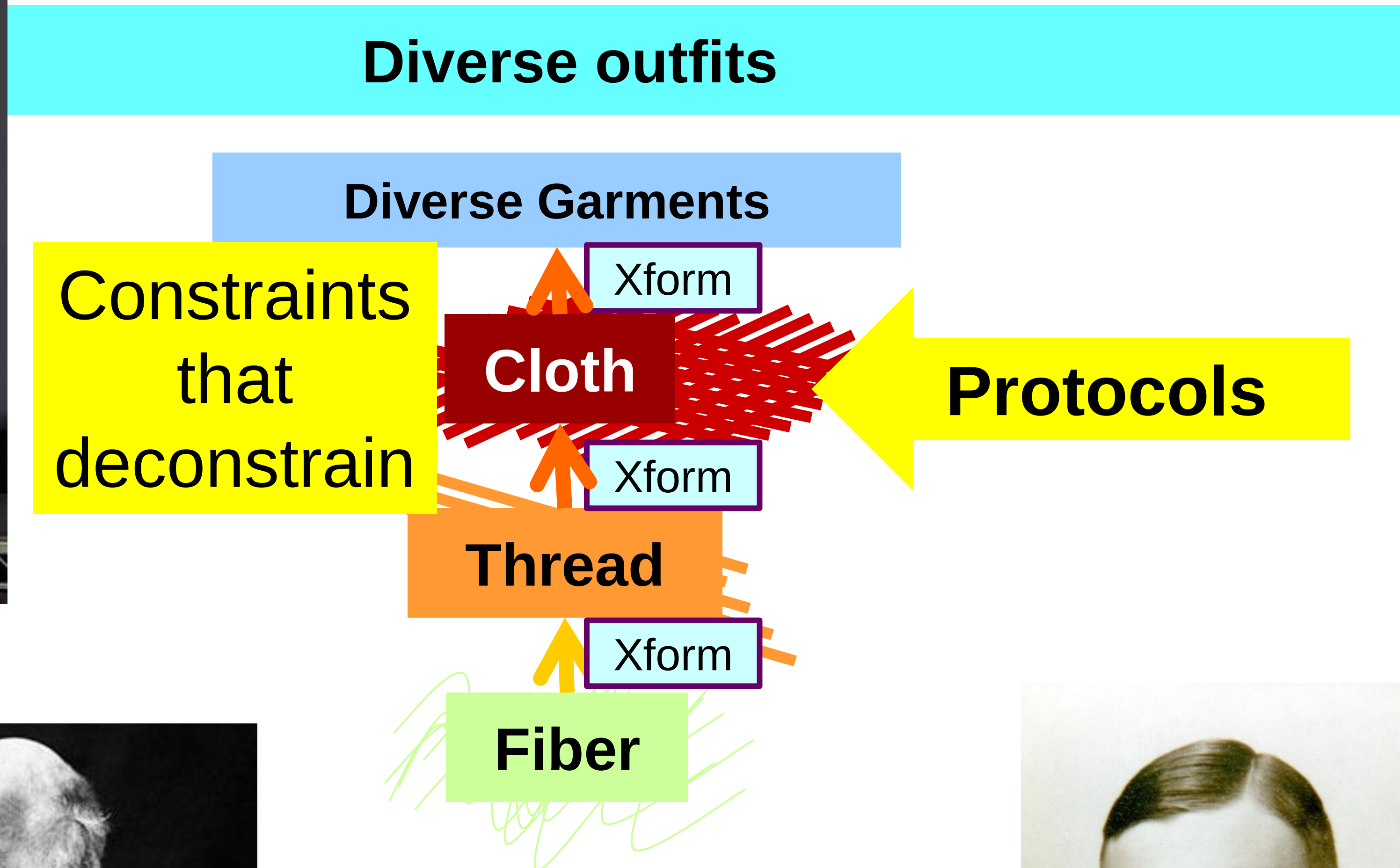
Mysteries in the gaps
No architecture

Huge gap
Supernatural

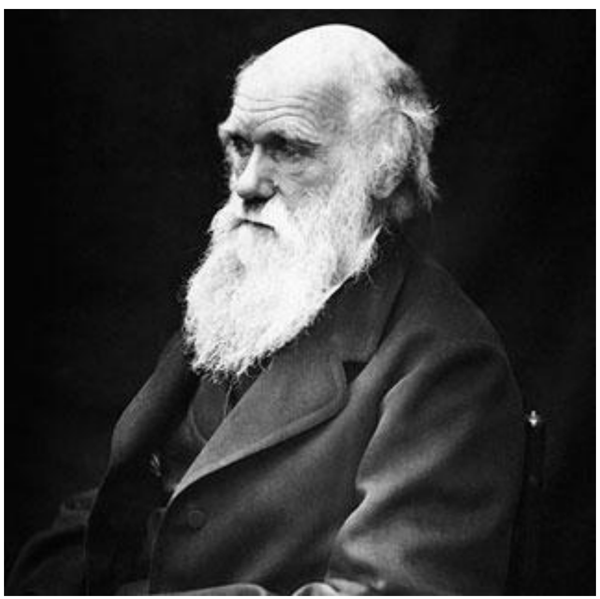


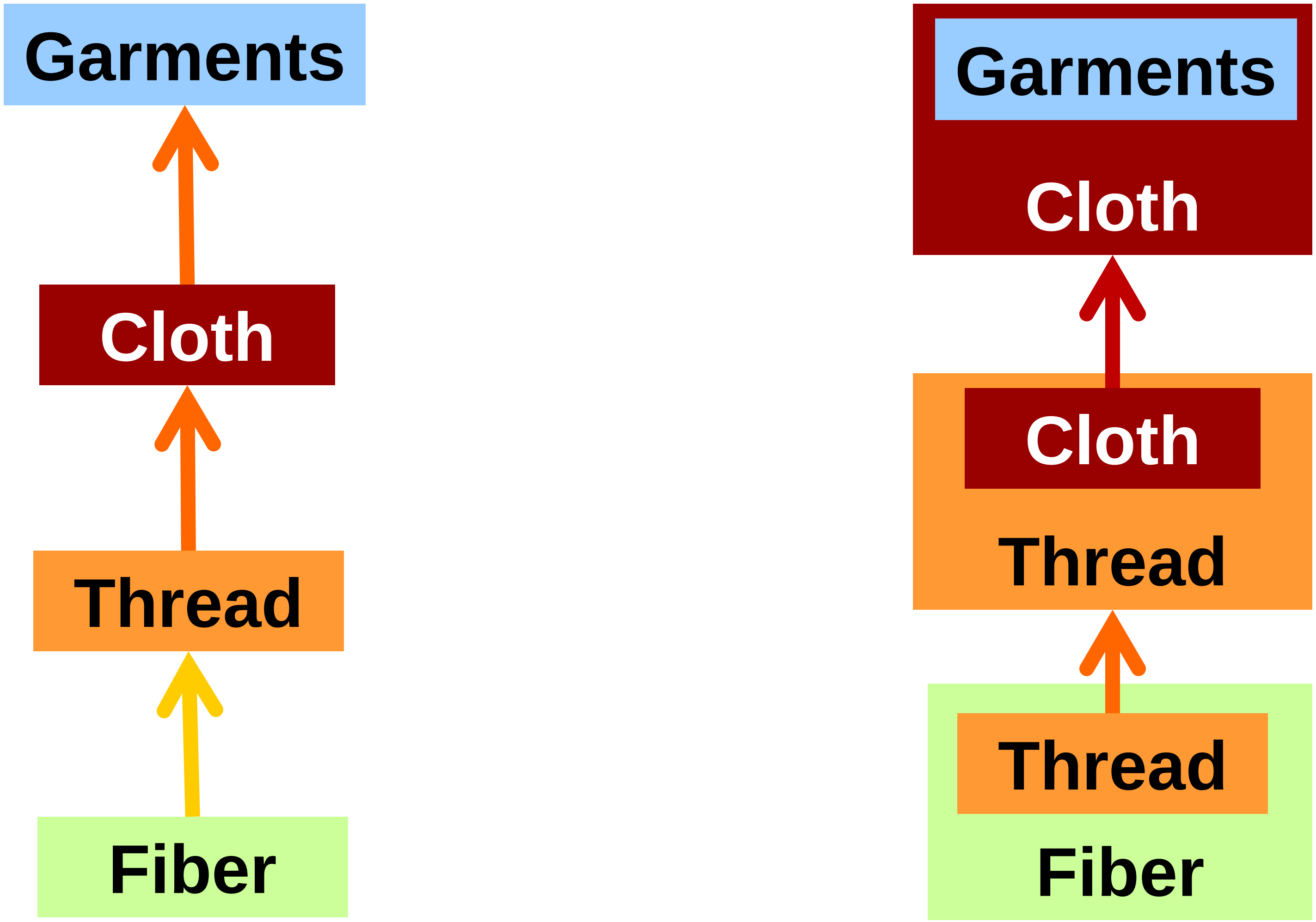
Small gap
Emergent

Mainstream

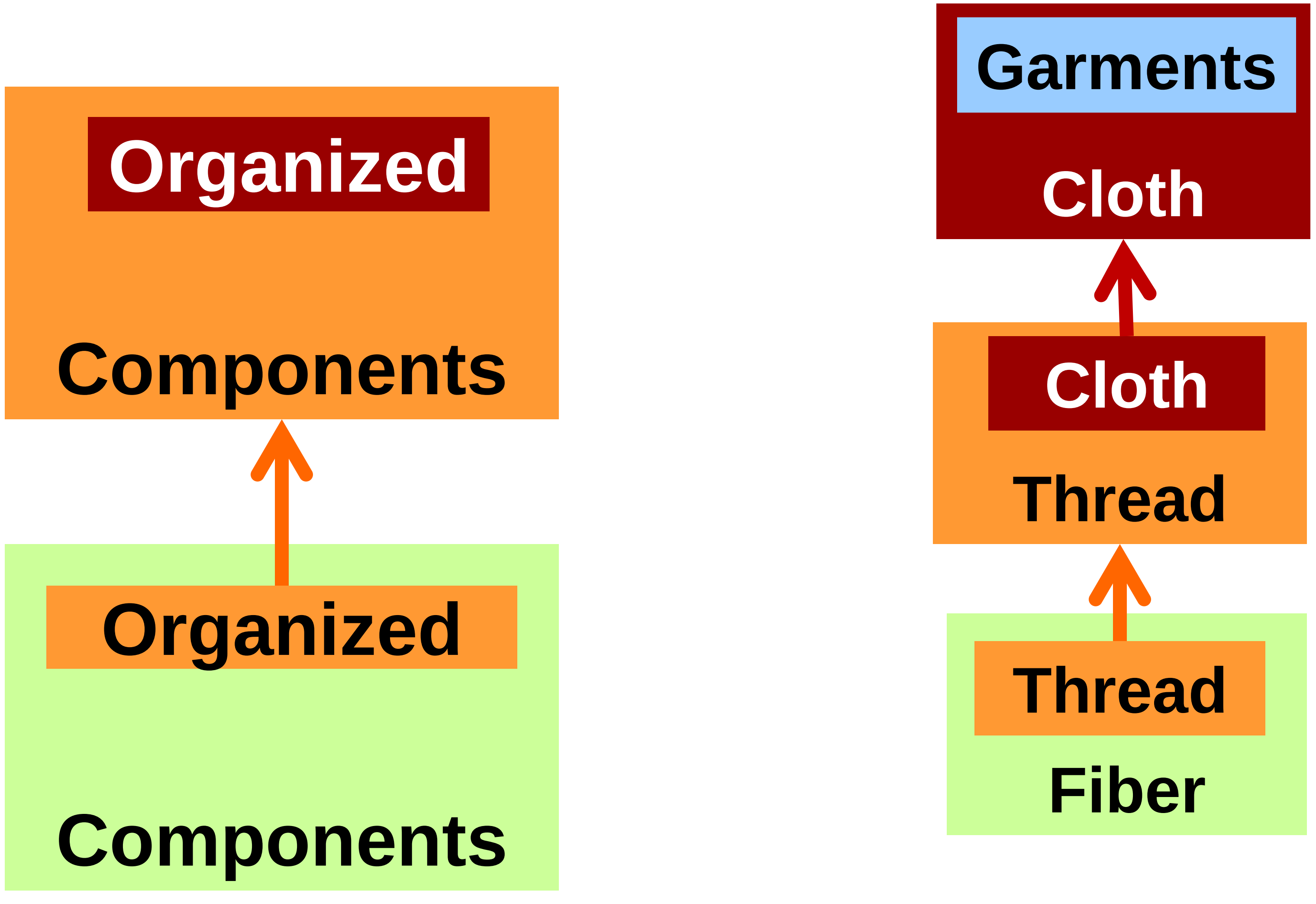


Diverse outfits
Diverse Garments
Constraints that deconstrain
Xform
Cloth
Protocols
Xform
Thread
Xform
Fiber




Garments
Cloth
Thread
Fiber
Garments
Cloth
Cloth
Thread
Thread
Fiber

Layered, large, thin



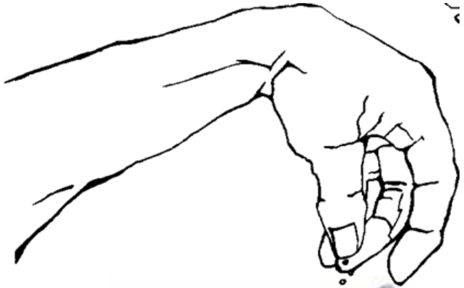
large thin

1 << # outfits << # heaps

Organized

Components

Components



heap

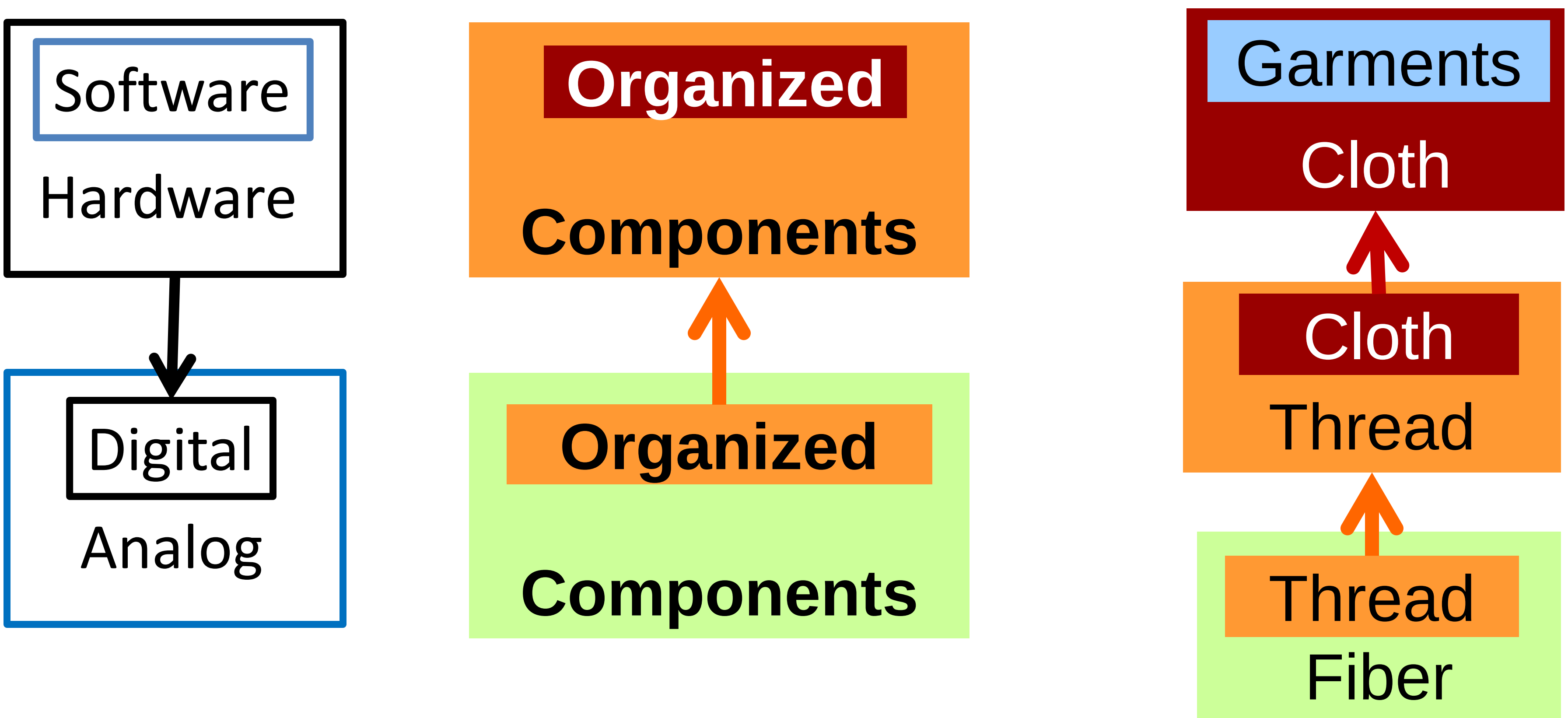
large **thin**

1 << # outfits << # heaps

Organized

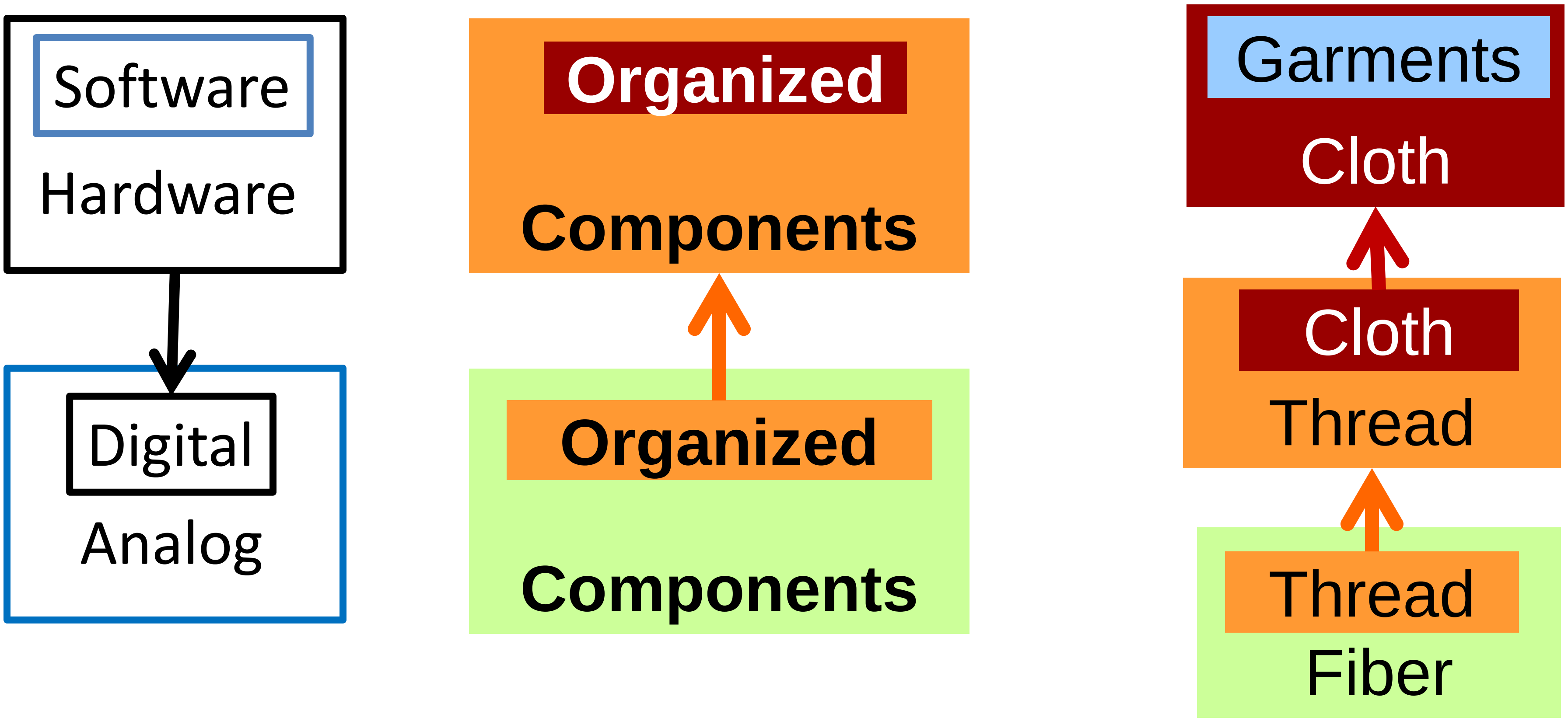
Components

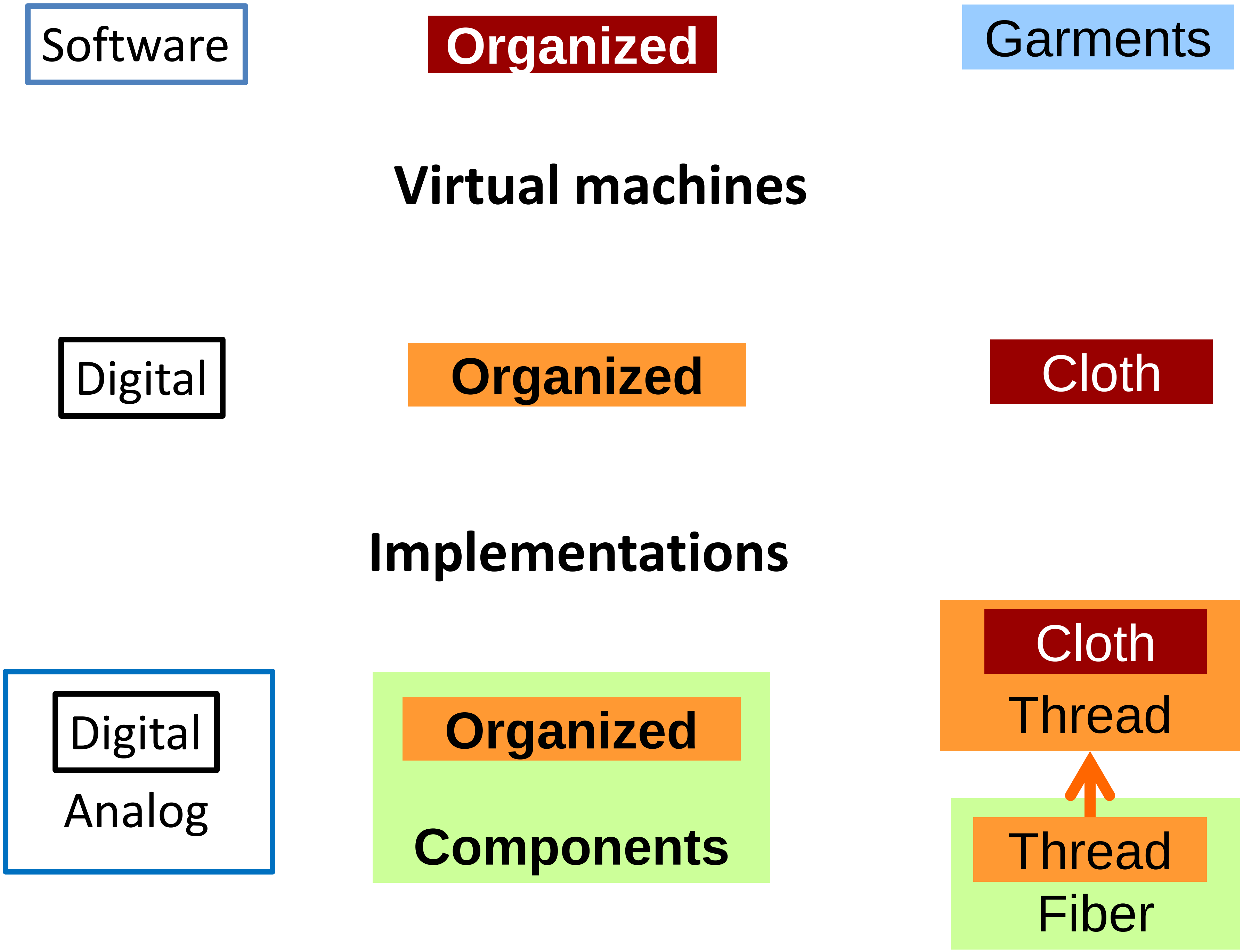
What is the “true functional ~~unit~~?” Architecture



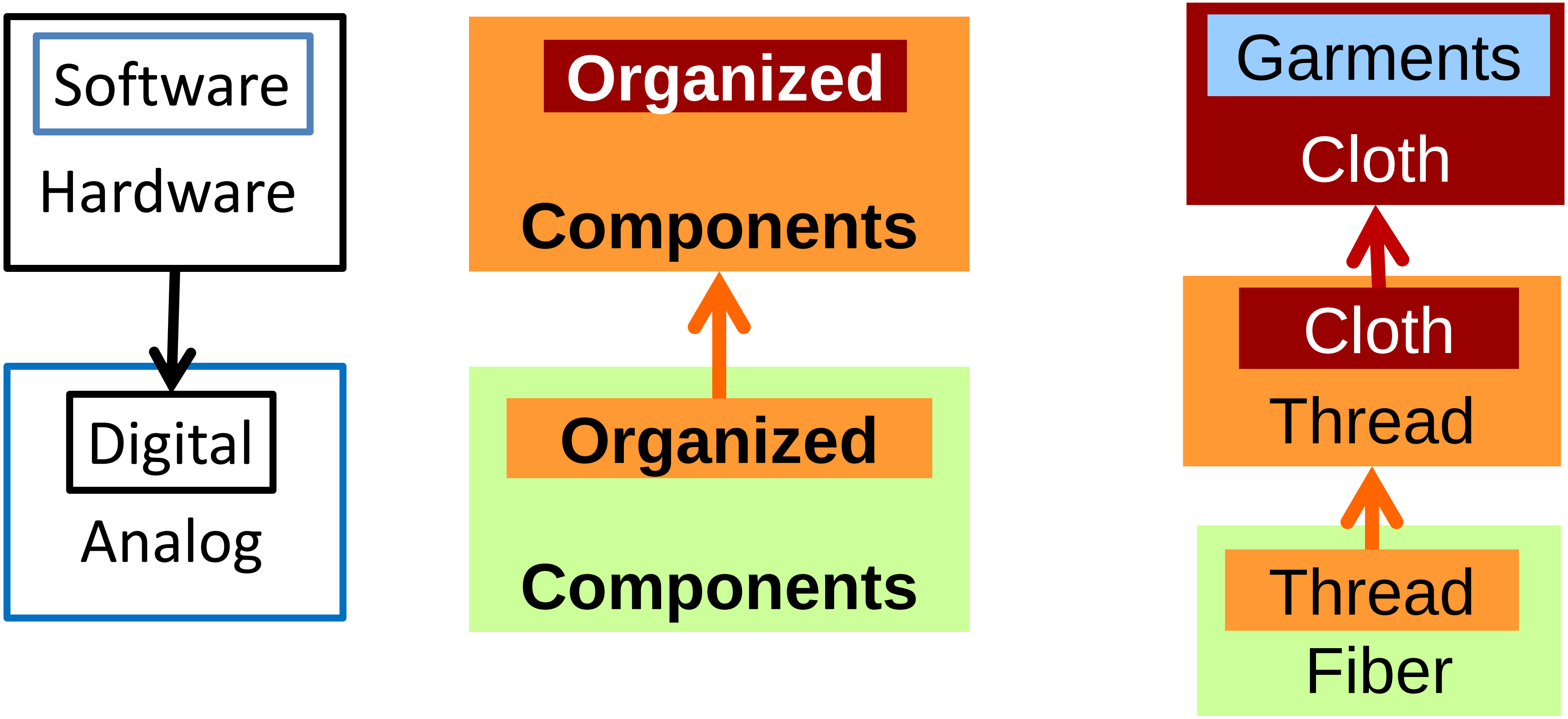
Virtual machines

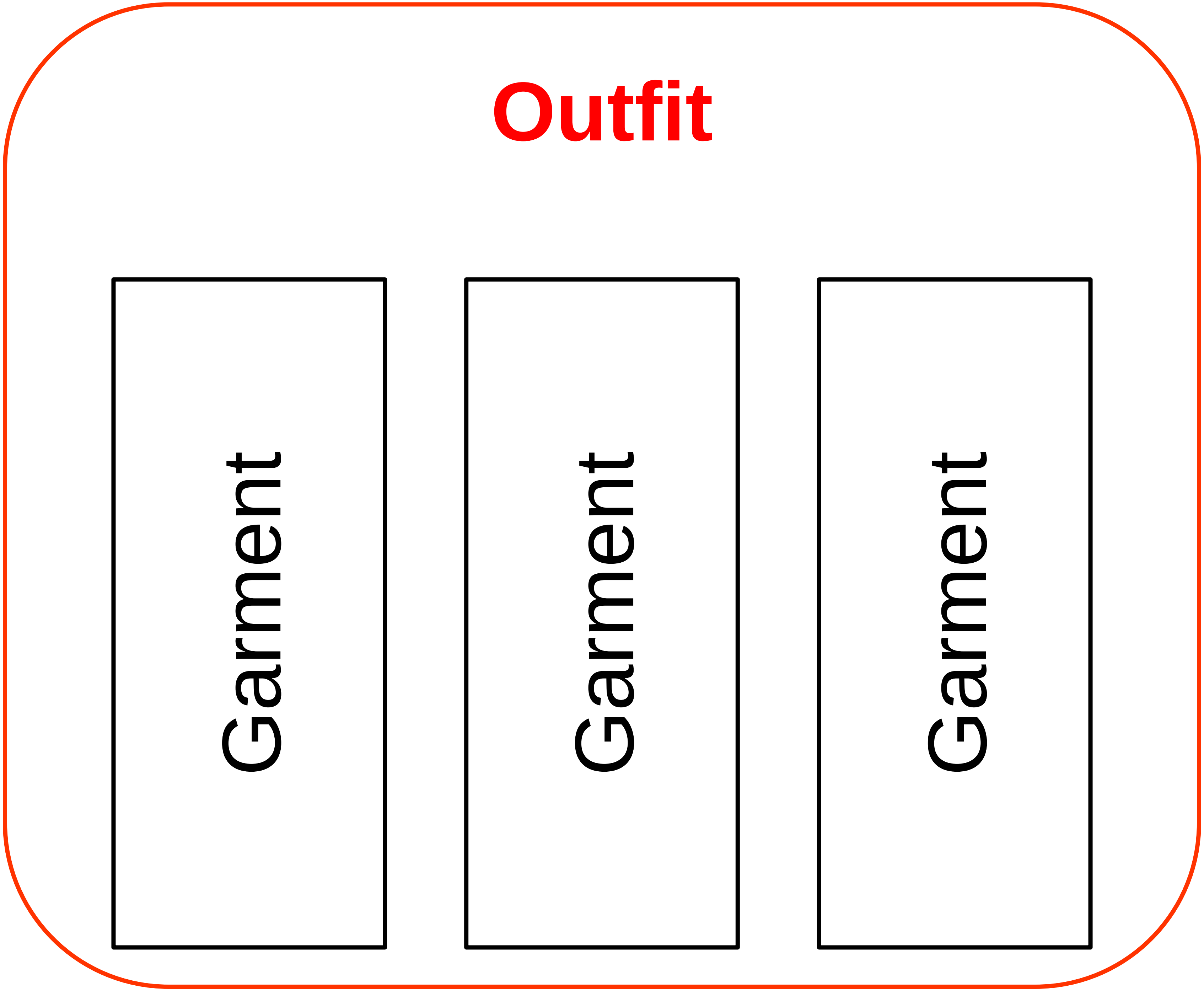
Implementations

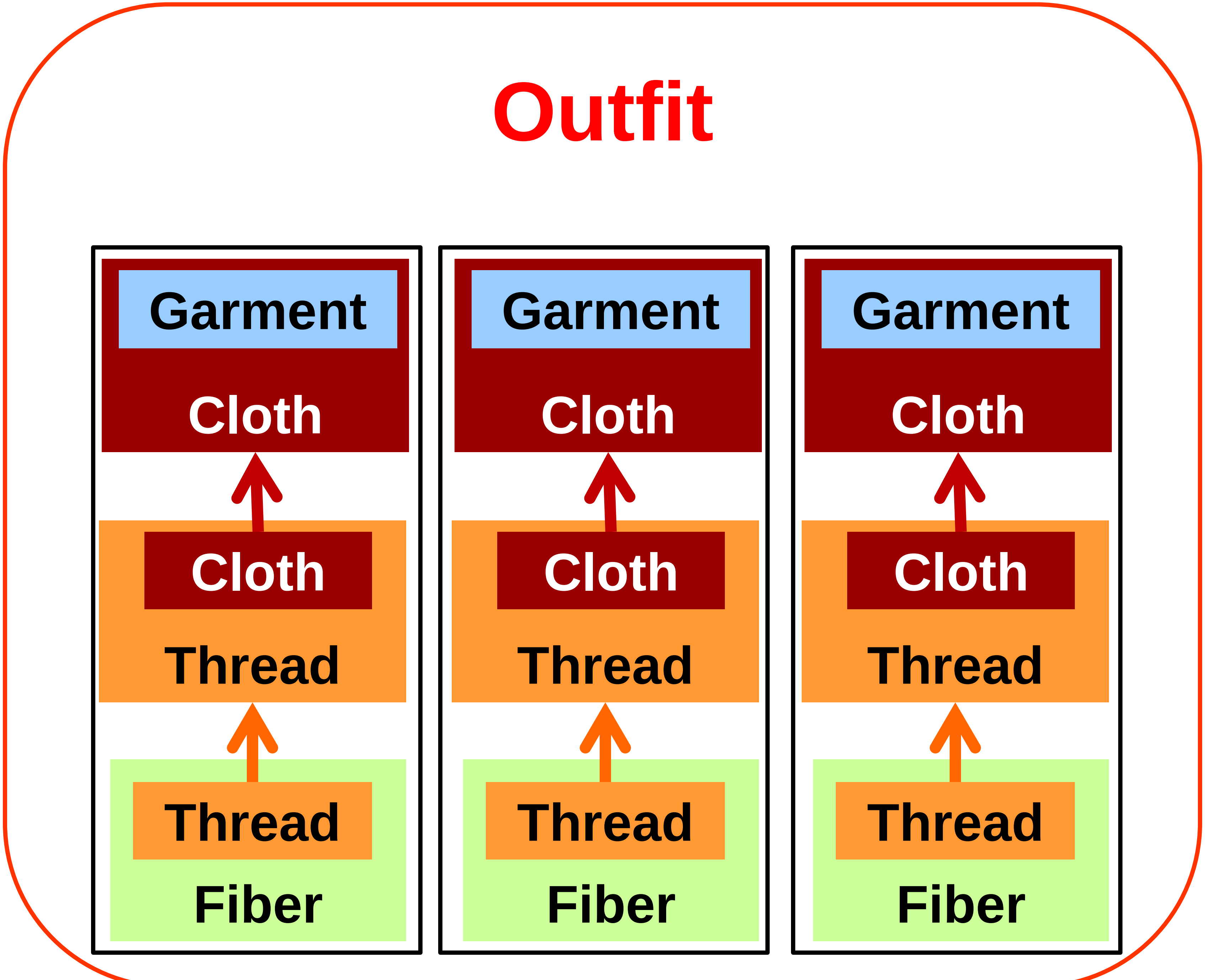



Software
Organized
Garments
Virtual machines
Digital
Organized
Cloth
Implementations
Cloth
Thread
Digital
Analog
Organized
Components
Thread
Fiber

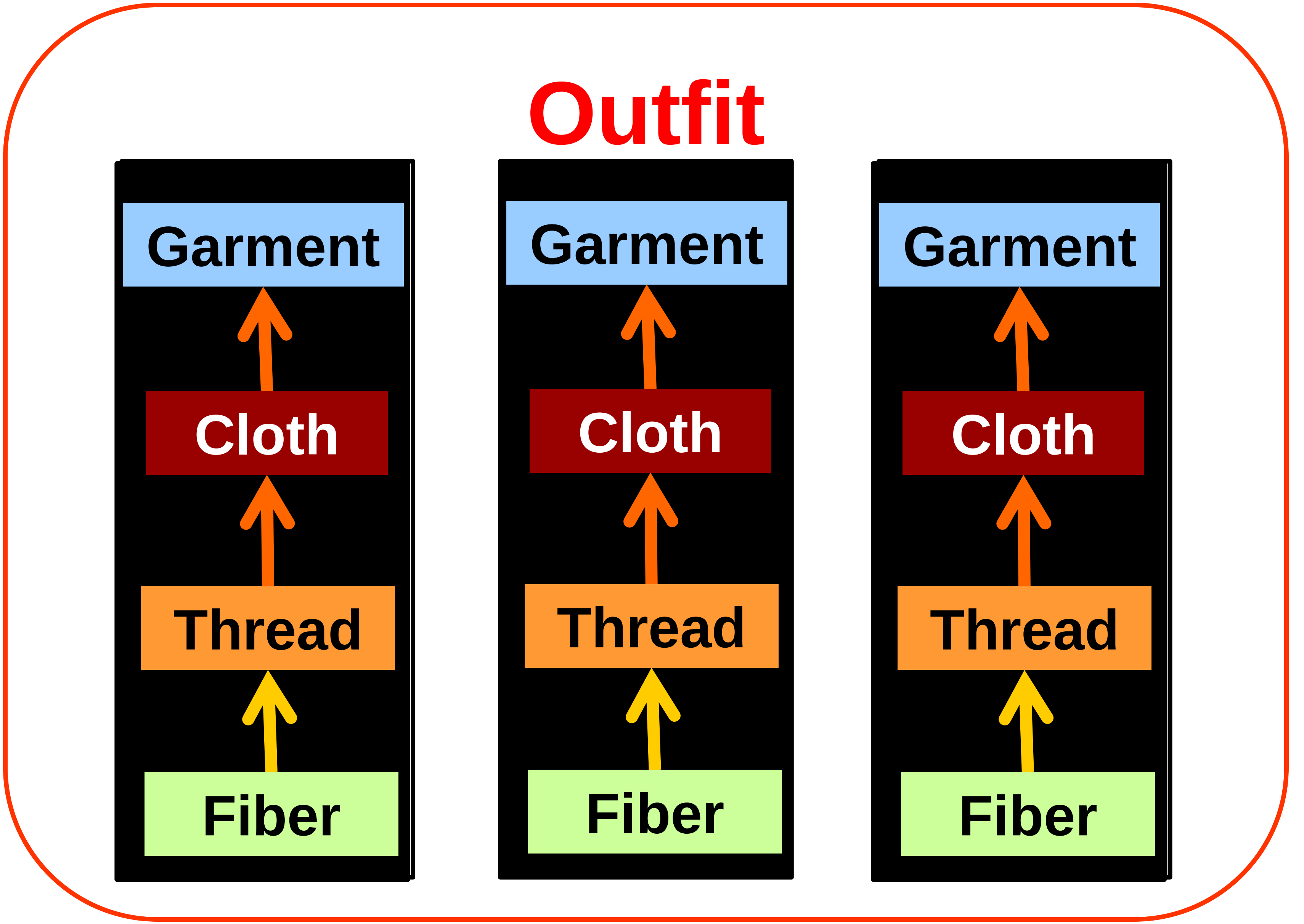
Layered, large, thin
Hidden
Virtualized

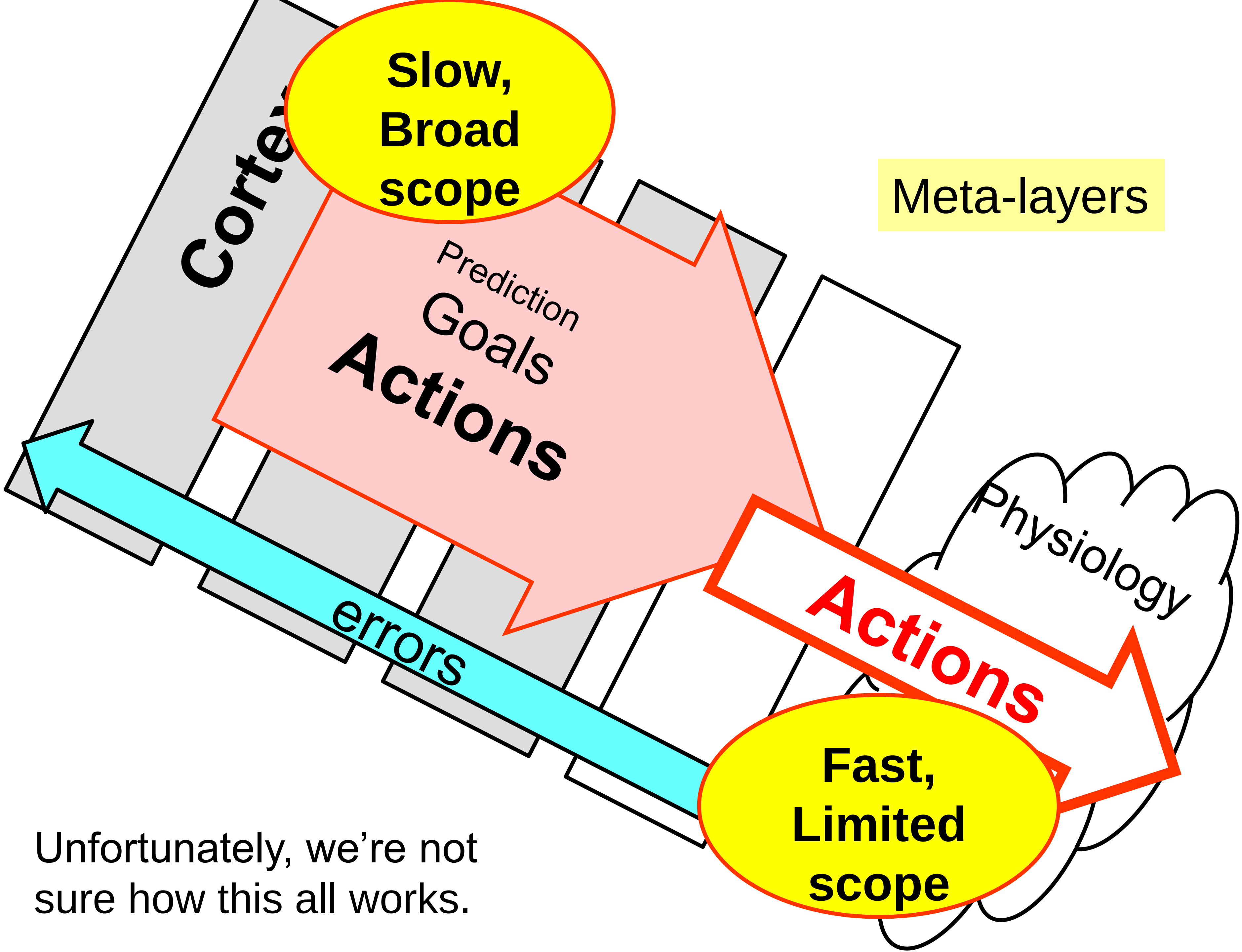



Outfit
Garment
Garment
Garment

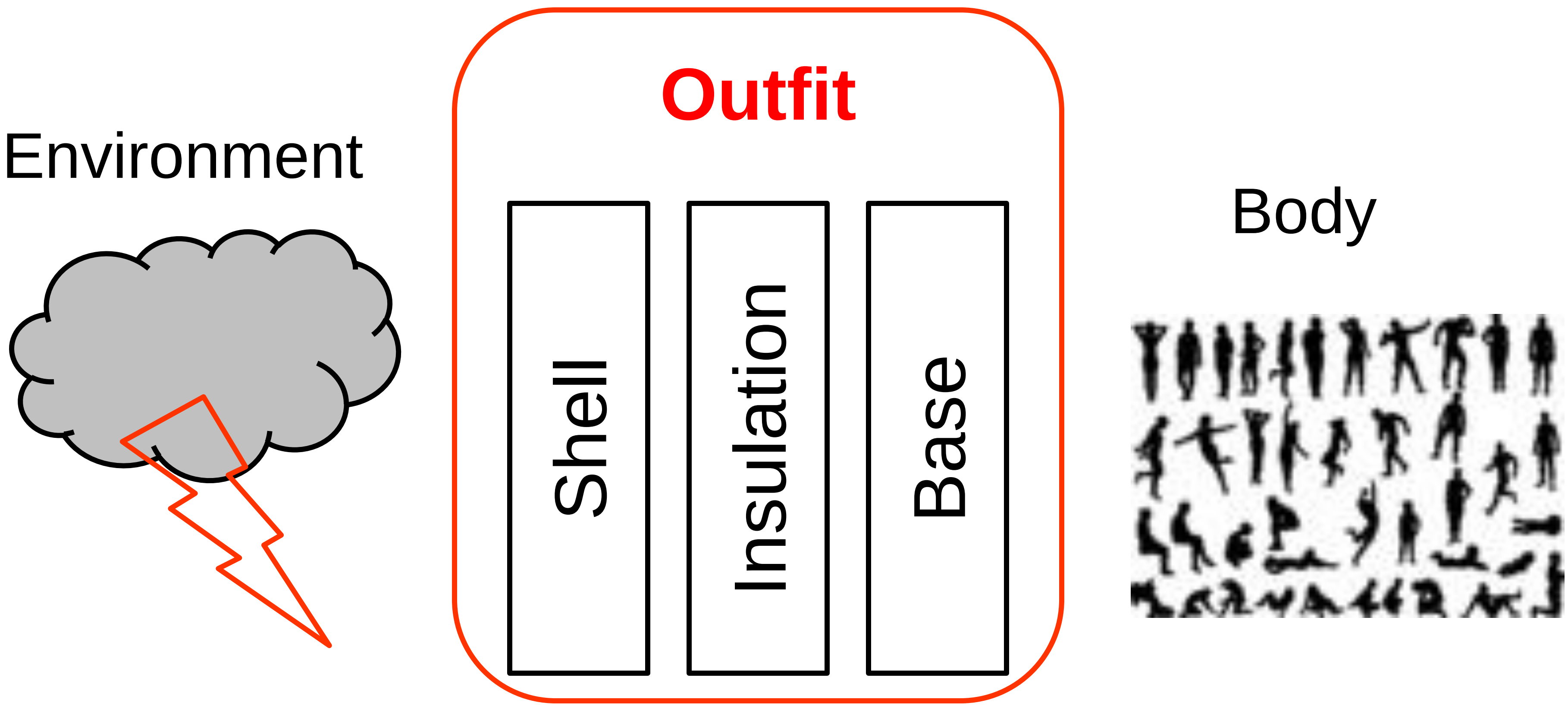

Outfit
Garment
Cloth
Cloth
Thread
Thread
Fiber
Garment
Cloth
Cloth
Thread
Thread
Fiber
Garment
Cloth
Cloth
Thread
Thread
Fiber

Layering within garments (textiles)

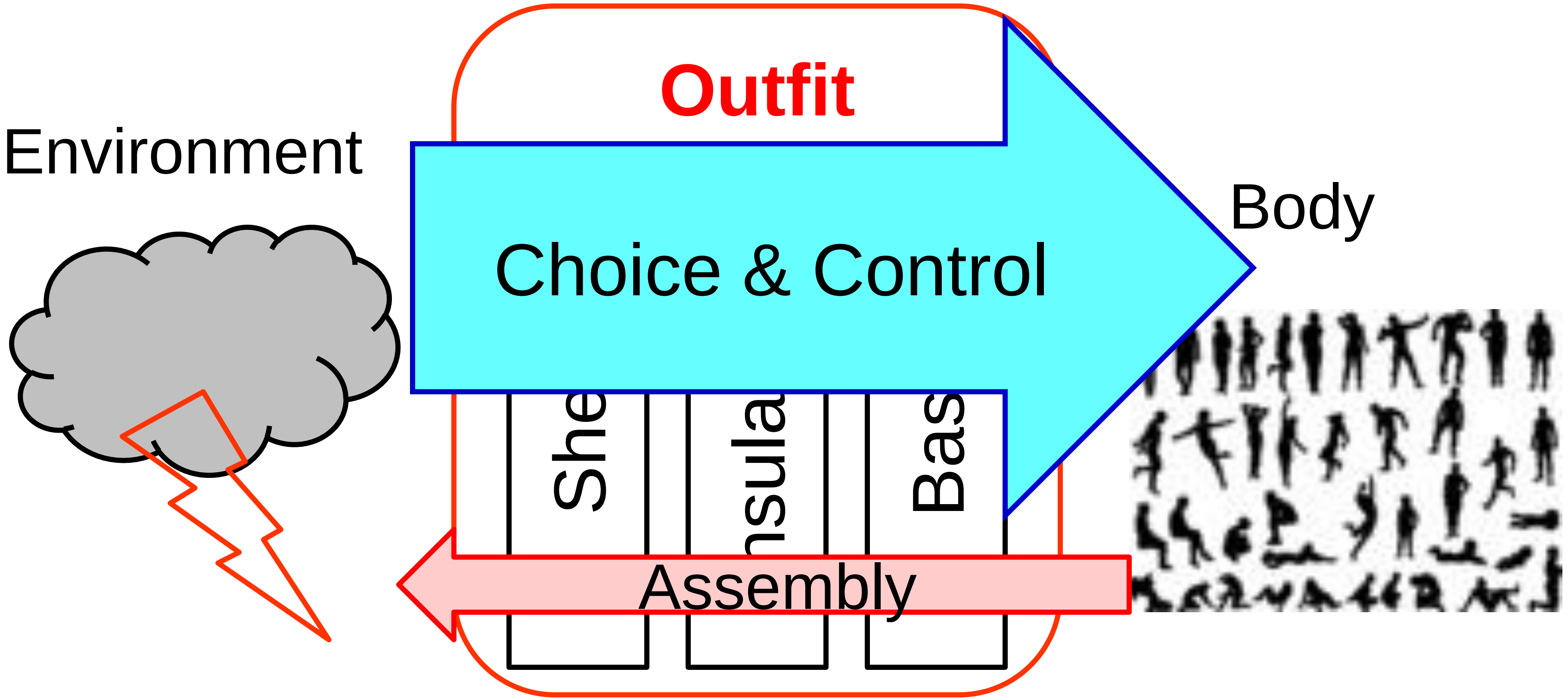


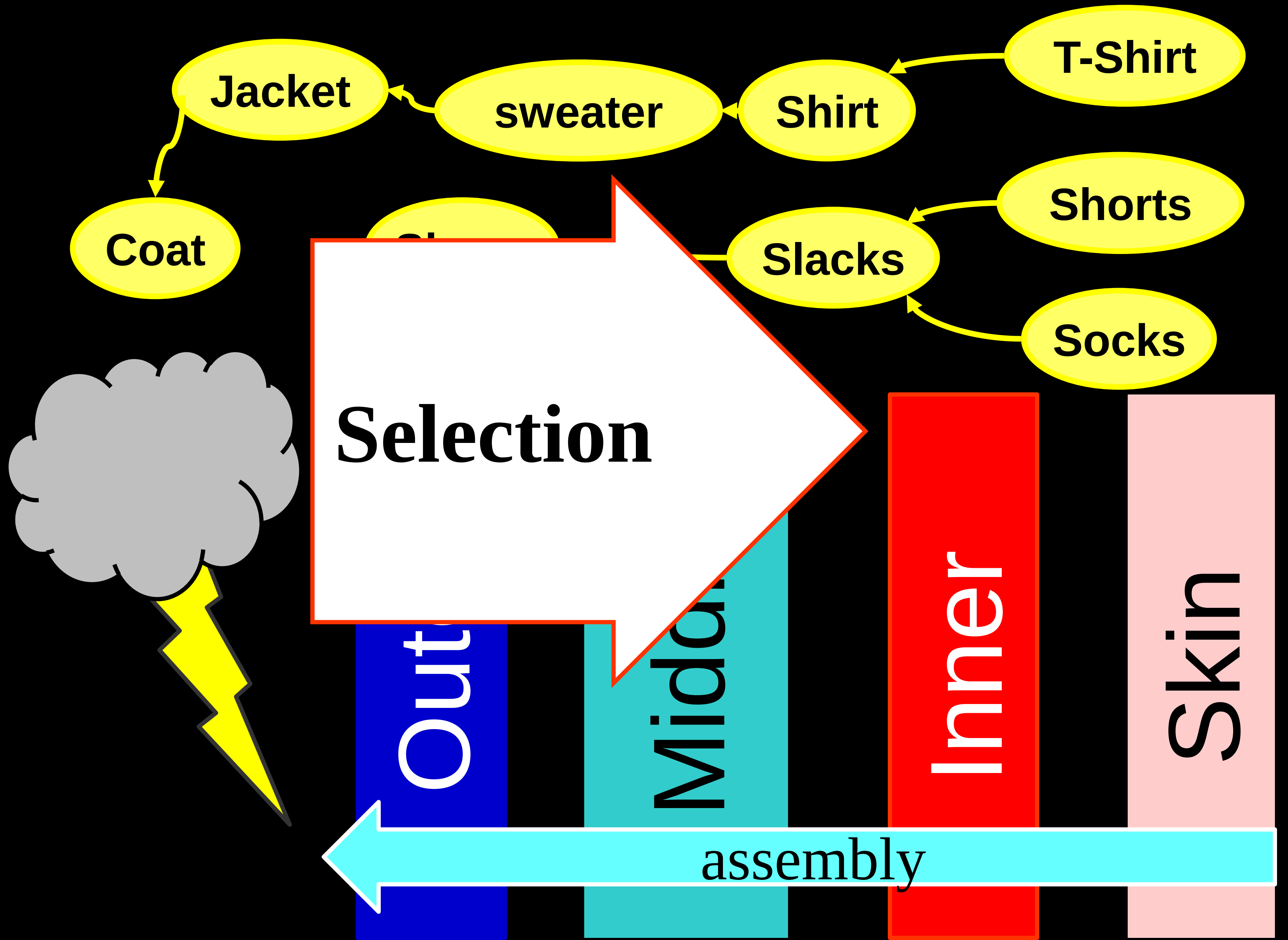


Unfortunately, we’re not sure how this all works.

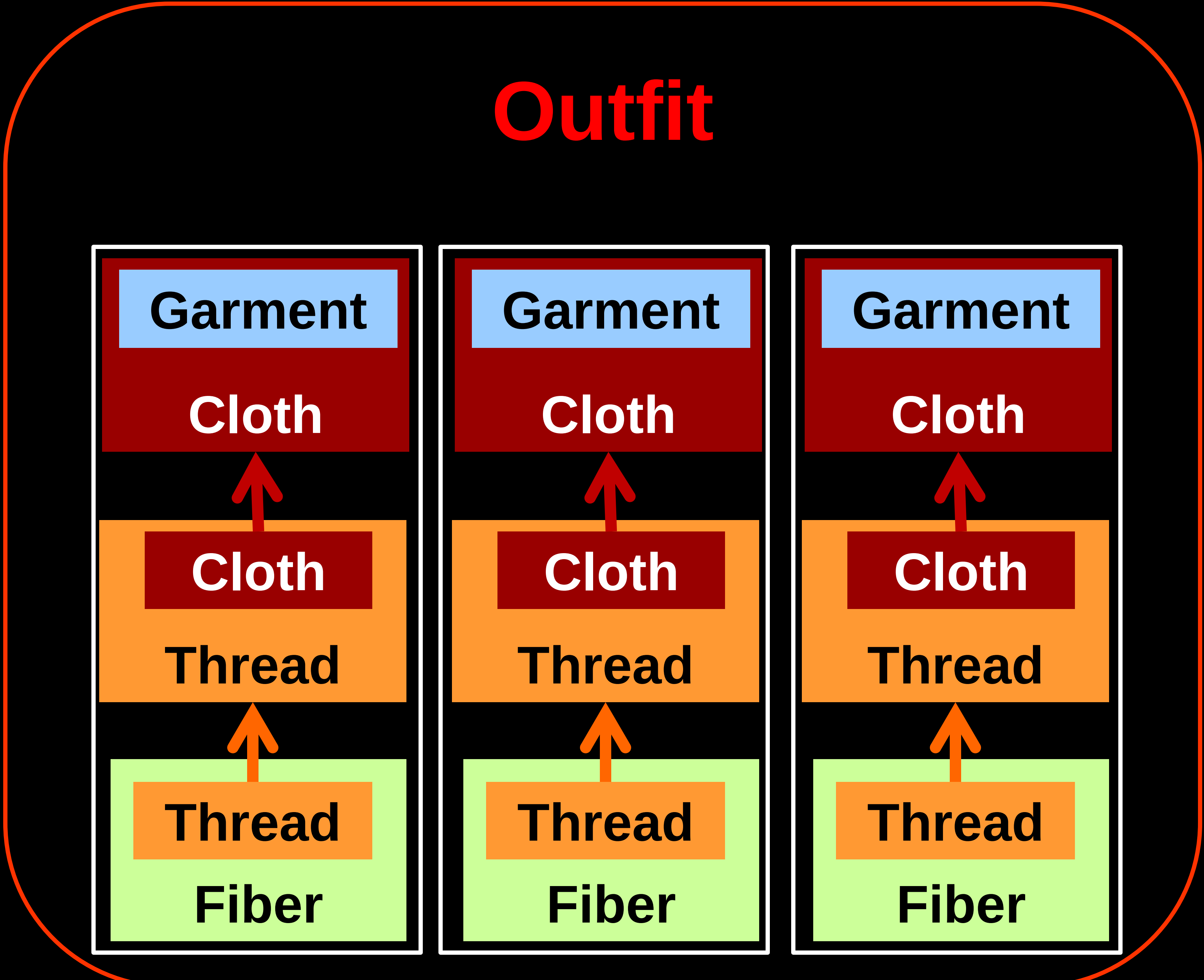

Environment
Outfit
Shell
Insulation
Base
Body

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

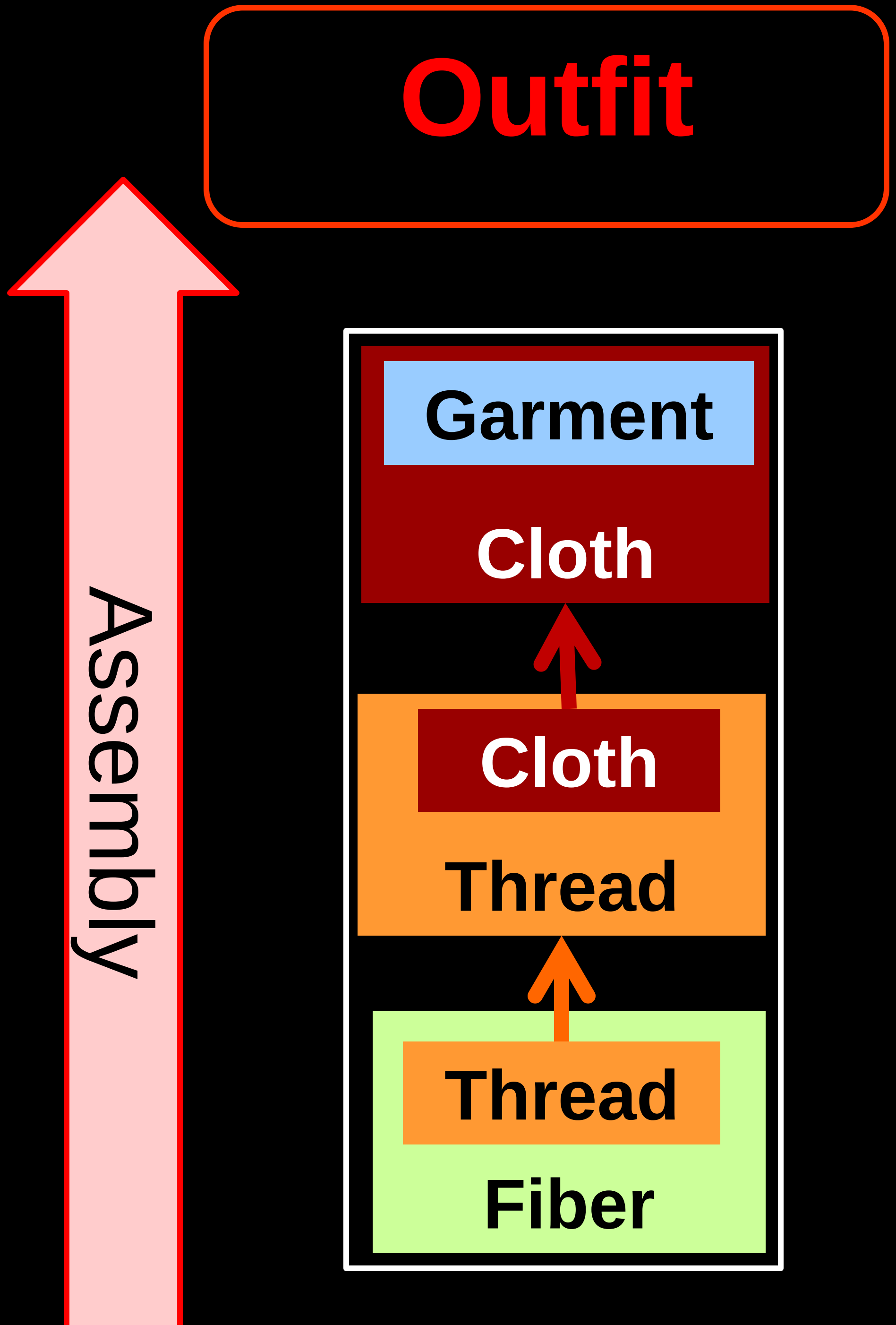




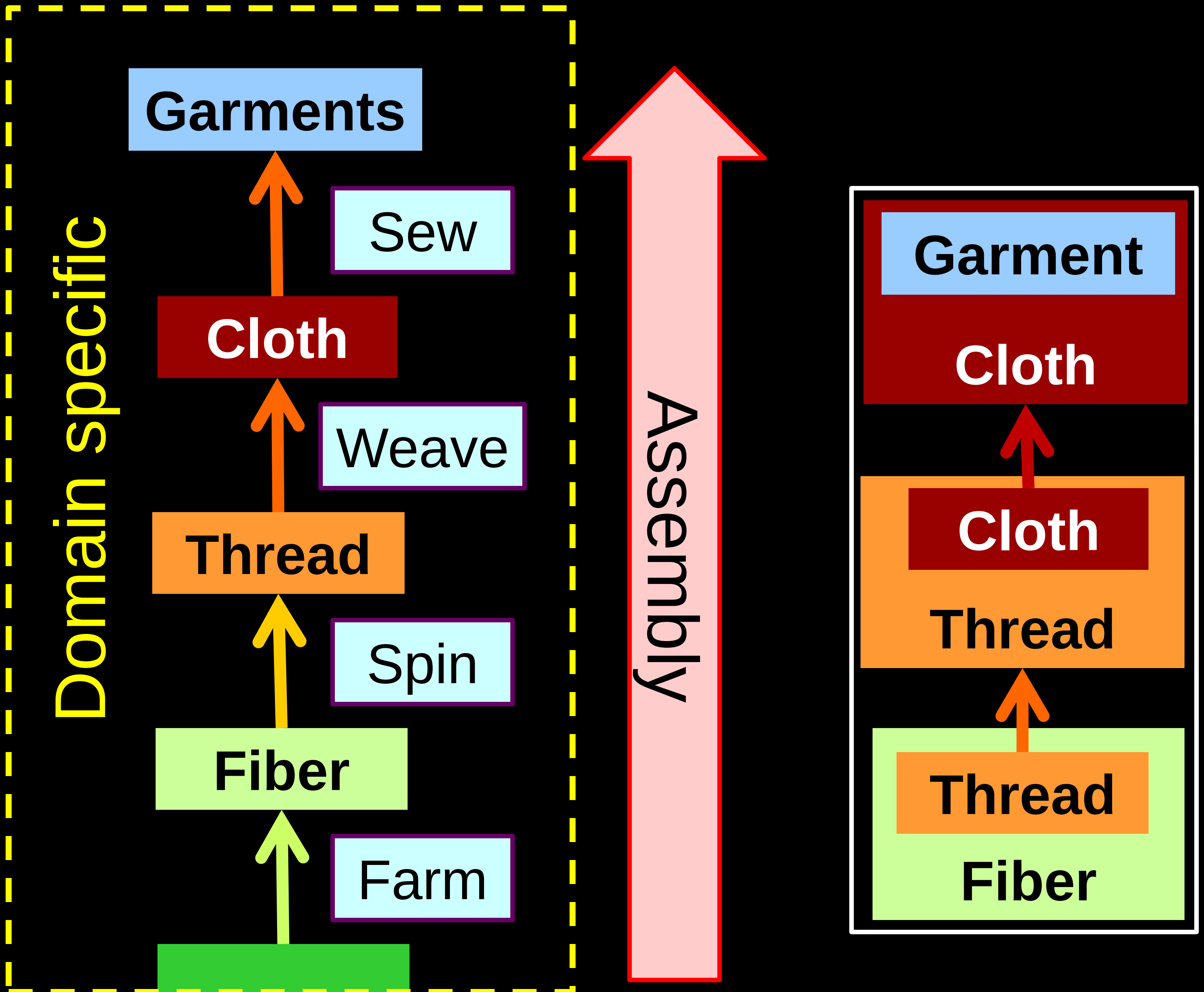
T-Shirt
Jacket
sweater
Shirt
Shorts
Coat
Slacks
Socks
Selection
Inner
Skin
assembly



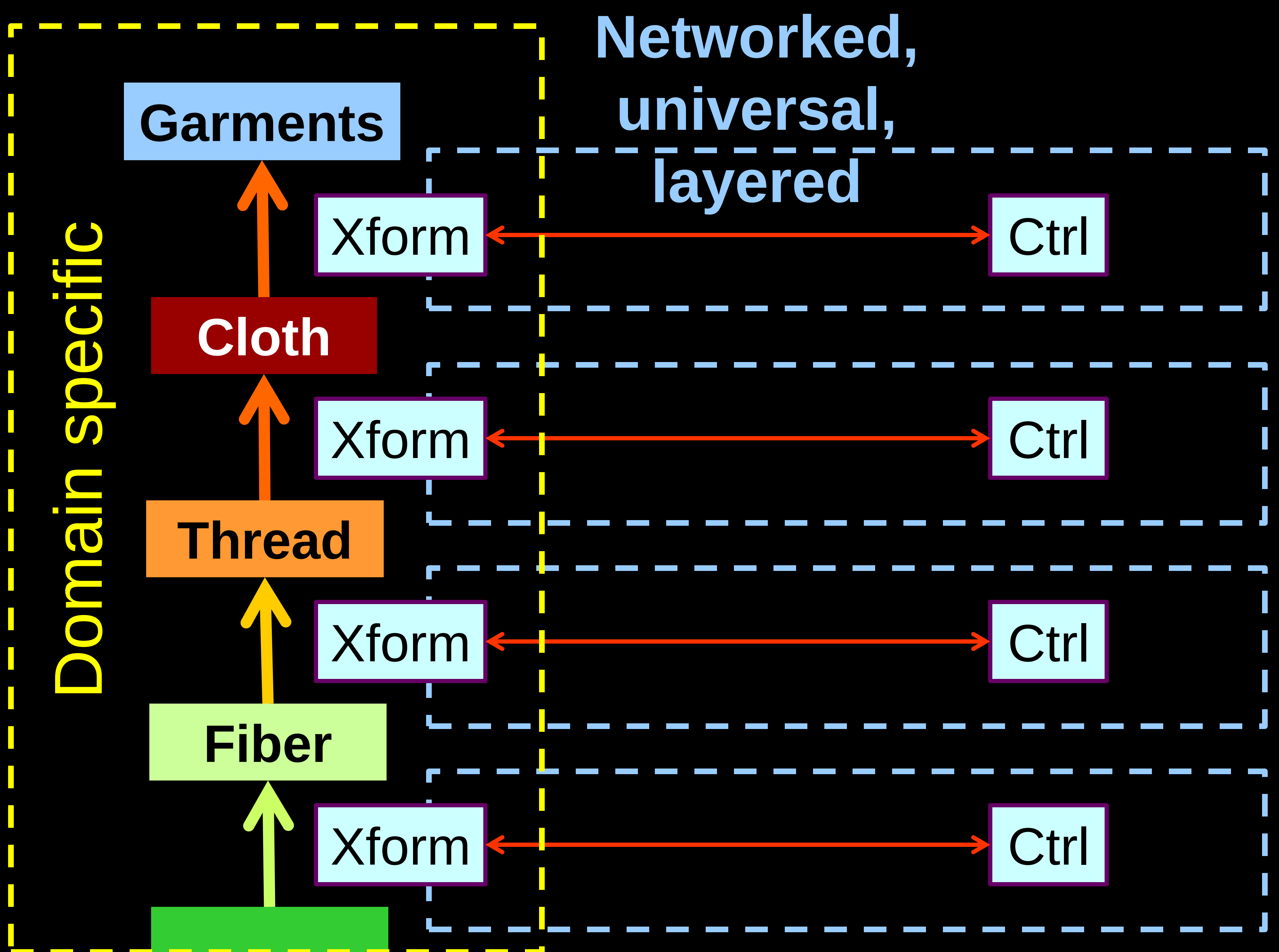
Outfit
Garment
Cloth
Cloth
Thread
Thread
Fiber
Garment
Cloth
Cloth
Thread
Thread
Fiber
Garment
Cloth
Cloth
Thread
Thread
Fiber

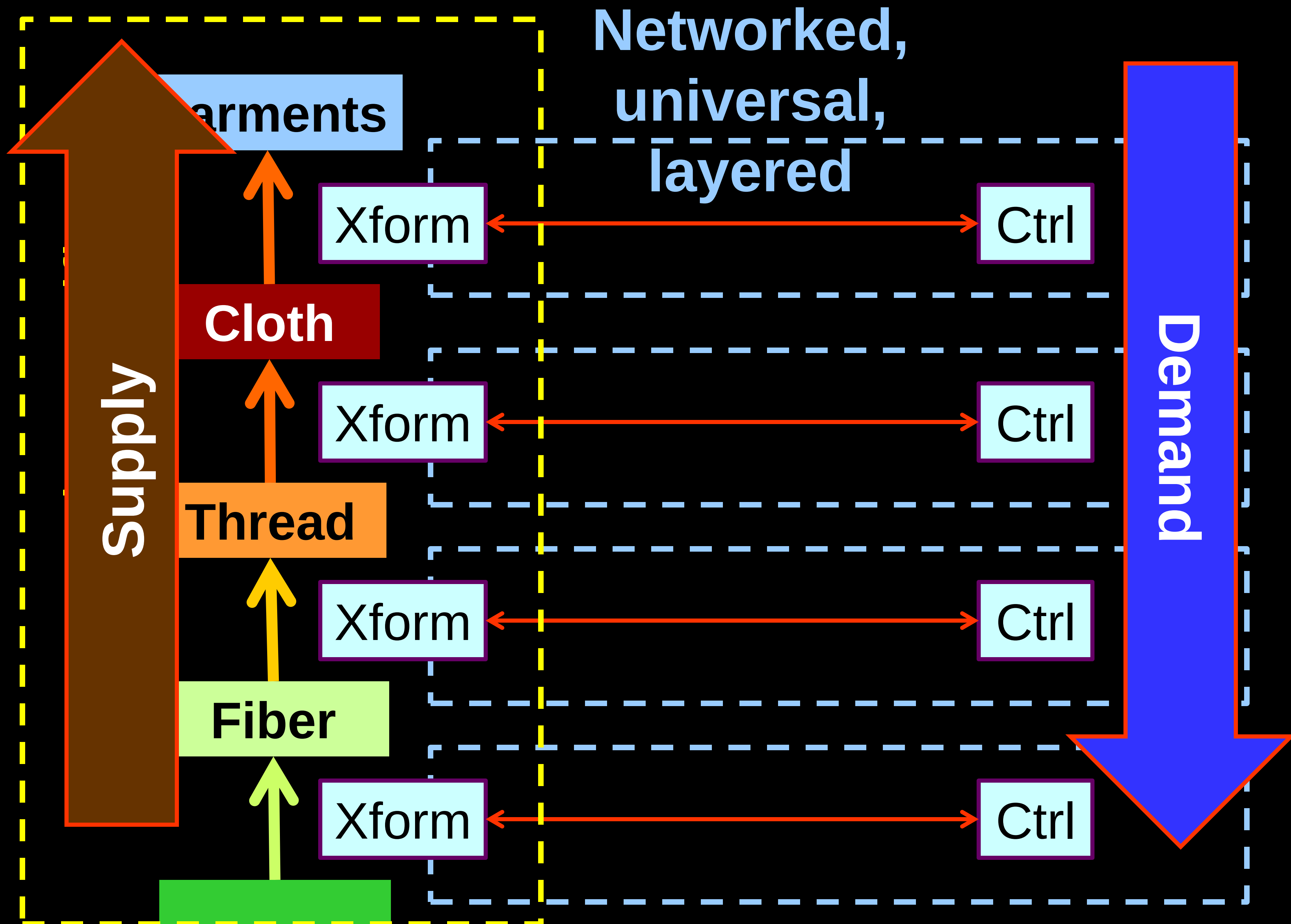


Outfit
Assembly
Garment
Cloth
Cloth
Thread
Thread
Fiber



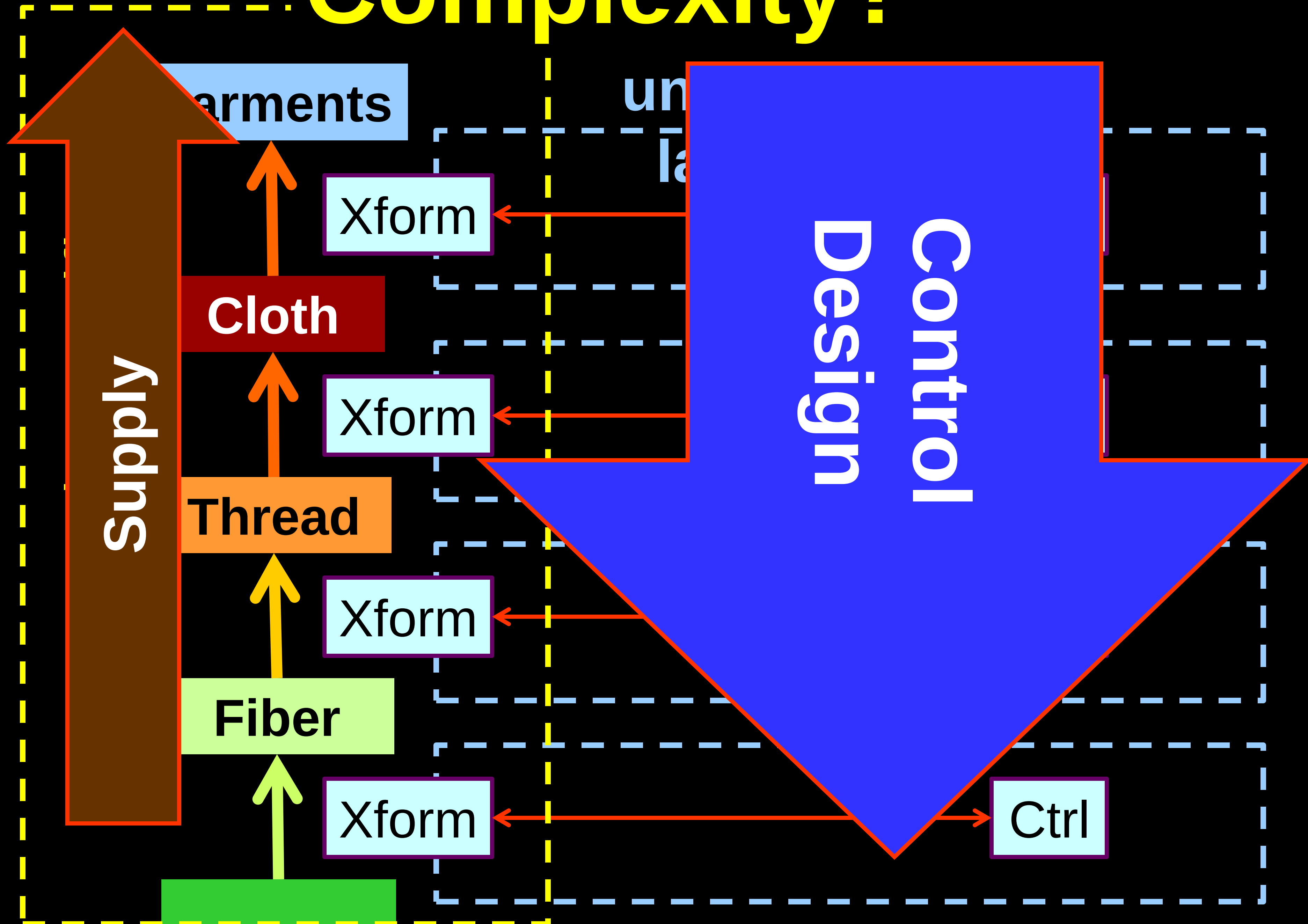
Domain specific
Garments
Sew
Cloth
Weave
Thread
Spin
Fiber
Farm
Assembly
Garment
Cloth
Cloth
Thread
Thread
Fiber


Networked, universal, layered
Garments
Cloth
Thread
Fiber
Domain specific
Xform
Ctrl
Xform
Ctrl
Xform
Ctrl
Xform
Ctrl

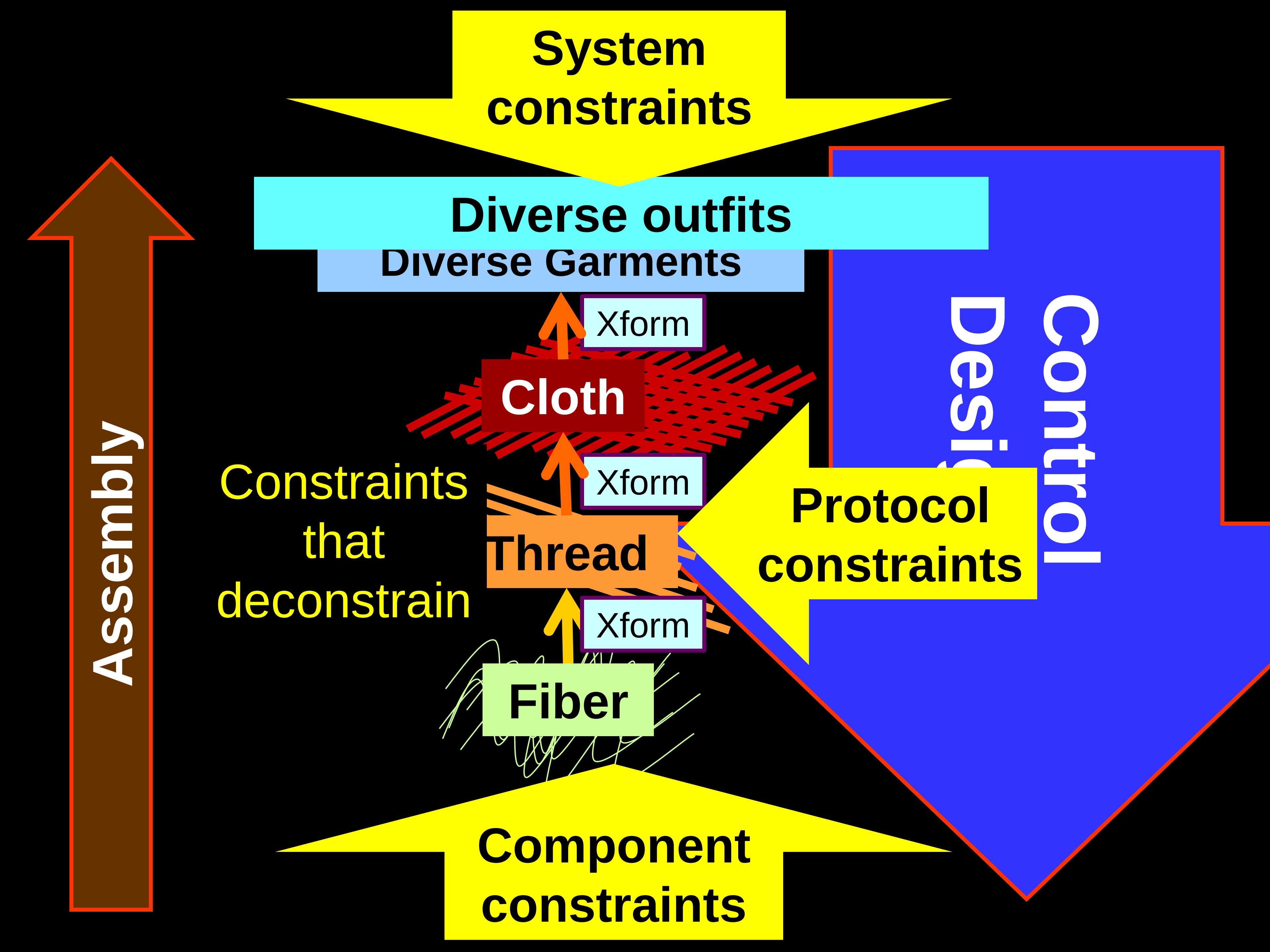


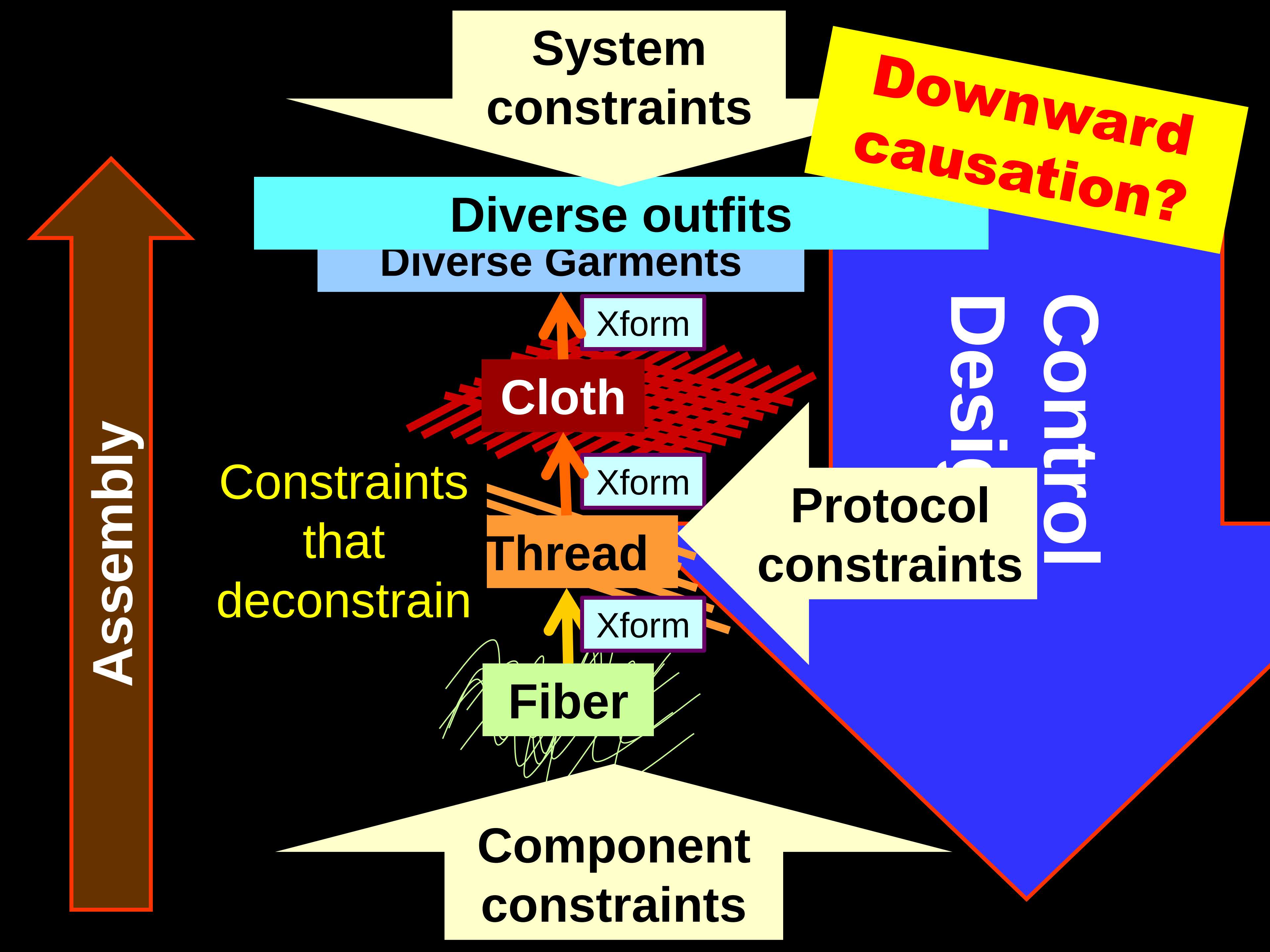
Networked,
universal,
layered
Garments
Cloth
Thread
Fiber
Xform
Xform
Xform
Xform
Ctrl
Ctrl
Ctrl
Ctrl
Supply
Demand

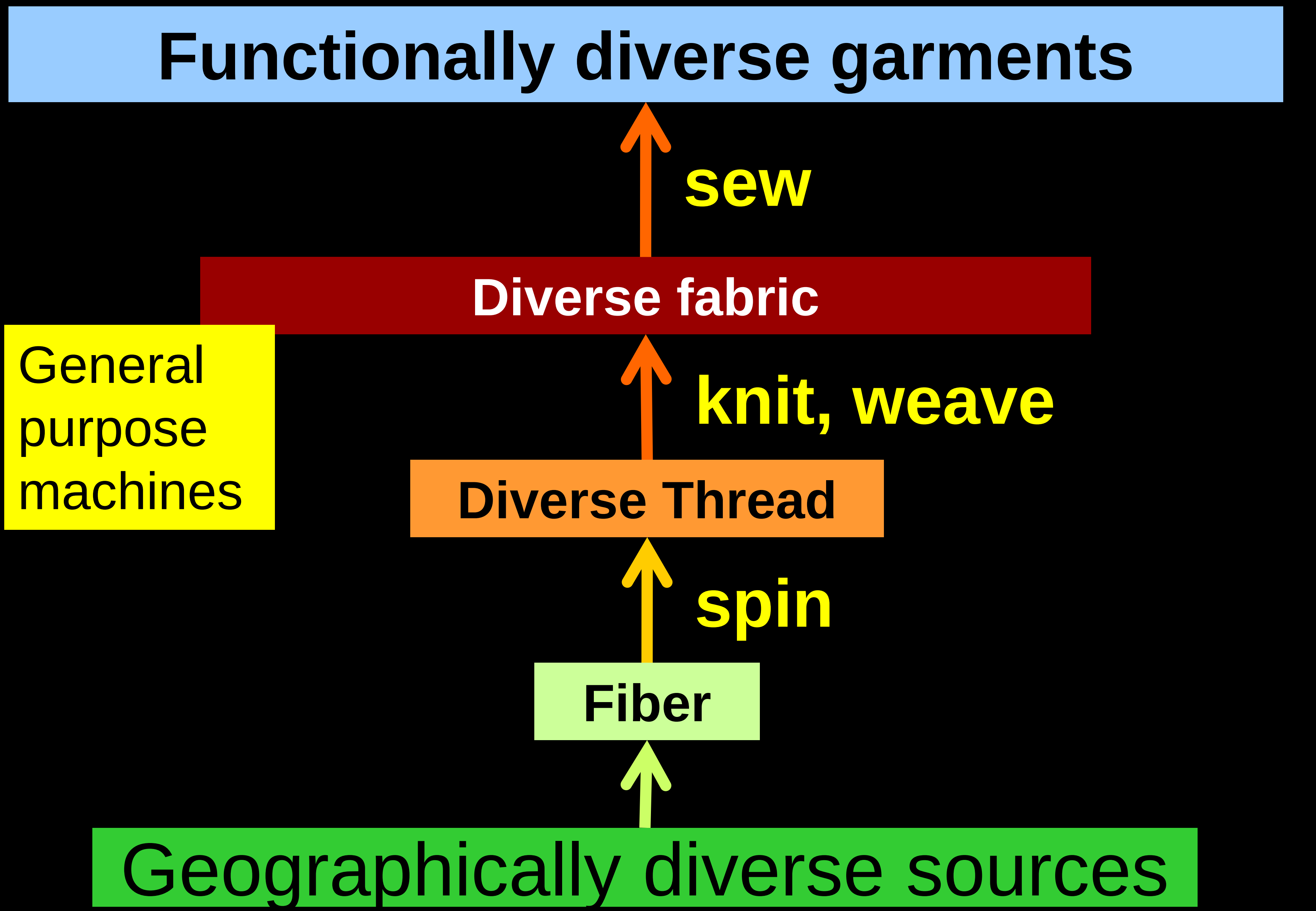
Complexity?



arments
Xform
Cloth
Xform
Thread
Xform
Fiber
Xform
Supply
Control Design
Ctrl

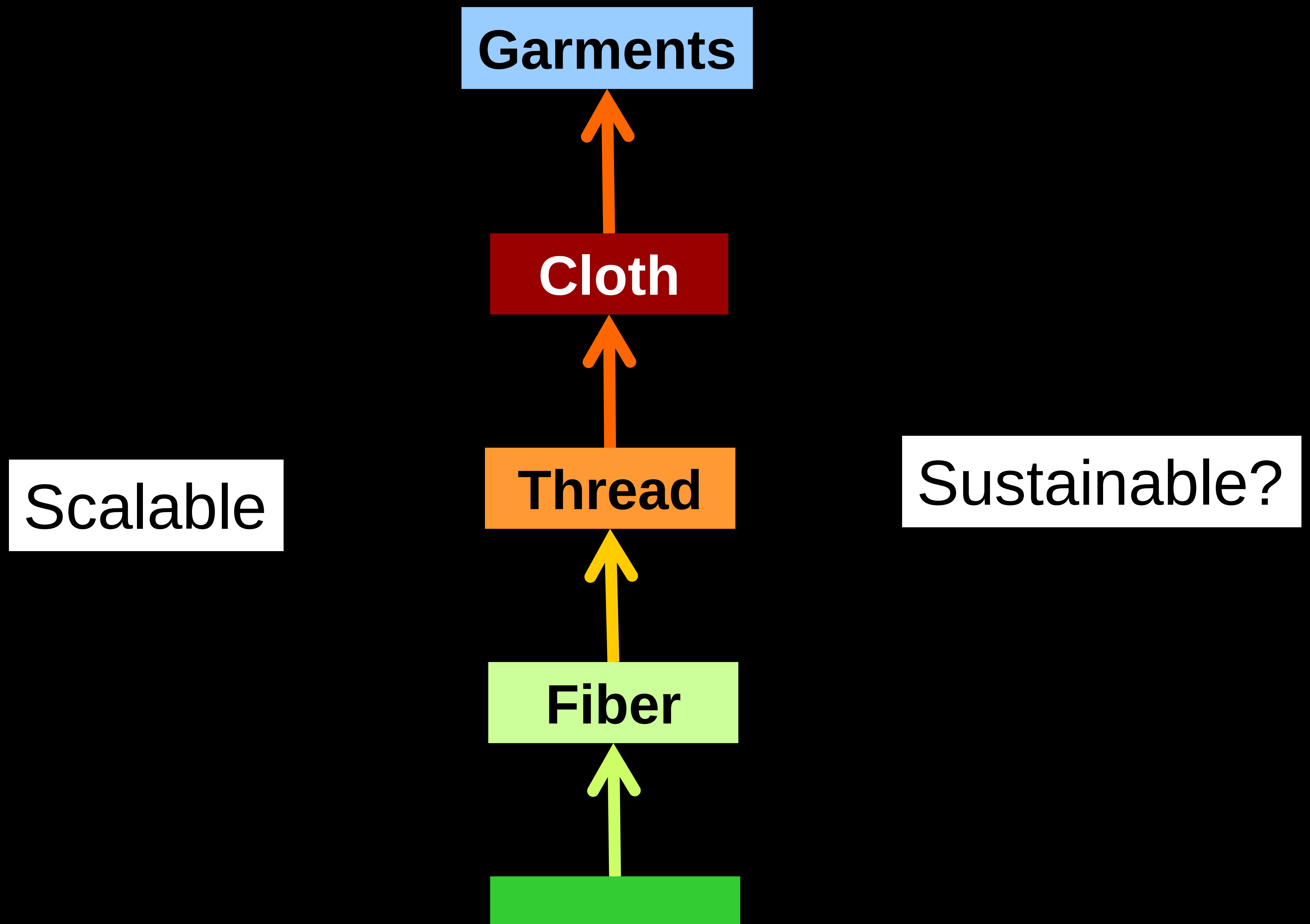

System constraints
Diverse outfits
Diverse Garments
Xform
Cloth
Xform
Constraints that deconstrain
Thread
Xform
Fiber
Protocol constraints
Control Desig
Assembly
Component constraints


System constraints
Downward causation?
Diverse outfits
Diverse Garments
Xform
Cloth
Control
Design
Constraints that deconstrain
Xform
Thread
Protocol constraints
Xform
Fiber
Assembly
Component constraints

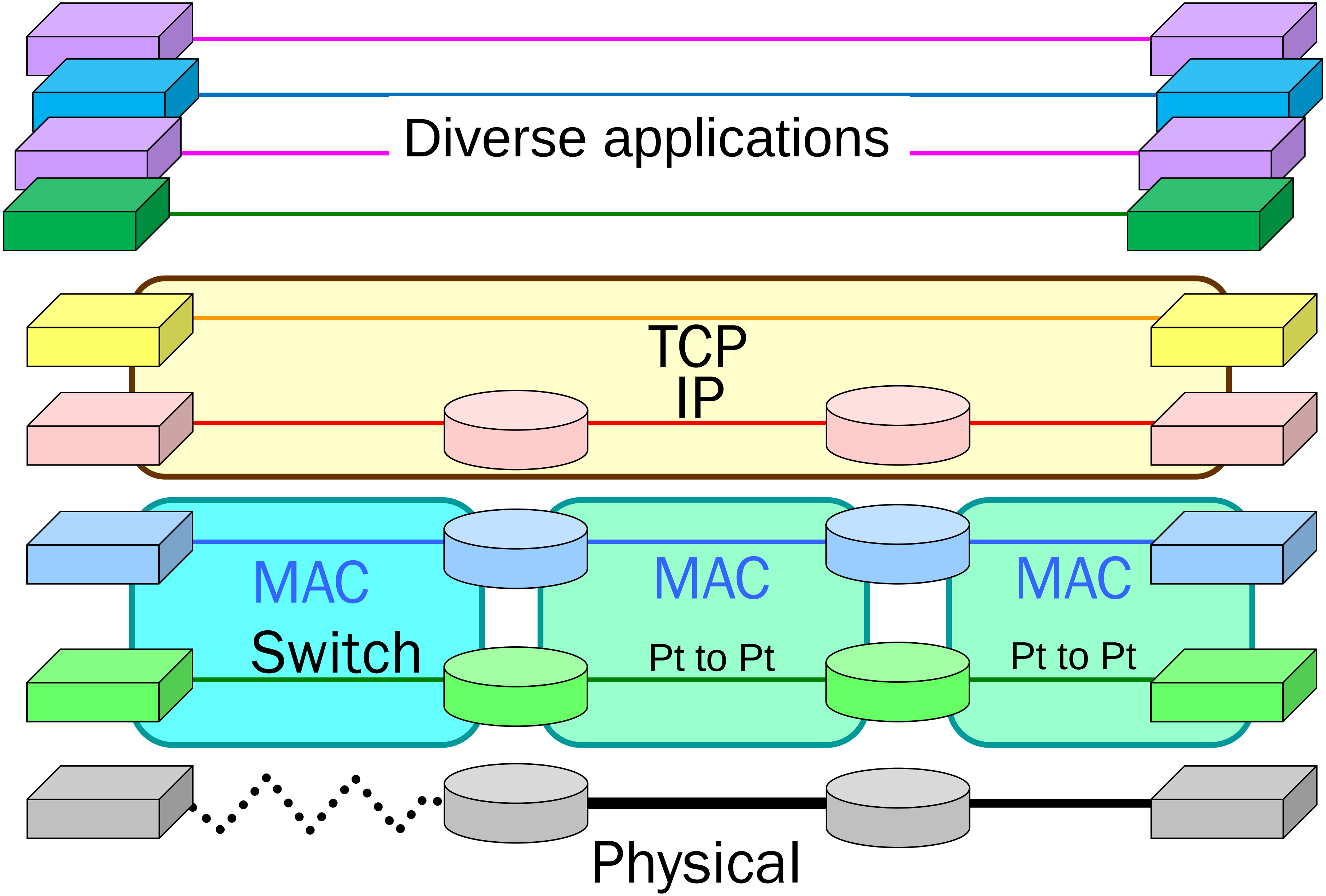

Functionally diverse garments
sew
Diverse fabric
General purpose machines
knit, weave
Diverse Thread
spin
Fiber
Geographically diverse sources

Functionally diverse garments

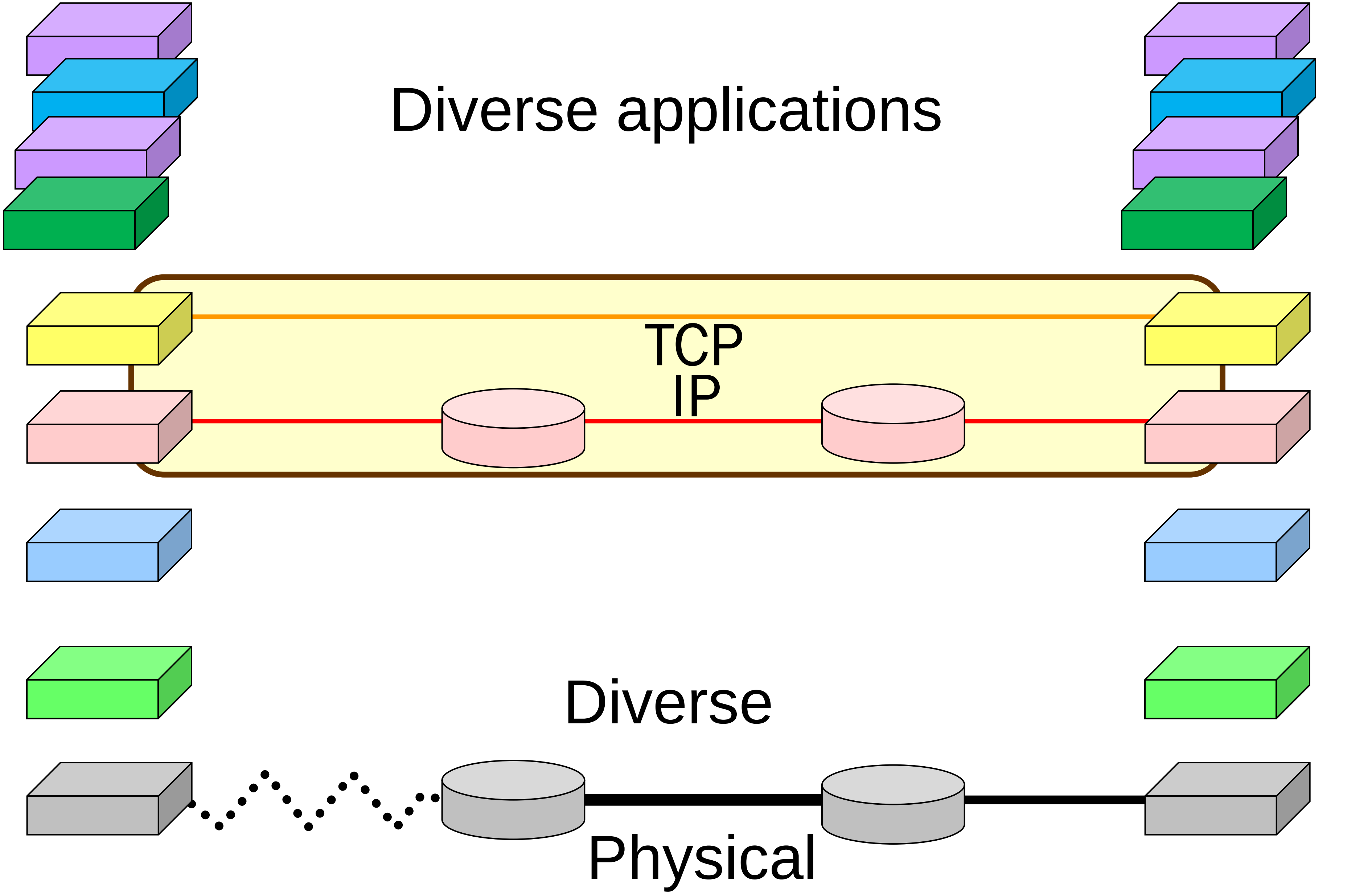

FASHION WARS
NEW YORK SPRING 2009
Garments
Fragilities?
Thread
Fiber


Garments
Cloth
Thread
Fiber
Scalable
Sustainable?

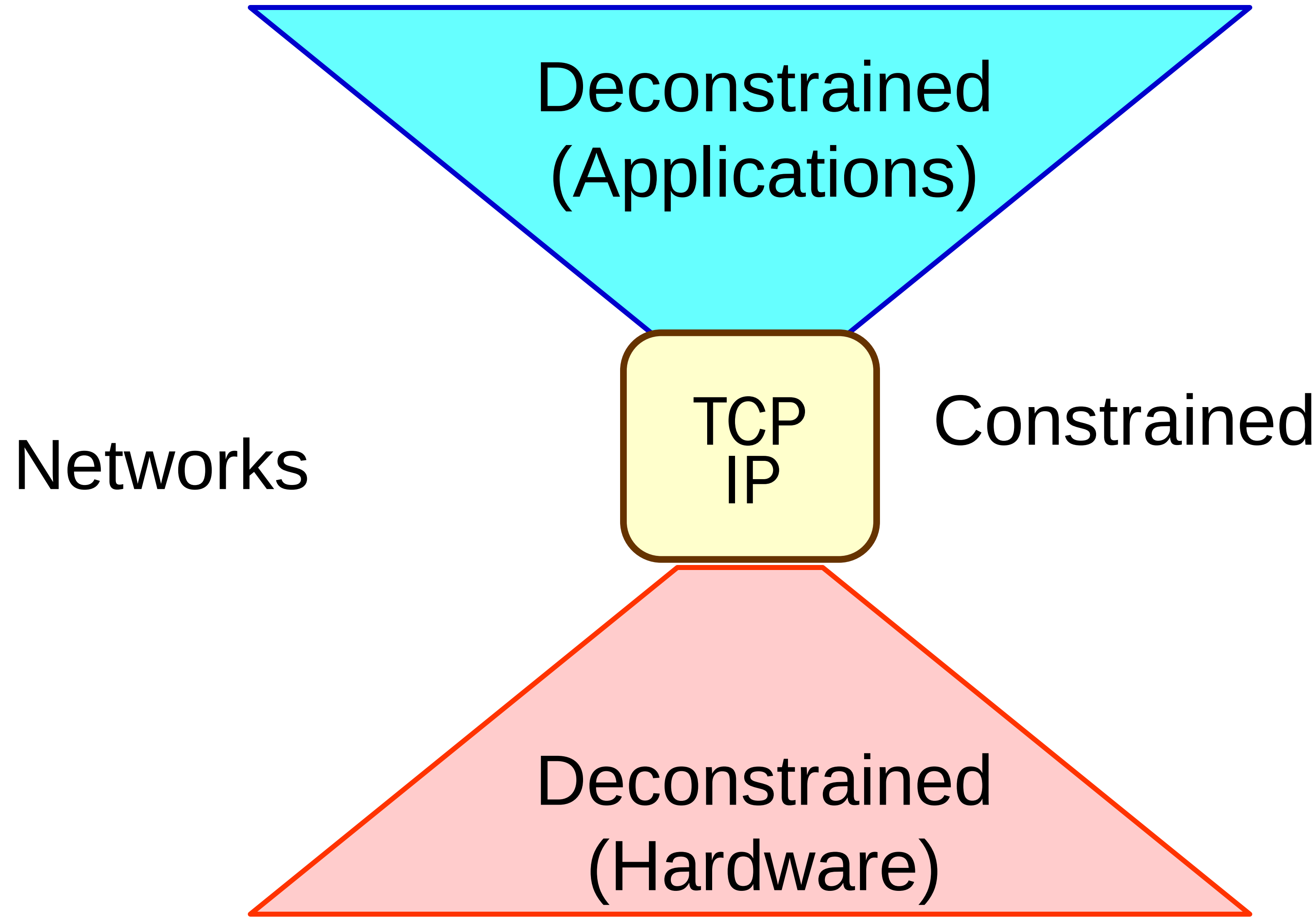
Layered architectures



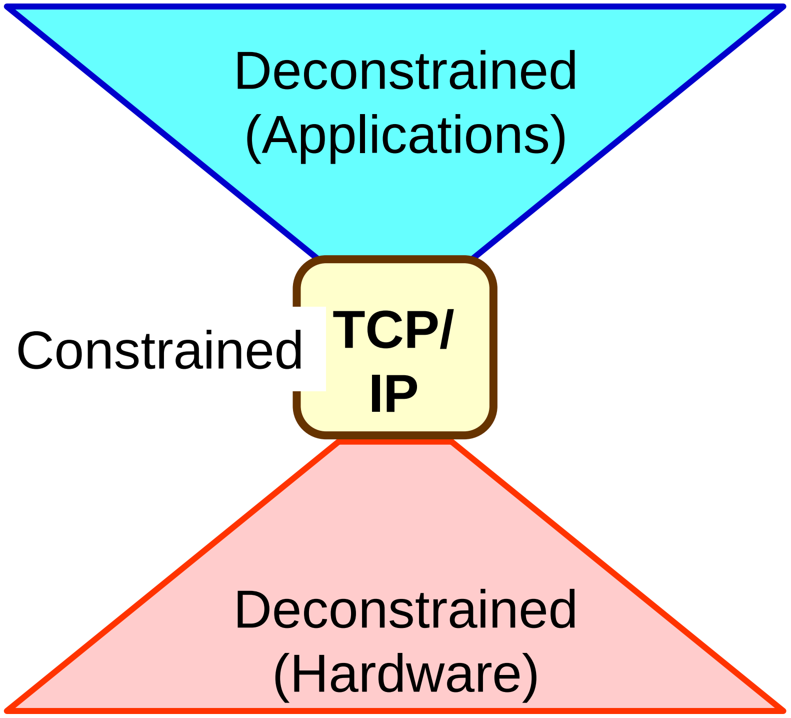
Too clever?



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

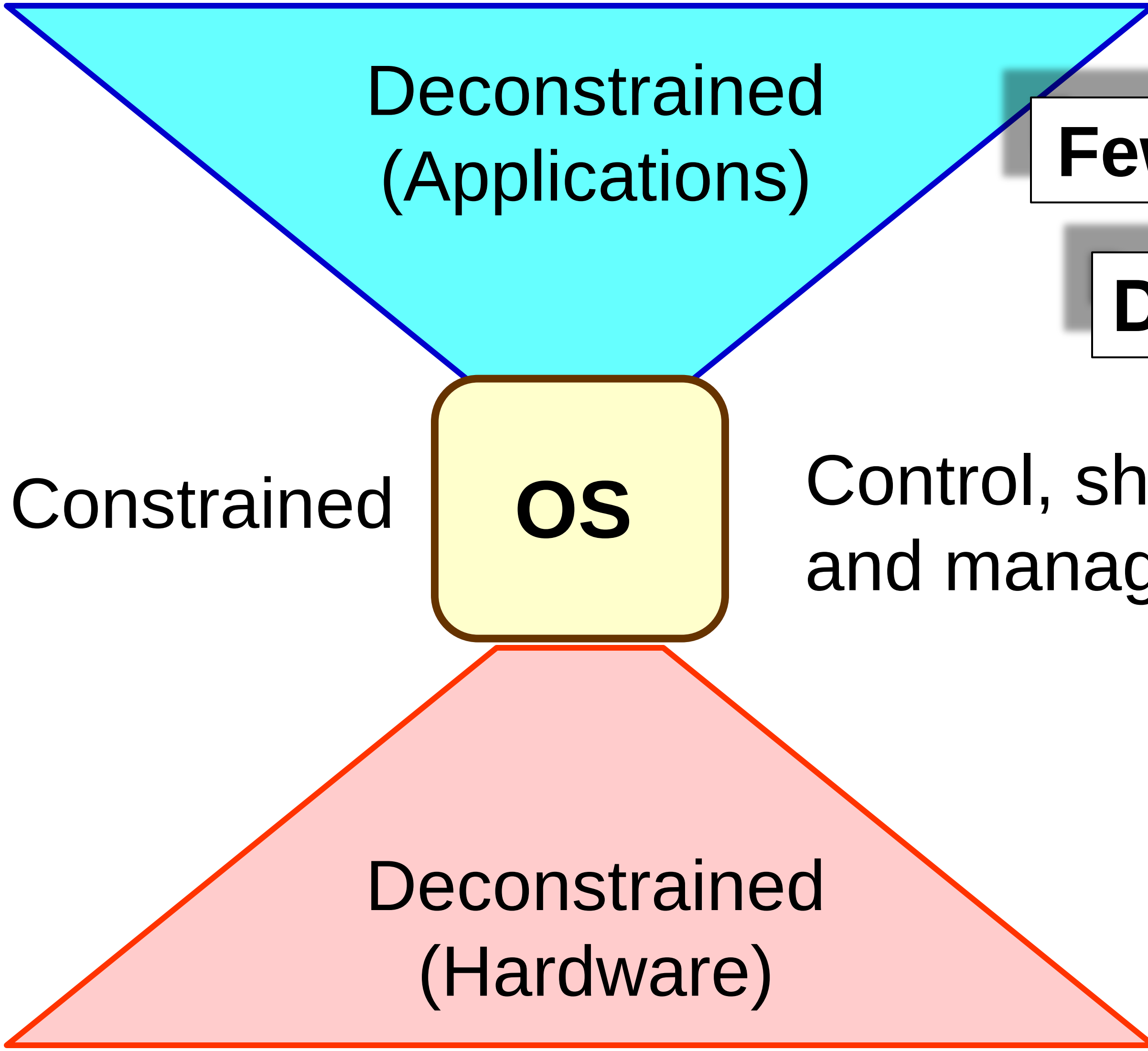
Created
- whole new ecosystem
- completely opposite

Why?

Architecture

Layered architectures

Essentials



Few global variables

Don’t cross layers

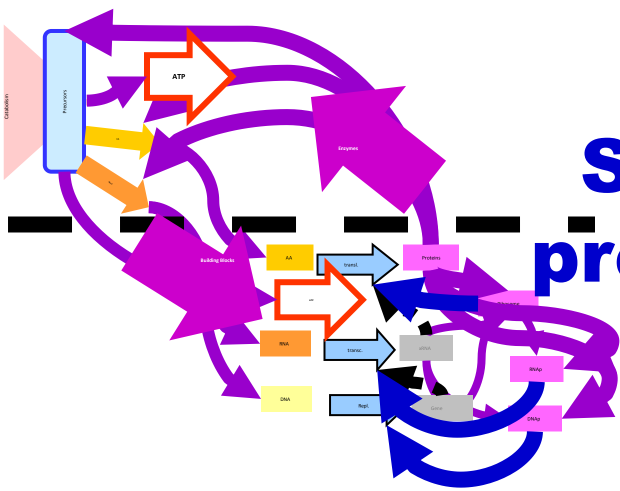
Control, share, virtualize, and manage resources

Processing
Memory
I/O

Layered architectures

Bacterial biosphere

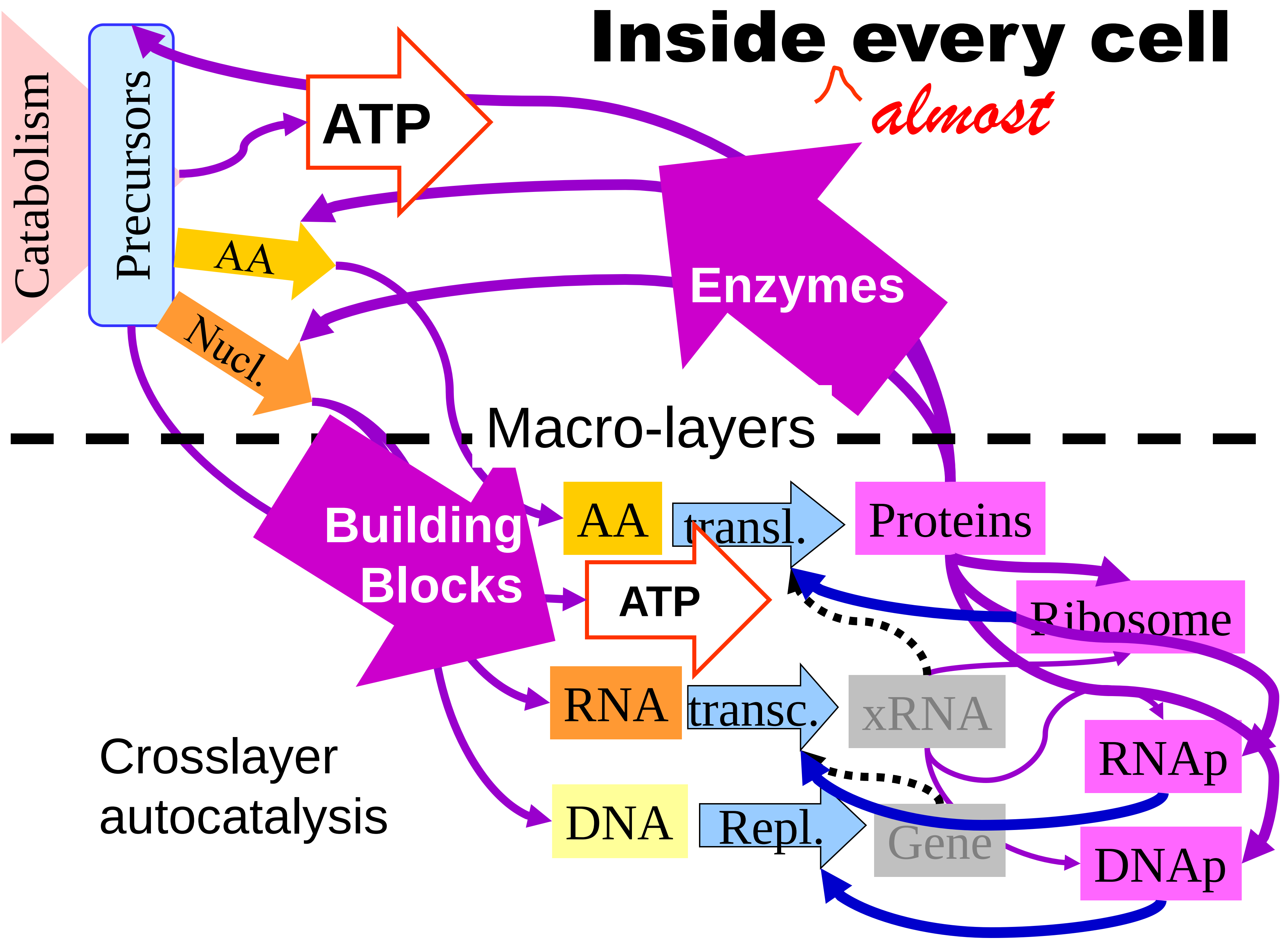
Deconstrained
(diverse)
Environments



Shared protocols

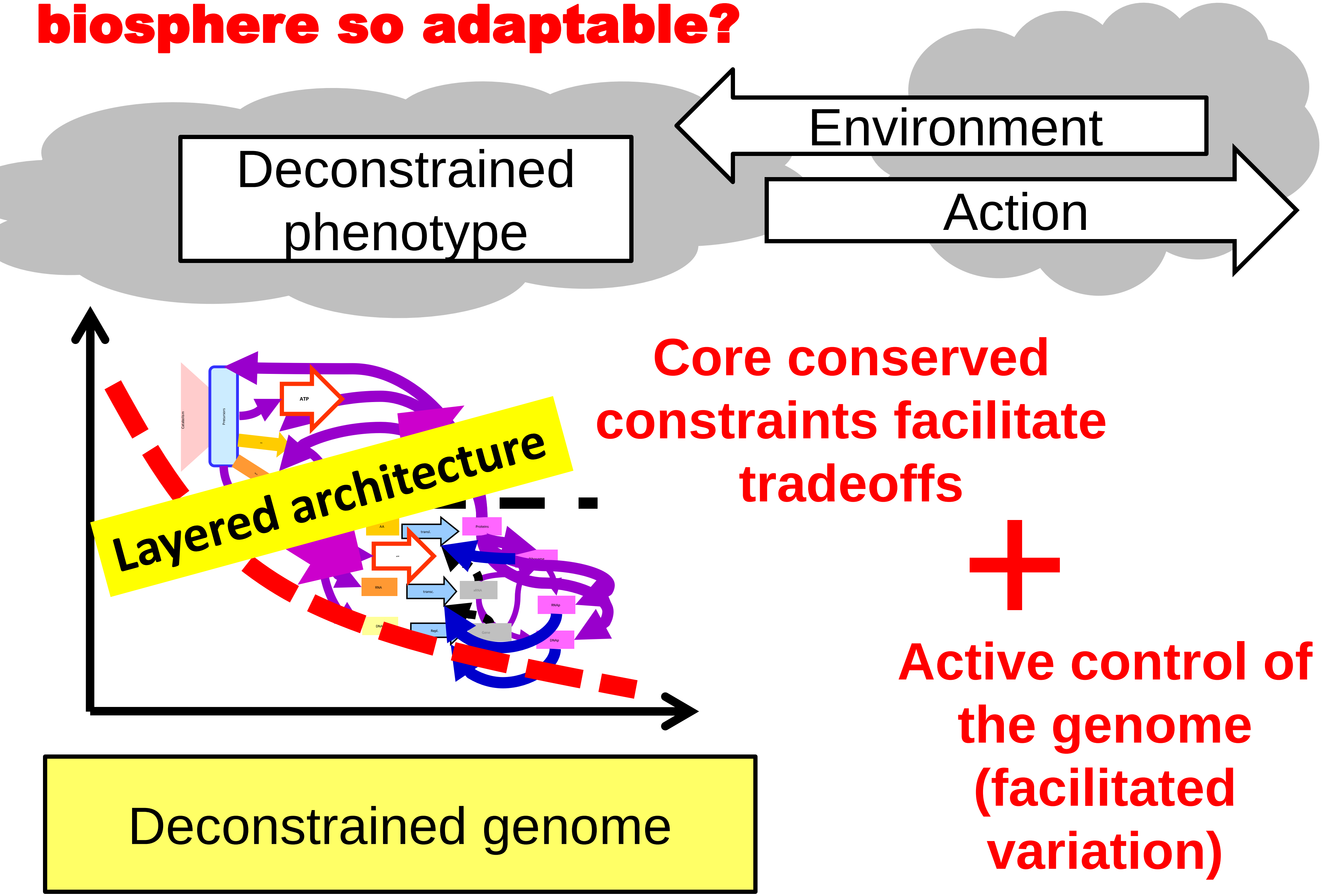
Architecture
=
Constraints
that
Deconstrain

Deconstrained (diverse)
Genomes



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

What makes the bacterial biosphere so adaptable?

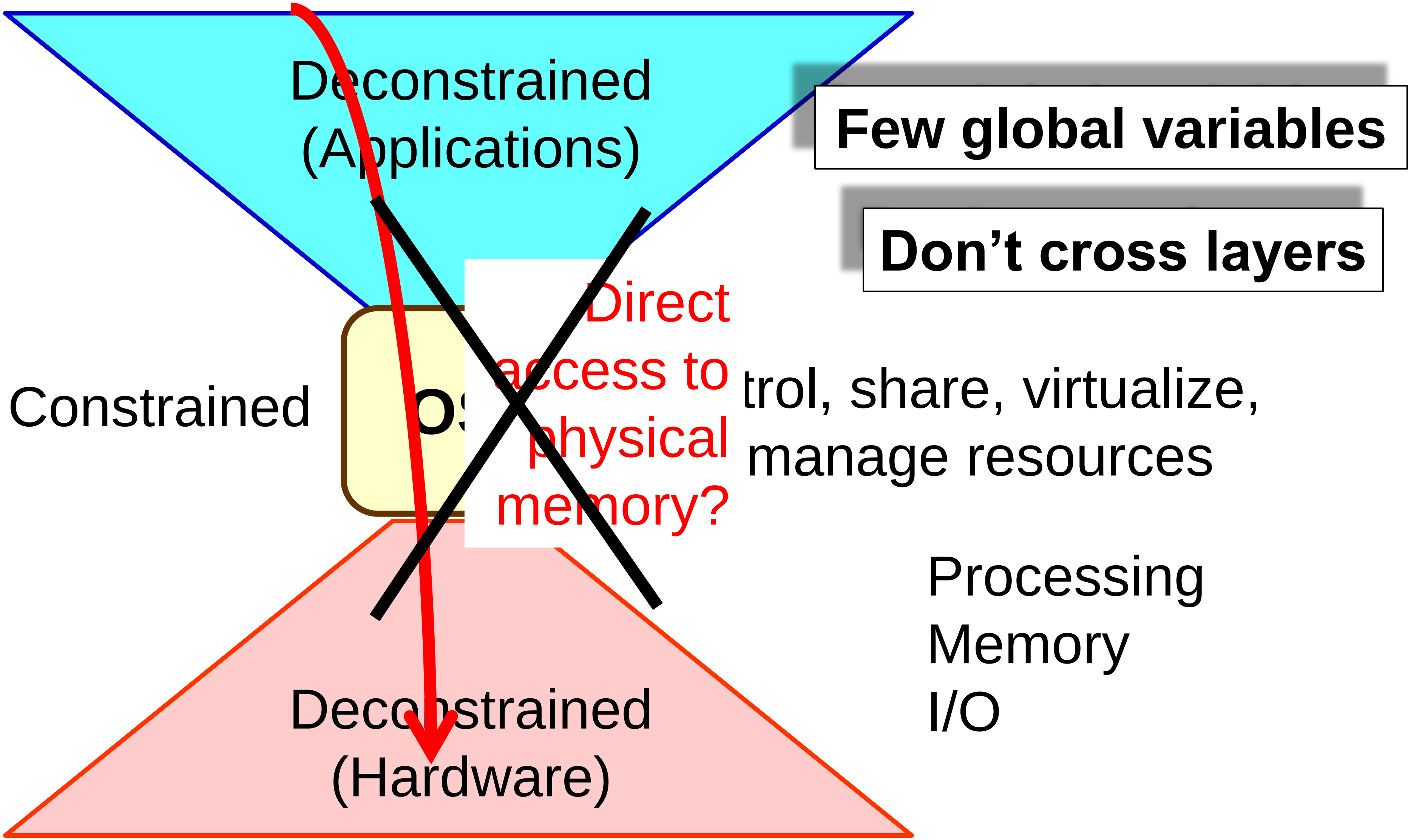


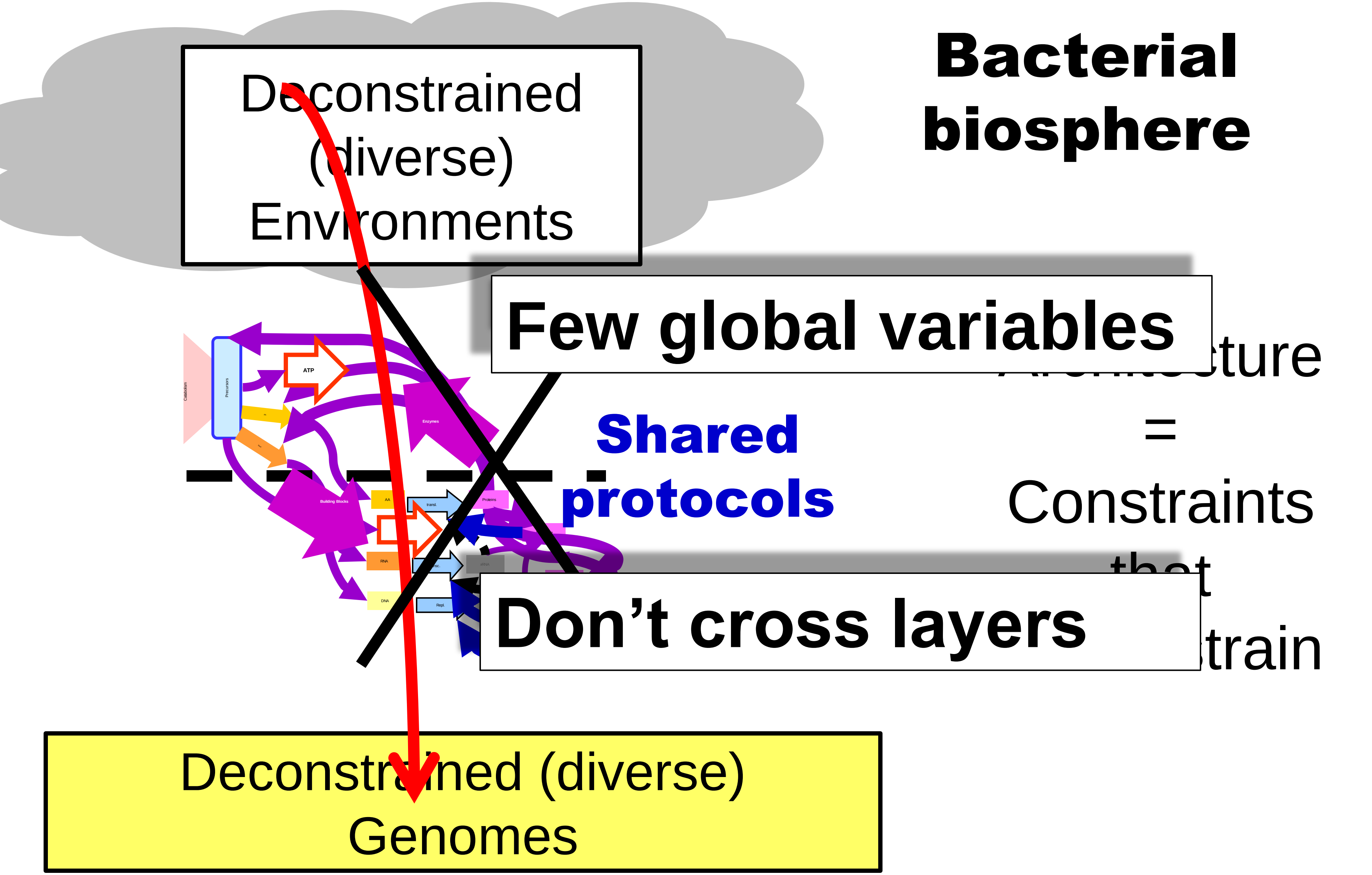
Core conserved constraints facilitate tradeoffs

+

Active control of the genome (facilitated variation)

Layered architectures




Bacterial biosphere
Deconstrained (diverse) Environments
Few global variables
cture
=
Constraints
that
train
Shared protocols
Don’t cross layers
ATP
Enzymes
Building Blocks
AA
transl.
Proteins
RNA
DNA
Repl.
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

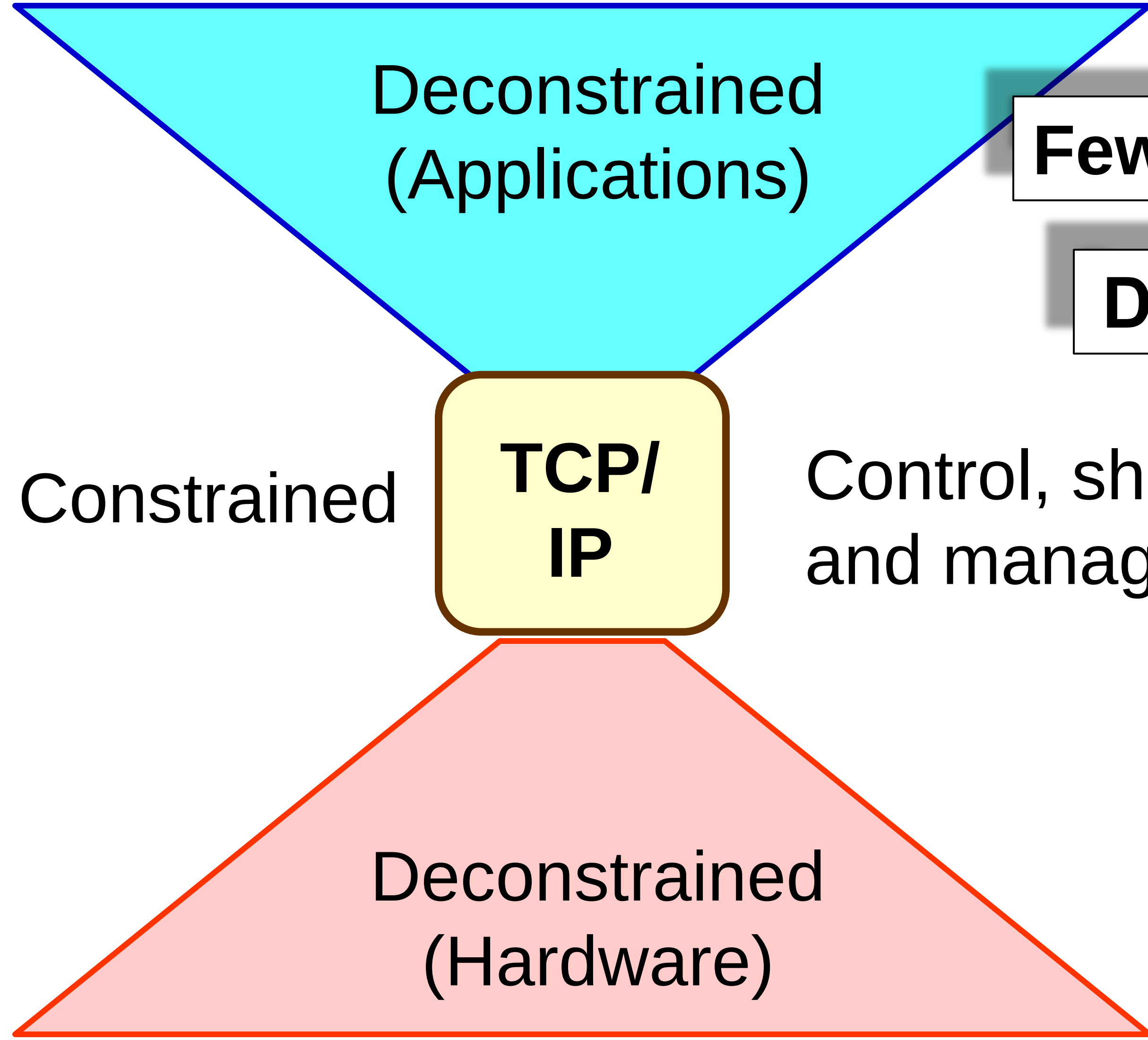
- Limits optimization/control by duality?

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

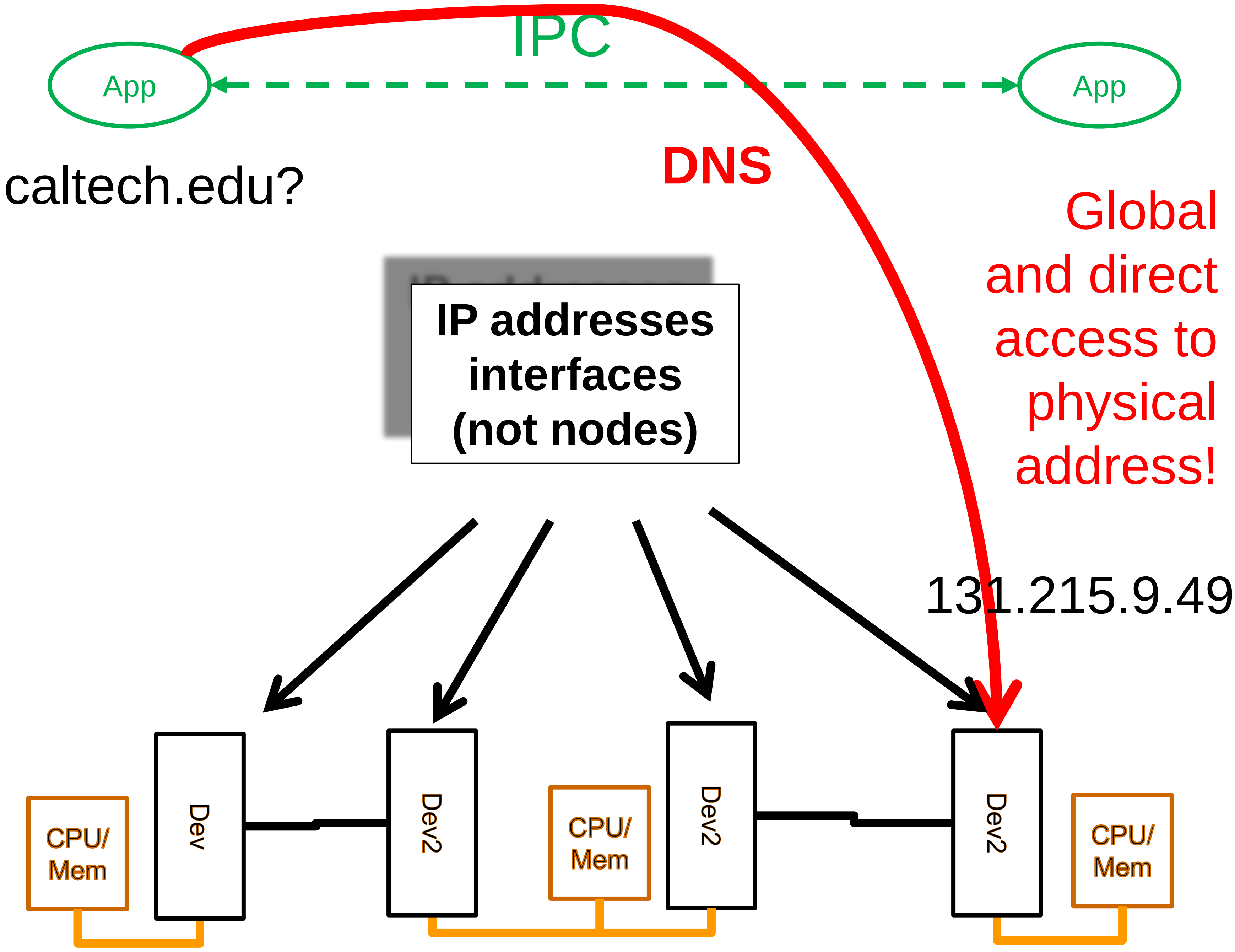


Few global variables?

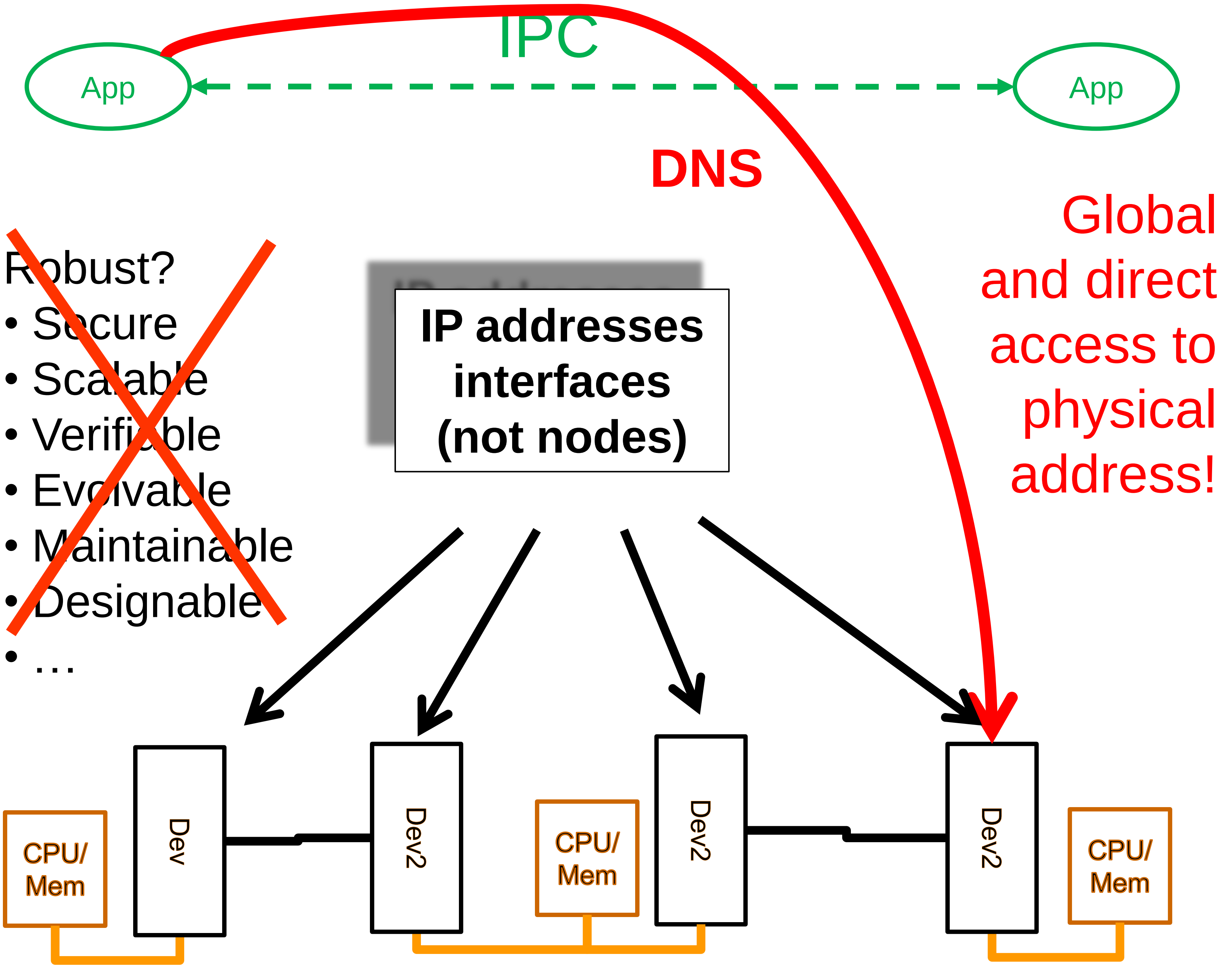
Don’t cross layers?

Control, share, virtualize, and manage resources

I/O
Comms
Latency?
Storage?
Processing?

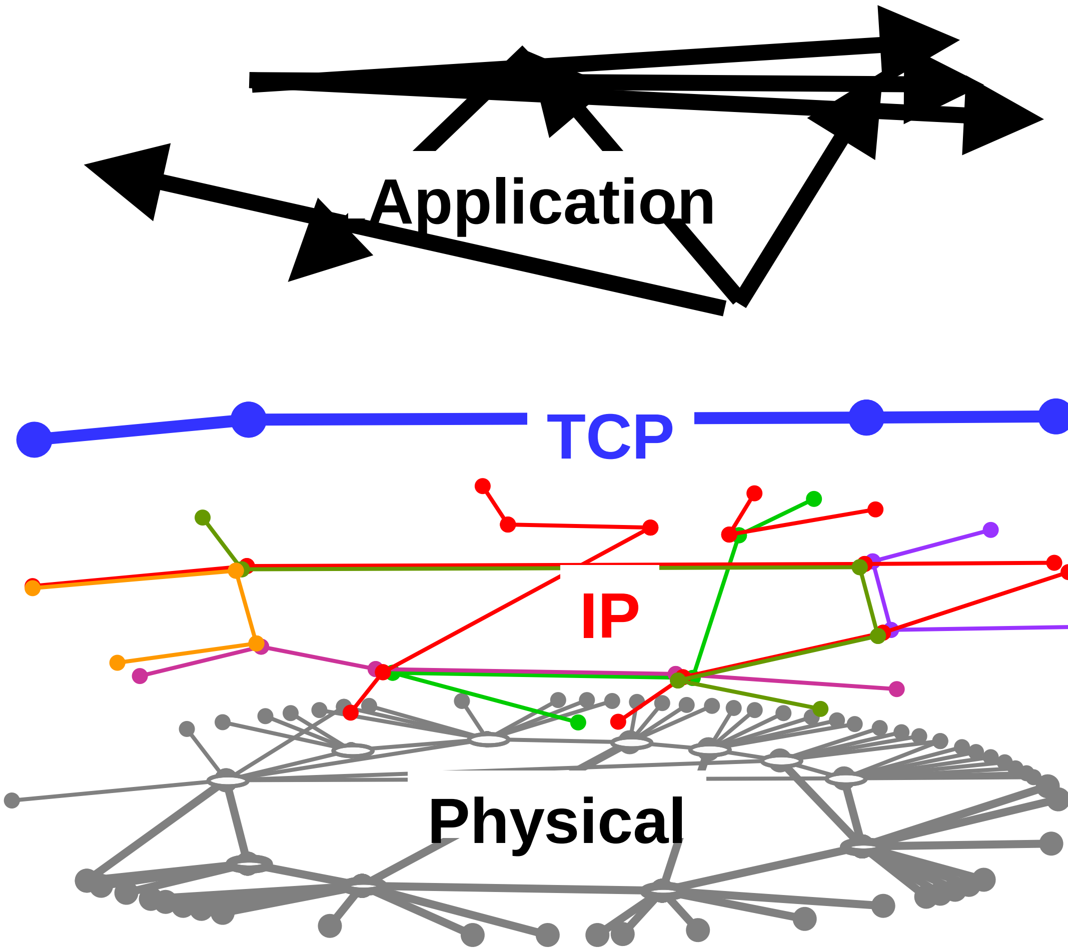


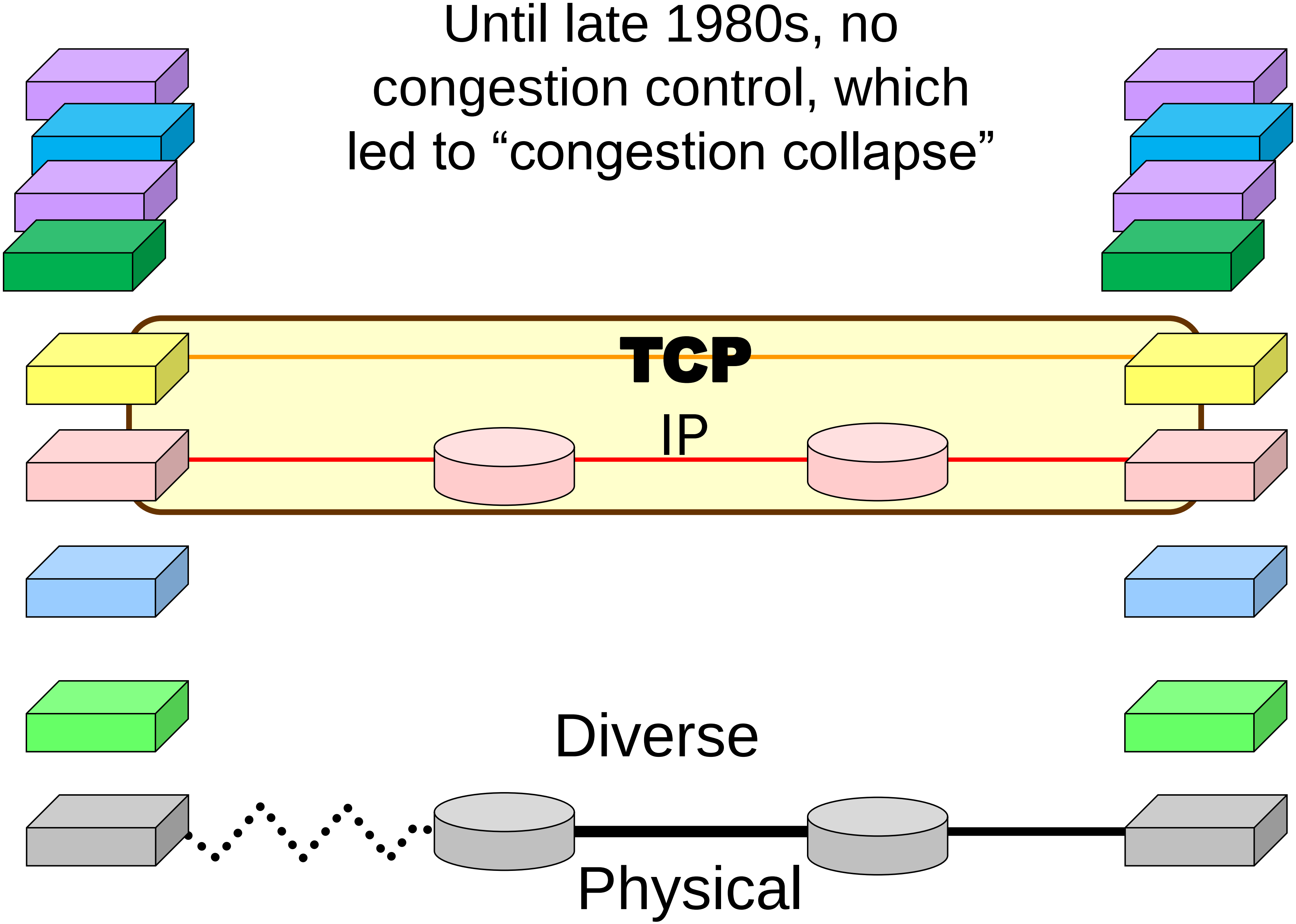
IPC
App
App
caltech.edu?
DNS
Global and direct access to physical address!
IP addresses interfaces (not nodes)
131.215.9.49
CPU/ Mem
Dev
Dev2
CPU/ Mem
Dev2
Dev2
CPU/ Mem


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

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

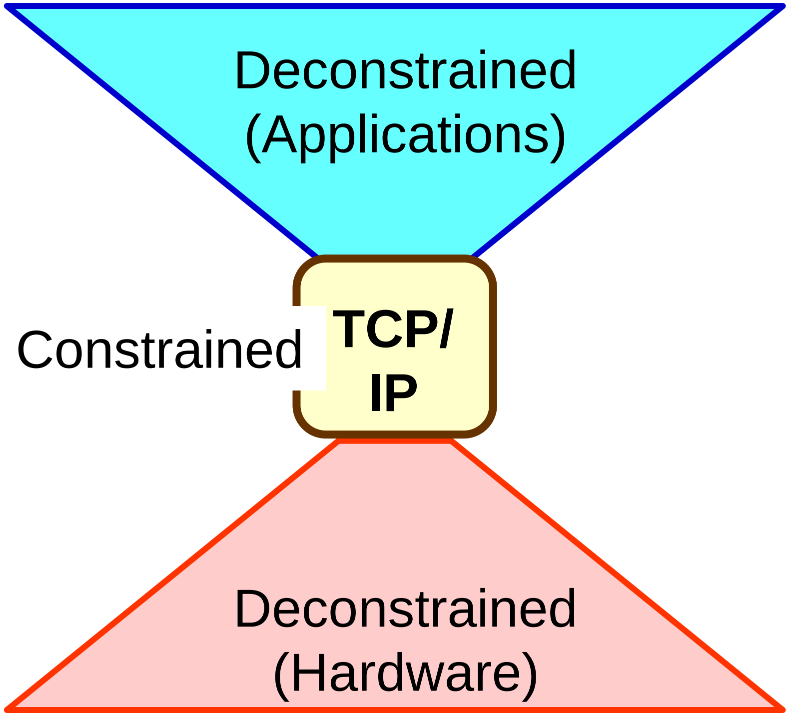
Related “issues”
- VPNs
- NATS
- Firewalls
- Multihoming
- Mobility
- Routing table size
- Overlays
- ...





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

Original design challenge?



Networked OS

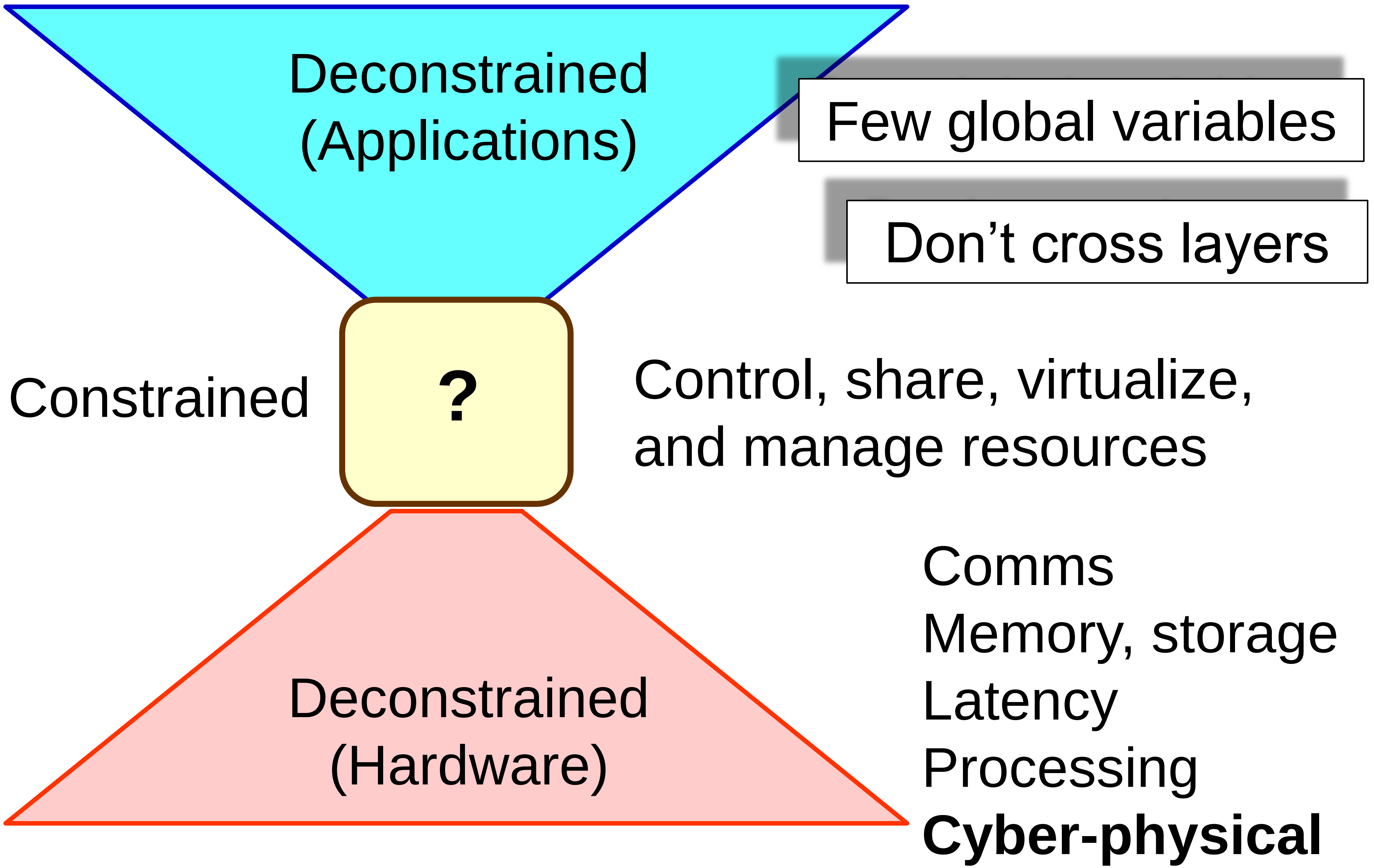
- ~~Expensive mainframes~~
- ~~Trusted end systems~~
- ~~Homogeneous~~
- ~~Sender centric~~
- Unreliable comms

Facilitated wild evolution

Created

- whole new ecosystem
- completely opposite

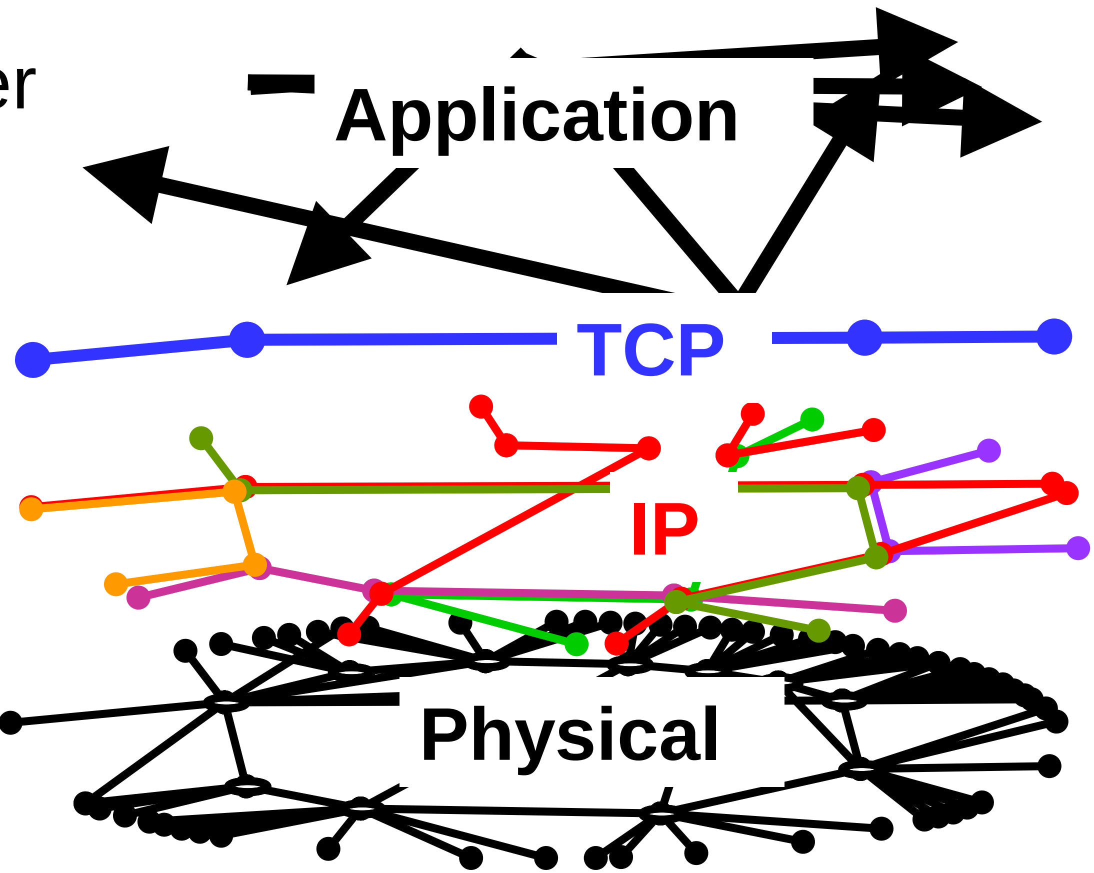
Next layered architectures



Persistent errors and confusion (“network science”)

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

Every layer has different diverse graphs.



Architecture facilitates arbitrary graphs.

PNAS

The "robust yet fragile" nature of the Internet

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

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

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

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

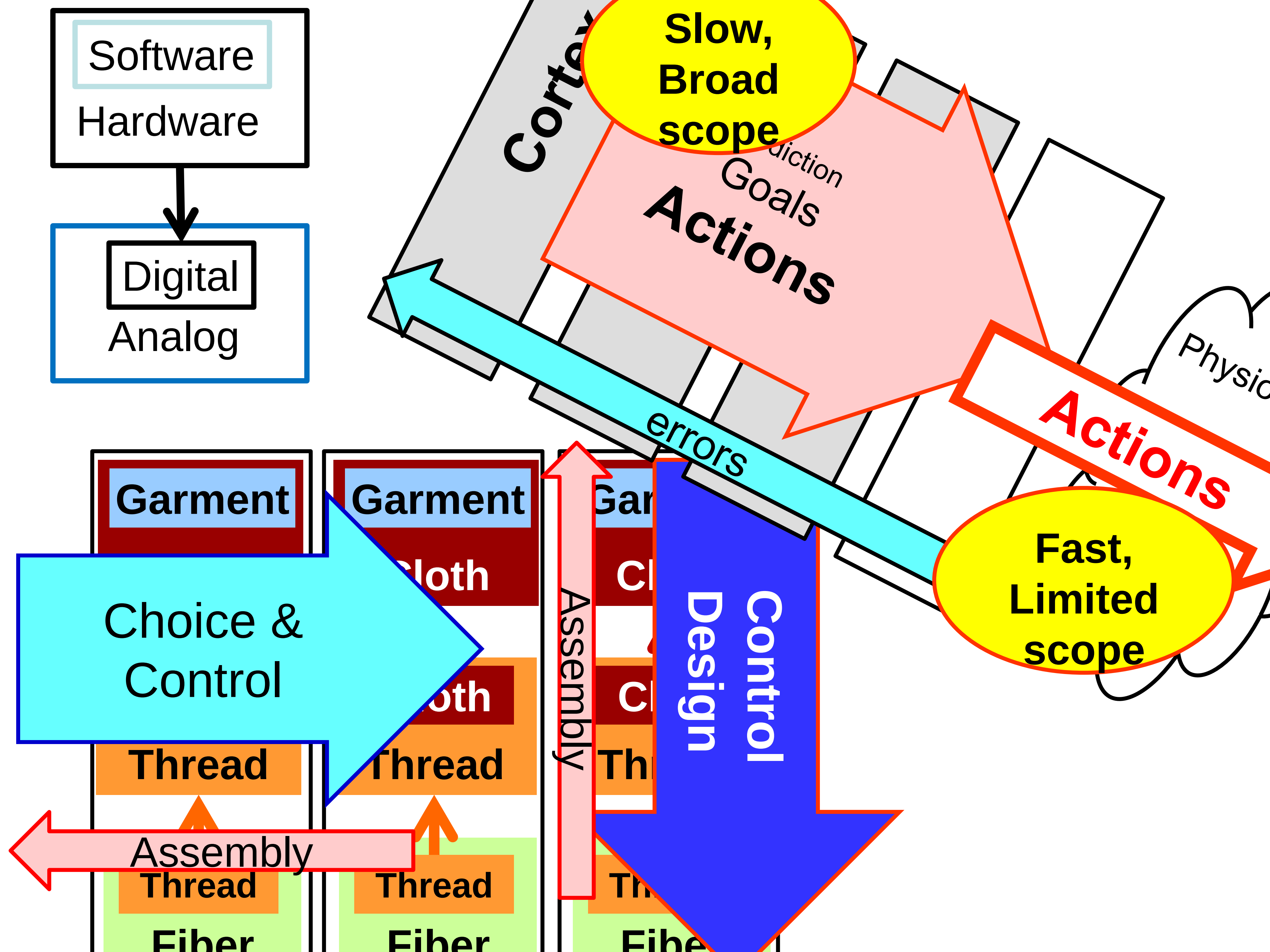
no self-loops or parallel edges) having the same graph degree
We will say that graphs $g \in G(D)$ have scaling-degree sequen

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

Notices of the AMS, 2009

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

Walter Willinger, David Alderson, and John C. Doyle



Software
Hardware
Digital
Analog
Cortex
Slow,
Broad
scope
Prediction
Goals
Actions
errors
Actions
Physio
Fast,
Limited
scope
Garment
Garment
Cloth
Cloth
Thread
Thread
Thread
Thread
Fiber
Fiber
Choice &
Control
Assembly
Assembly
Control
Design