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

Outline

- Recap robustness, neuro motivation
- Bowties: metabolism, reward
- Layered architectures
  - Large, thin, nonconvex
  - Clothing as layered architecture
  - Operating systems and Internet

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
Risk "management"	Obfuscate, amplify,…

- ☹ Fat accumulation
- ☹ Insulin resistance
- ☹ Proliferation
- ☹ Inflammation

Accident or necessity?

Robust

☺ Metabolism

☺ Regenerati

☺ Healing wo

Fragile

☹ Obesity, diabetes

une/Inflame

☹ Fat accumulation

☹ Insulin resistance

☹ Proliferation

☹ Inflammation

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

Both

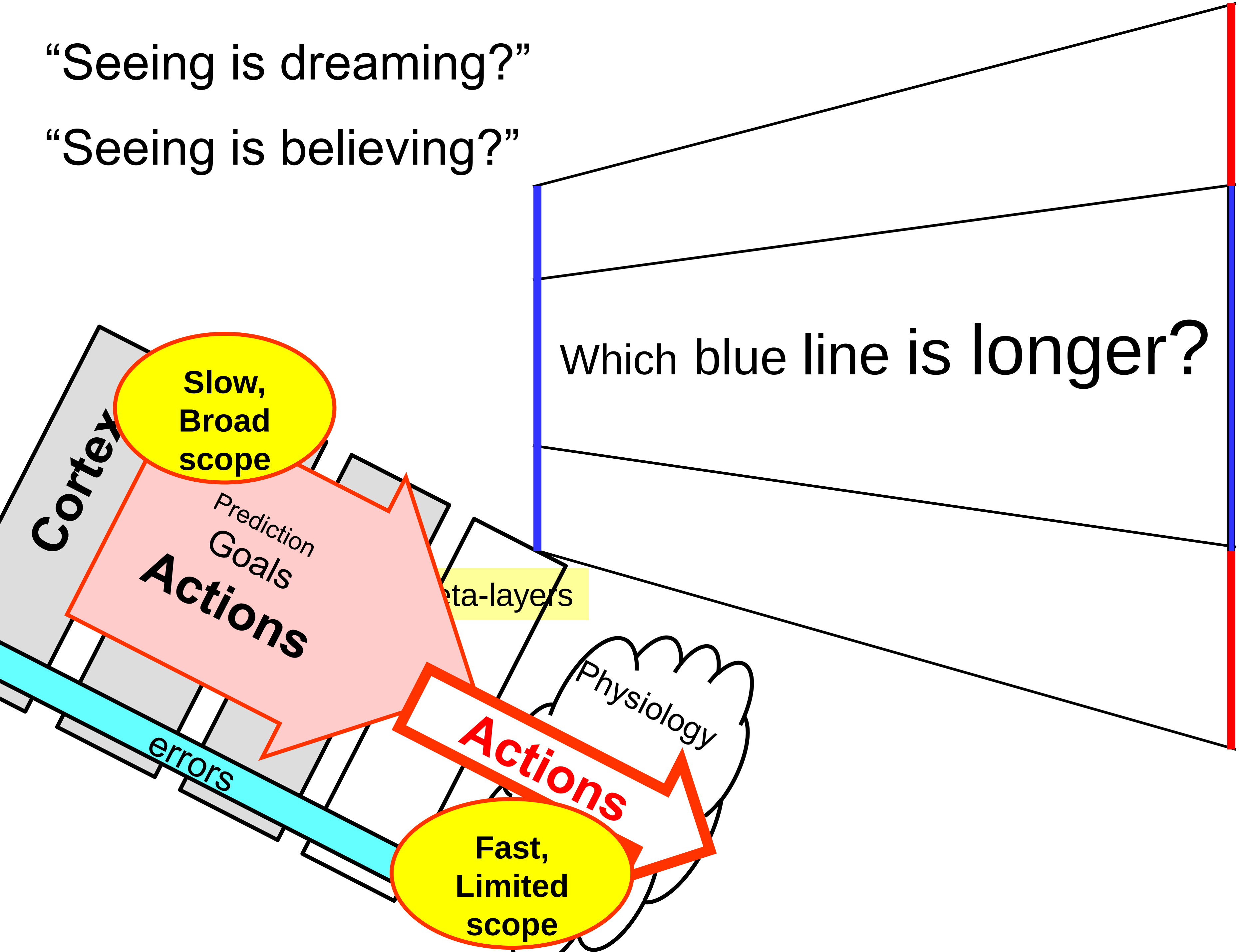
Accident or necessity?

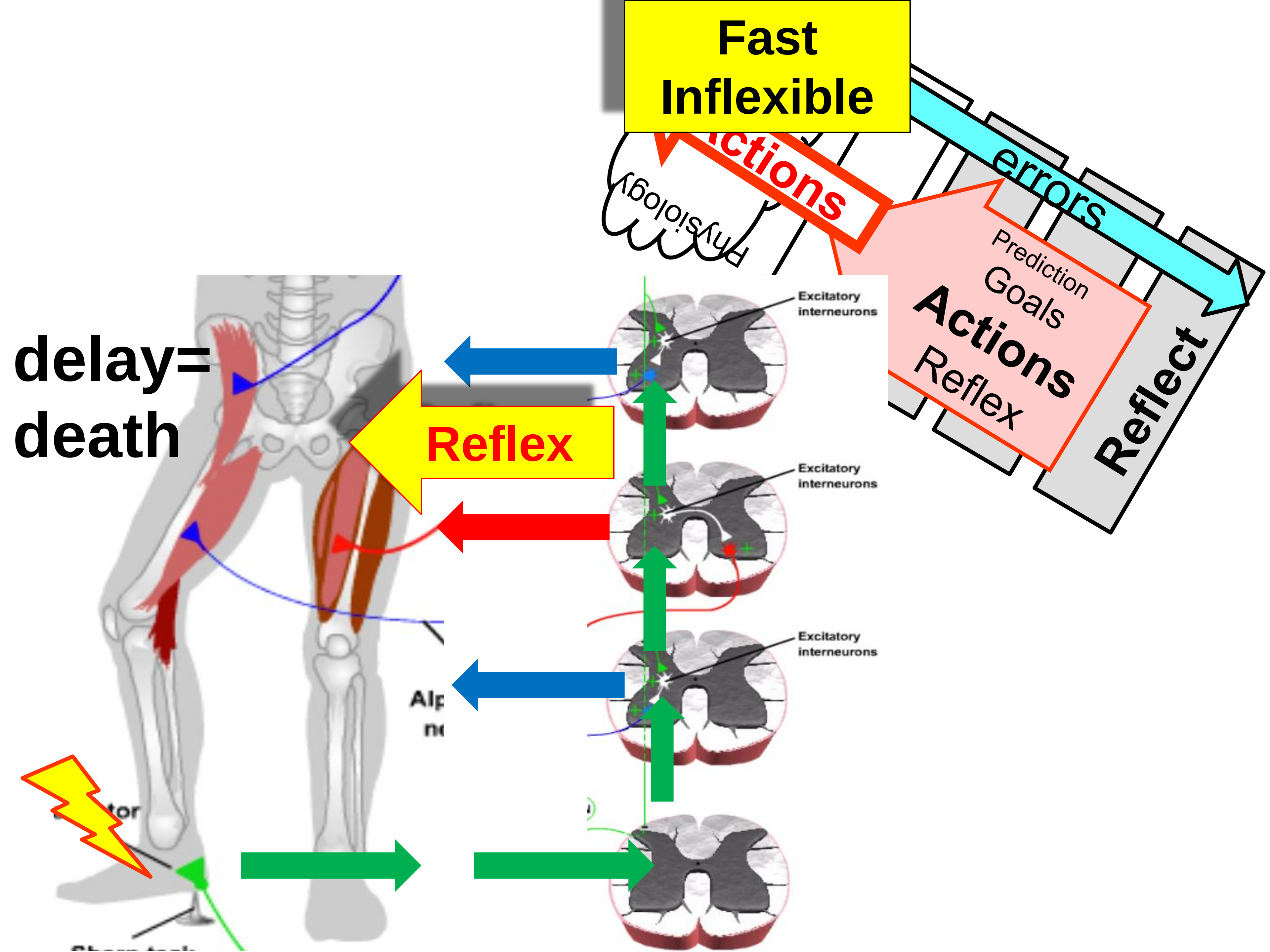
Robust		Fragile
Modular	*and*	Distributed
Simple	~~***xor***~~	Complex
Plastic		Frozen
Evolvable		Frozen

tradeoffs

“Seeing is dreaming?”

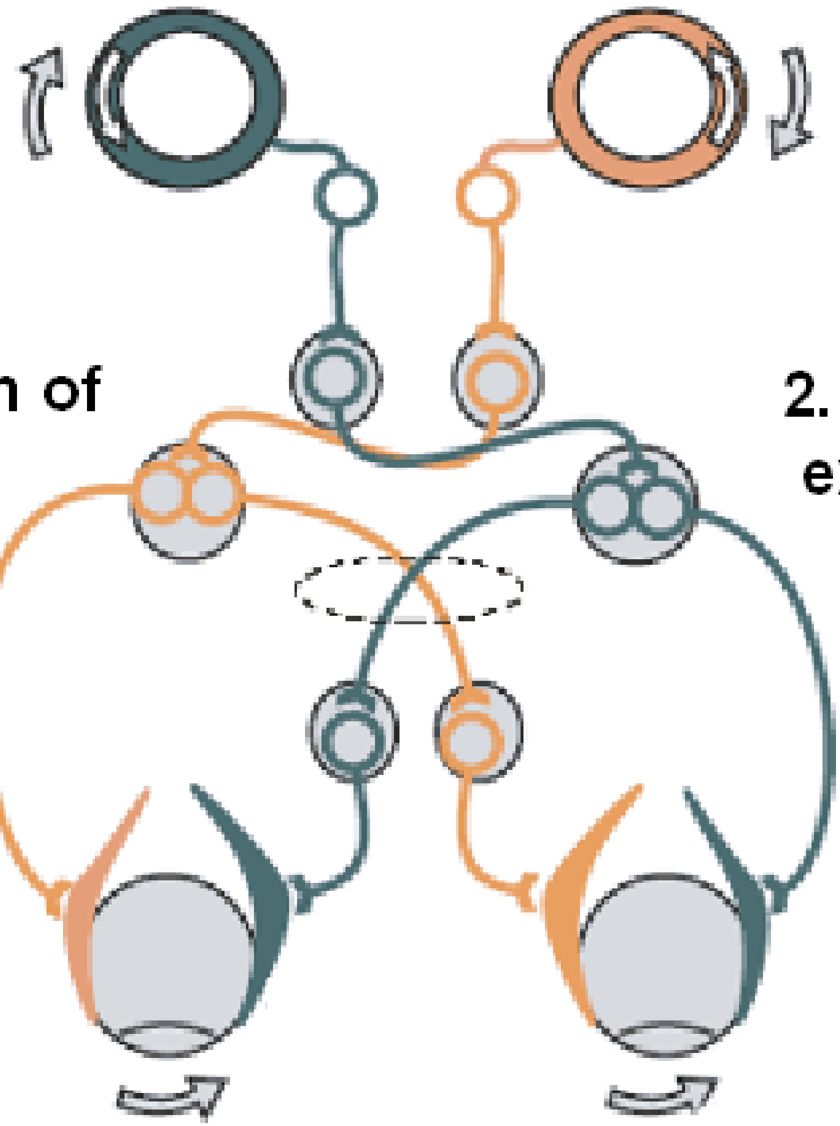
“Seeing is believing?”

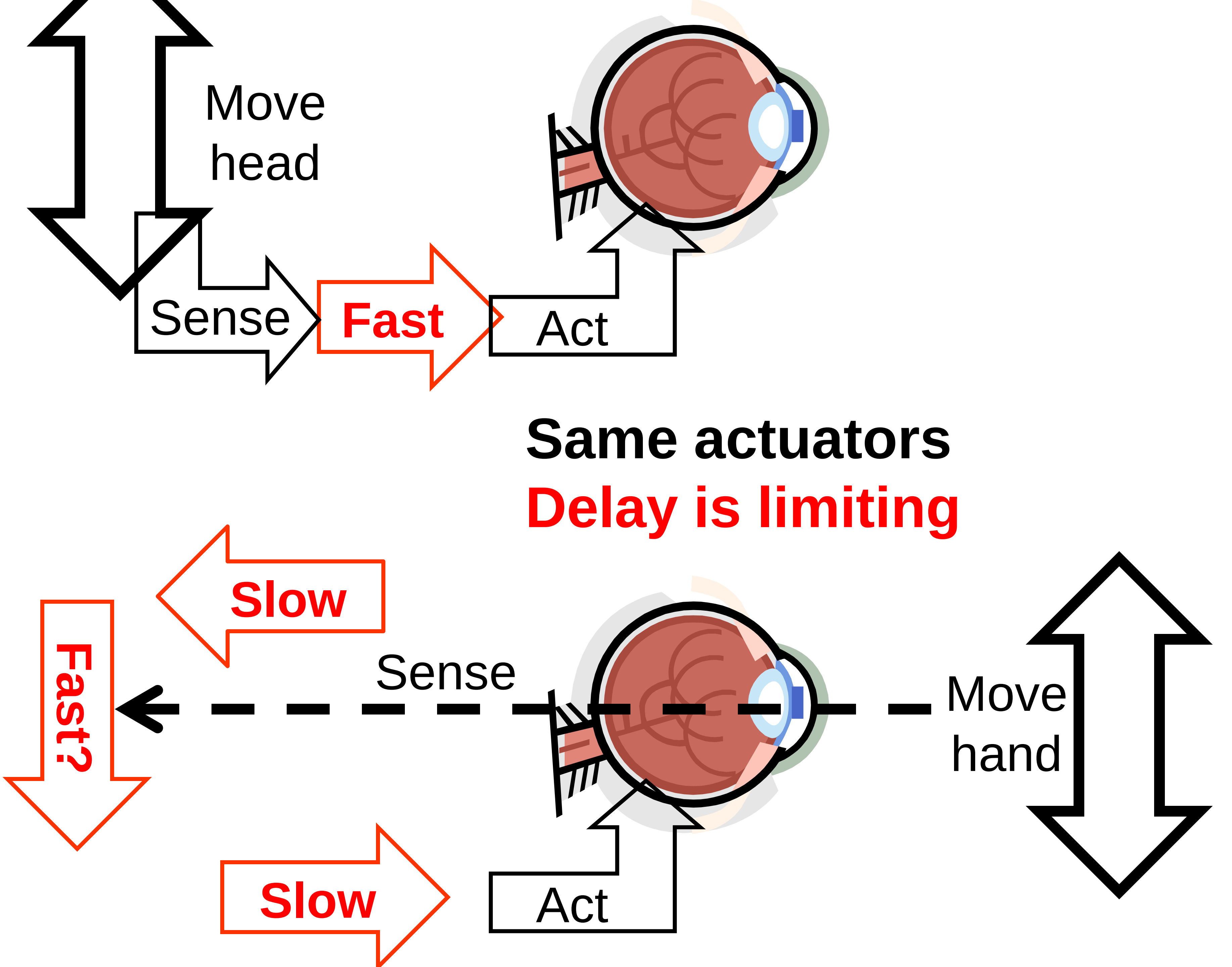




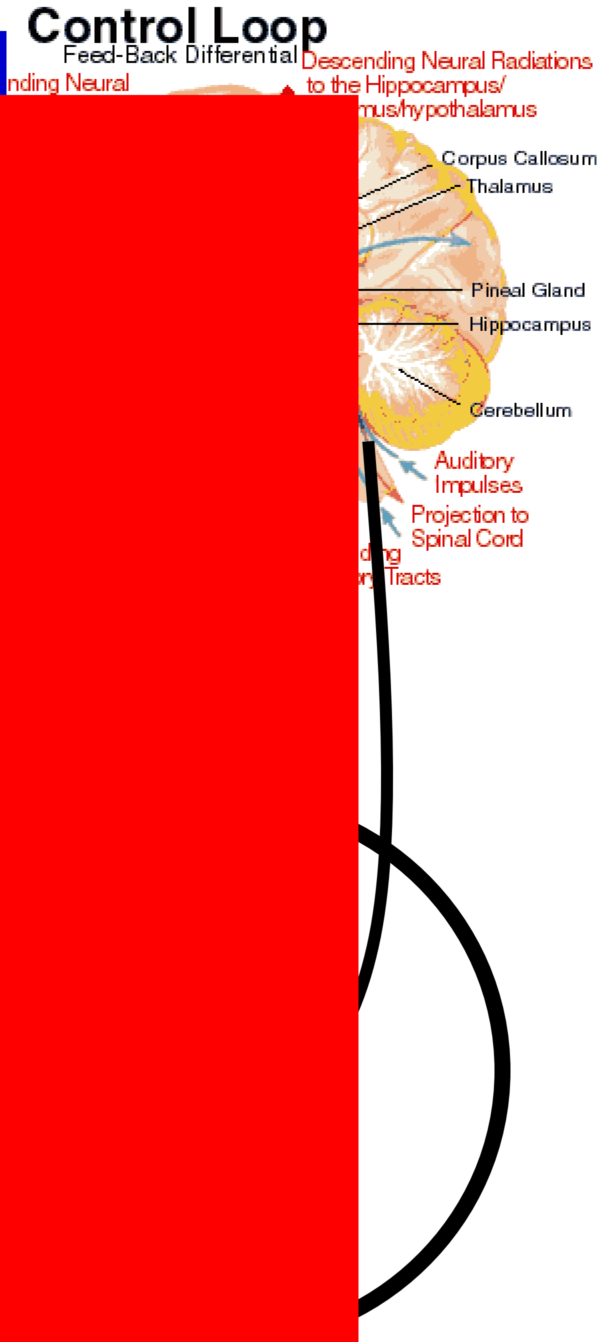
Fast
Inflexible
delay=
death
Reflex
Physiology
Actions
errors
Prediction
Goals
Actions
Reflex
Reflect
Excitatory
interneurons
Excitatory
interneurons
Excitatory
interneurons

Vestibulo-ocular reflex

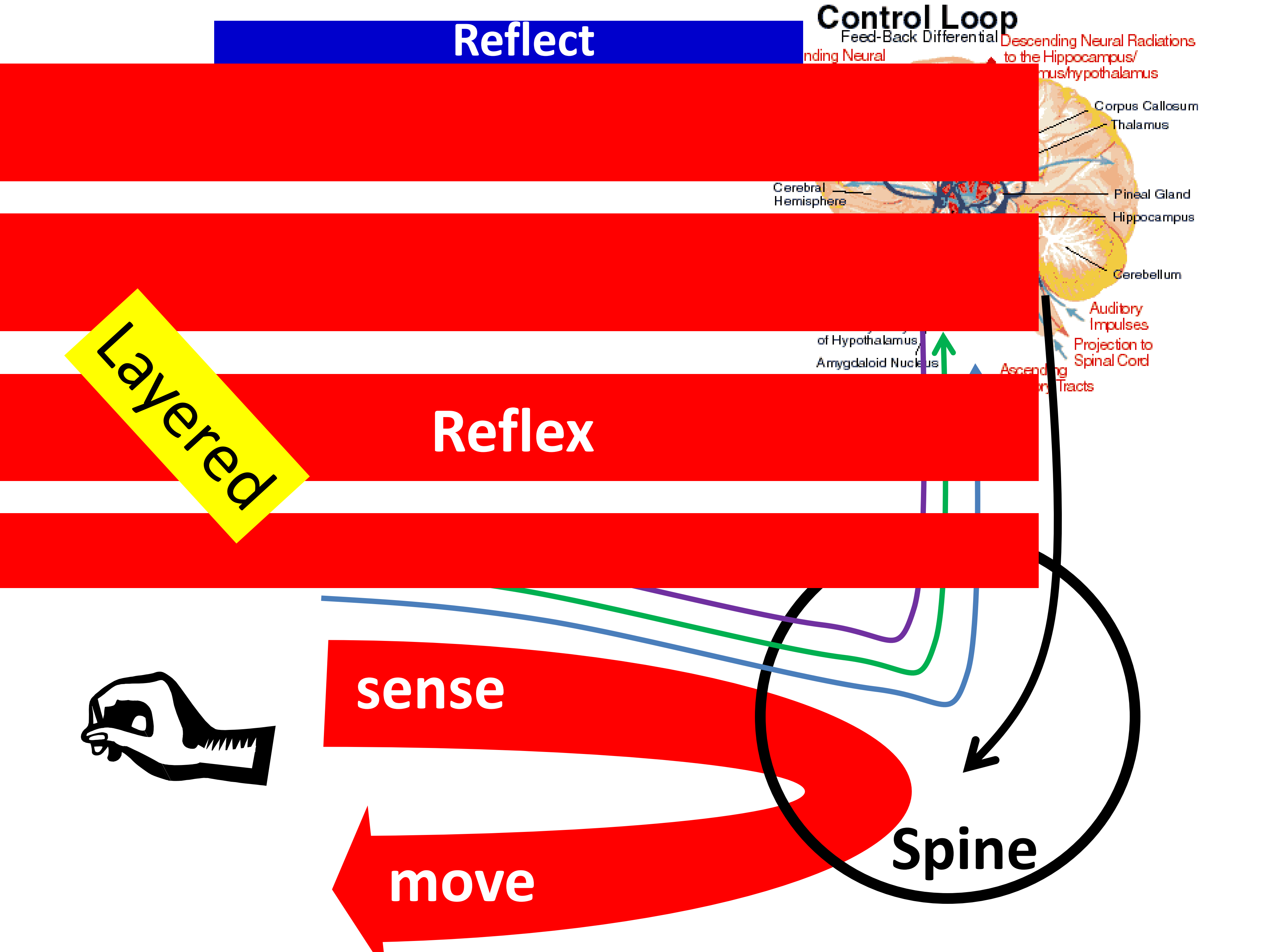



Move
head
Sense
Fast
Act
Same actuators
Delay is limiting
Slow
Fast?
Sense
Move
hand
Slow
Act

Reflect

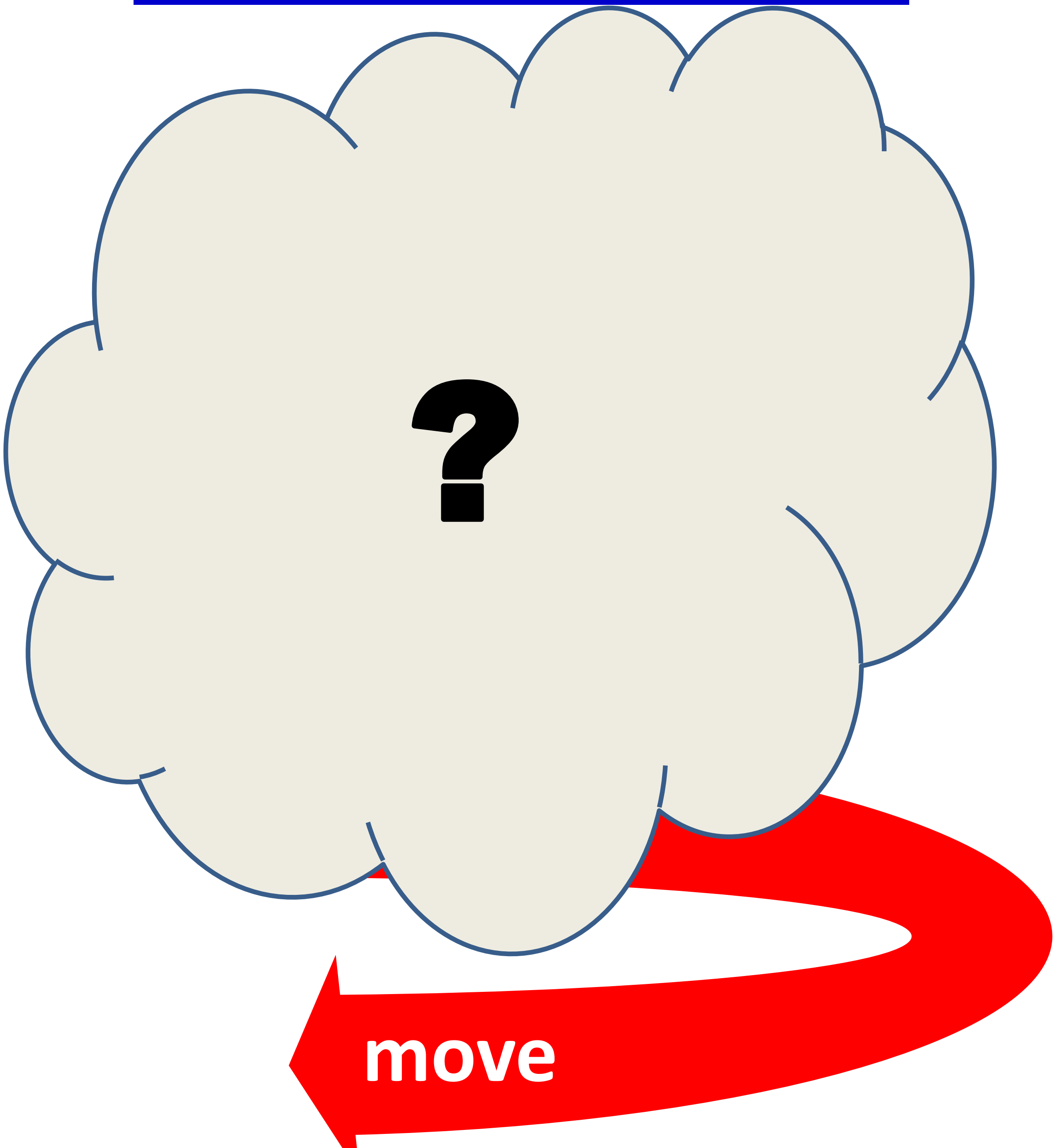


Reflex

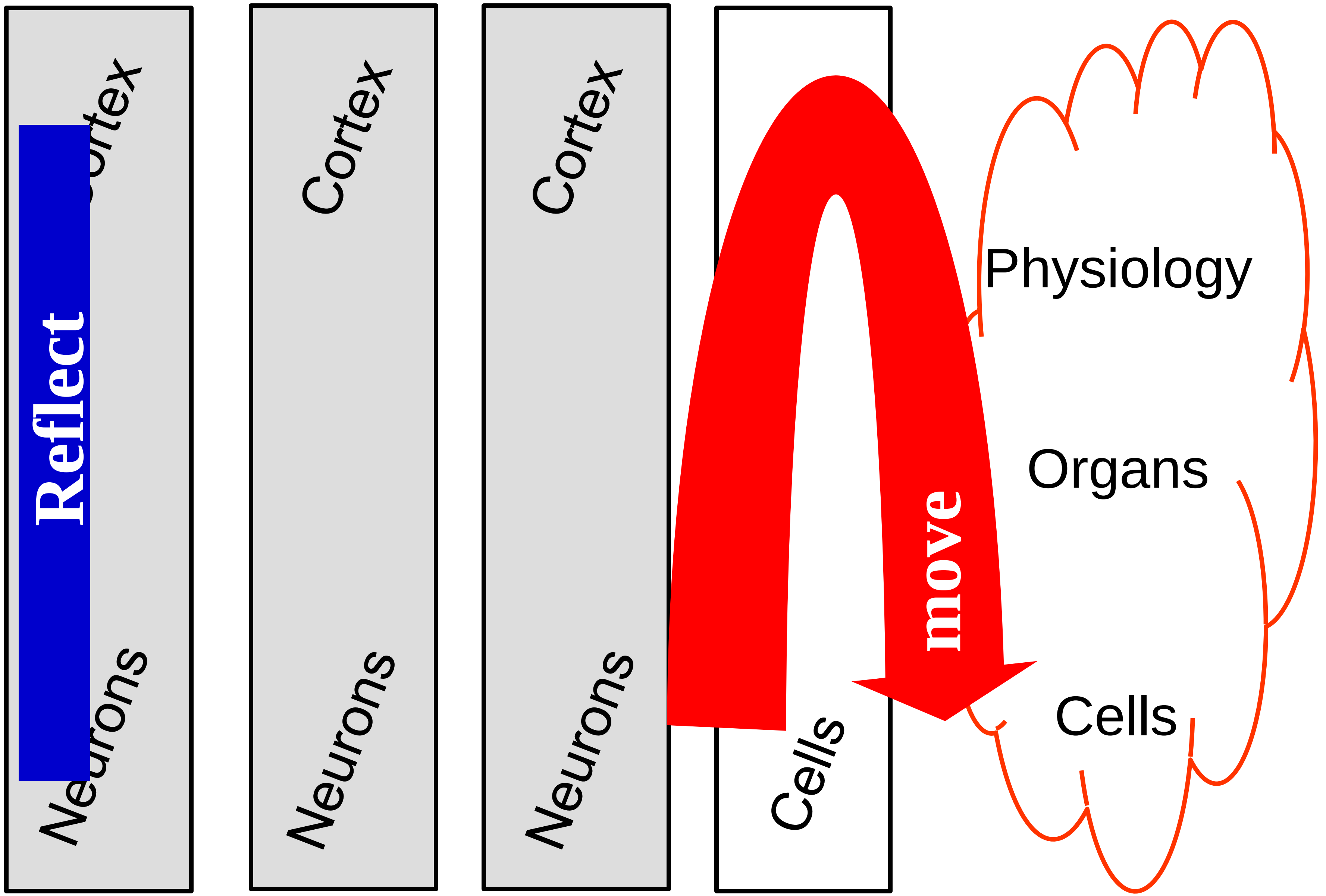


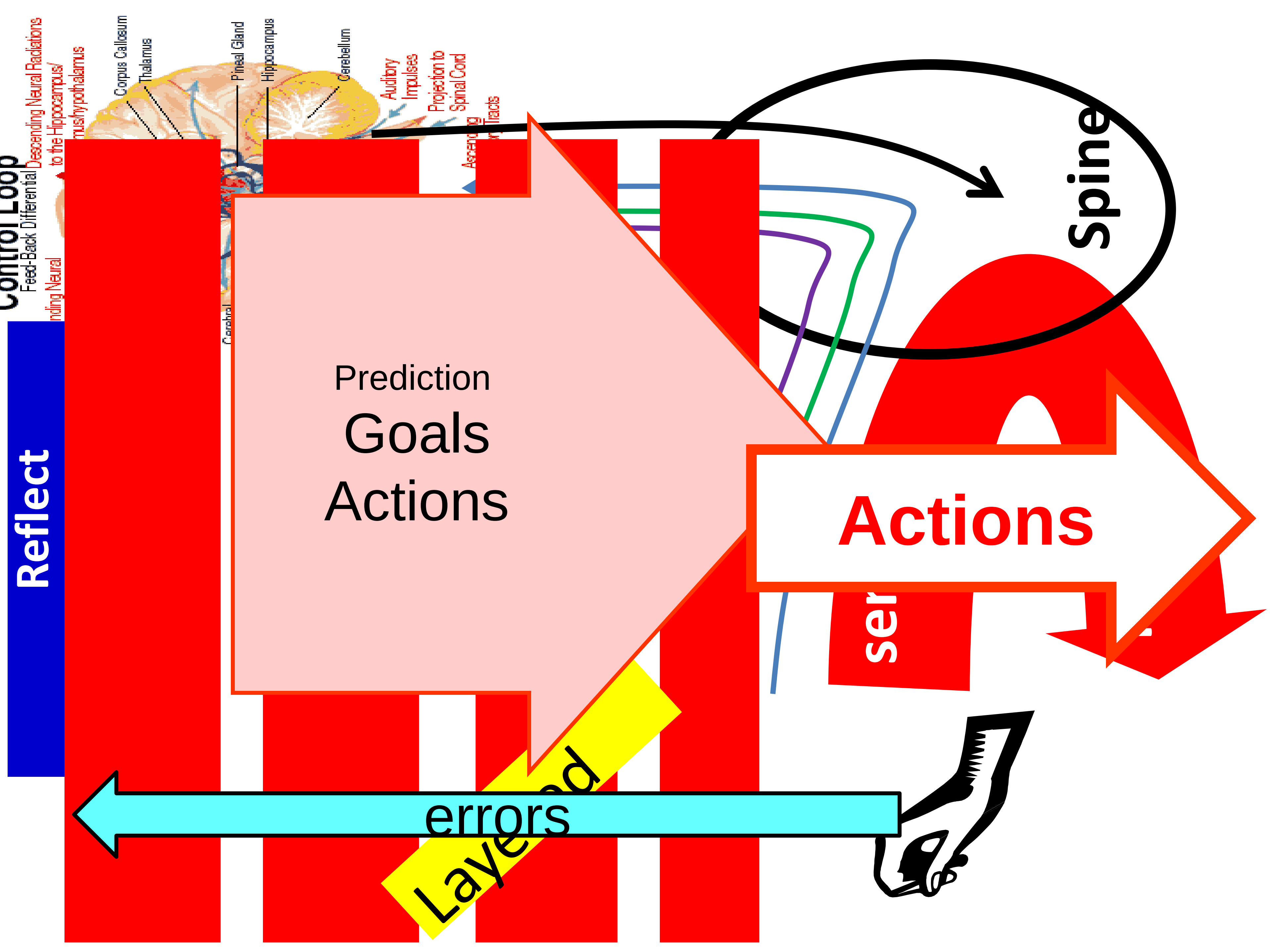
Reflect
Control Loop
Feed-Back Differential
Descending Neural Radiations
to the Hippocampus/
Corpus Callosum
Thalamus
Cerebral
Hemisphere
Pineal Gland
Hippocampus
Cerebellum
Auditory
Impulses
Projection to
Spinal Cord
of Hypothalamus
Amygdaloid Nucleus
Layered
Reflex
sense
move
Spine

Reflect

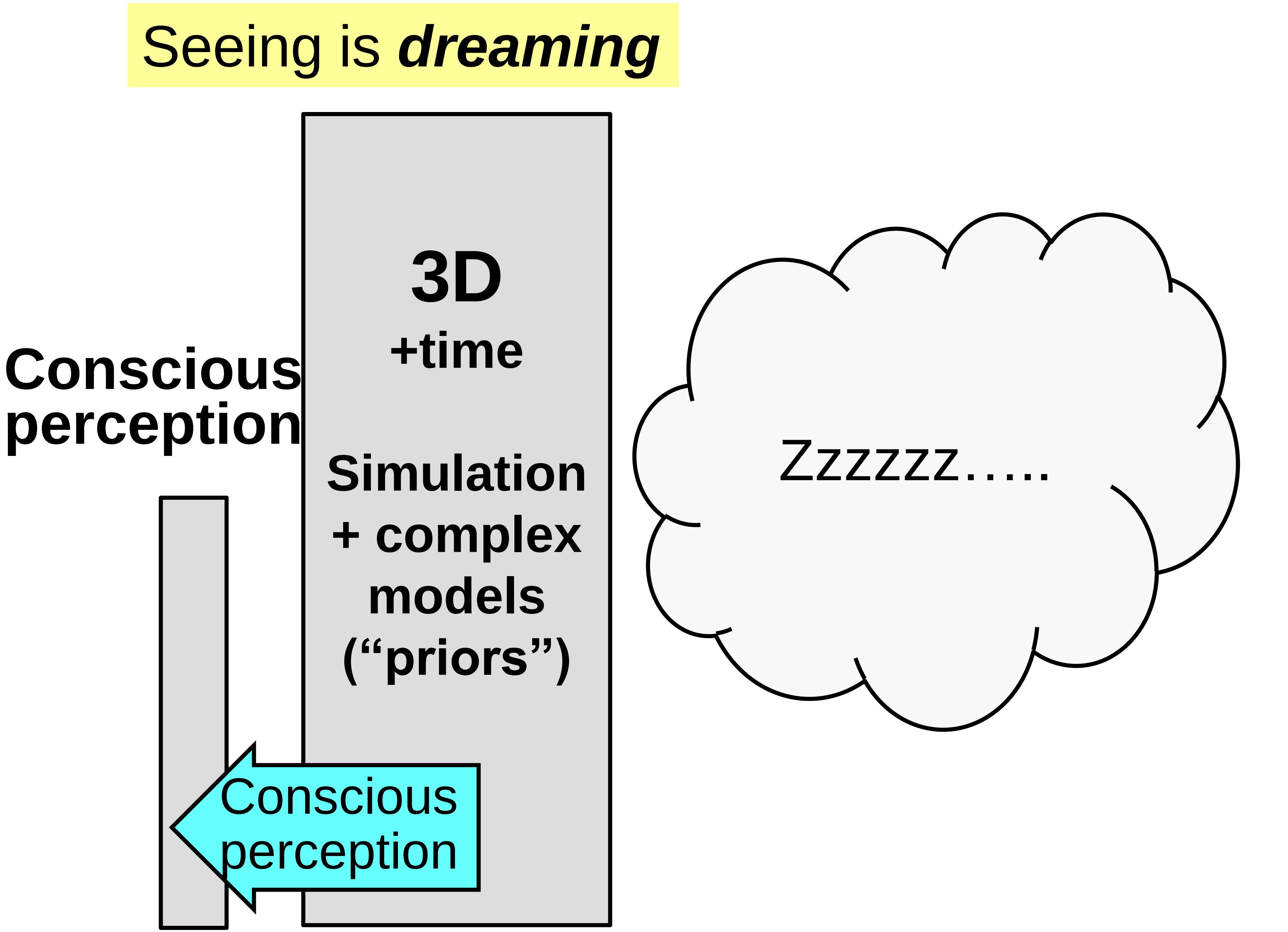


Layered architectures



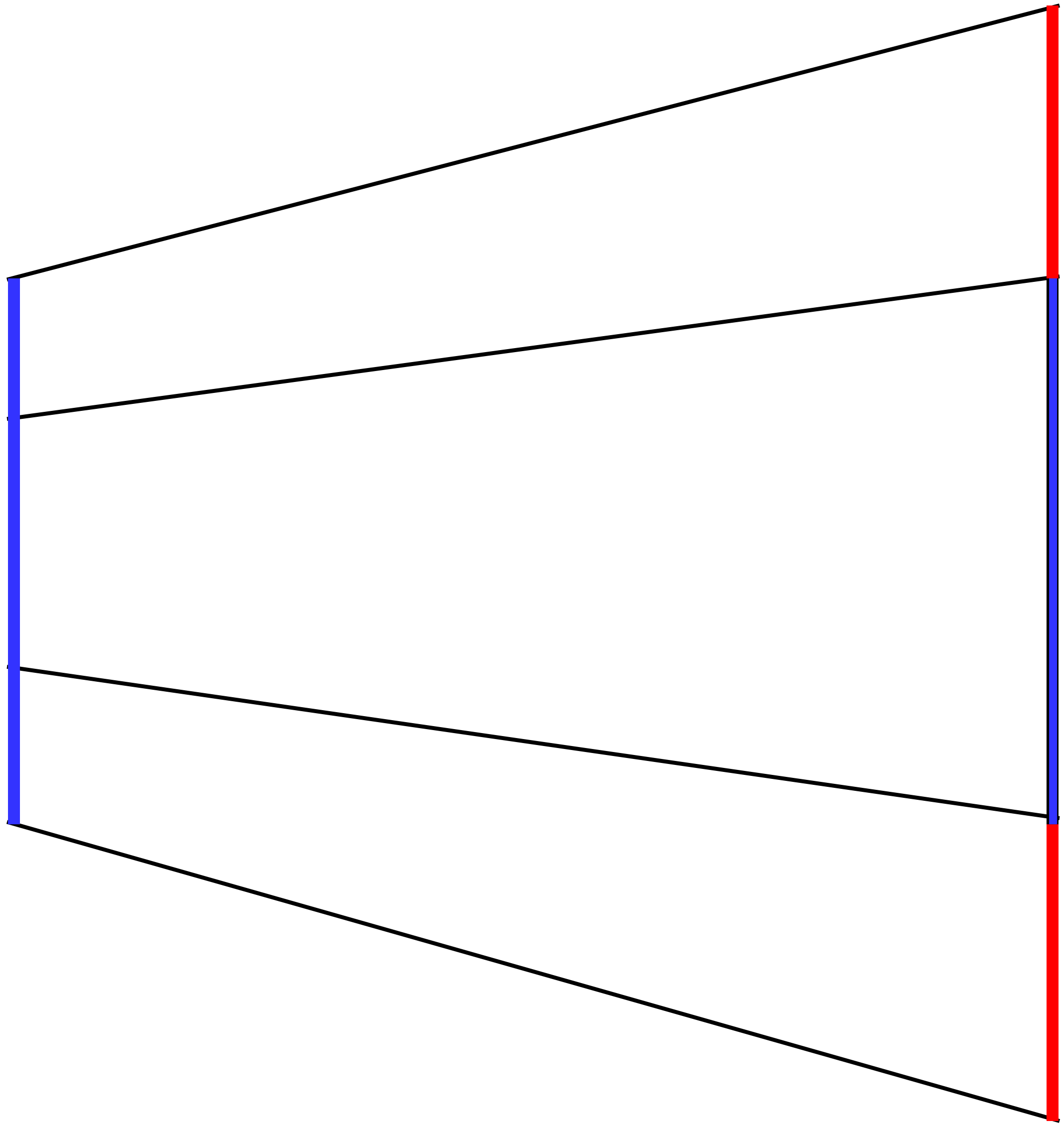


Control Loop
Feed-Back Differential
Corpus Callosum
Thalamus
Pineal Gland
Hippocampus
Cerebellum
Auditory Impulses
Projection to Spinal Cord
Spine
Reflect
Prediction
Goals
Actions
Actions
errors

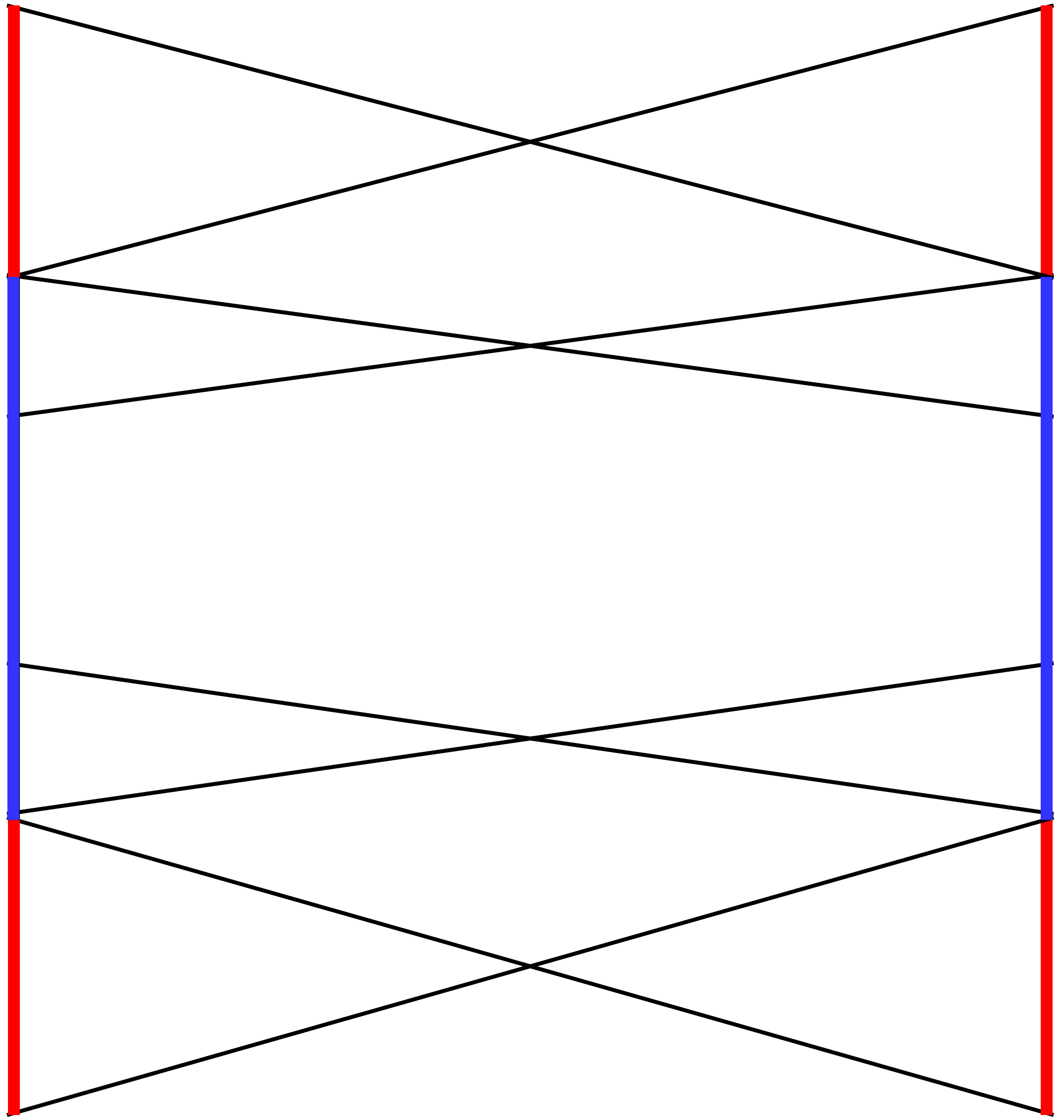

Seeing is ***dreaming***
Conscious perception
3D
+time
Simulation + complex models ("priors")
Zzzzzz…..
Conscious perception

Which blue line is longer?

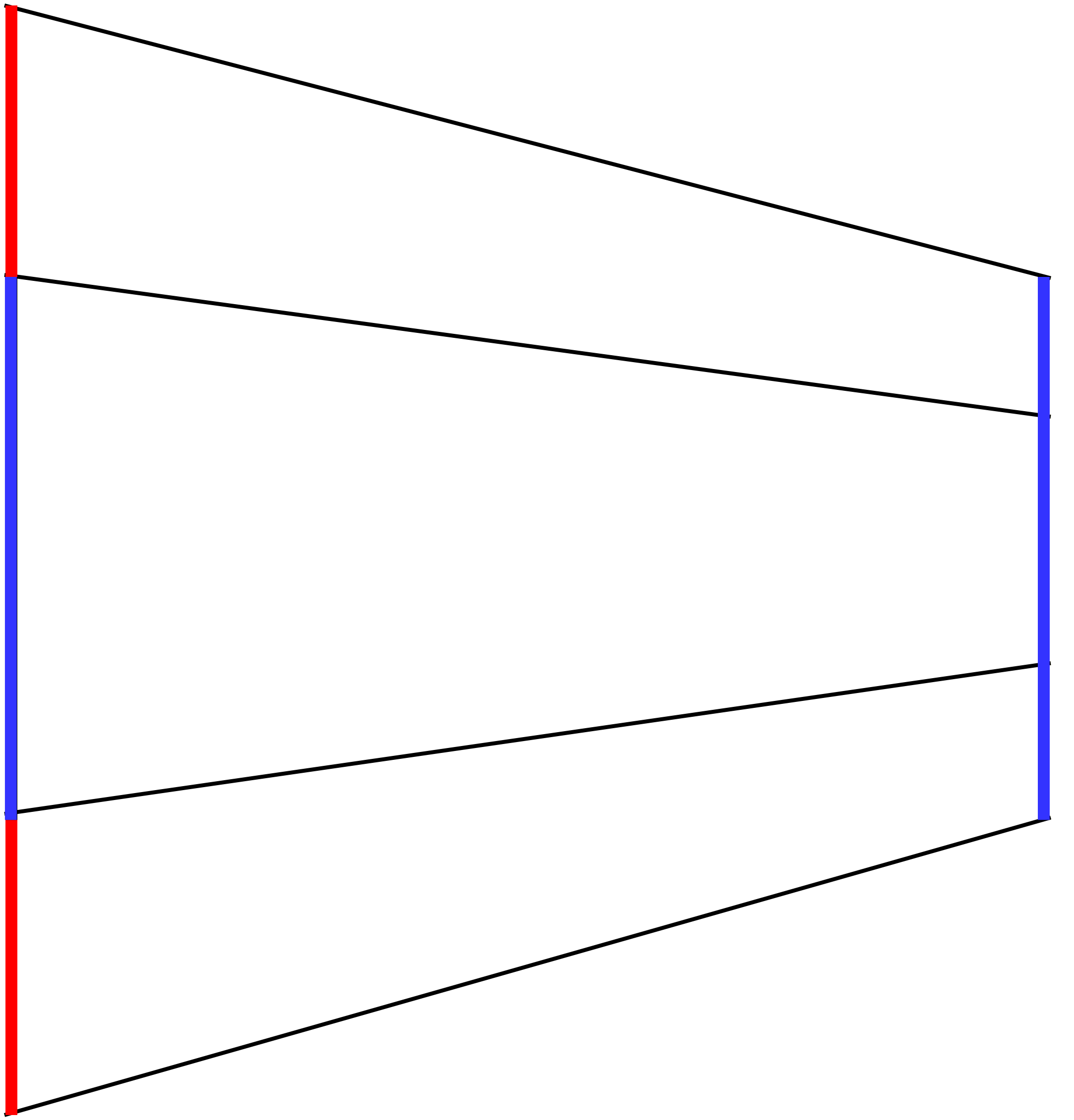
Which blue line is longer?

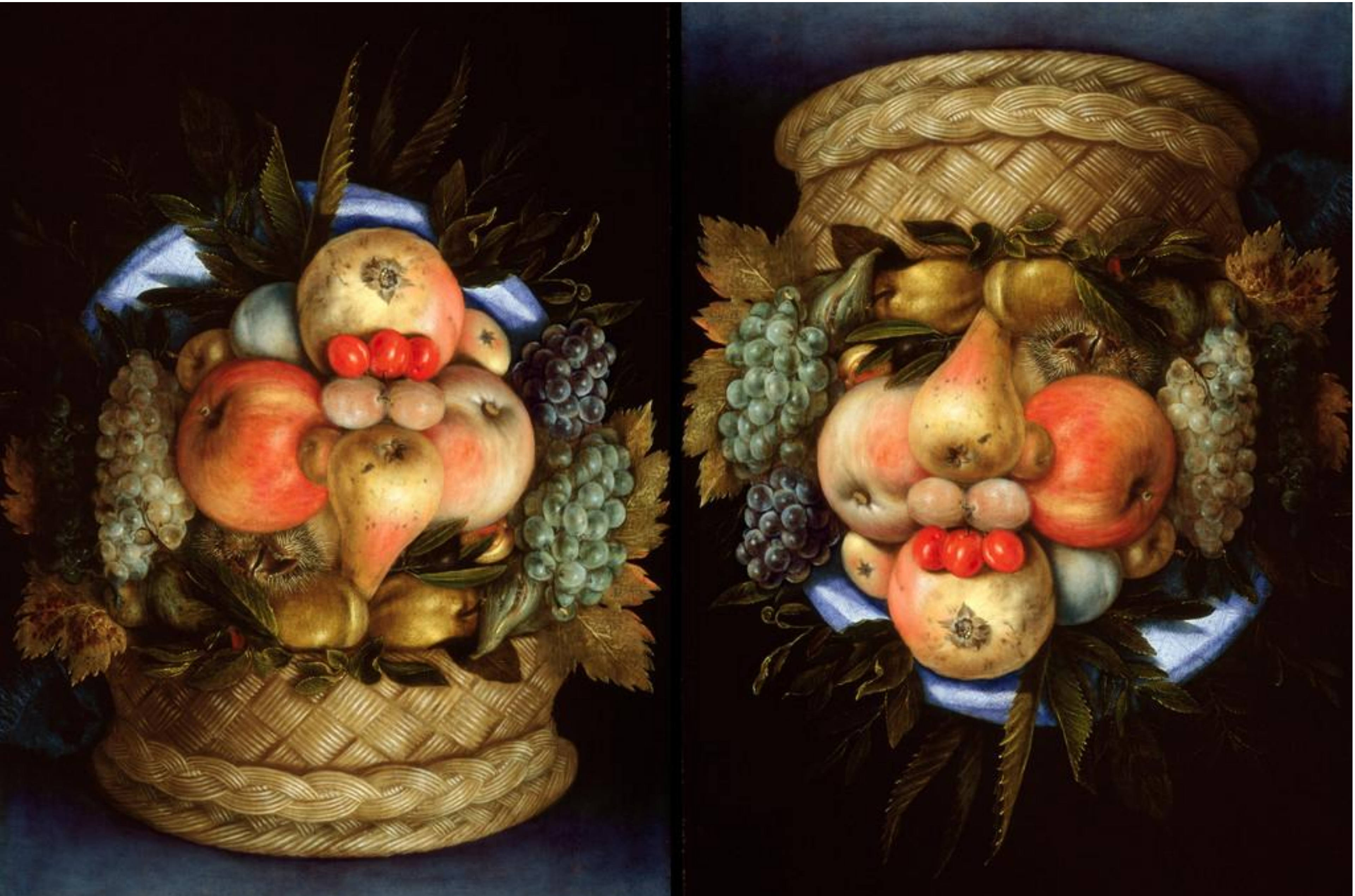


Which blue line is longer?



Which blue line is longer?

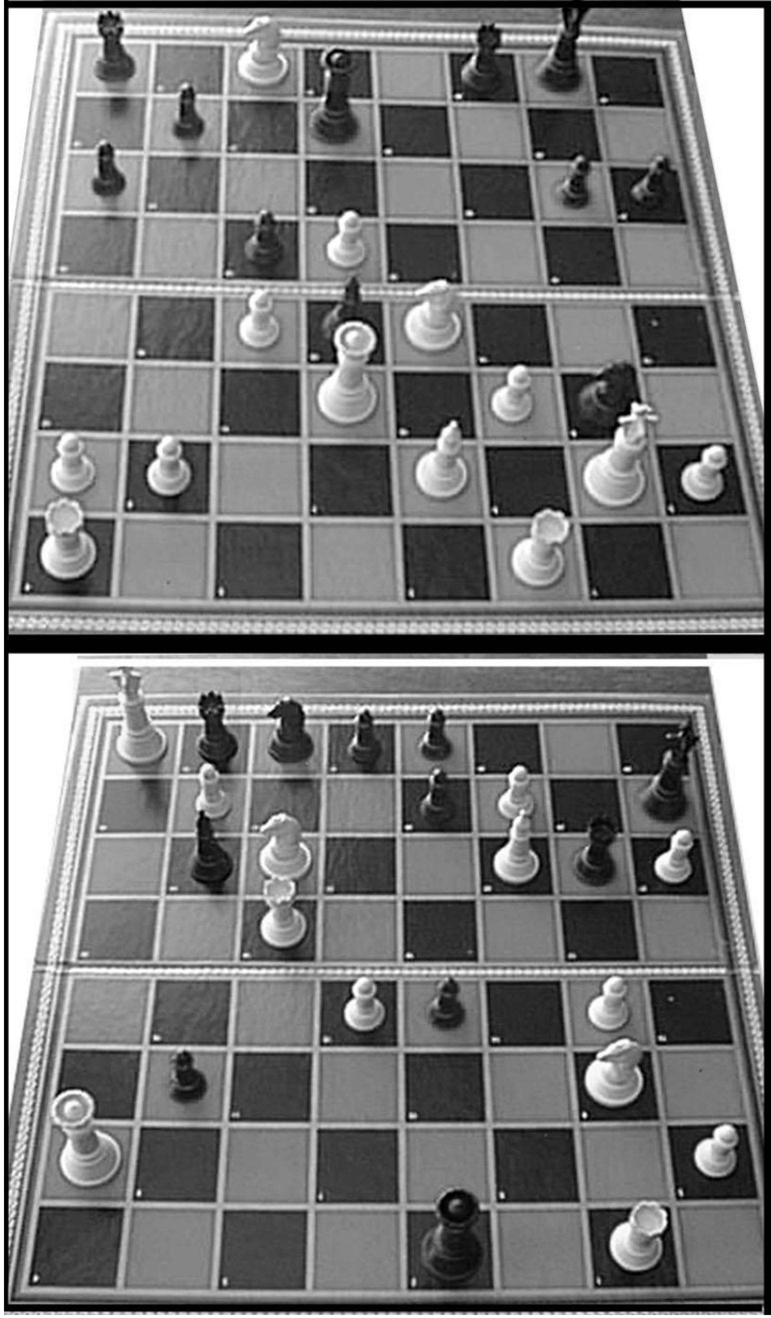




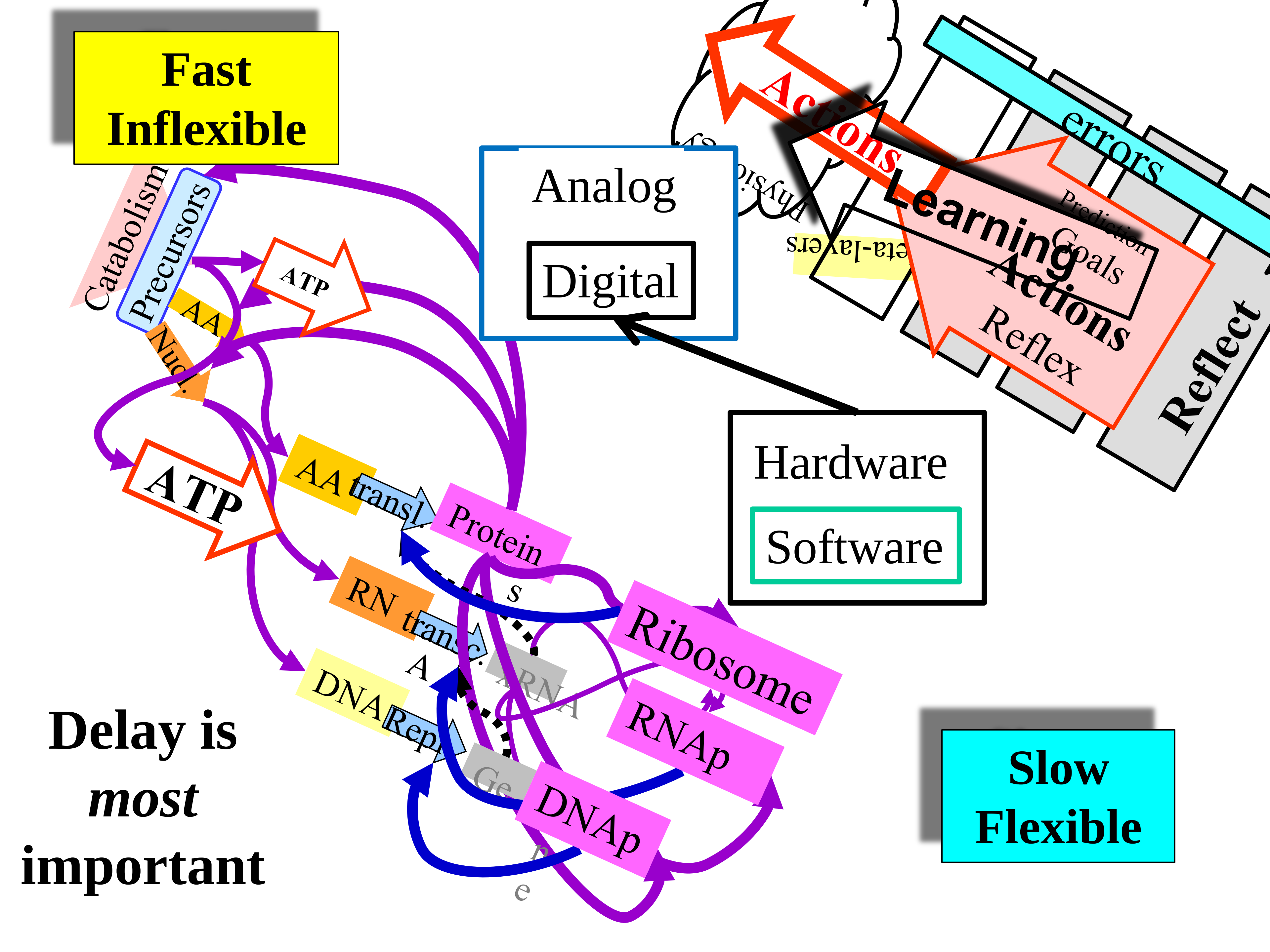
Chess experts

- 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

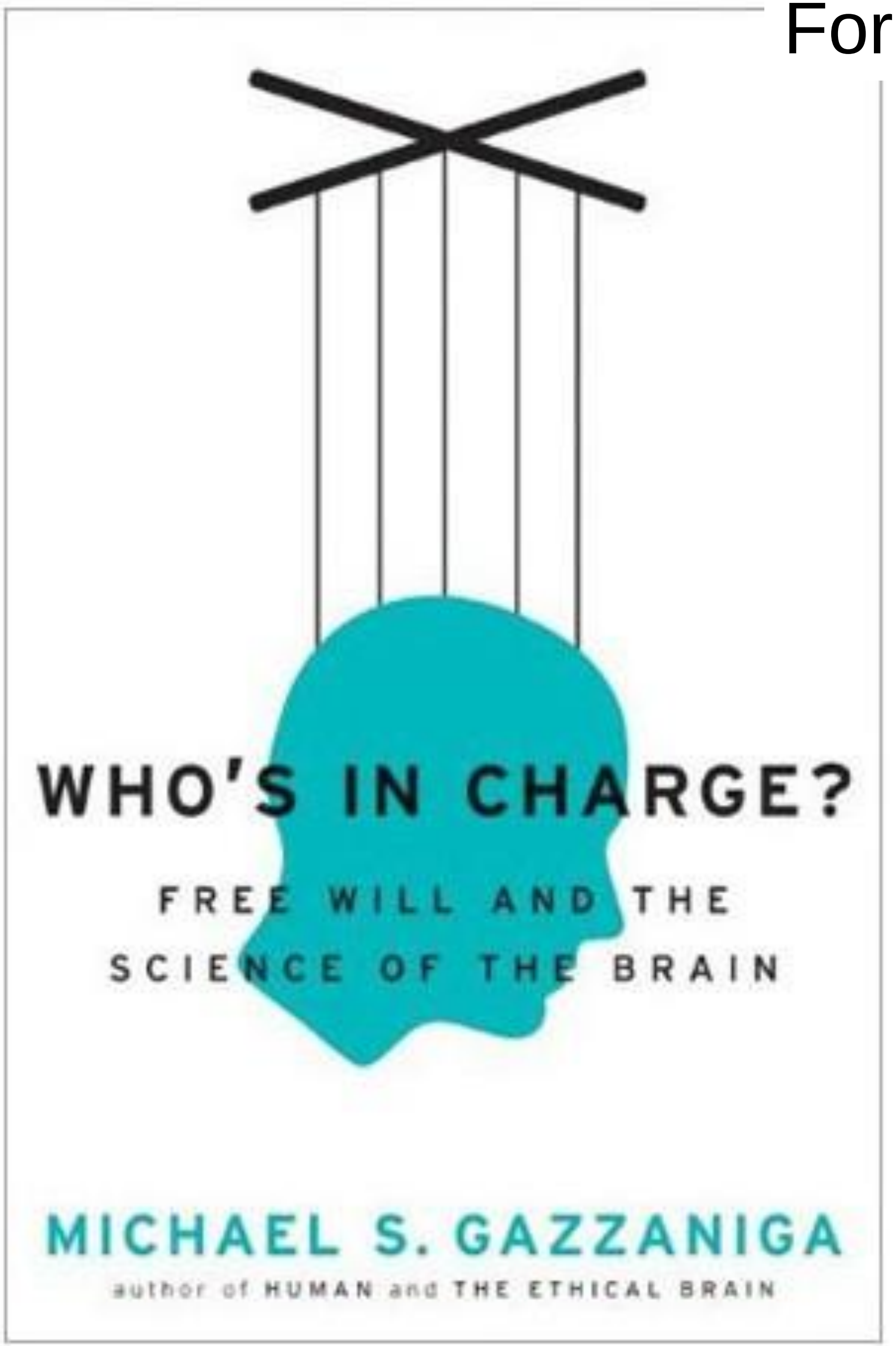
(Simon and Gilmartin, de Groot)

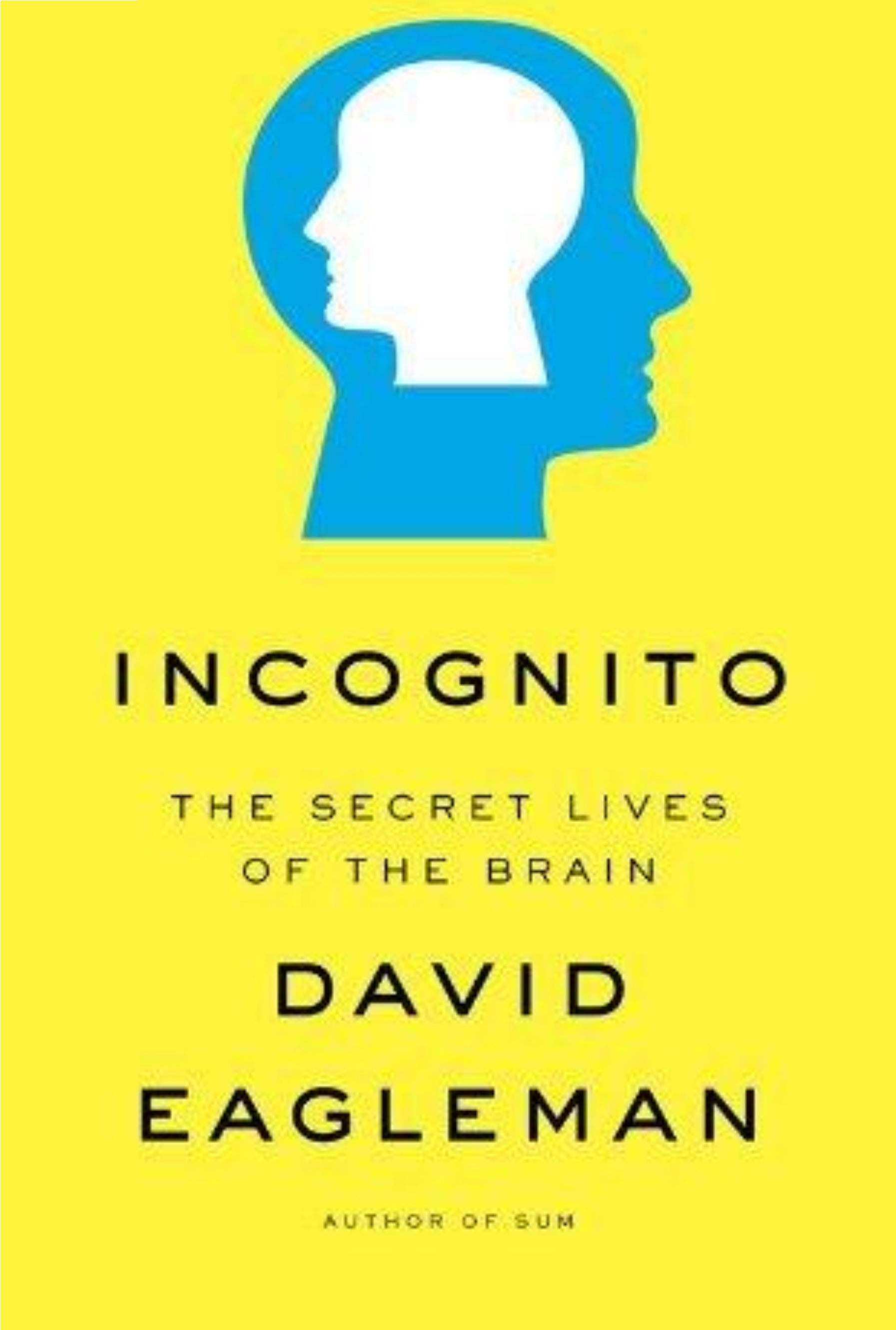


www.psywww.com/intropsych/ch07_cognition/expertise_and_domain_specific_knowledge.html


Fast
Inflexible
Catabolism
Precursors
ATP
AA
Nucl.
ATP
AA transl.
Protein
RN transc.
DNA Repl.
Ribosome
RNAp
DNAp
tRNA
Analog
Digital
Hardware
Software
Actions
Learning
Actions
errors
Prediction
Goals
Reflex
Reflect
Slow
Flexible
Delay is
most
important

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

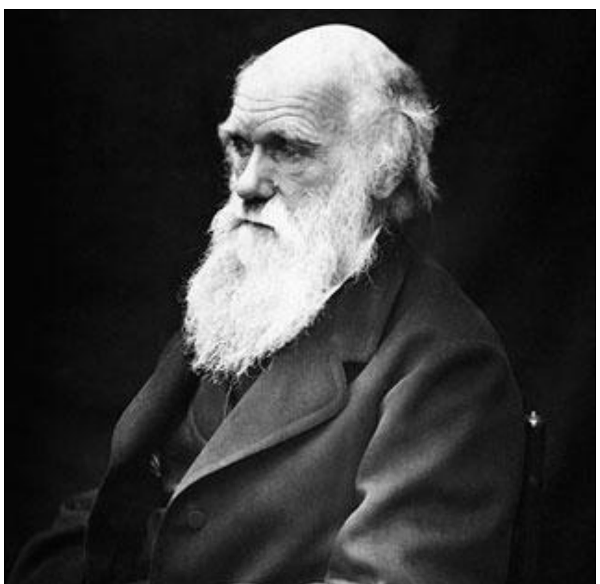
Facilitated variation

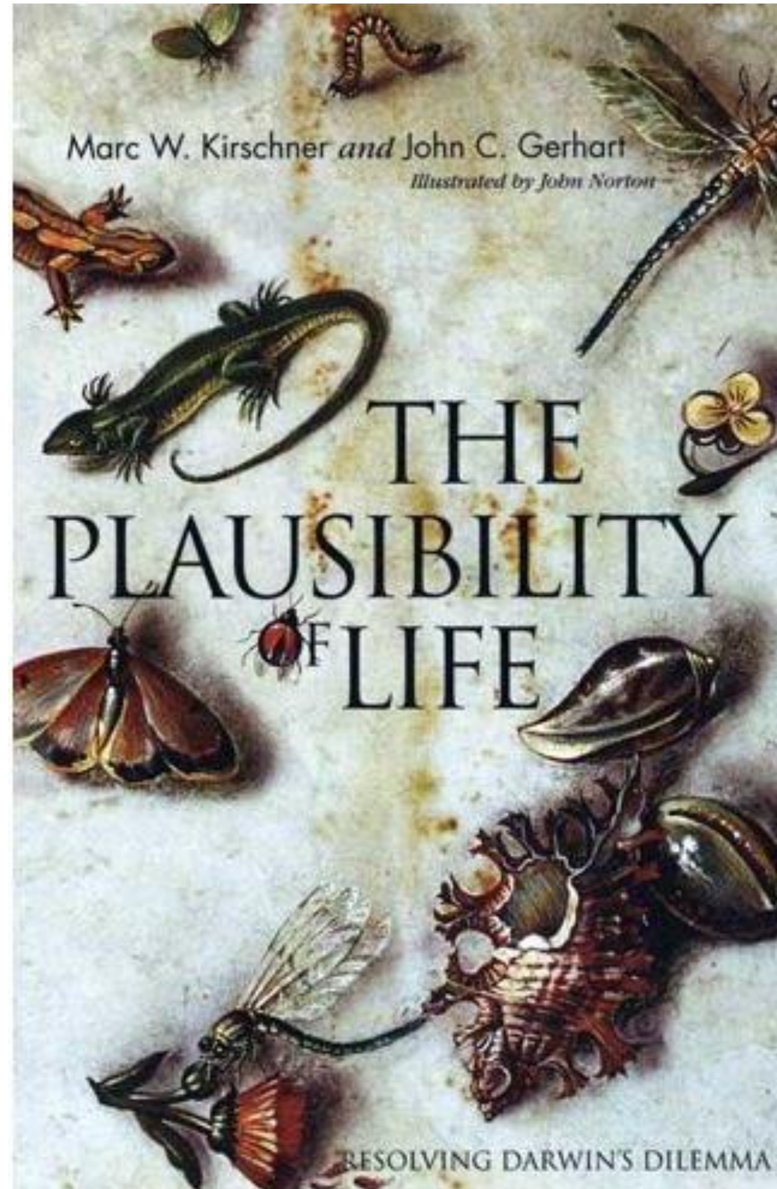
Architecture =

Constraints that deconstrain

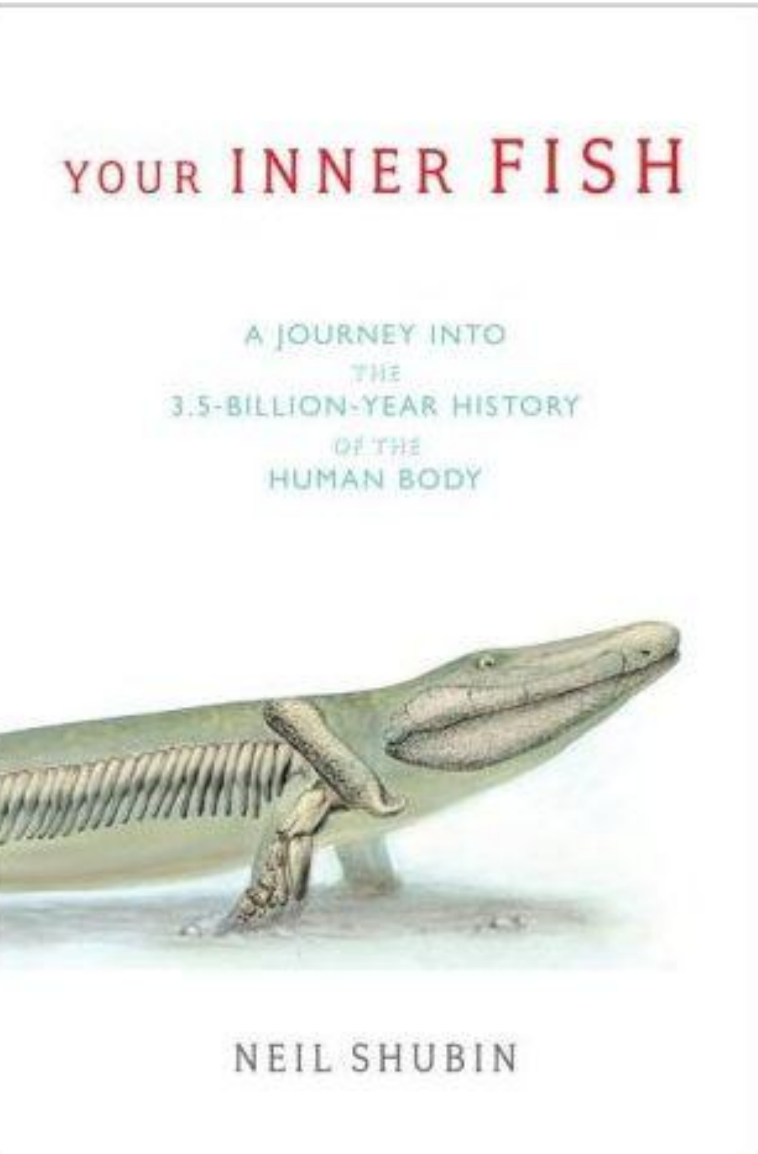
- Weak linkage
- Exploratory mechanisms
- Compartmentalization

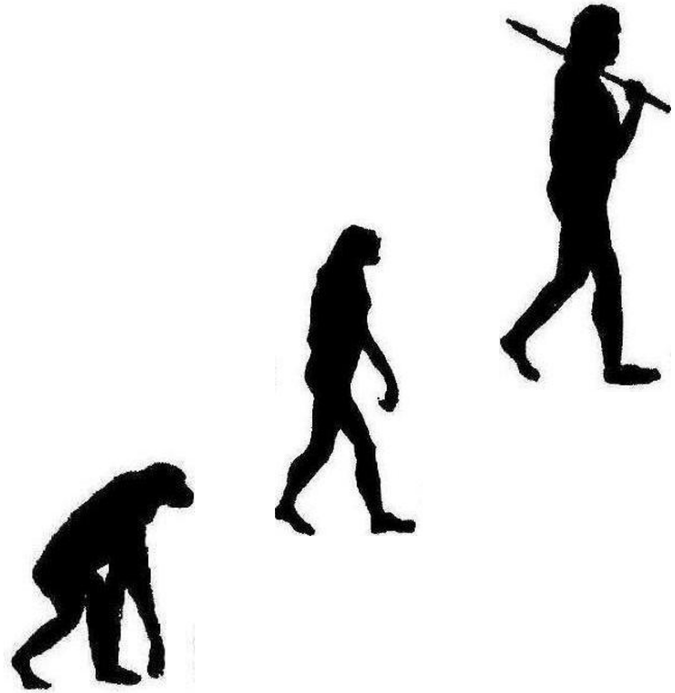
Kirschner and Gerhart



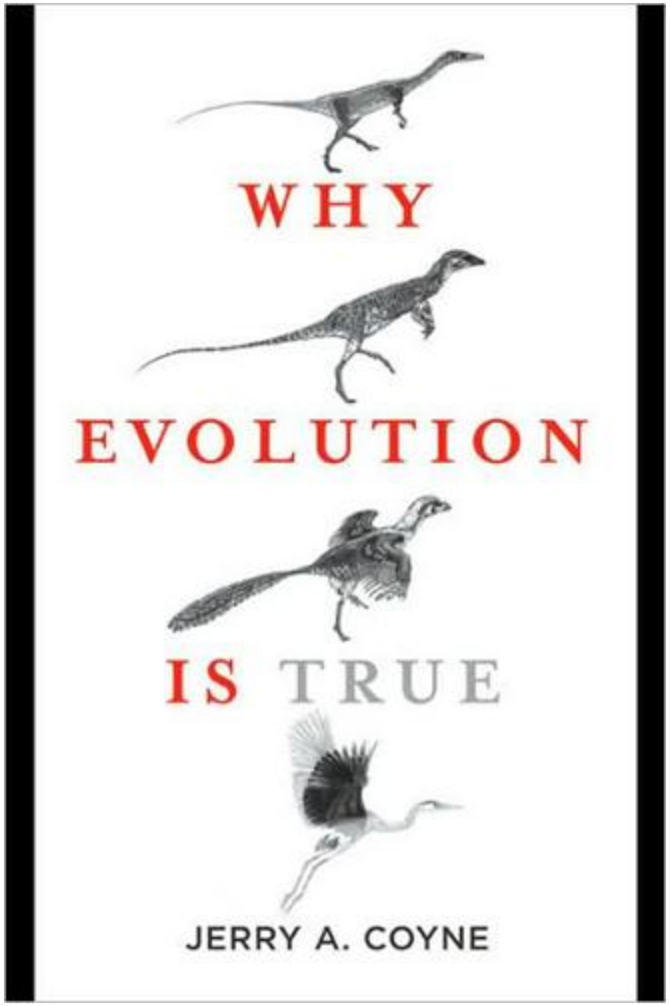


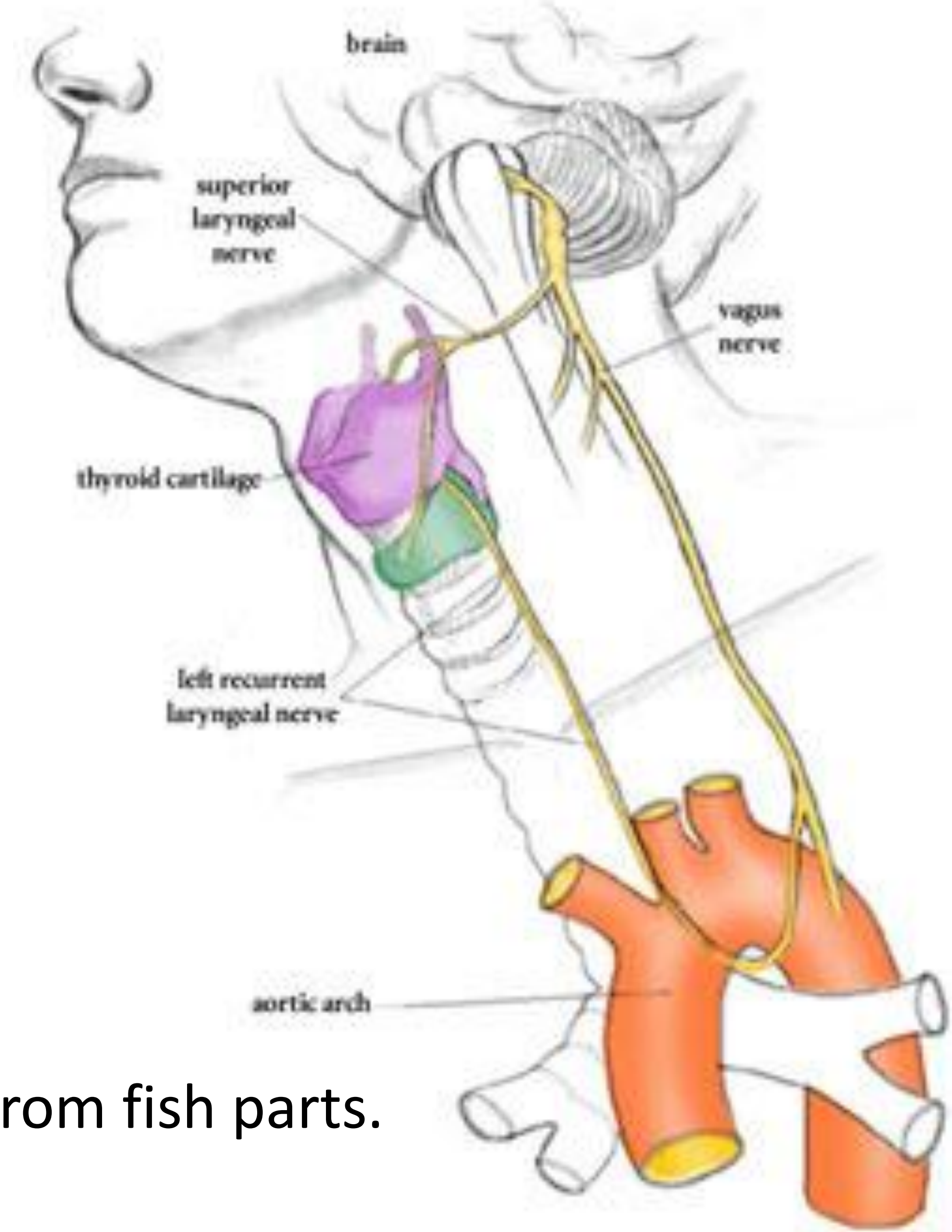
Unfortunately, not intelligent design





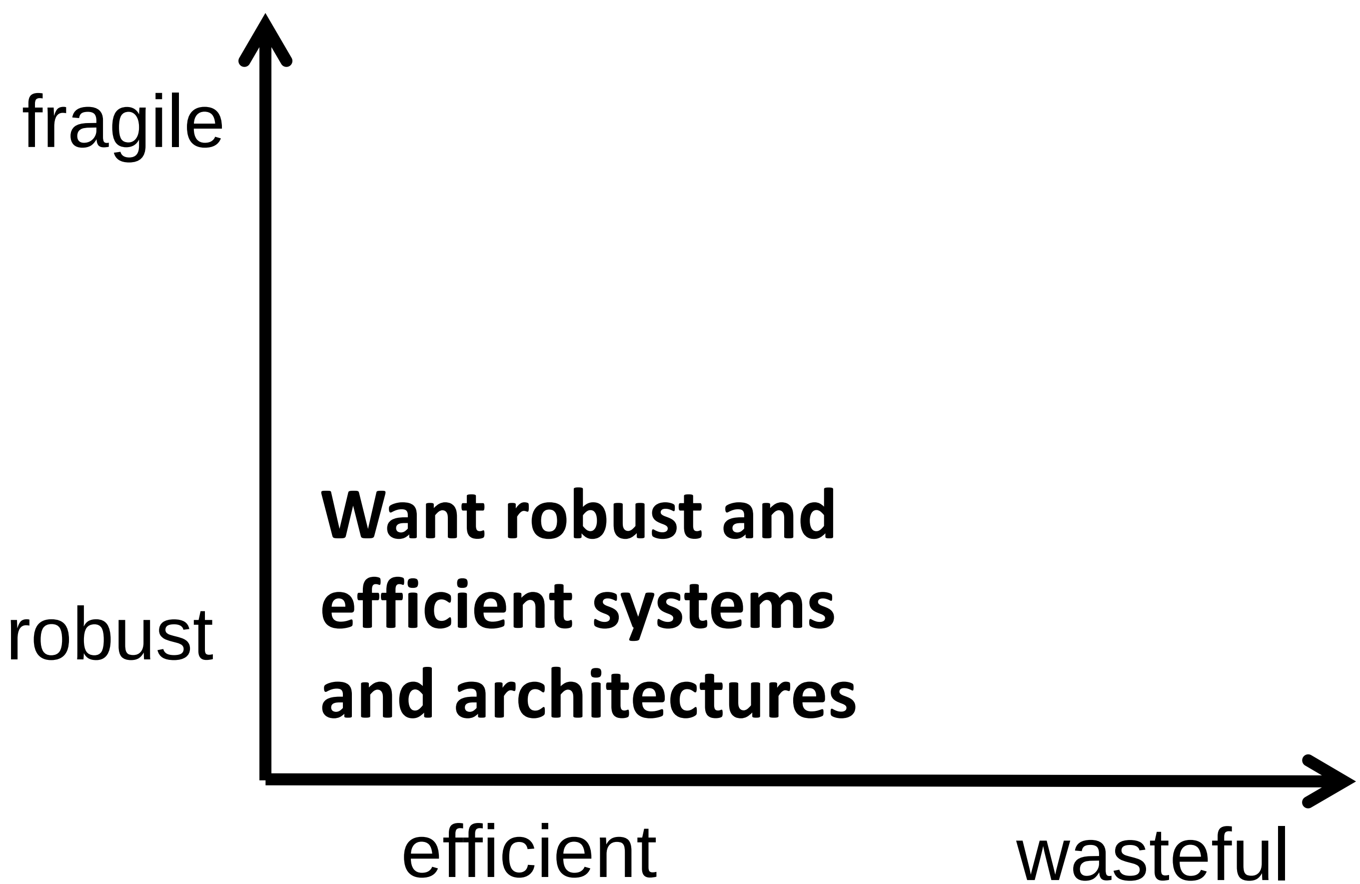
Ouch.



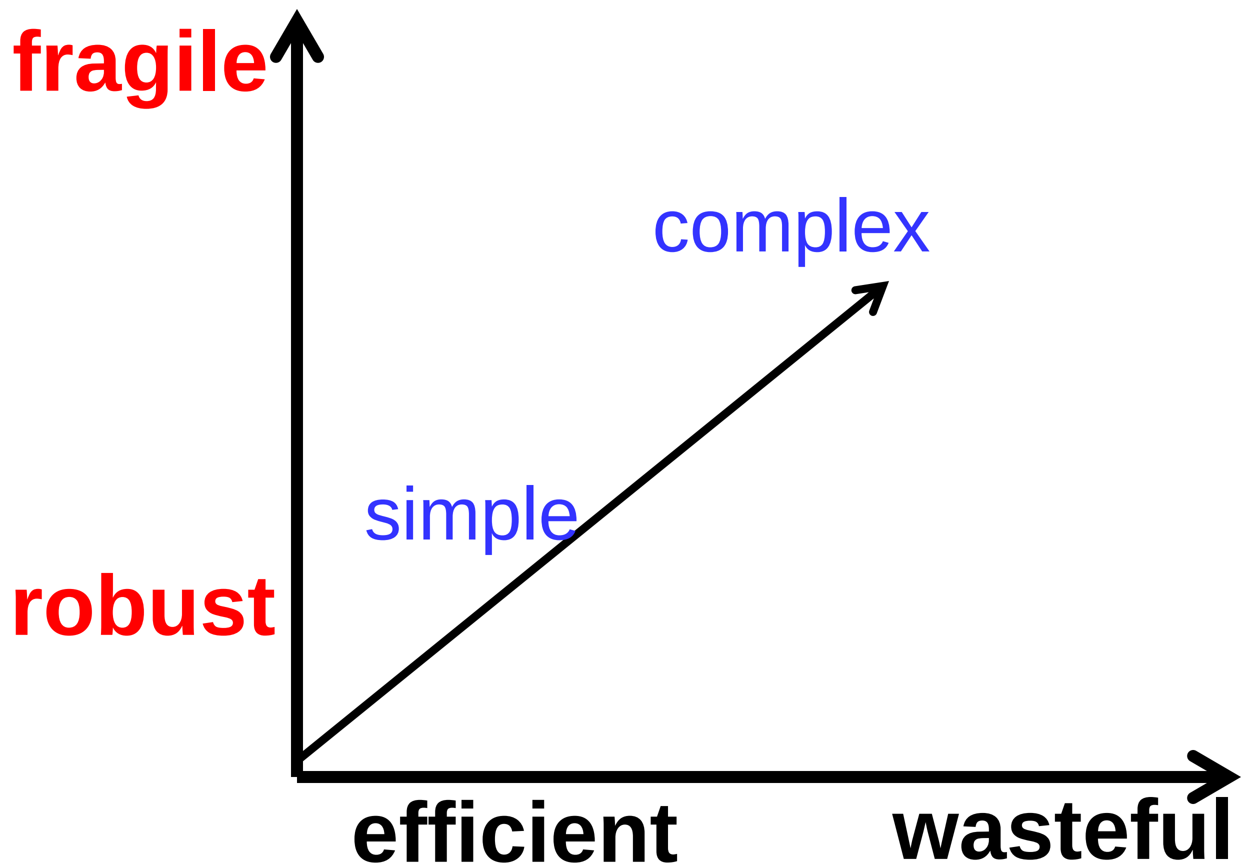


Making humans from fish parts.

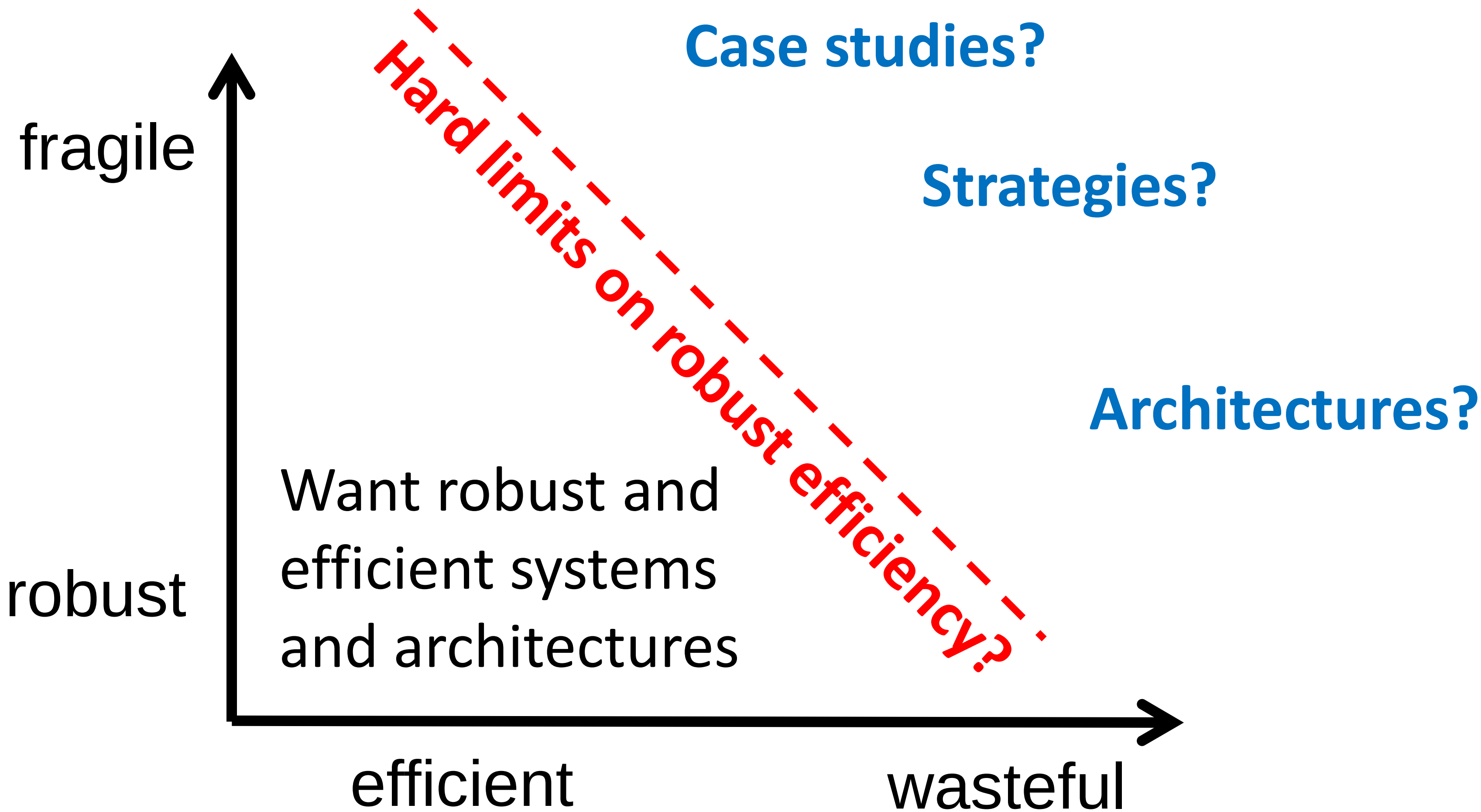
Want to understand the space of systems/architectures



Requirements on systems and architectures



Want to understand the space of systems/architectures



Control, OR

Kalman

Comms

Pontryagin

Bode

Shannon

Nash

Theory?

Deep, but fragmented, incoherent, incomplete

Von Neumann

Carnot

Turing

Boltzmann

Godel

Heisenberg

Compute

Einstein

Physics

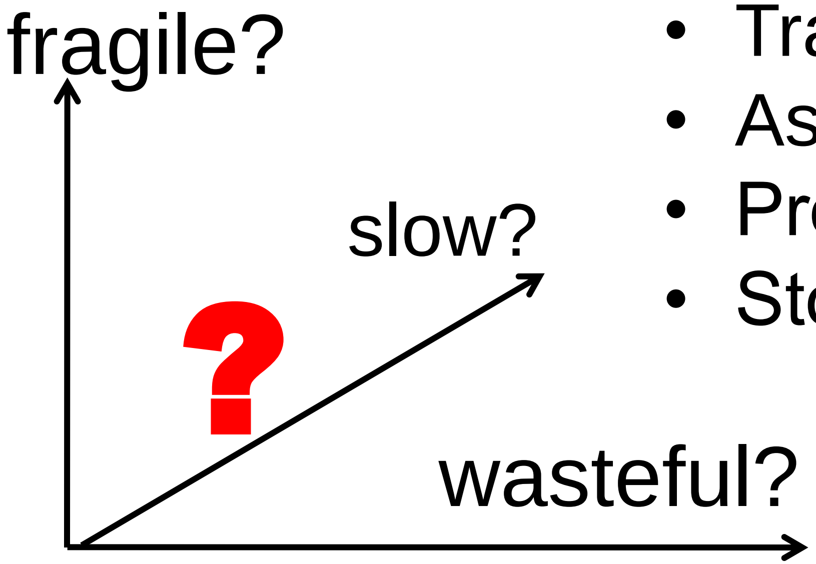
Control

Comms

Bode

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

Chandra, Buzi, and Doyle

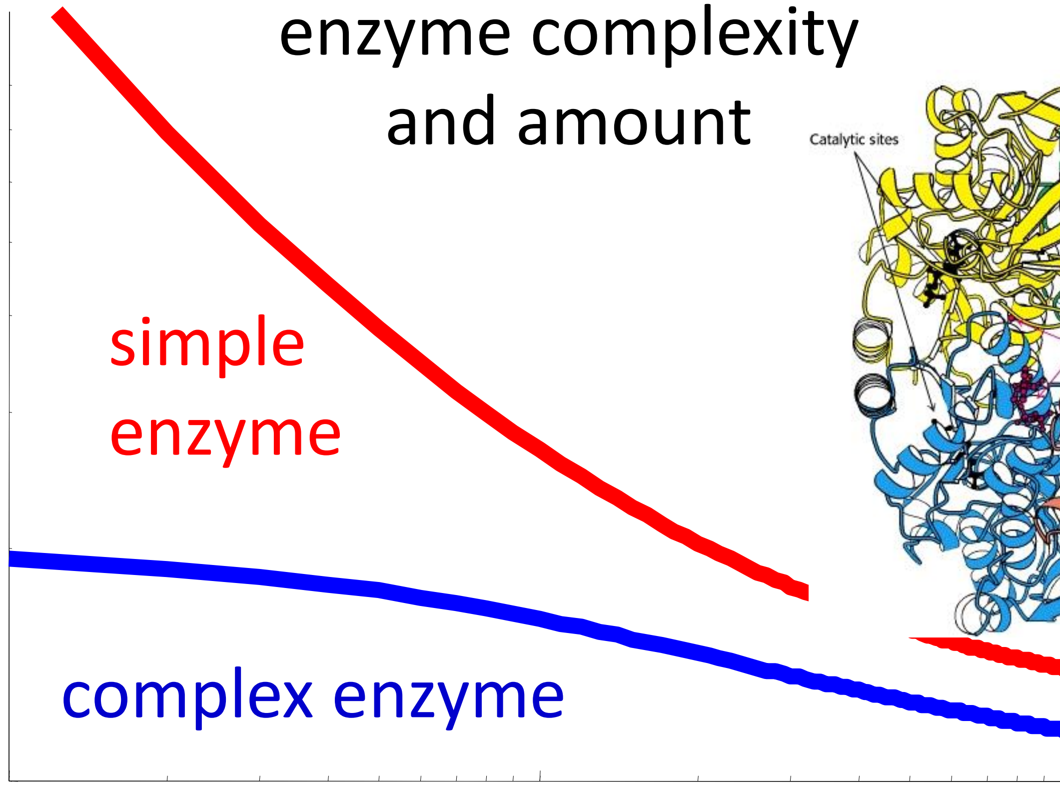
Most important paper so far.

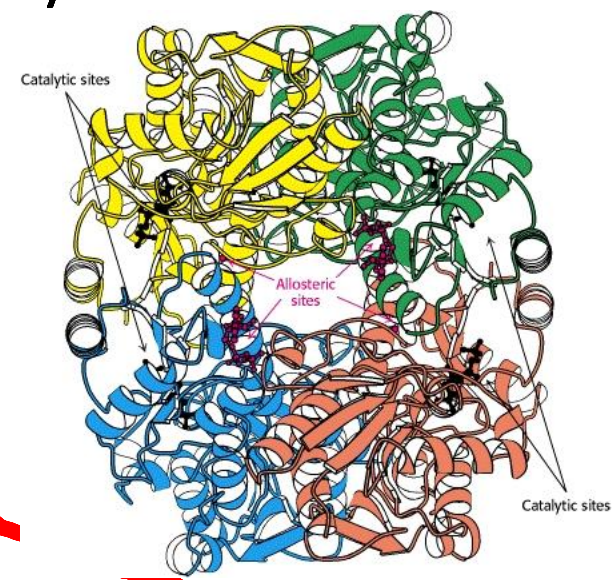
Theorem!

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

z and p functions of enzyme complexity and amount

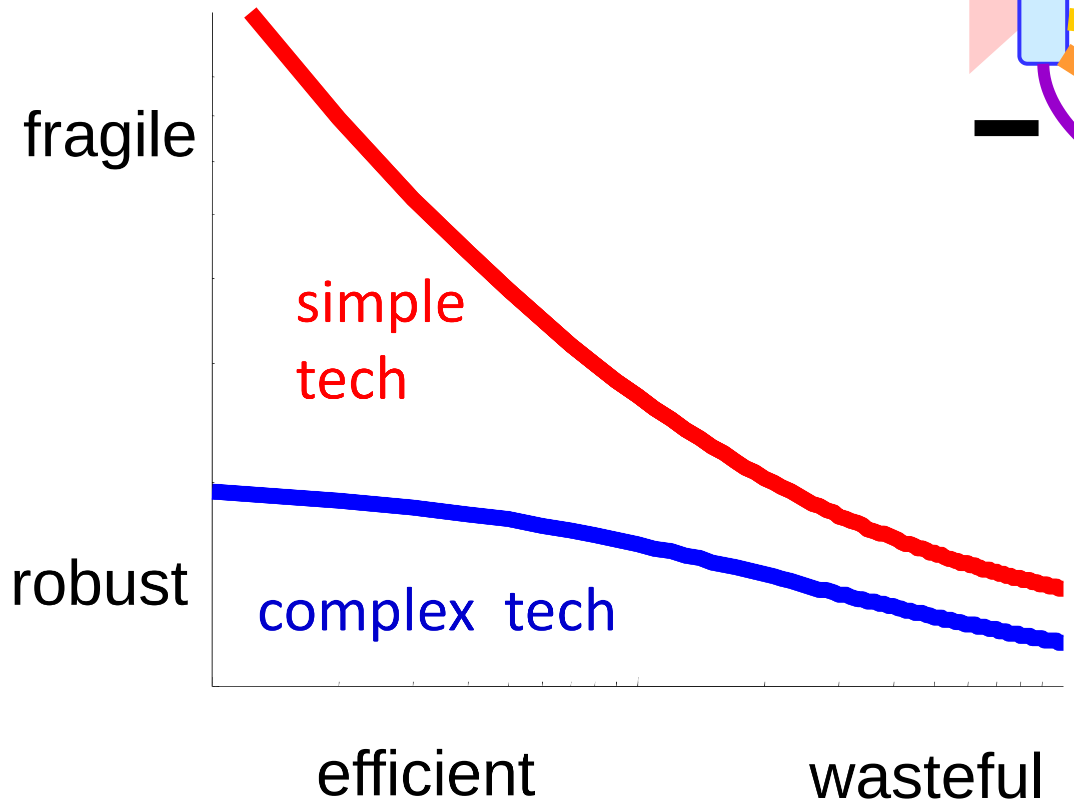
$$\ln\left|\frac{z+p}{z-p}\right|$$

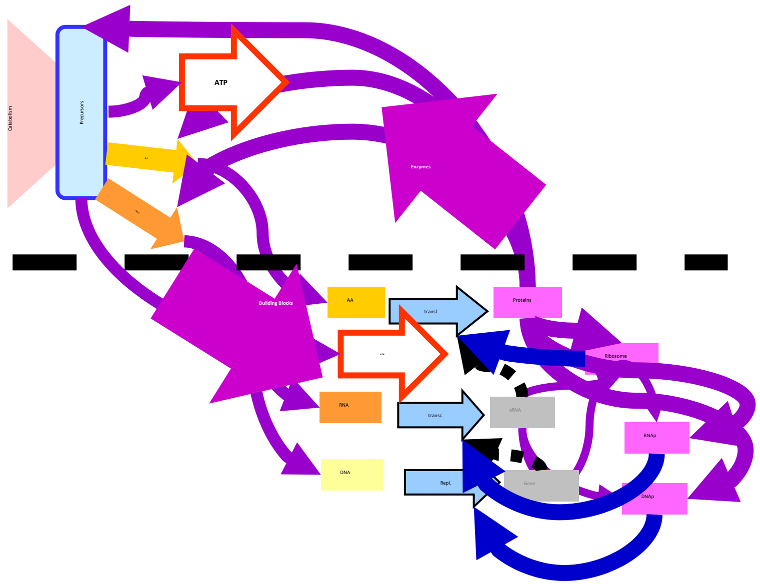




Savageaumics

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





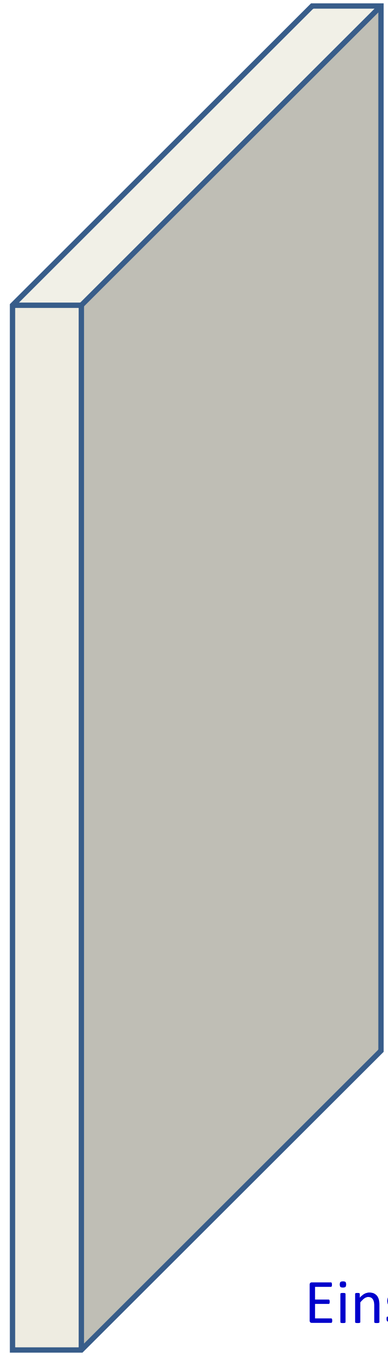
Control, OR

Bode

Delay is *most* important

Turing

Compute



Communications

Shannon

Delay is *least* important

Carnot

Boltzmann

Heisenberg

Einstein

Physics

Control, OR

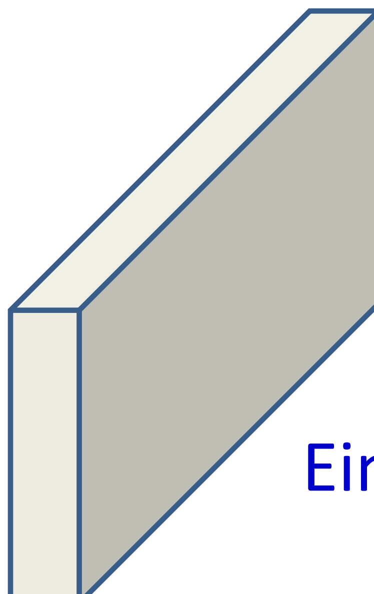
Communications

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)

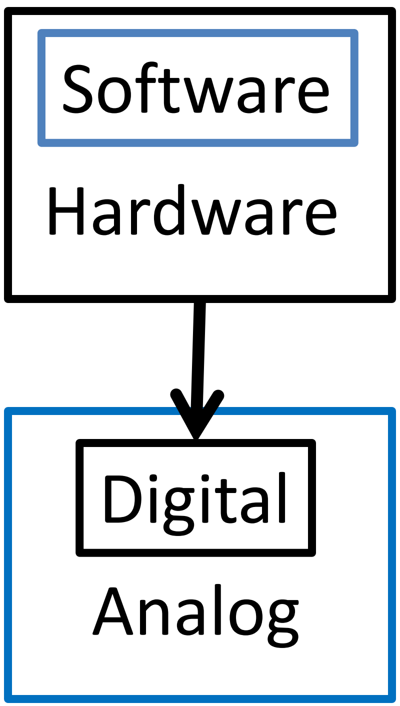
Compute

*Also world-class runner.

Turing as "new" starting point?

Essentials:

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

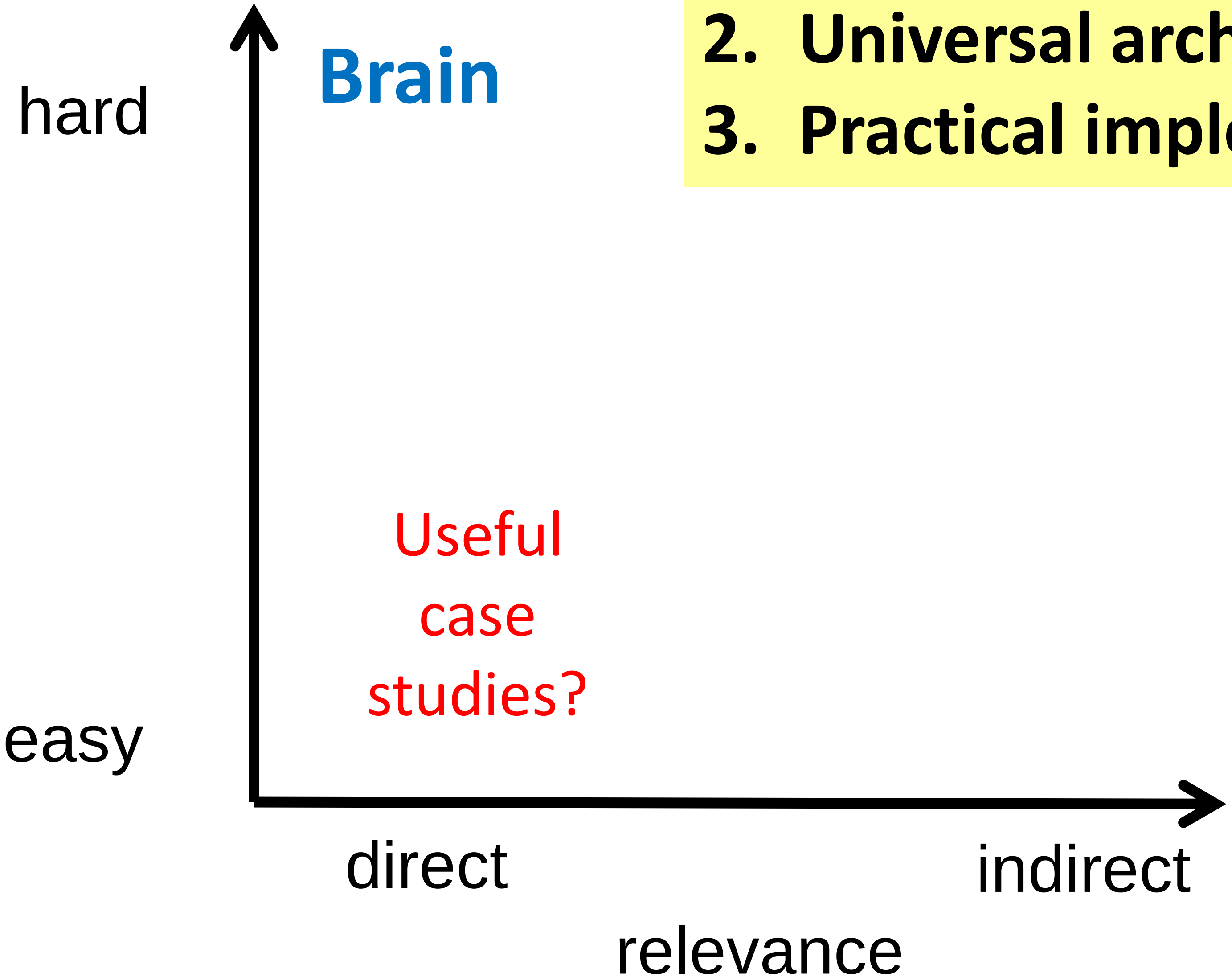


Turing's 3 step research:

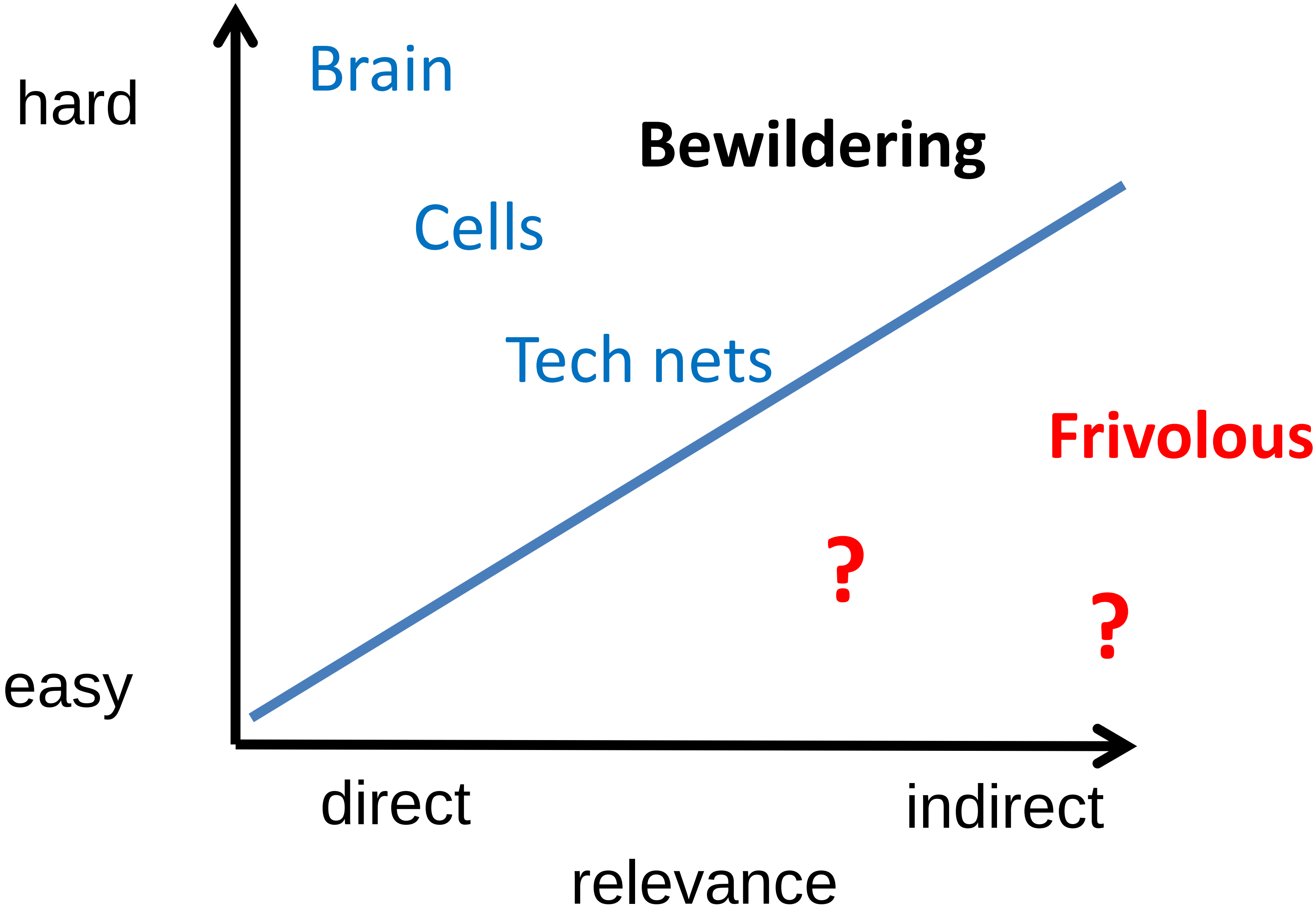
0. Virtual (TM) machines
1. hard limits, (un)decidability using standard model (TM)
2. Universal architecture achieving hard limits (UTM)
3. Practical implementation in digital electronics (biology?)

Essentials:

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



3. Universal architecture
4. Practical implementation

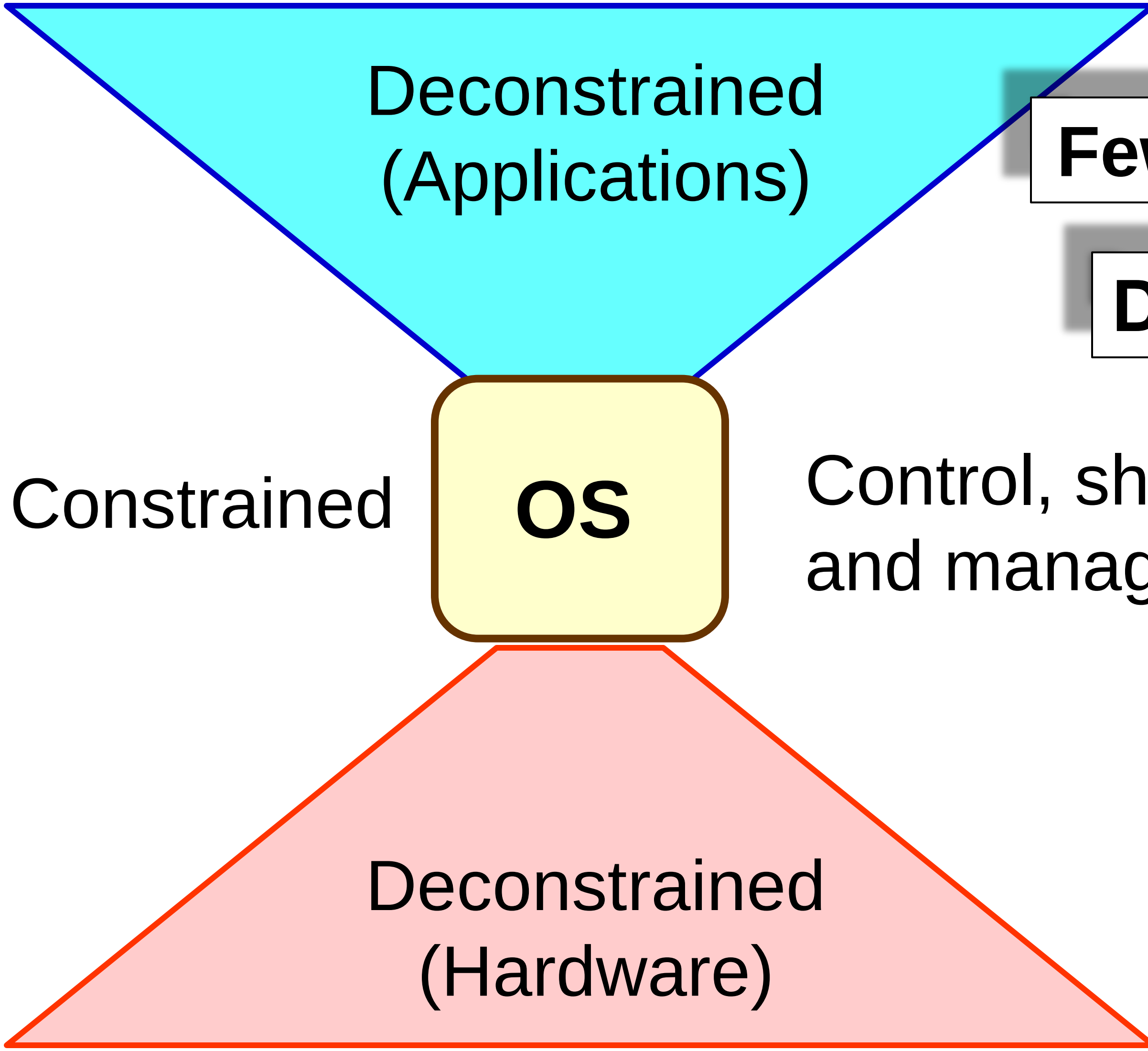


Layered architectures

Essentials

Few global variables

Don’t cross layers



Constrained

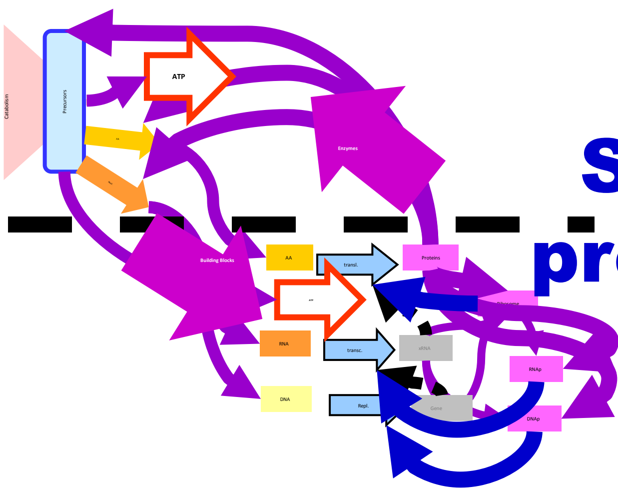
Control, share, virtualize, and manage resources

Processing
Memory
I/O

Layered architectures

Bacterial biosphere

Deconstrained (diverse) Environments

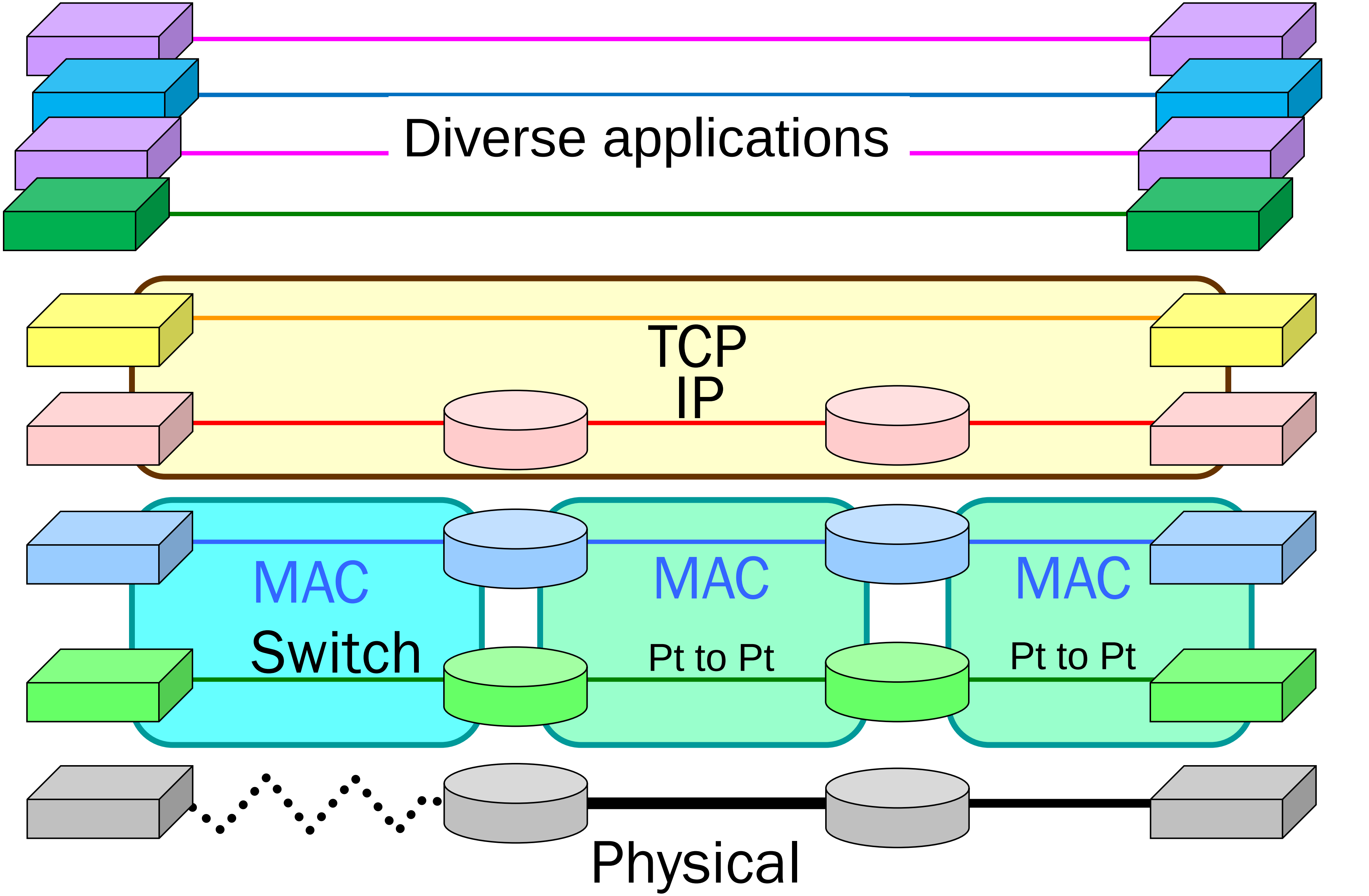


Shared protocols

Architecture = Constraints that Deconstrain

Deconstrained (diverse) Genomes

Layered architectures



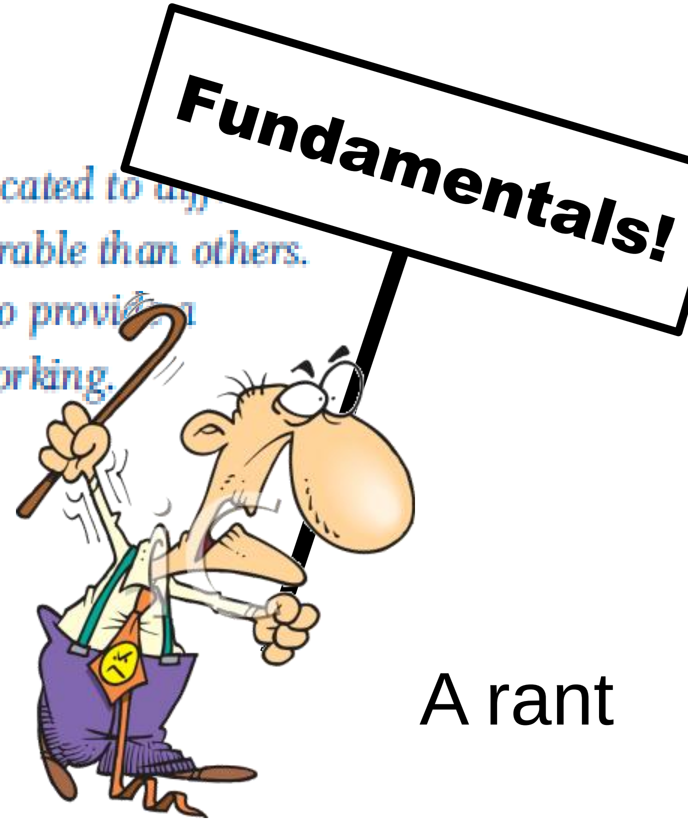
Proceedings of the IEEE, Jan 2007

OR optimization

Layering as Optimization Decomposition: A Mathematical Theory of Network Architectures

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

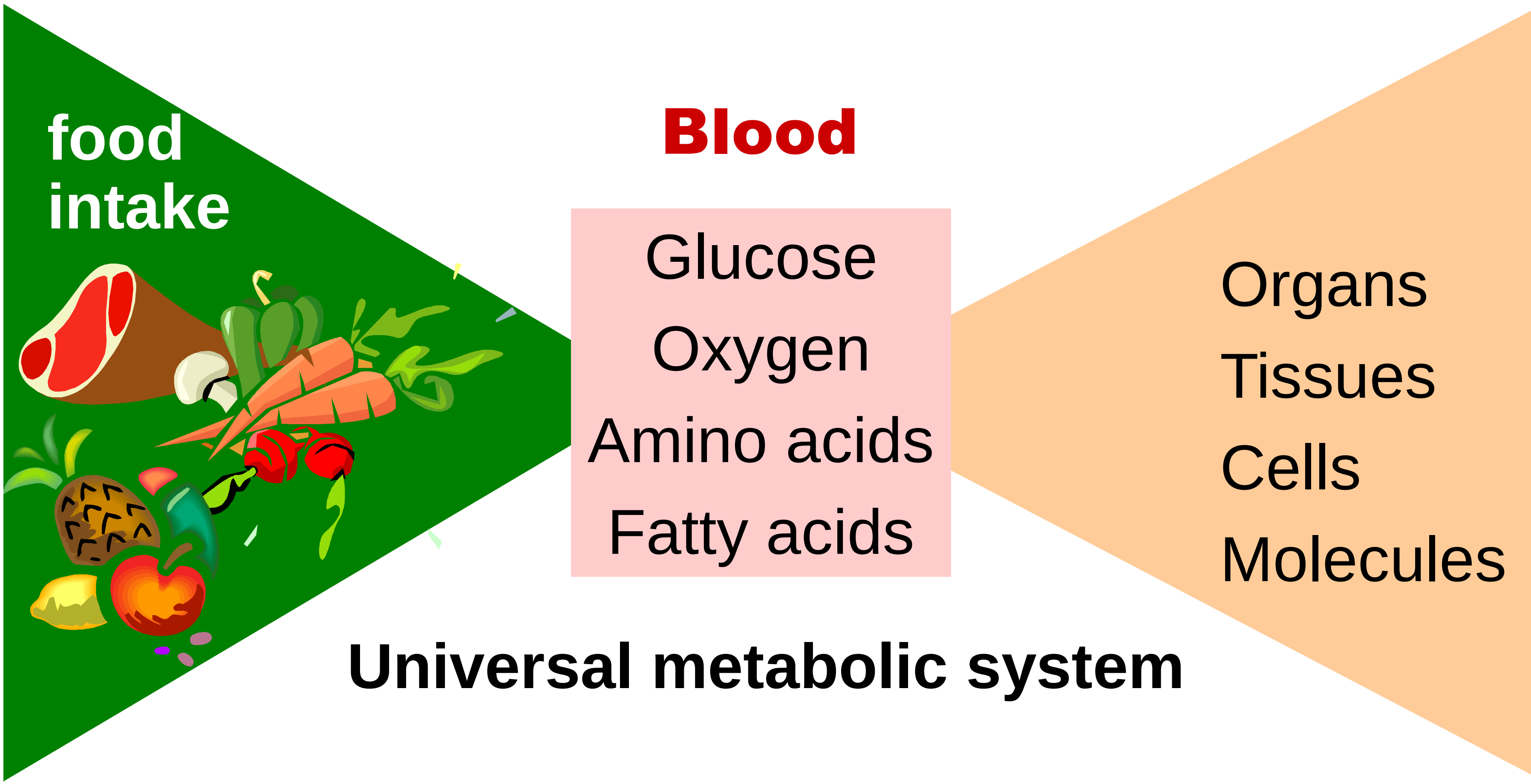
By MUNG CHIANG, *Member IEEE*, STEVEN H. LOW, *Senior Member IEEE*, A. ROBERT CALDERBANK, *Fellow IEEE*, AND JOHN C. DOYLE

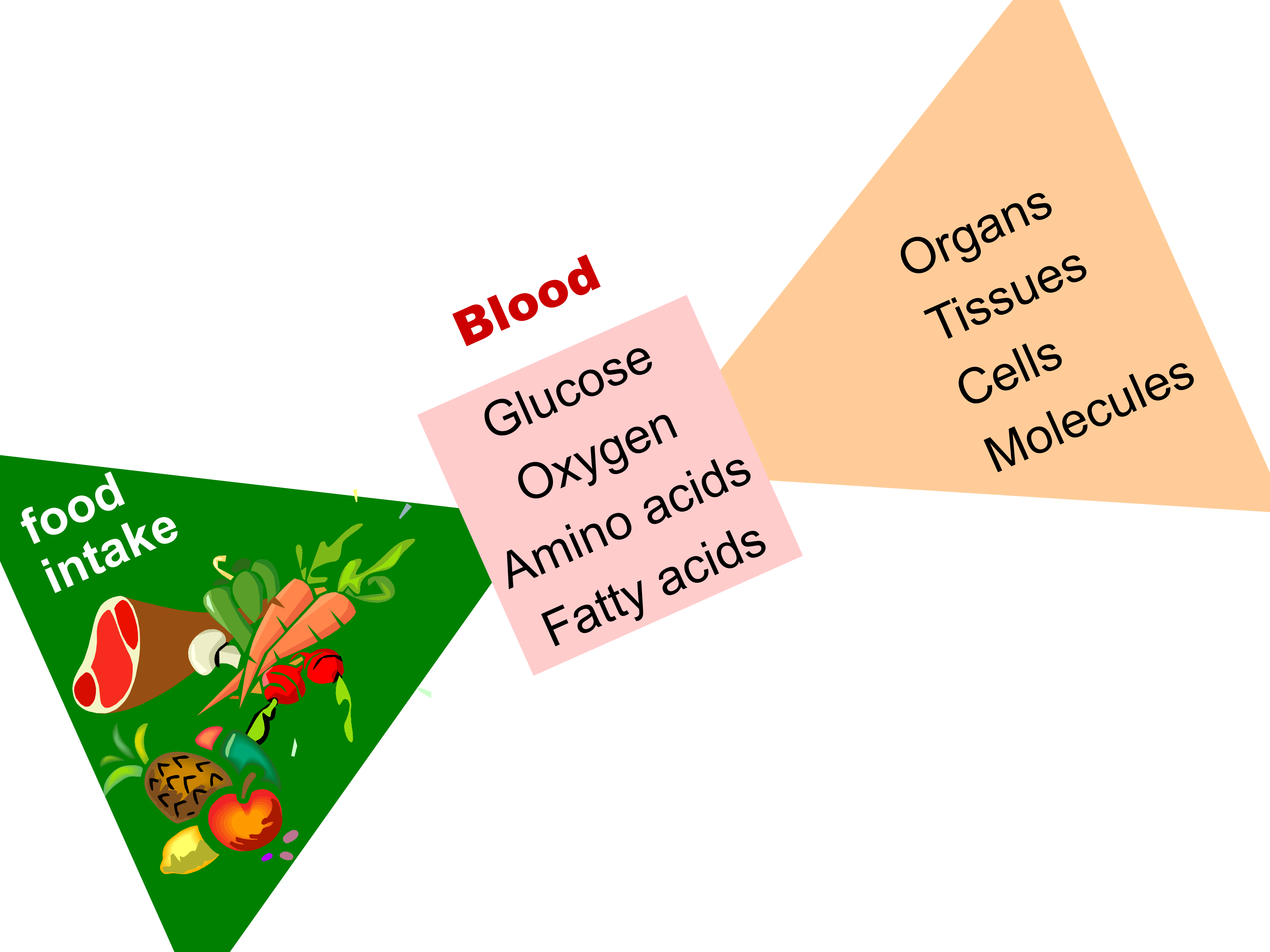


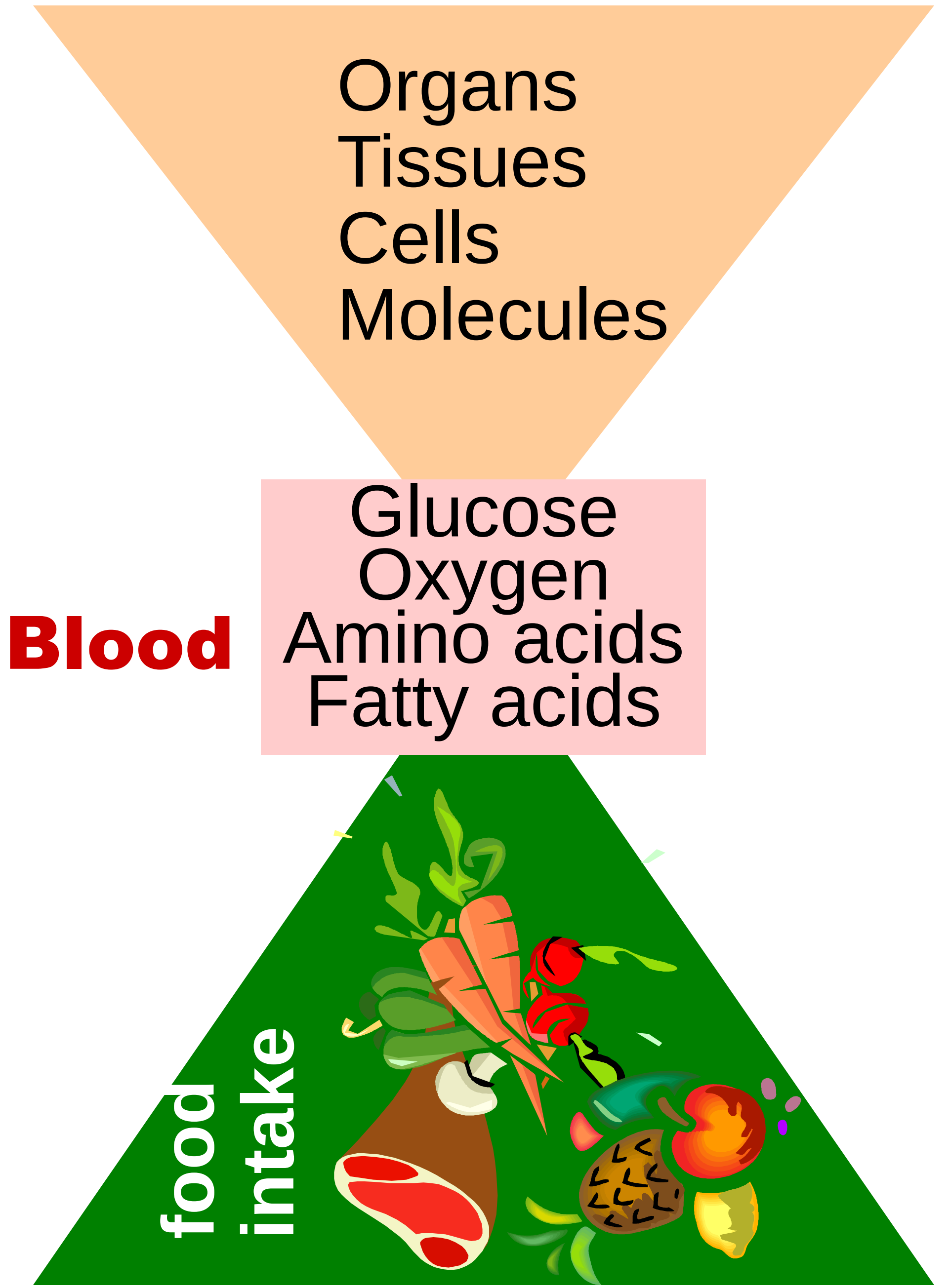
Chang, Low, Calderbank, Doyle

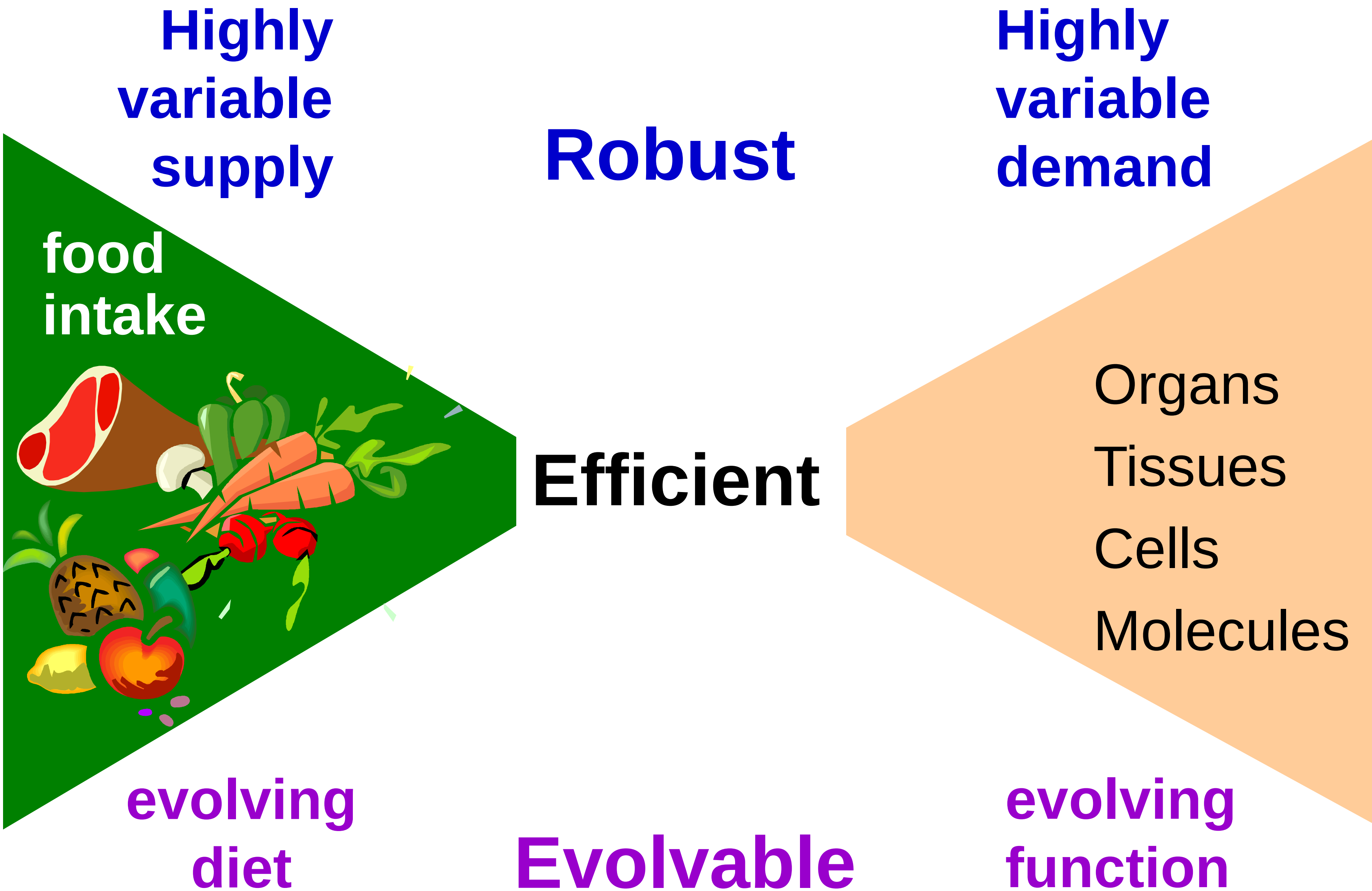
A rant

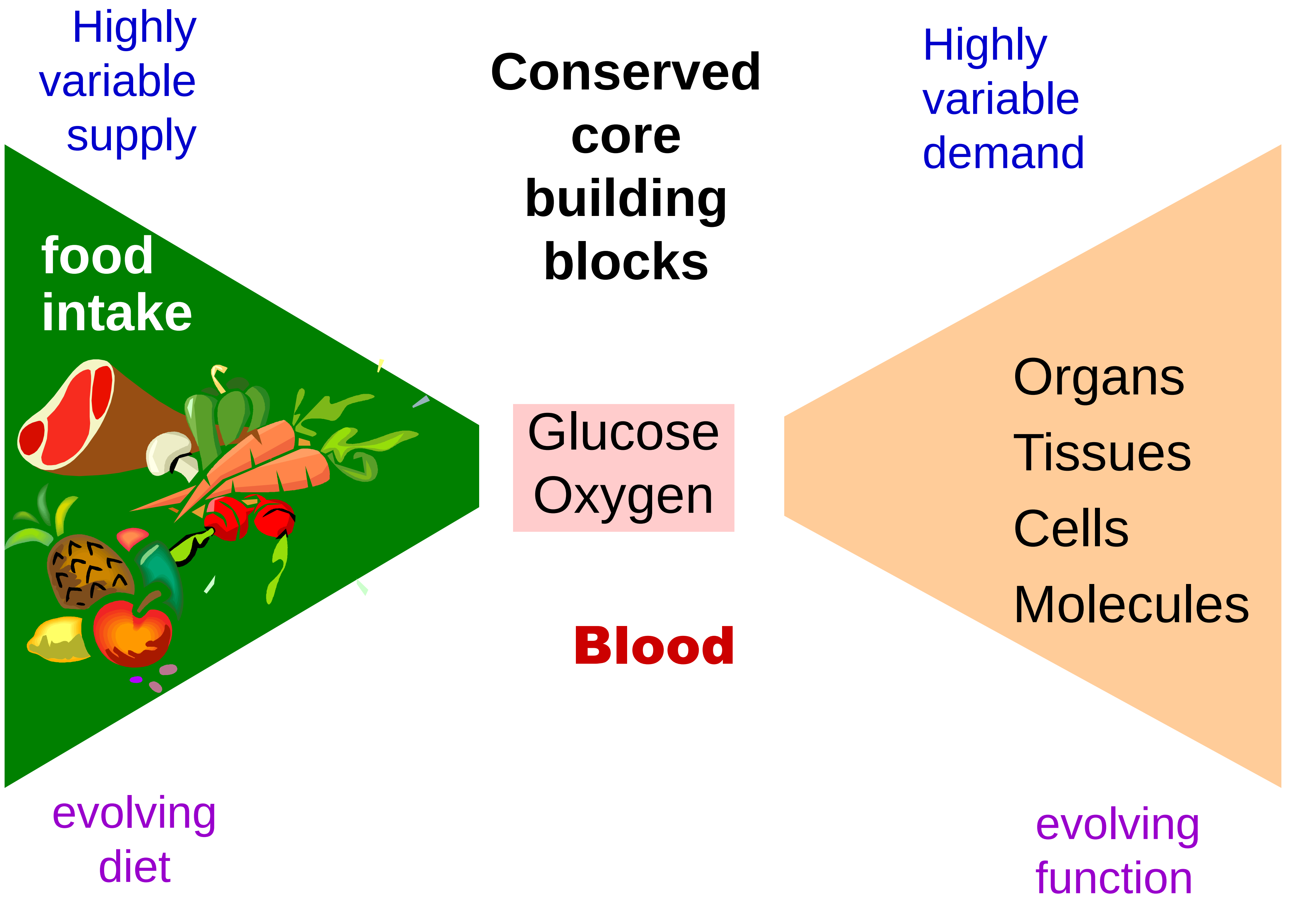
Peter Sterling and Allostasis



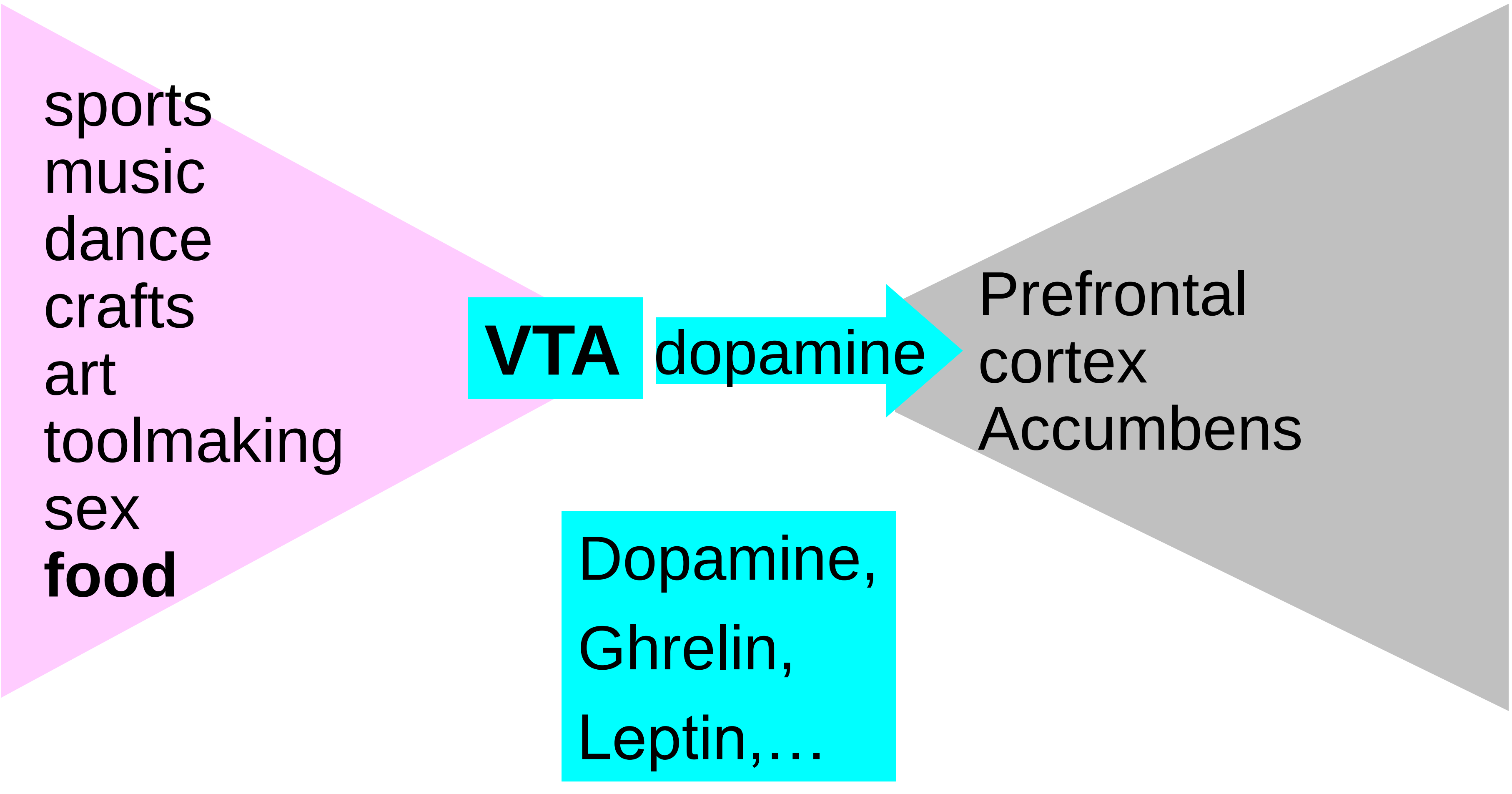

food
intake
Blood
Glucose
Oxygen
Amino acids
Fatty acids
Organs
Tissues
Cells
Molecules


Organs
Tissues
Cells
Molecules
Glucose
Oxygen
Amino acids
Fatty acids
Blood
food
intake

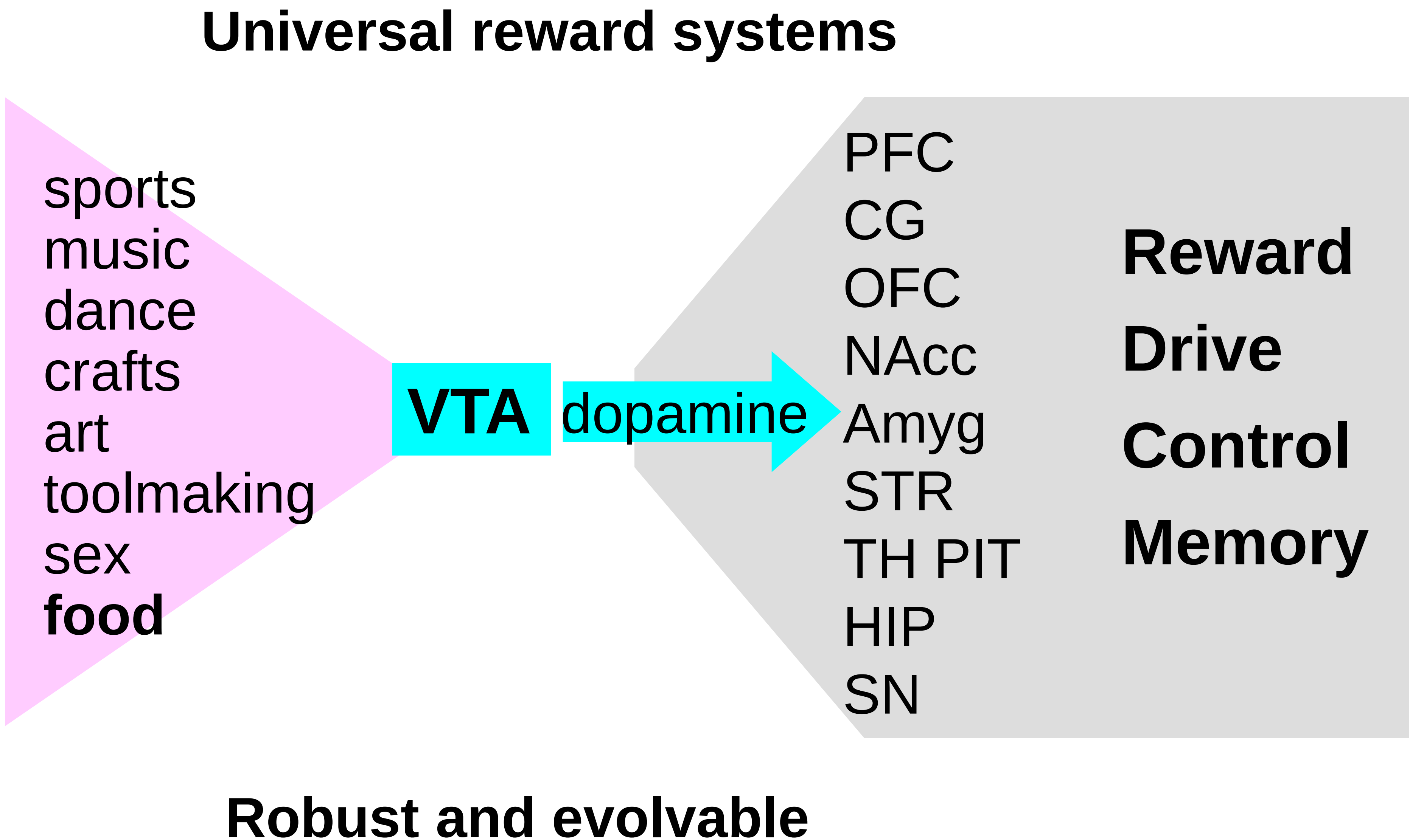

Highly variable supply
Robust
Highly variable demand
food intake
Efficient
Organs
Tissues
Cells
Molecules
evolving diet
Evolvable
evolving function

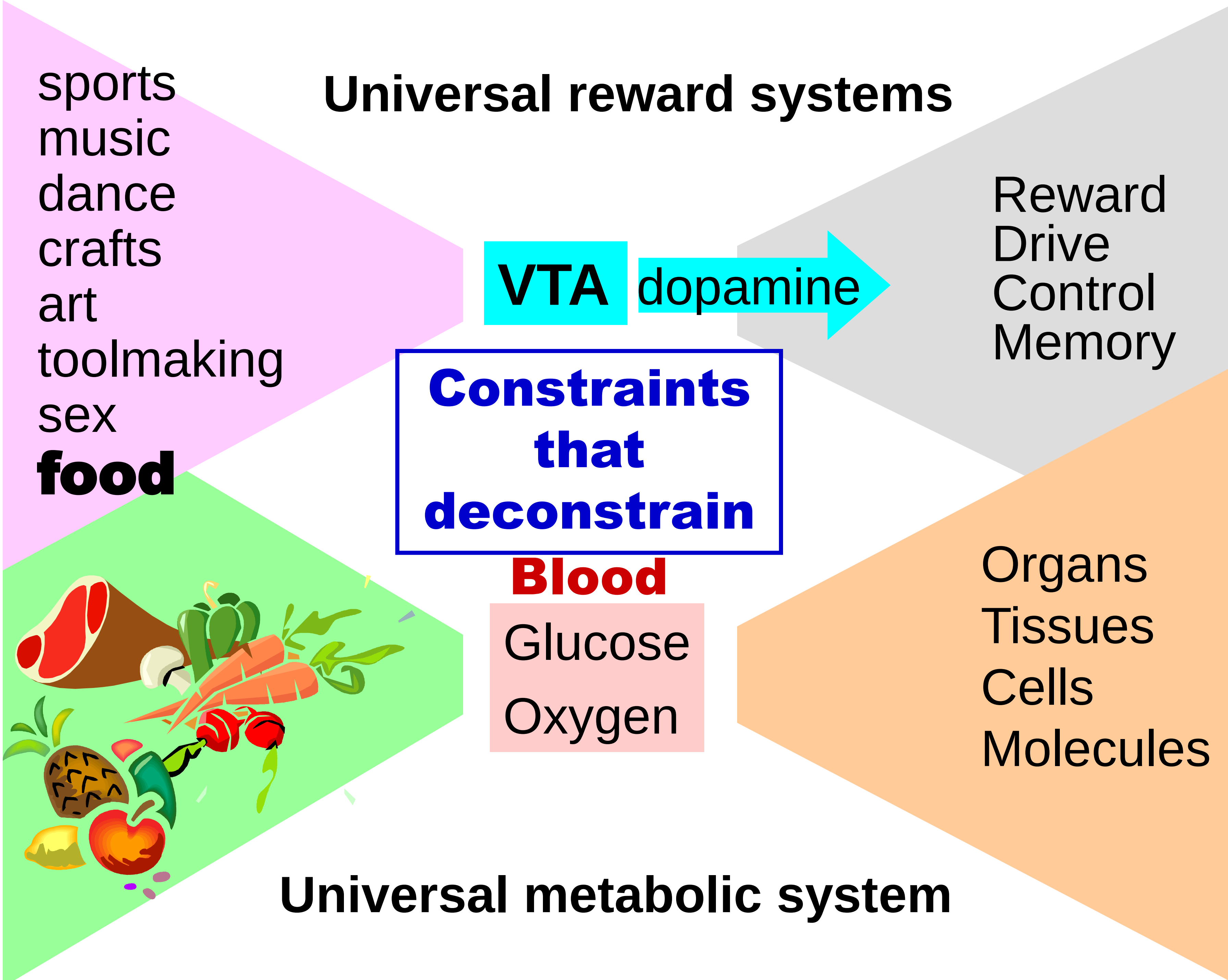

Highly variable supply
Conserved core building blocks
Highly variable demand
food intake
Glucose
Oxygen
Organs
Tissues
Cells
Molecules
Blood
evolving diet
evolving function

Universal reward systems



Ridiculous oversimplification


Universal reward systems
sports
music
dance
crafts
art
toolmaking
sex
food
VTA
dopamine
PFC
CG
OFC
NAcc
Amyg
STR
TH PIT
HIP
SN
Reward
Drive
Control
Memory
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

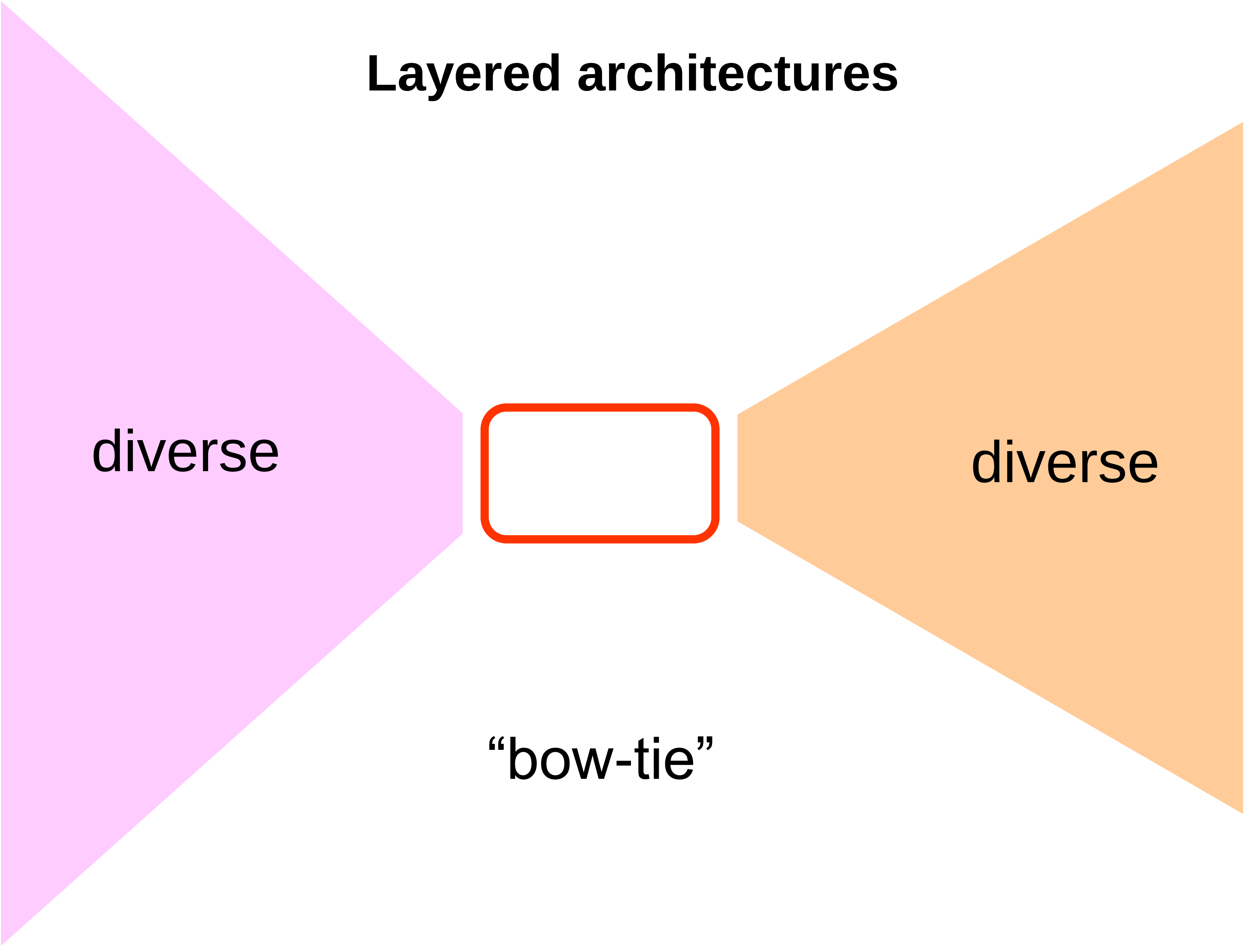
sports
music
dance
crafts
art
toolmaking
sex
food

that deconstrain

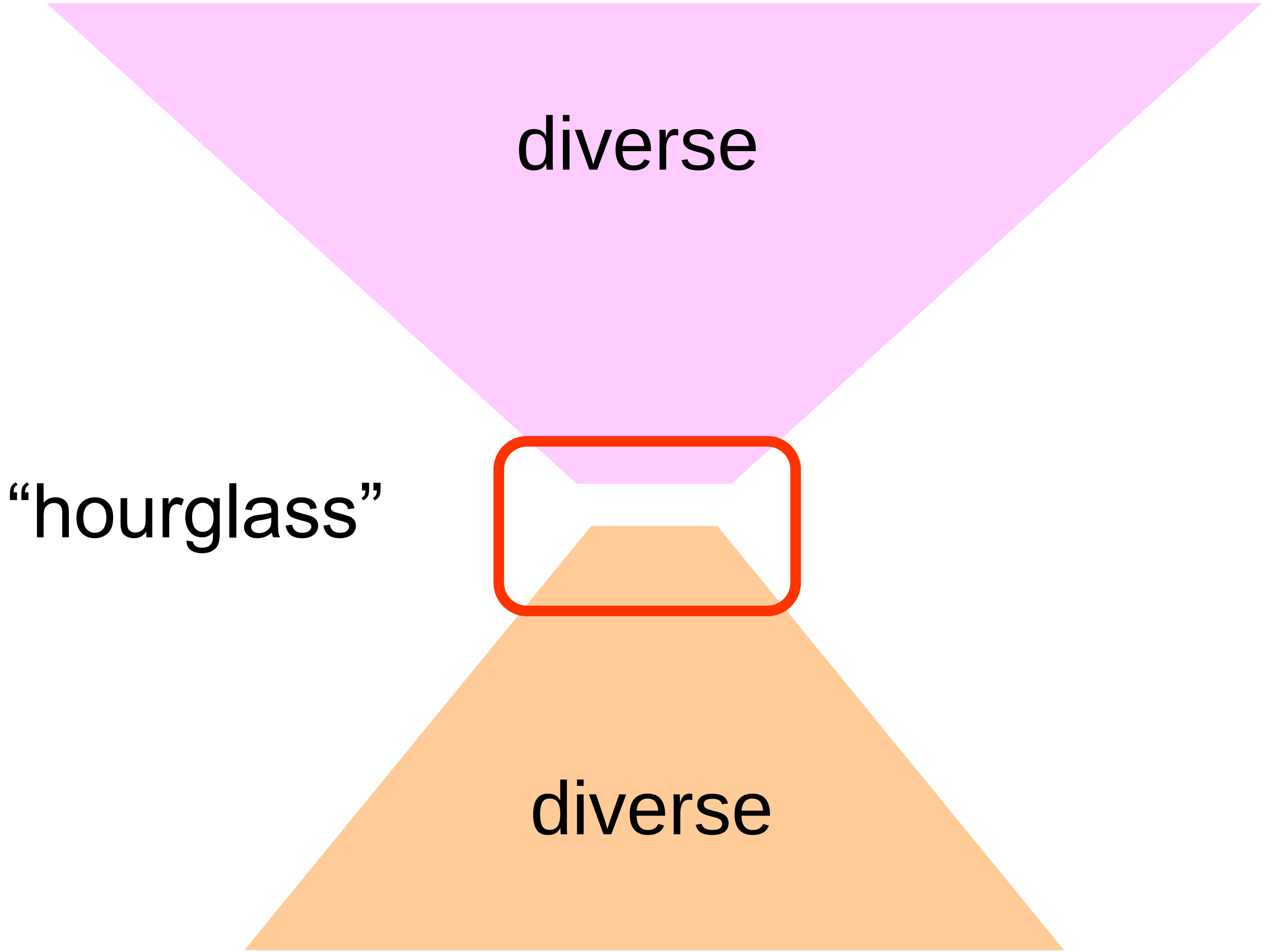
Reward
Drive
Control
Memory

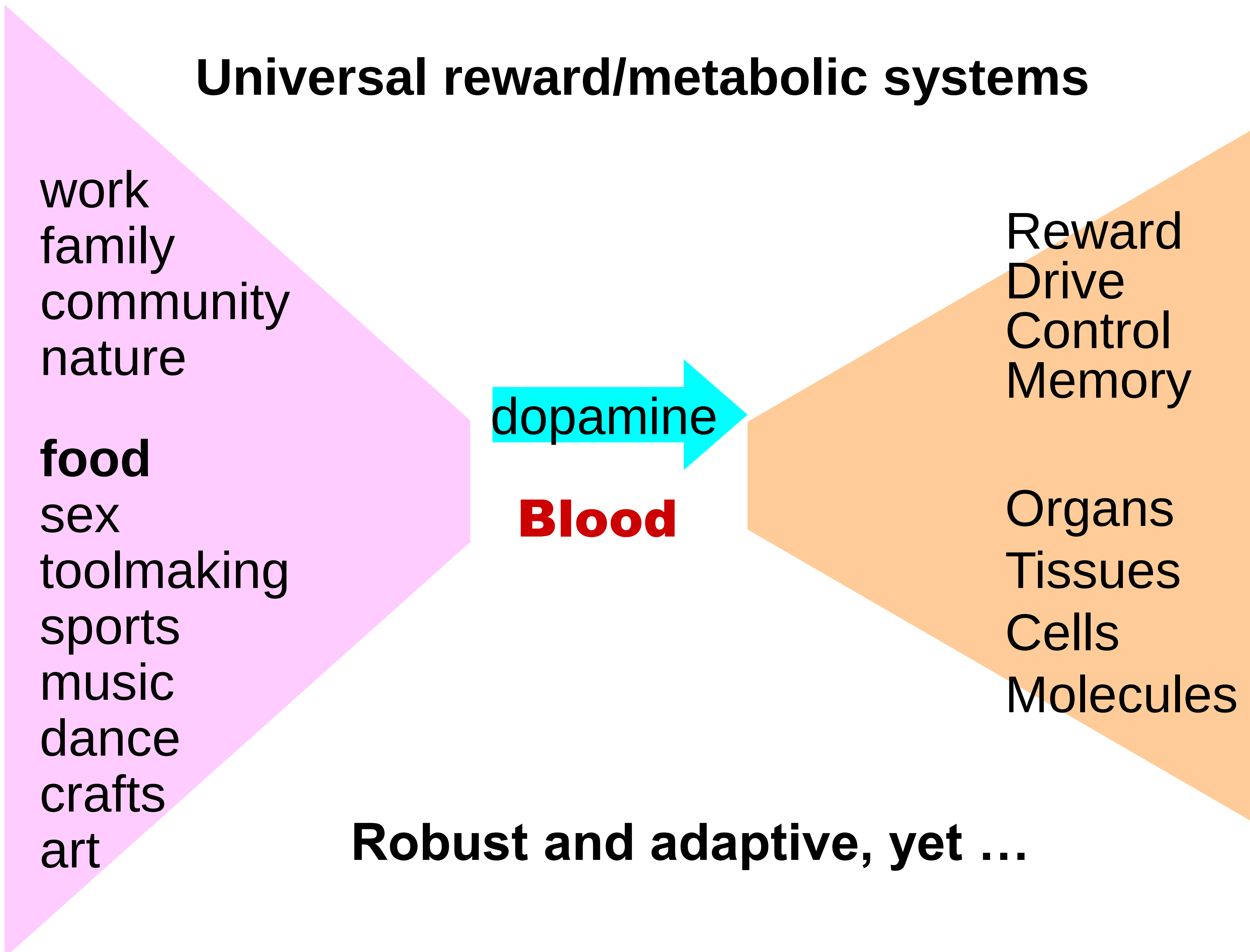
Organs
Tissues
Cells
Molecules

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”

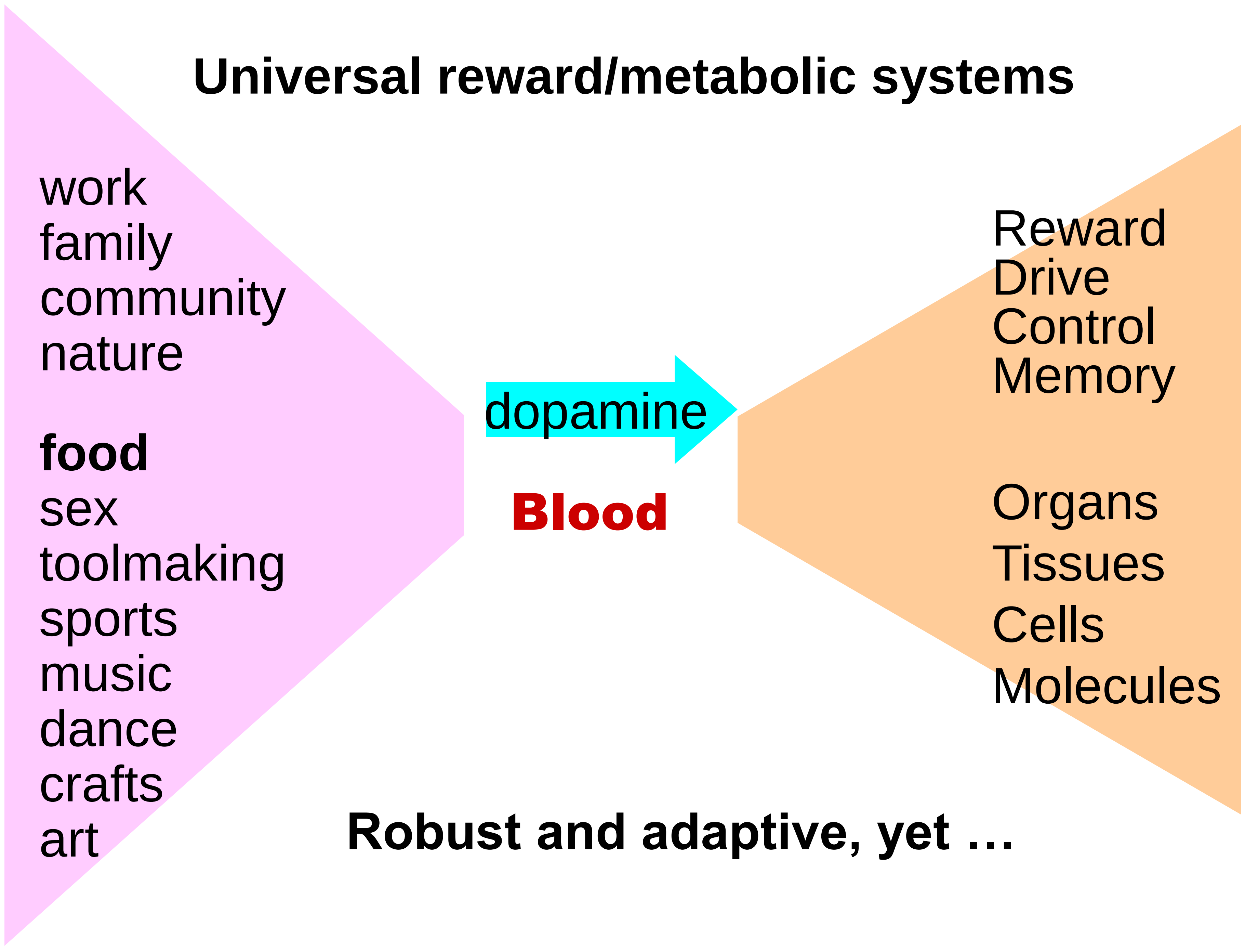
Modularity 2.0

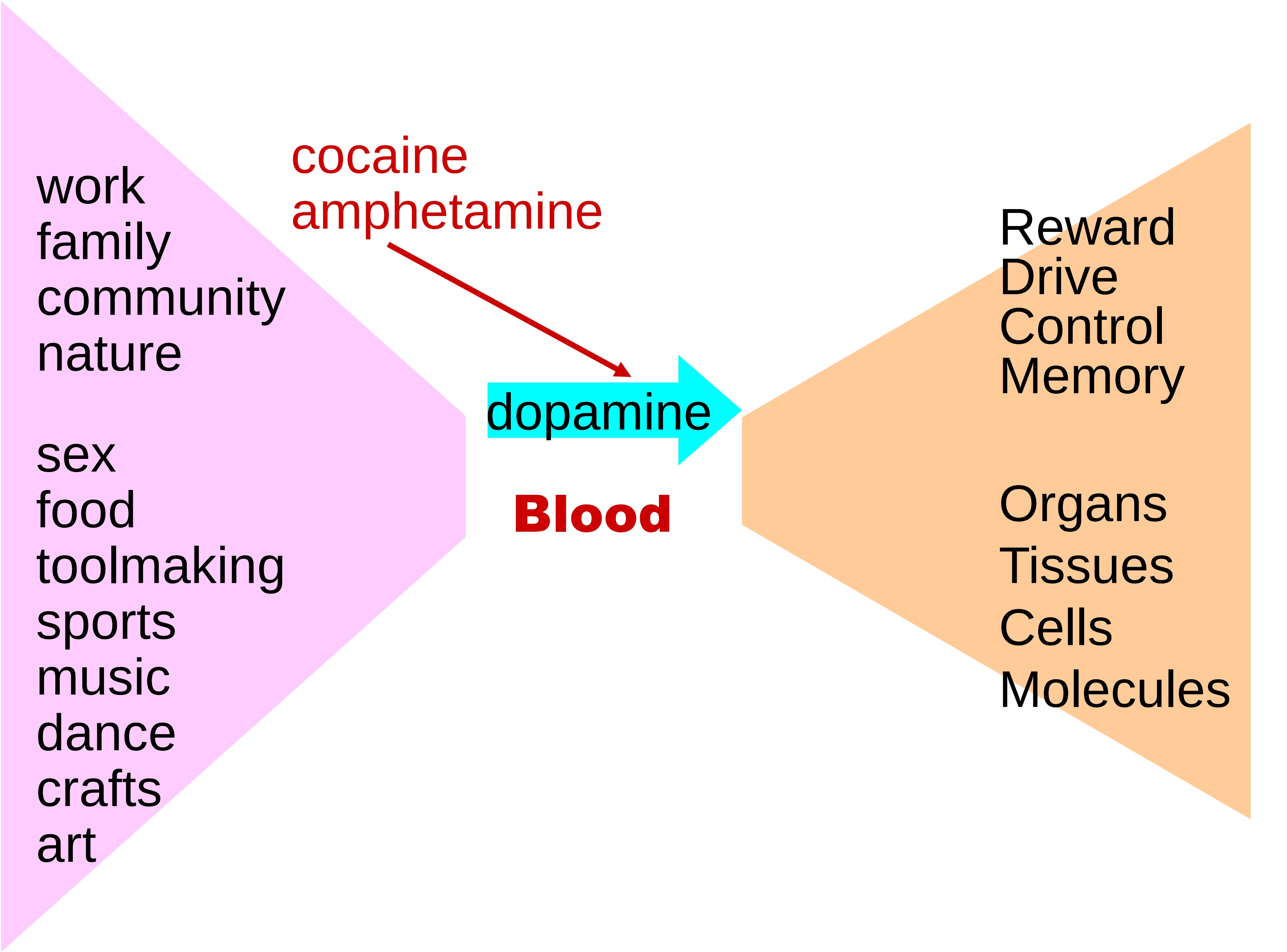
Most important “modules”

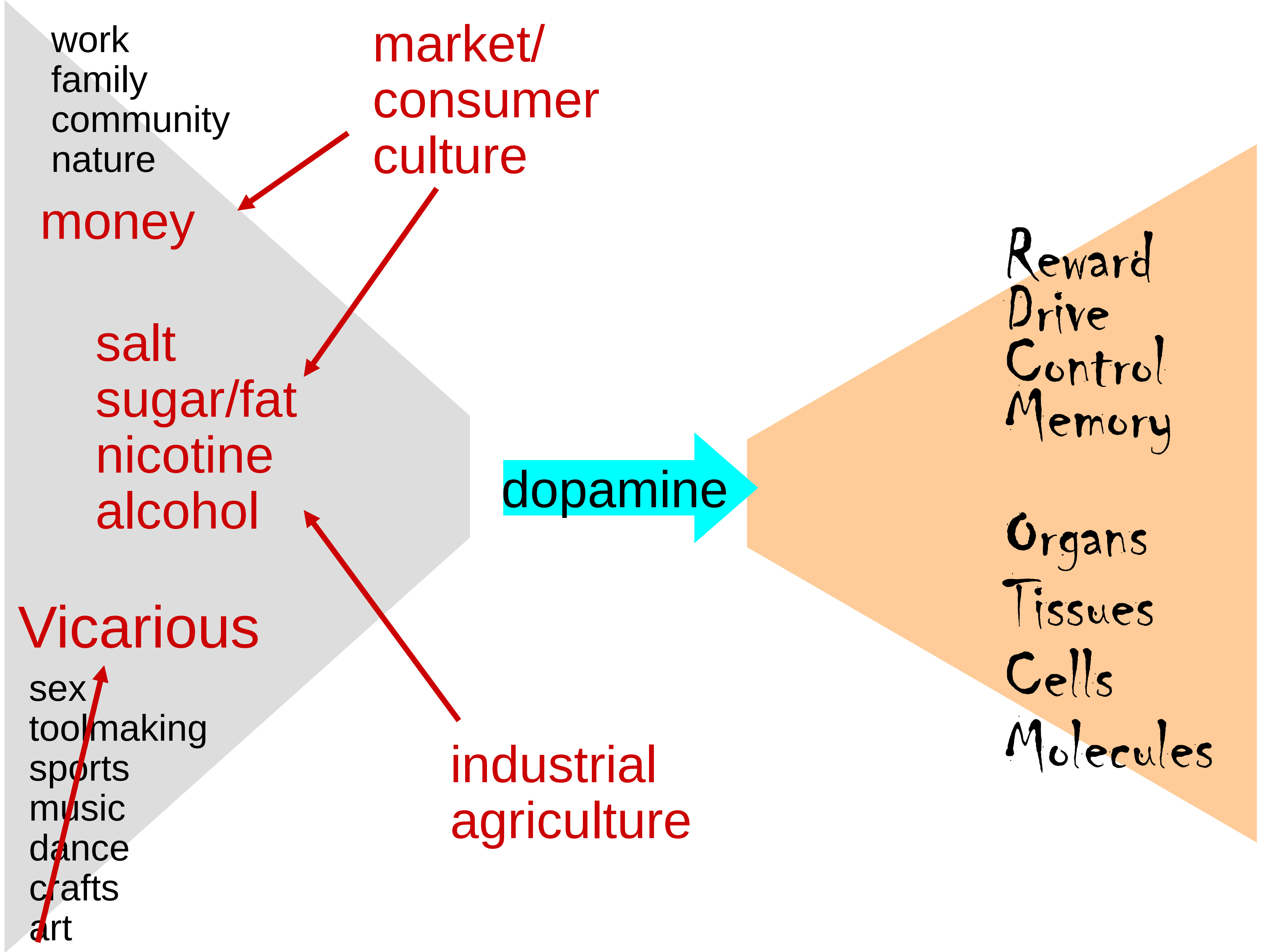
dopamine

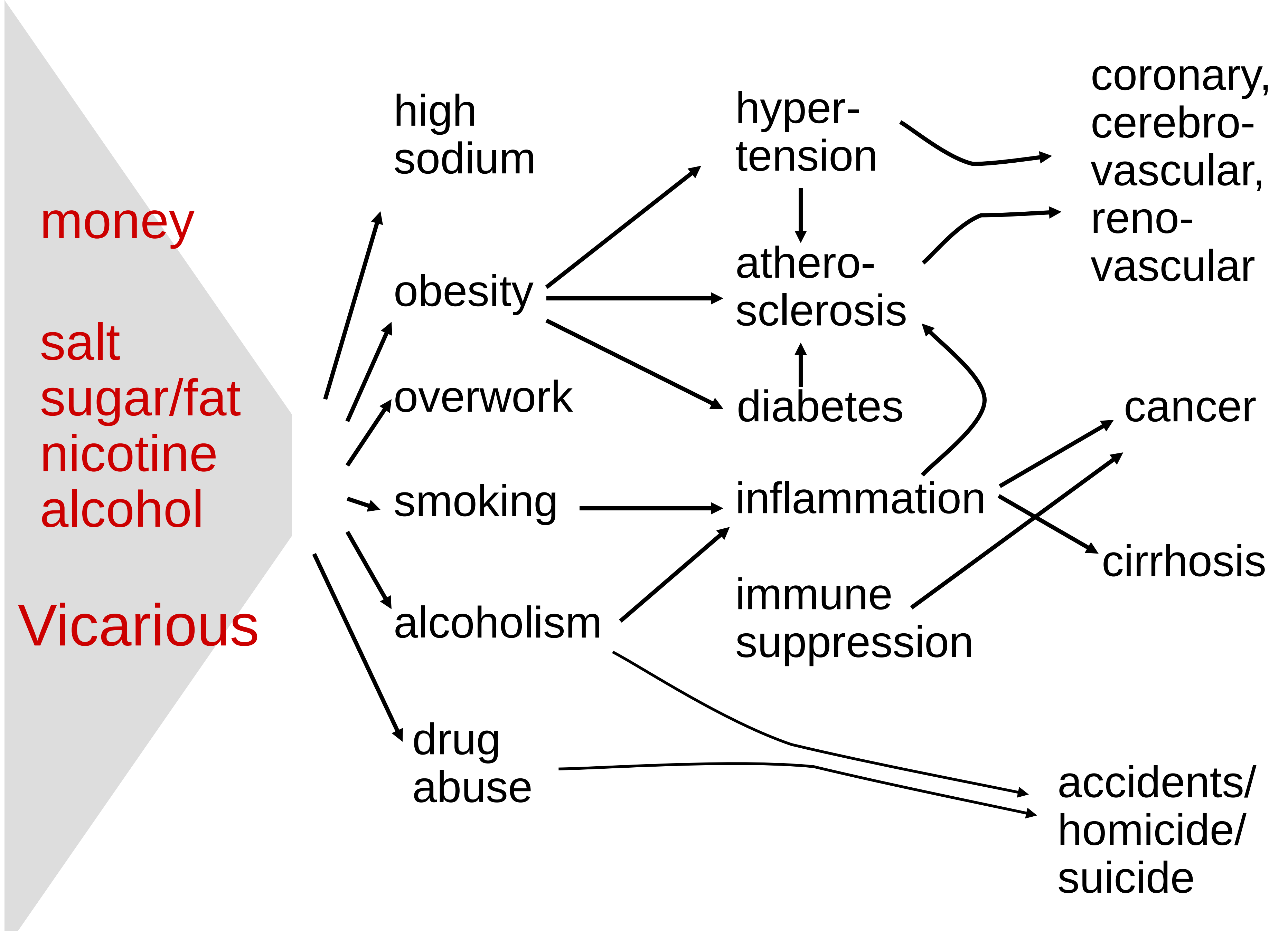
Blood

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

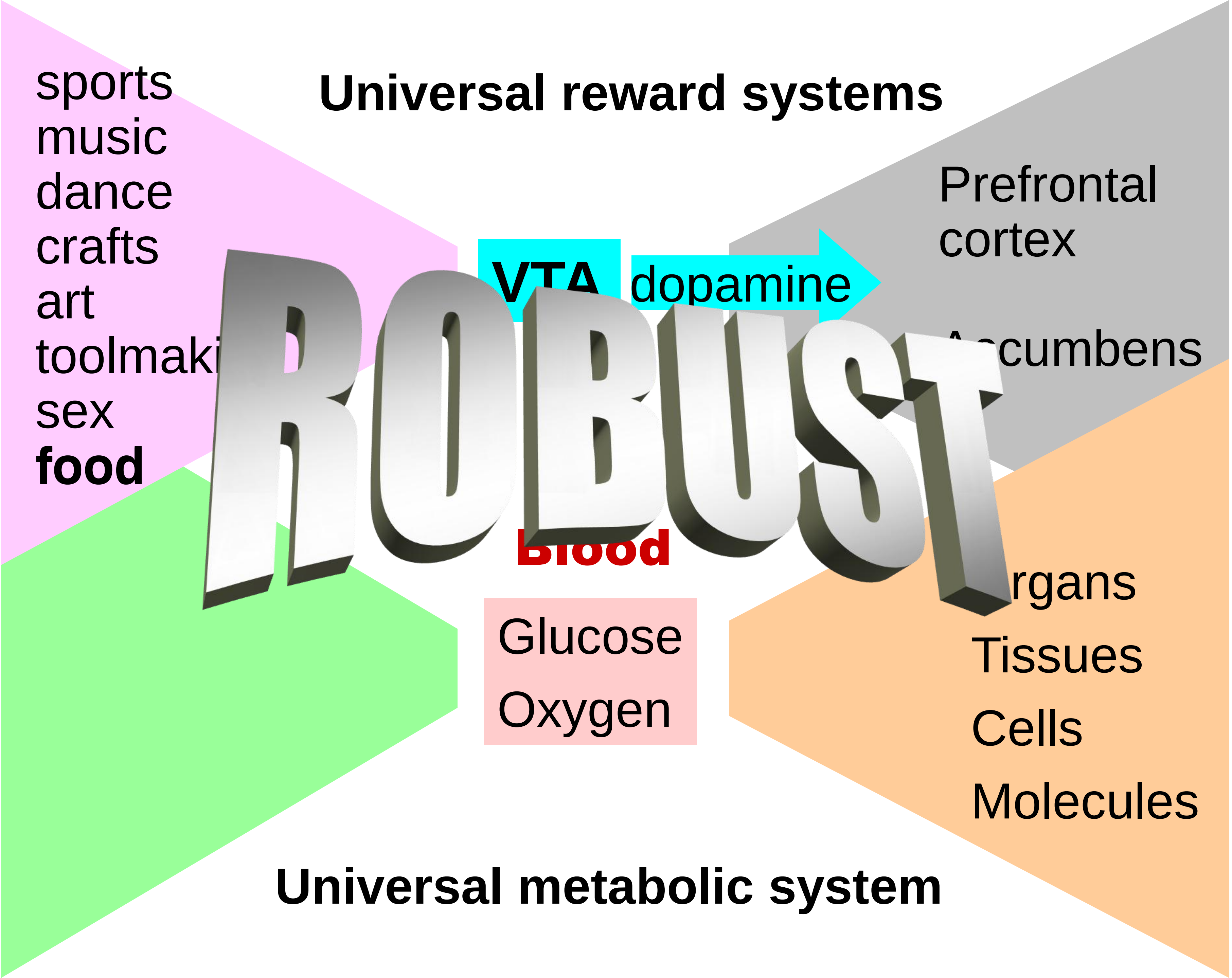

Universal reward/metabolic systems
work
family
community
nature
food
sex
toolmaking
sports
music
dance
crafts
art
dopamine
Blood
Reward
Drive
Control
Memory
Organs
Tissues
Cells
Molecules
Robust and adaptive, yet …

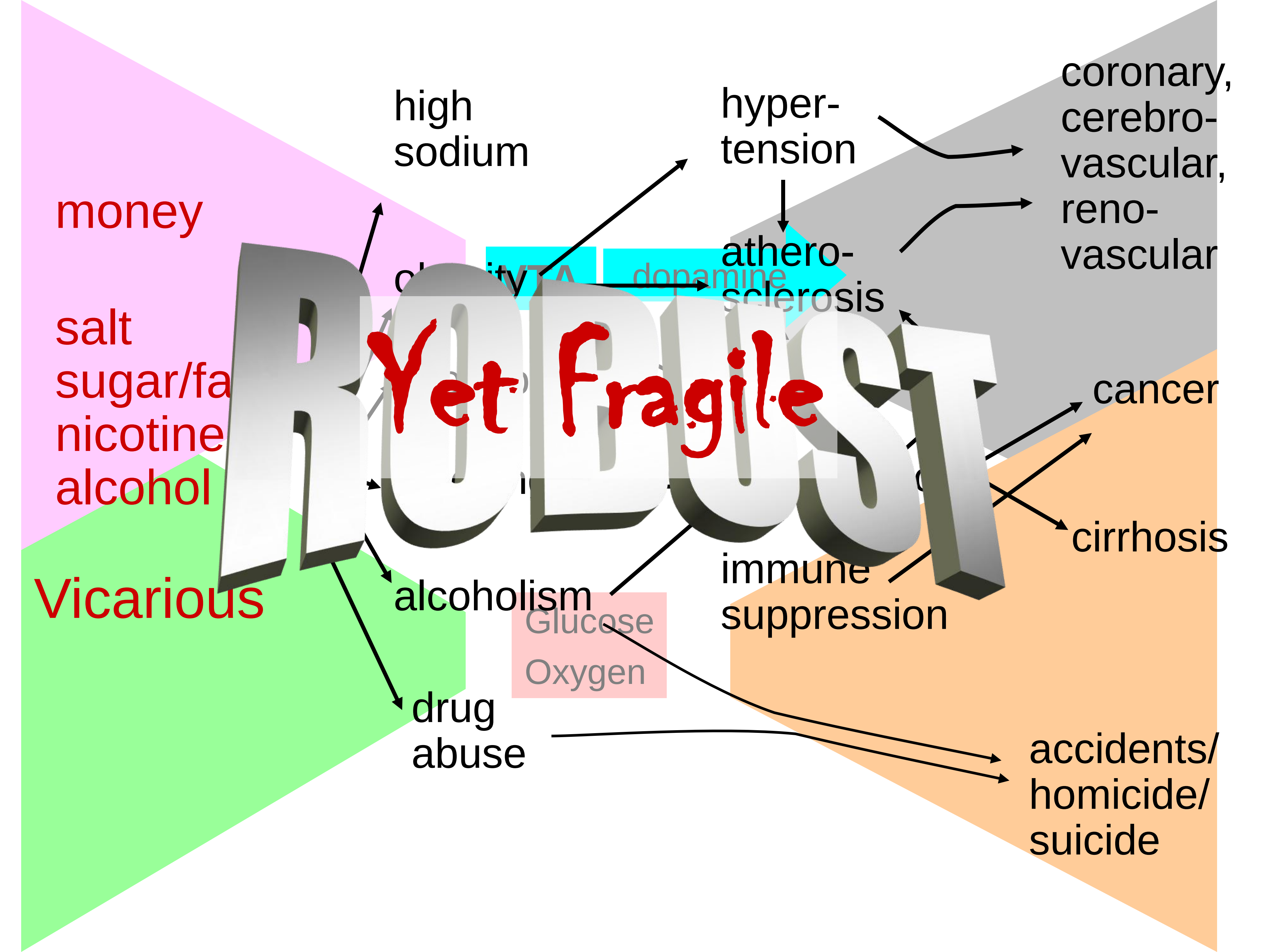

work
family
community
nature
sex
food
toolmaking
sports
music
dance
crafts
art
cocaine
amphetamine
dopamine
Blood
Reward
Drive
Control
Memory
Organs
Tissues
Cells
Molecules


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



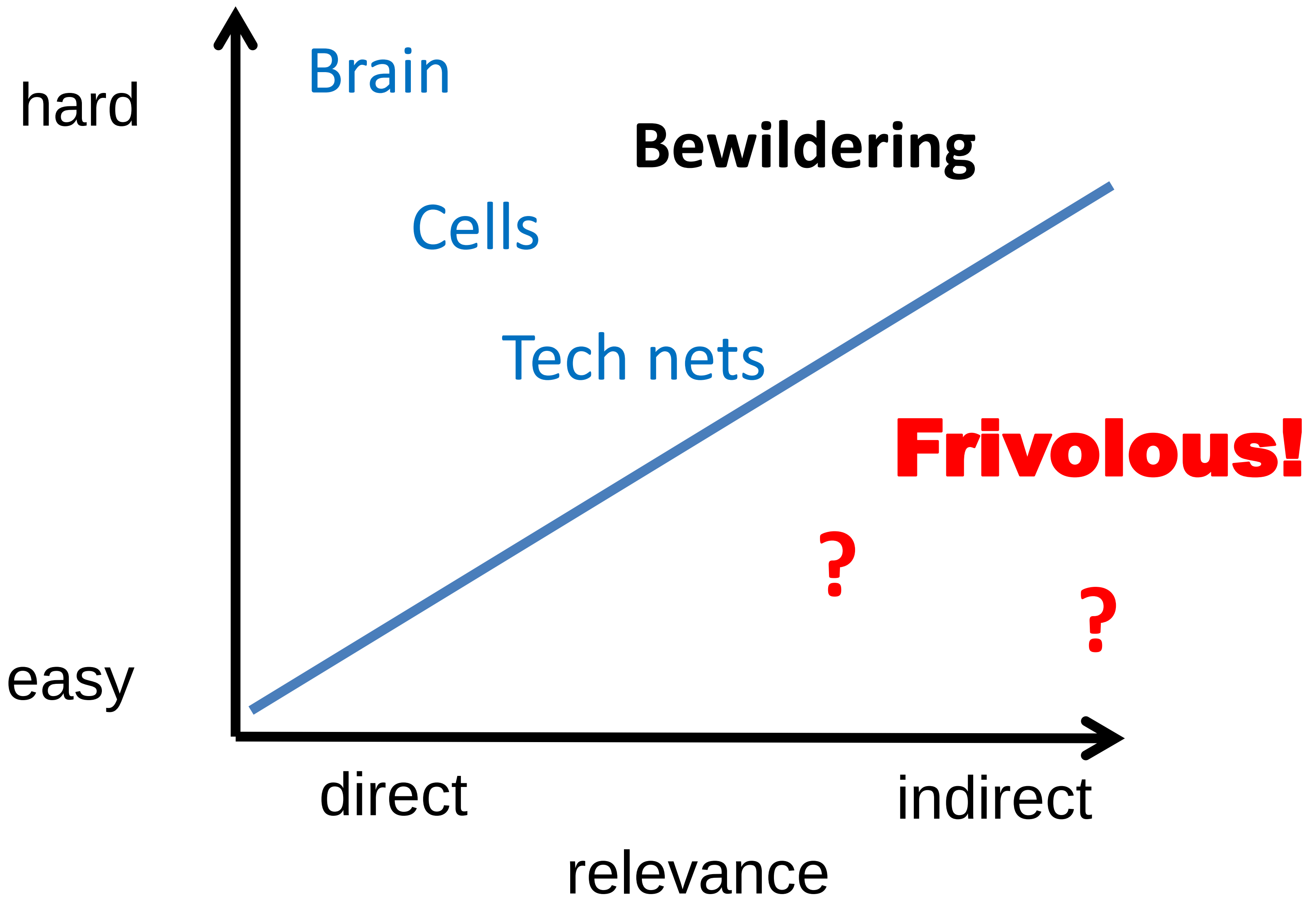
From Sterling


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



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

3. Universal architecture
4. Practical implementation




FASHION WARS
NEW YORK SPRING 2009
Garments
Cloth
Thread
Fiber
Frivolous!

Other examples

Words

Lego

Clothing

Cell biology

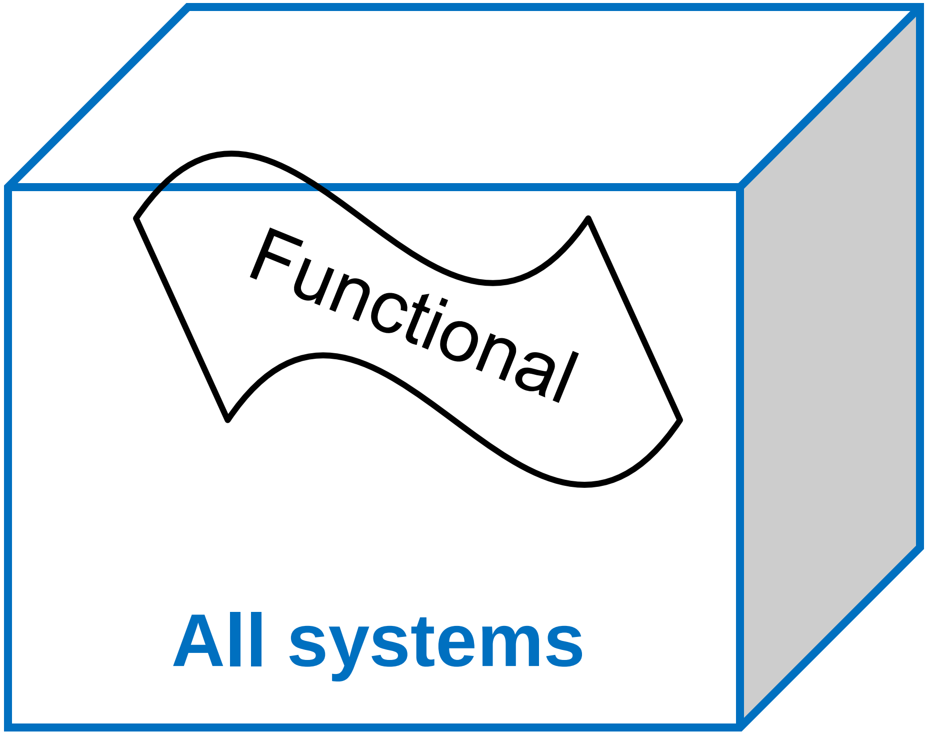
Internet

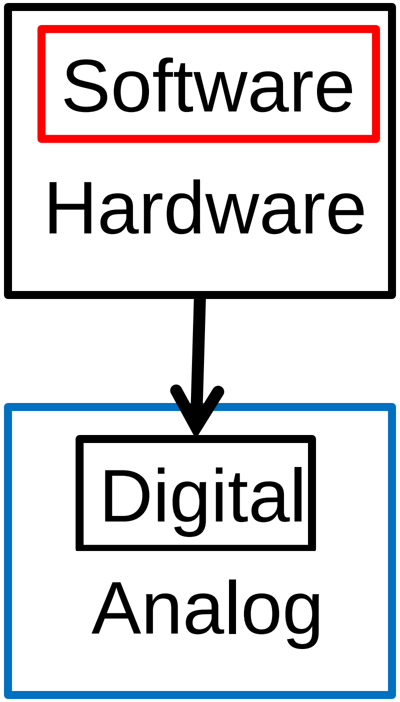
Cyberphysical

Money

“solution sets” (a la Marder, Prinze, etc)

large, thin, nonconvex





Letters and words

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

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

large **thin**

Computer programs

- Almost any computer language
- Large # of working programs
- Much larger # of non-working programs
- "Nonconvex" = simple mashups of working programs don't work

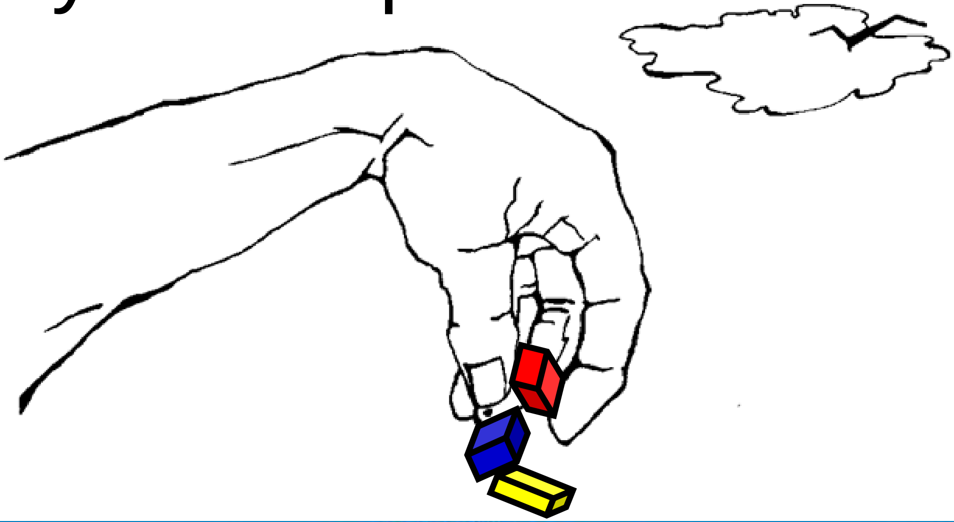
1 << (# programs) << (# non-programs)

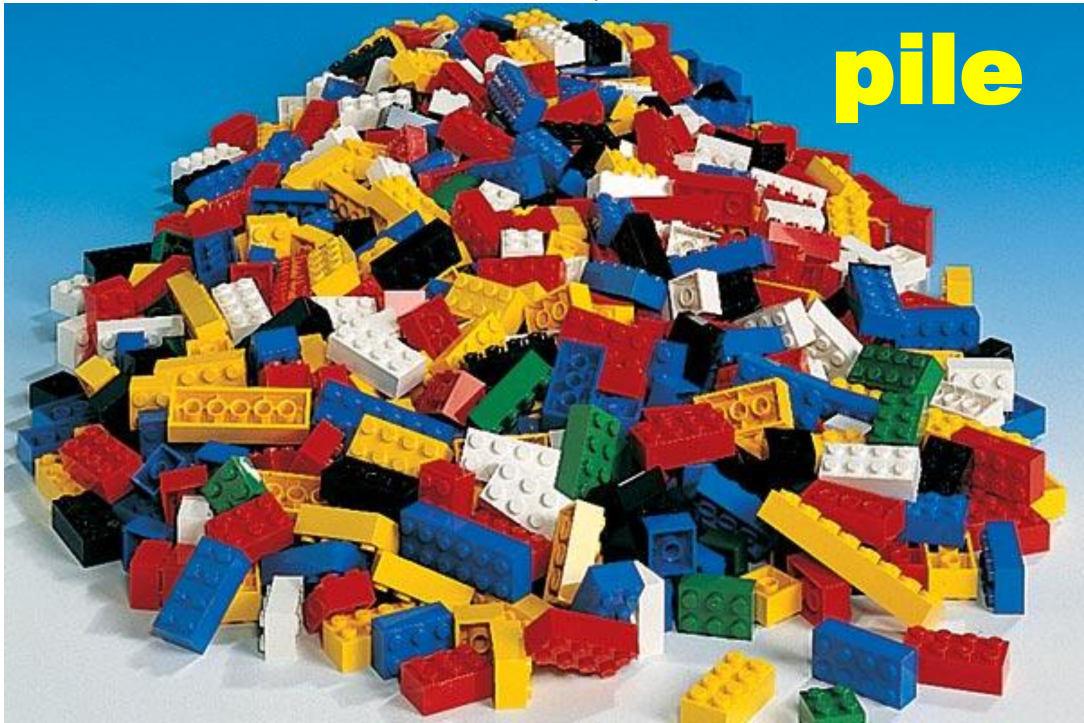
large **thin**

large thin

1 << # toys << # piles

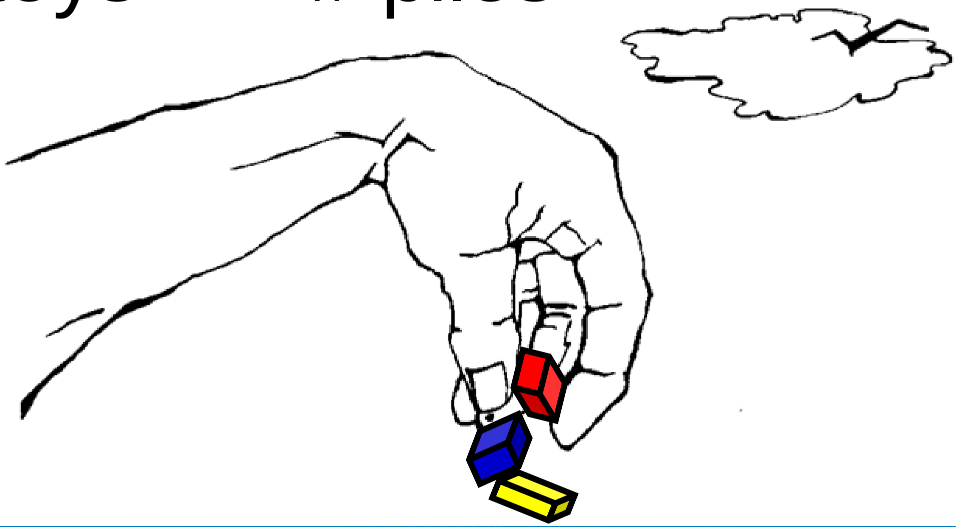
toys





large thin

1 << # toys << # piles



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

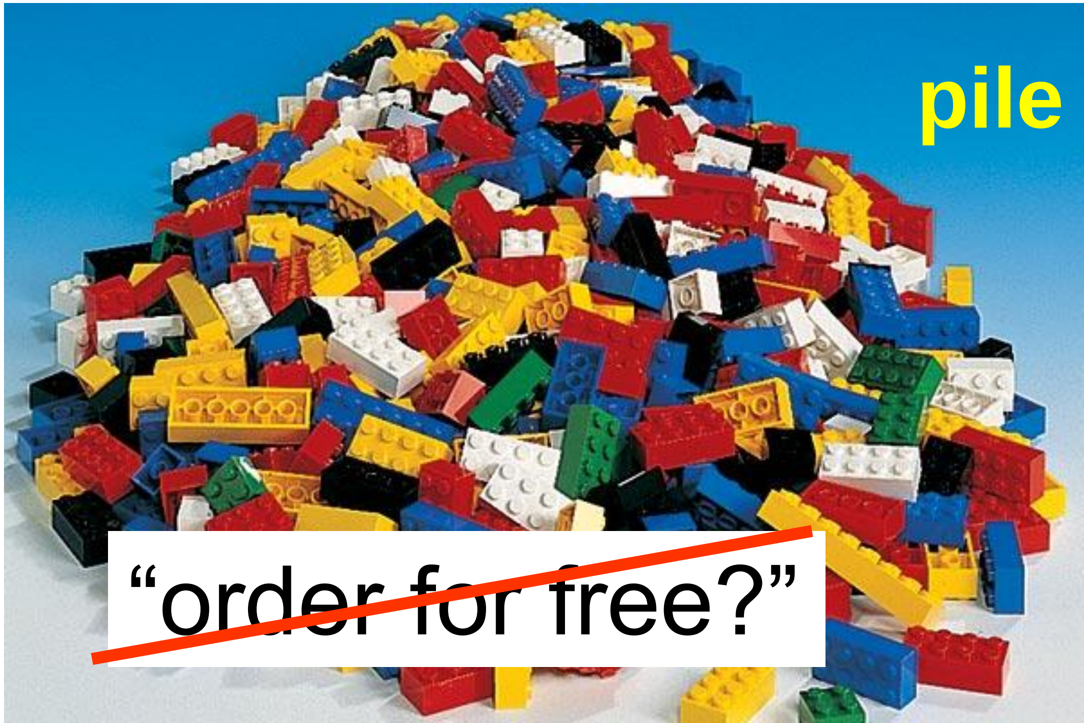
statistical physics
random ensembles
minimally tuned
phase transitions
bifurcations

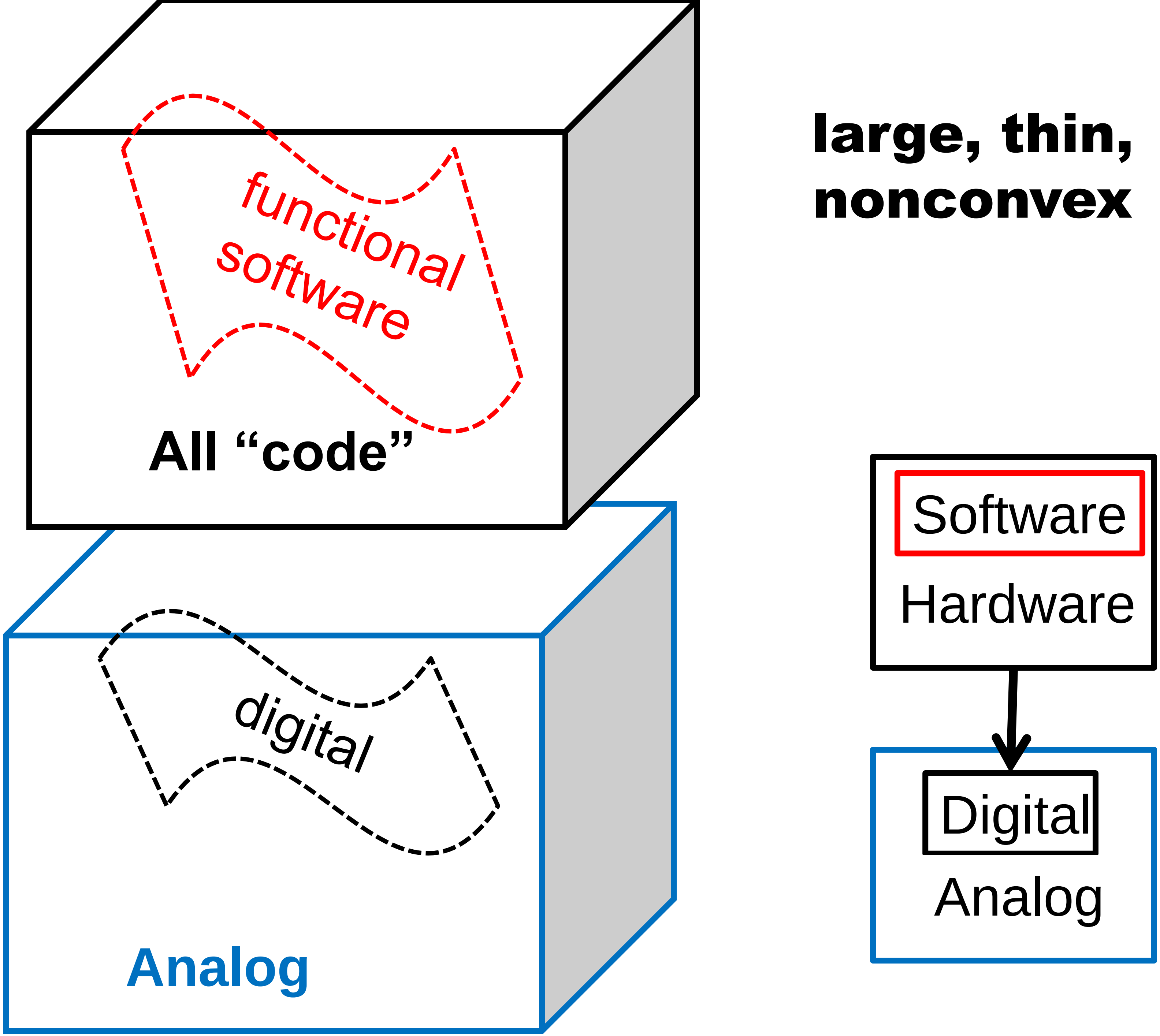
large **thin**

1 << # toys << # piles

nonconvex

toys




functional software
All "code"
digital
Analog
large, thin, nonconvex
Software
Hardware
Digital
Analog

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.

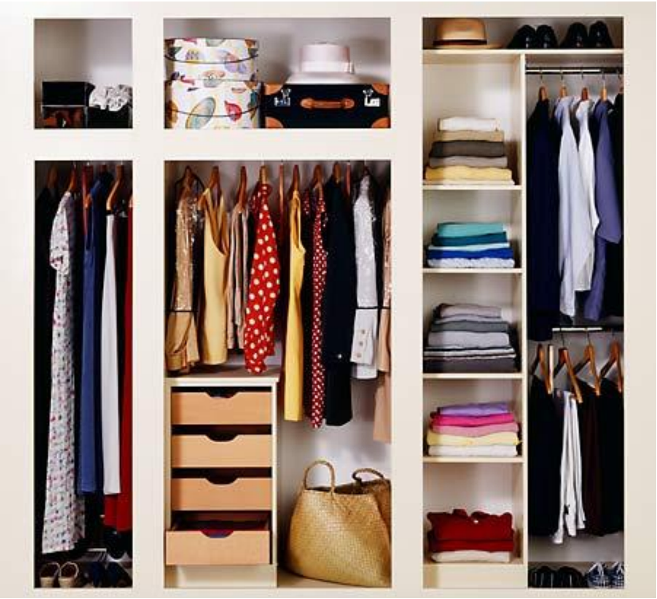
ty in components or the

Biologists and biophy
ing complex networks ofte
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 advan

Csete and Doyle

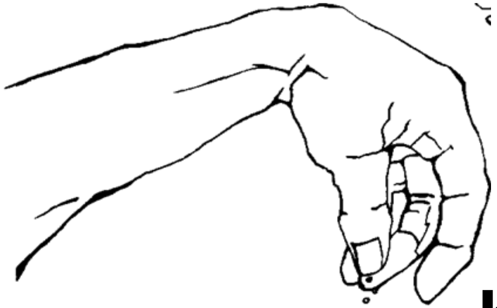
1 MARCH 2002 VOL 295 SCIENCE www.sciencemag.org

wardrobe



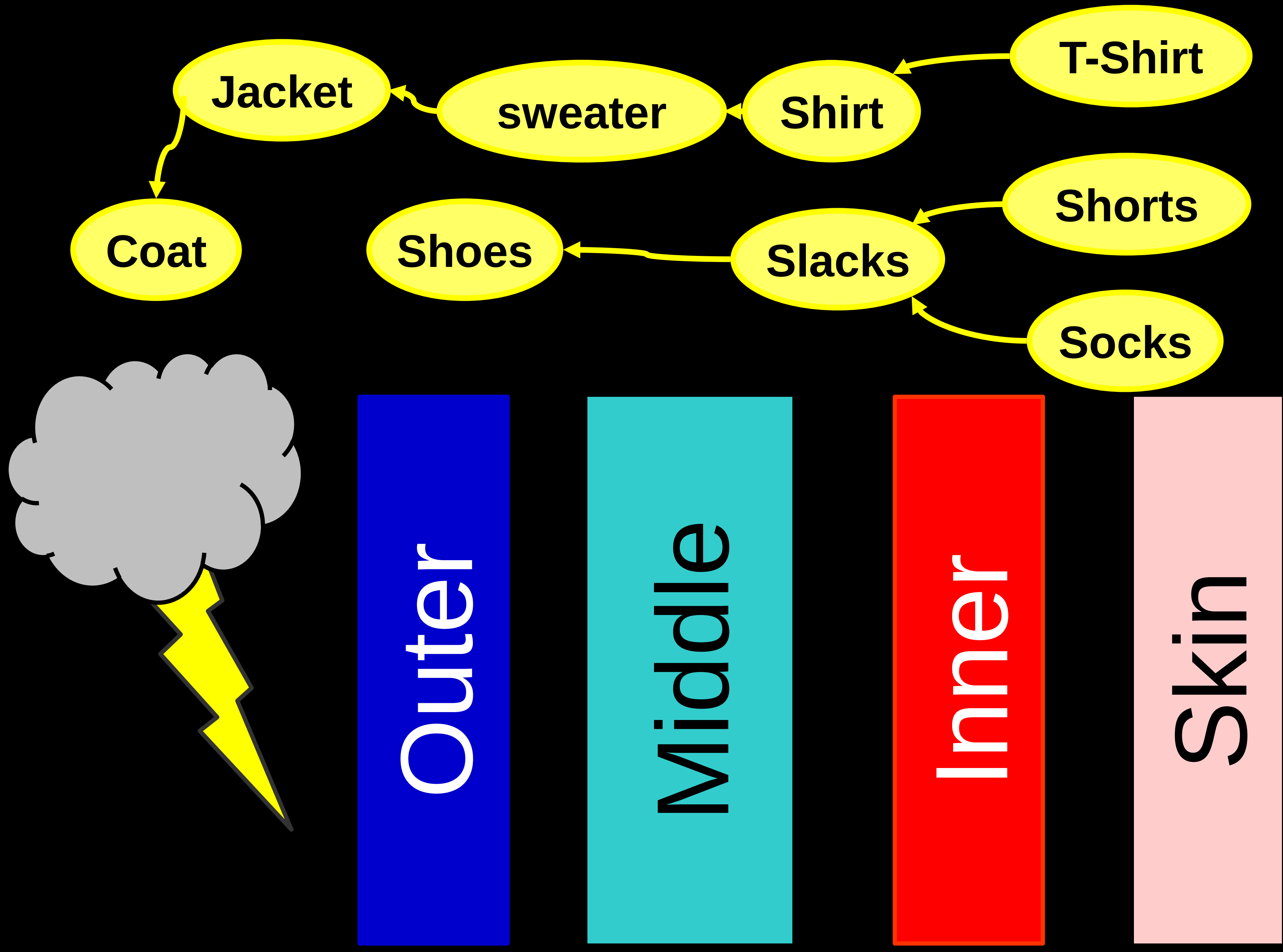
large **thin**

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



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

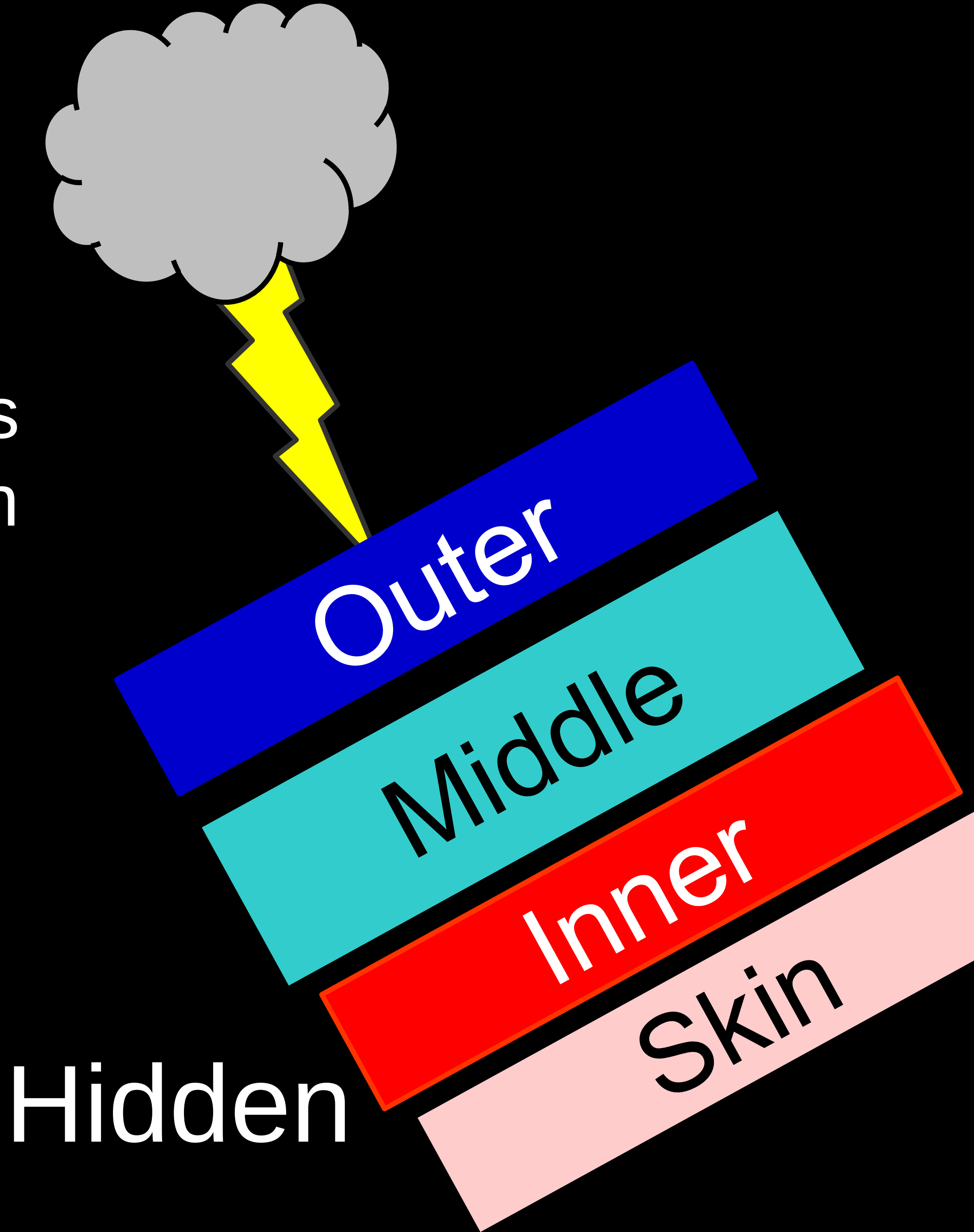


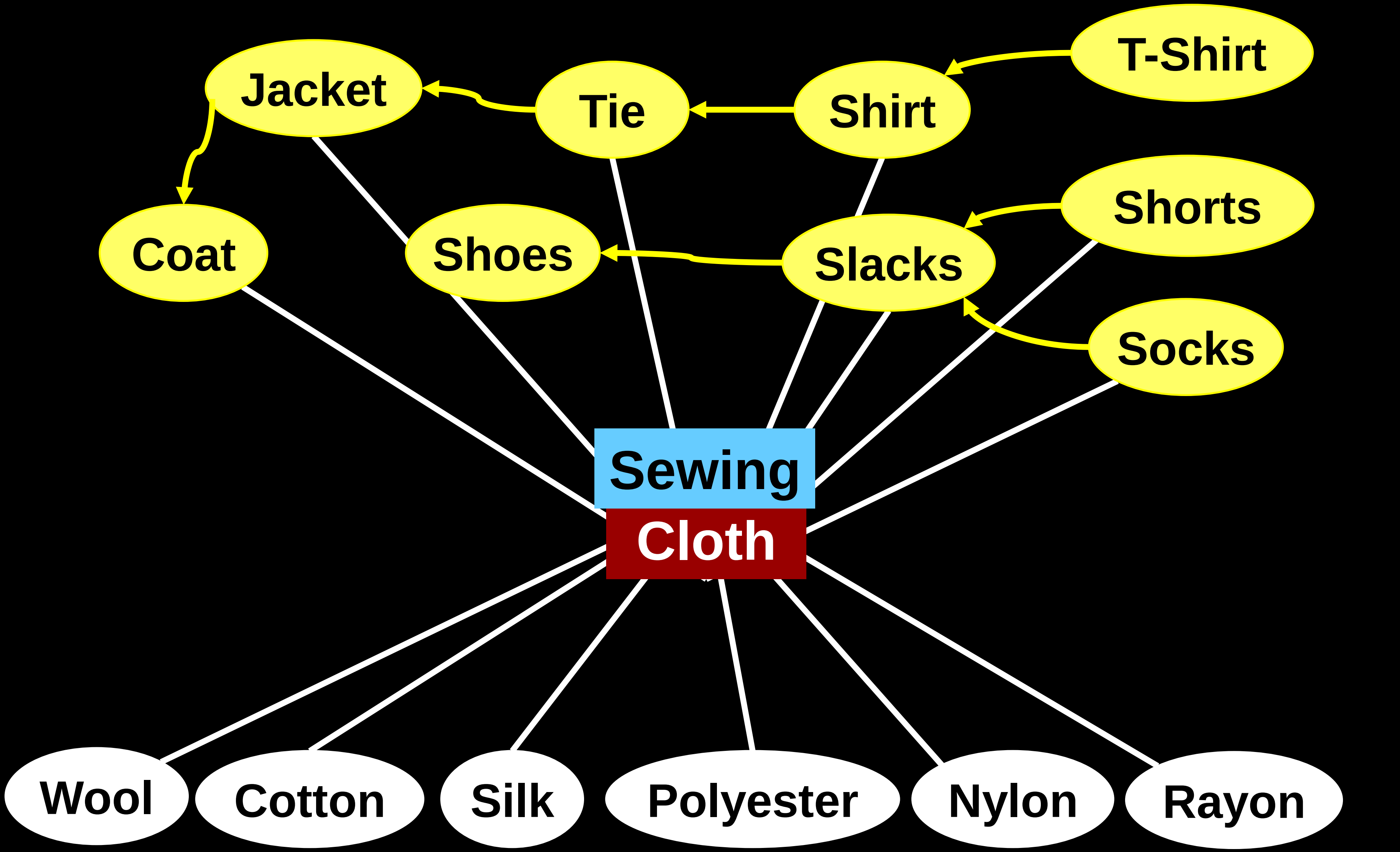
T-Shirt
Jacket
sweater
Shirt
Shorts
Coat
Shoes
Slacks
Socks
Outer
Middle
Inner
Skin

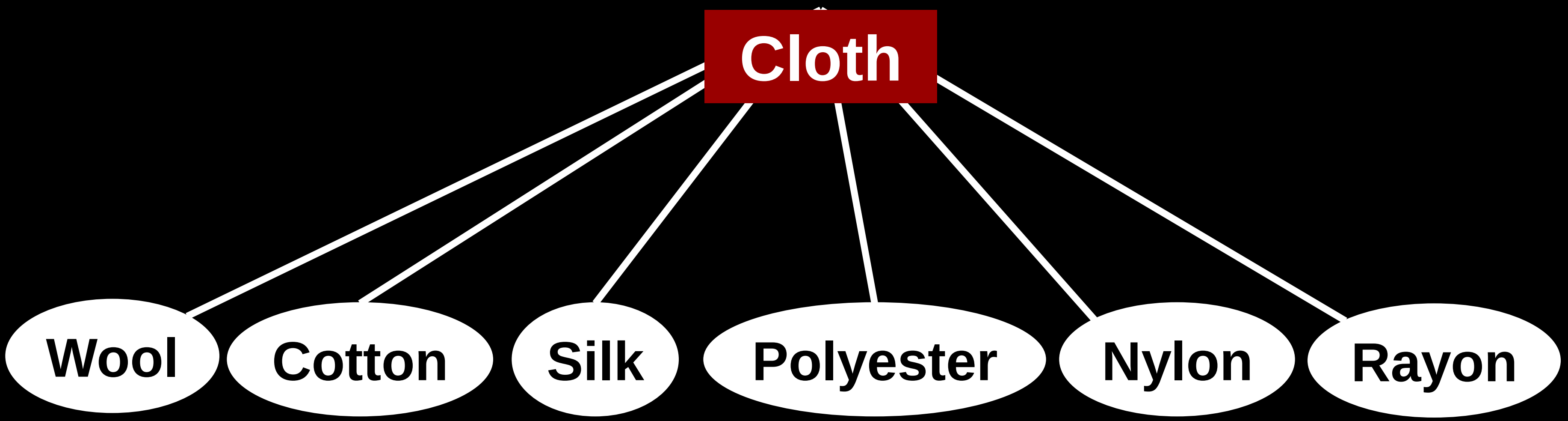
System constraints

Robust to variations and requirements in

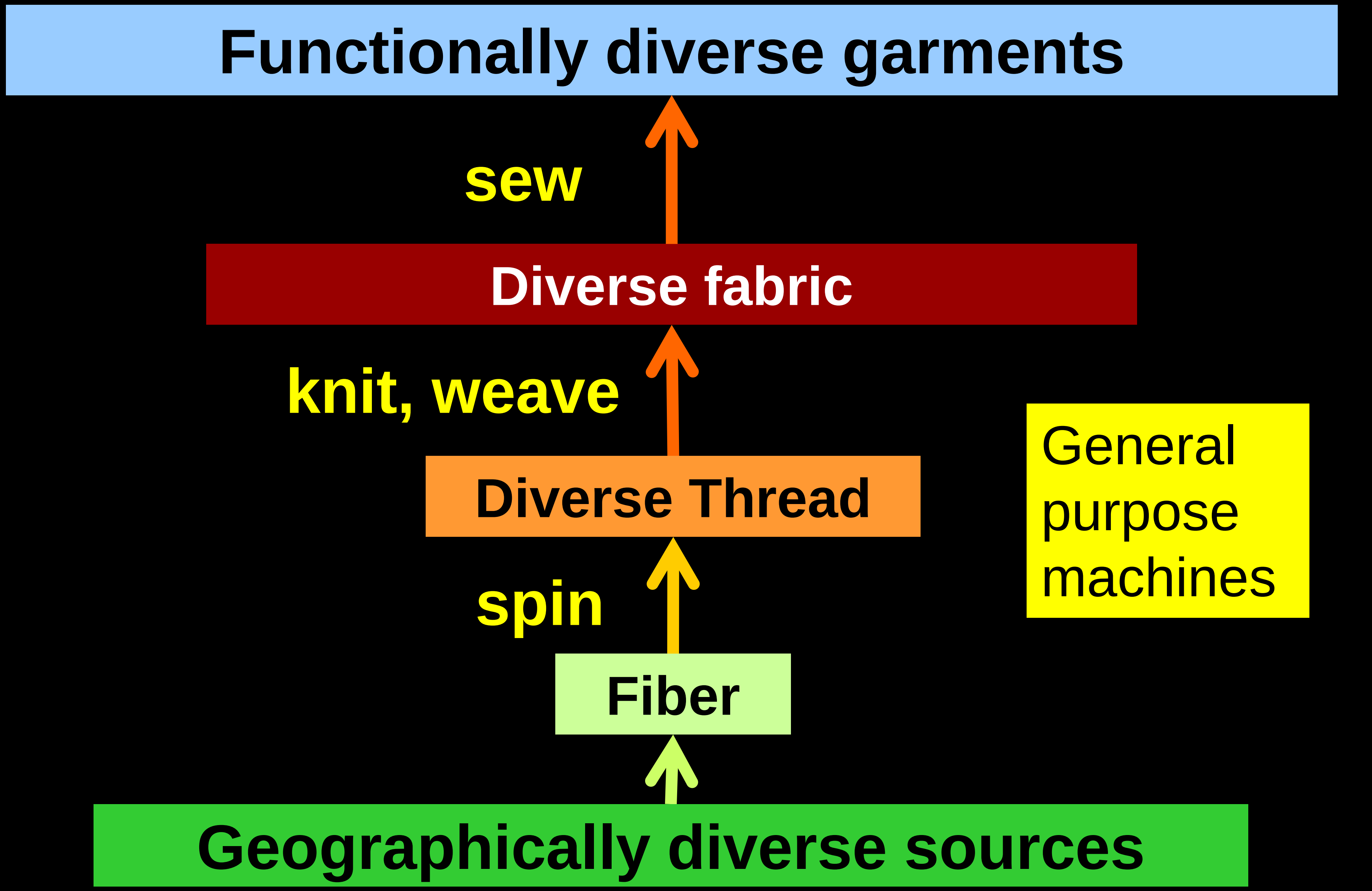
- weather
- activity
- appearance
- wear and tear
- washing



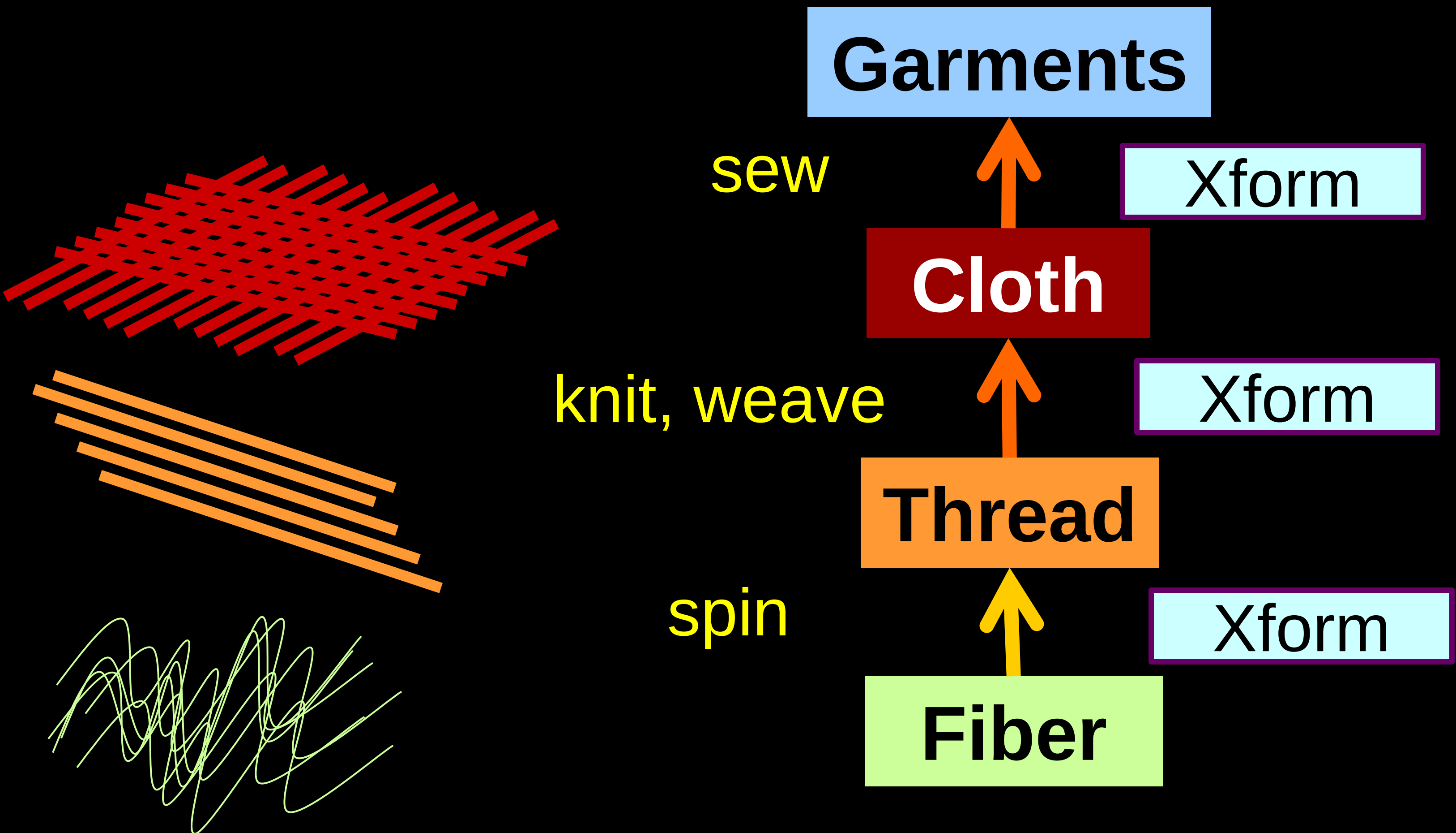

T-Shirt
Jacket
Tie
Shirt
Shorts
Coat
Shoes
Slacks
Socks
Sewing
Cloth
Wool
Cotton
Silk
Polyester
Nylon
Rayon



Component constraints

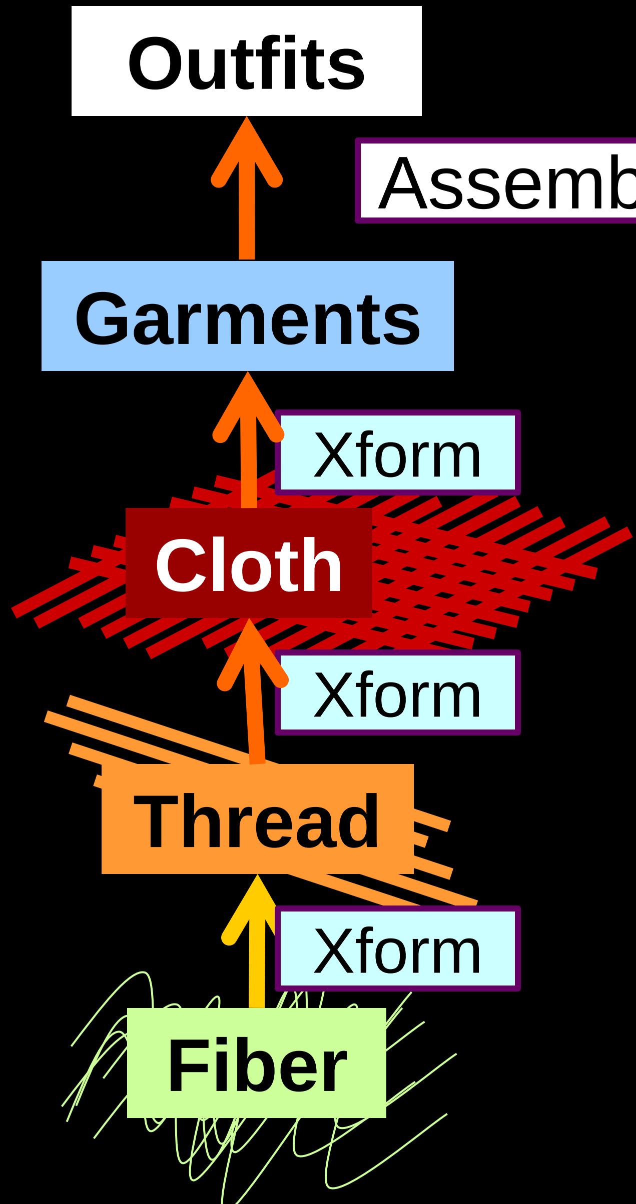

Functionally diverse garments
sew
Diverse fabric
knit, weave
Diverse Thread
spin
Fiber
Geographically diverse sources
General purpose machines

Architecture and Modularity 2.0



Prevents unraveling of lower layers

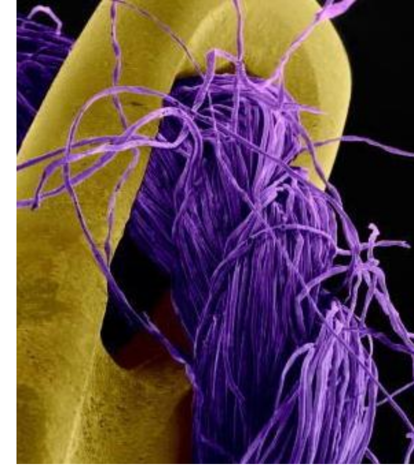
Hidden, large, thin, nonconvex



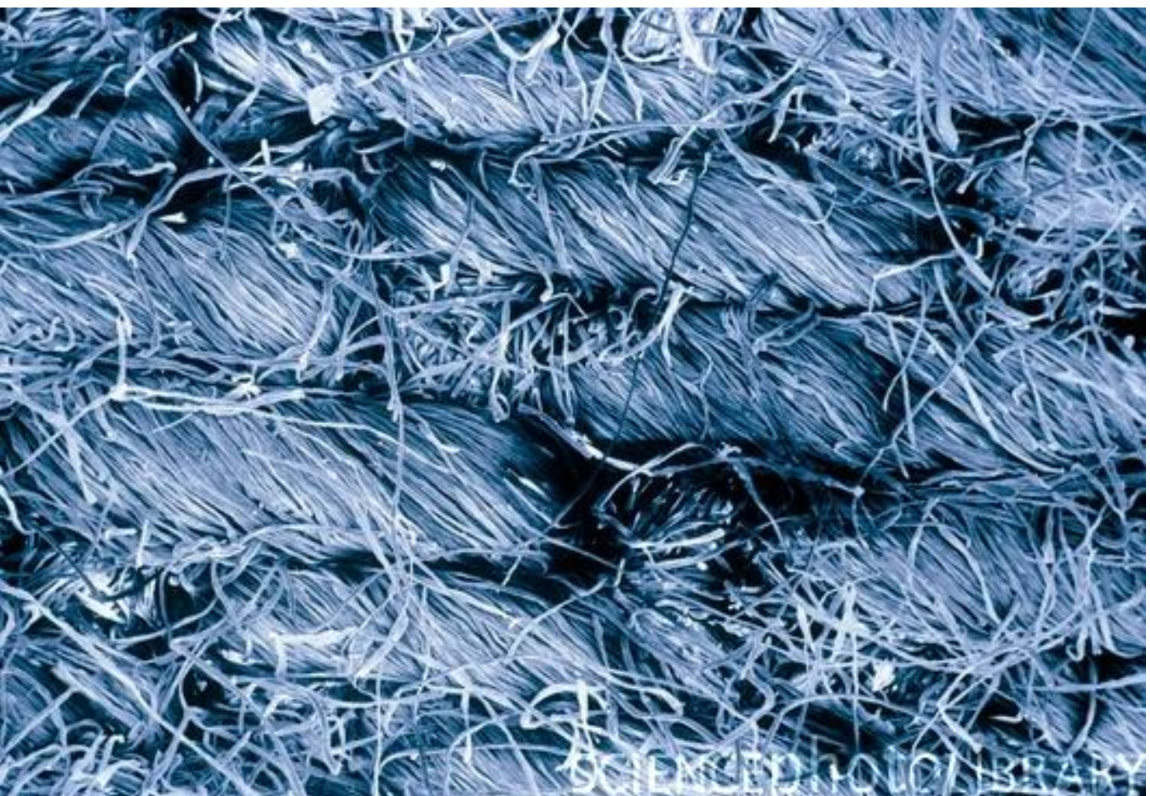
are *necessary*

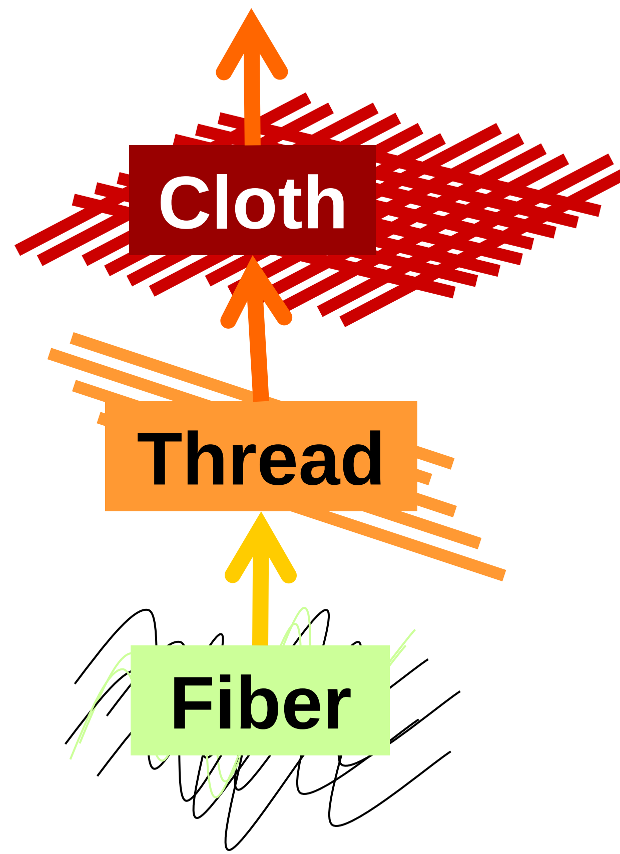
500μm

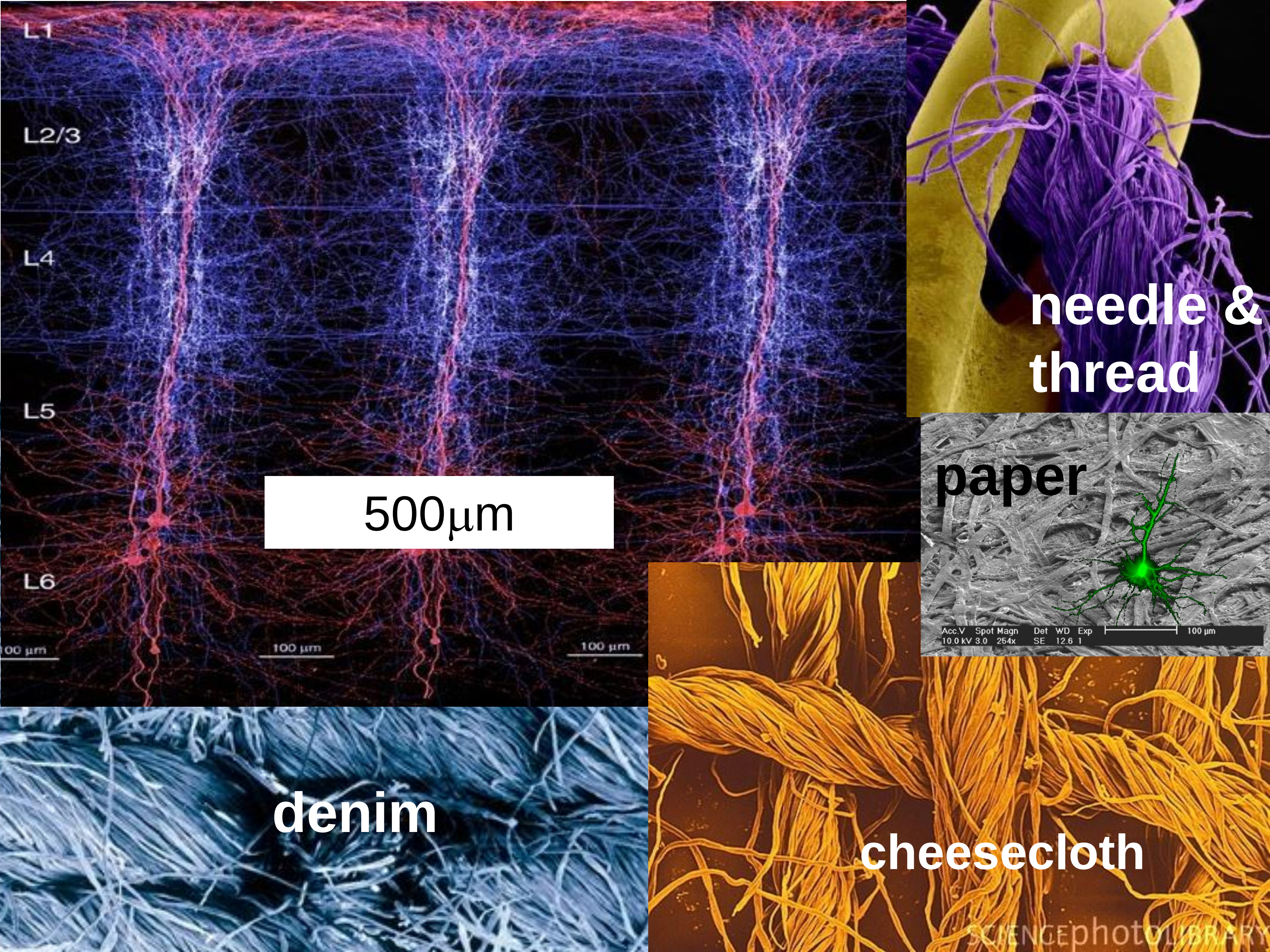
.5mm

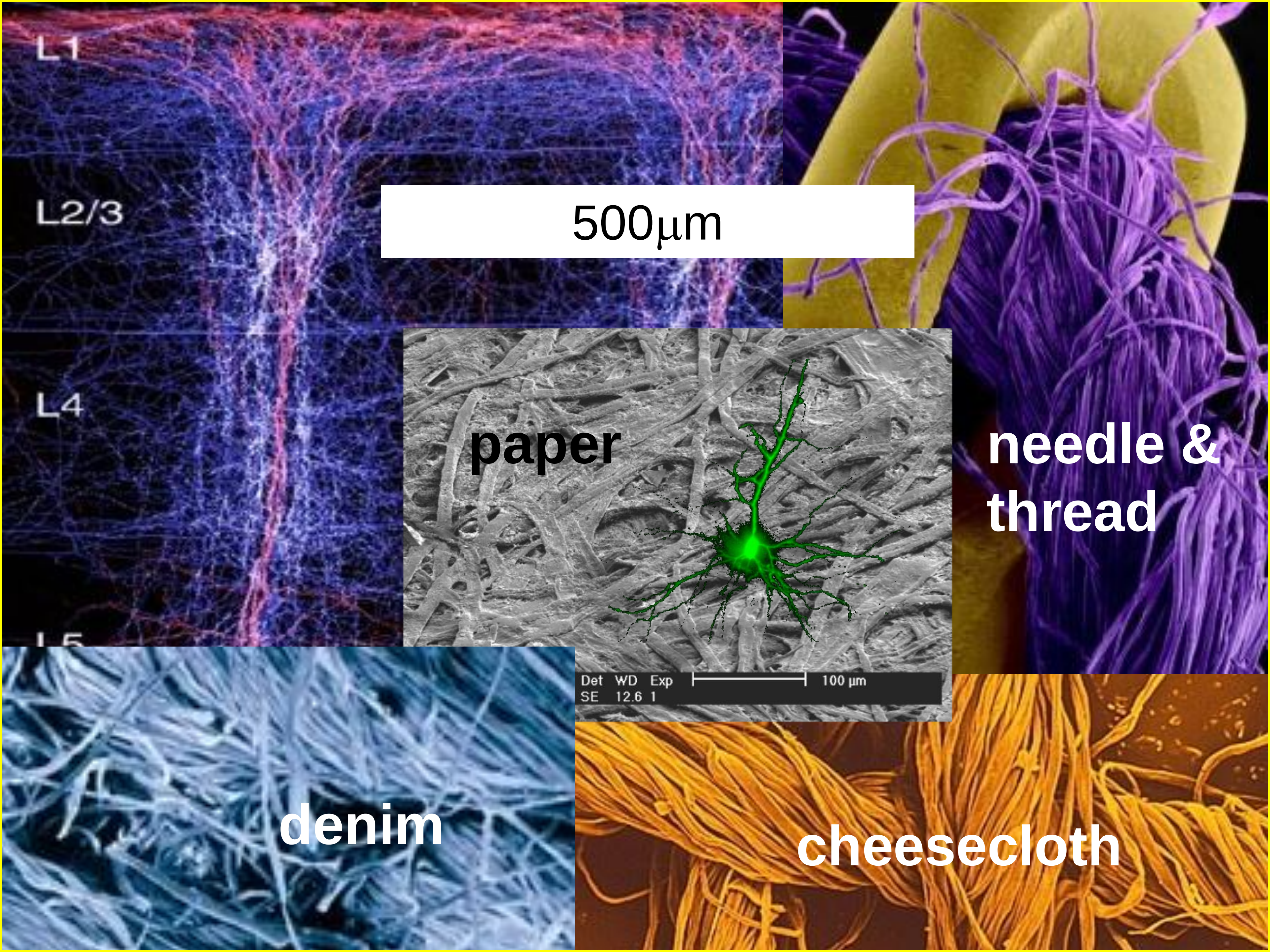


denim





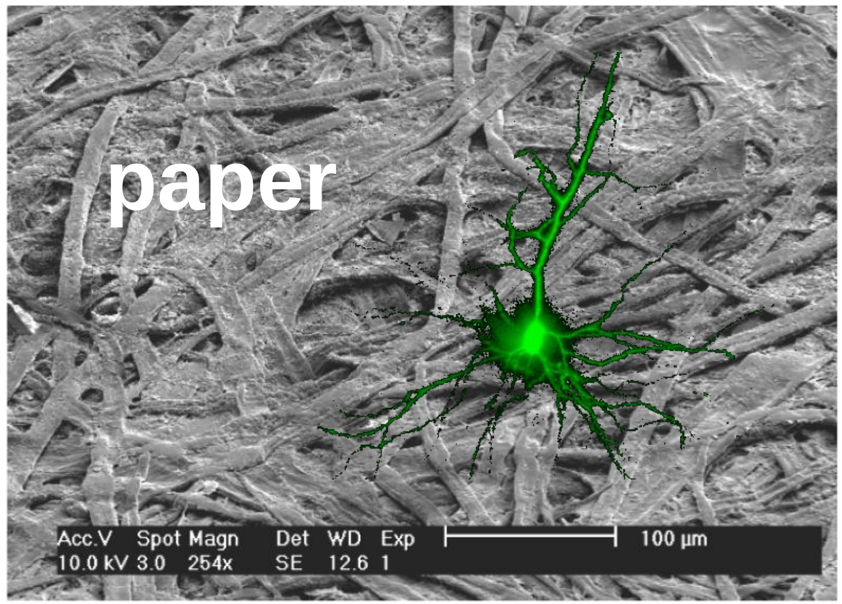

L1
L2/3
L4
L5
L6
100 µm
100 µm
100 µm
500µm
needle & thread
paper
Acc.V Spot Magn Det WD Exp 100 µm
10.0 kV 3.0 254x SE 12.6 1
denim
cheesecloth
SCIENCEphotoLIBRARY

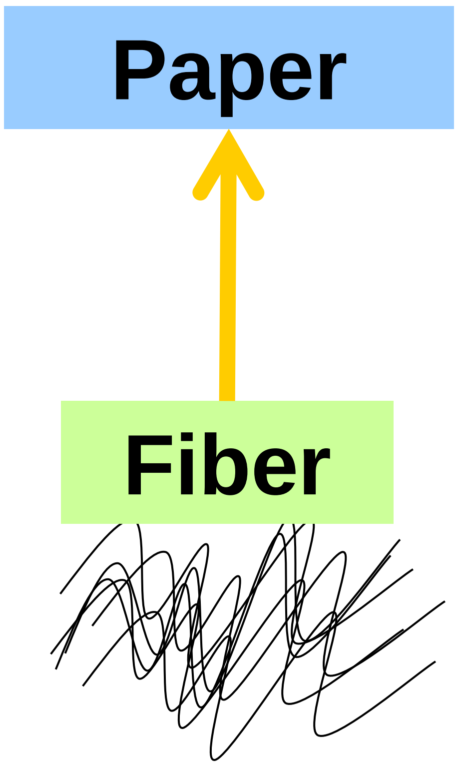


L1
L2/3
L4
L5
500µm
paper
Det WD Exp
SE 12.6 1
100 µm
needle & thread
denim
cheesecloth

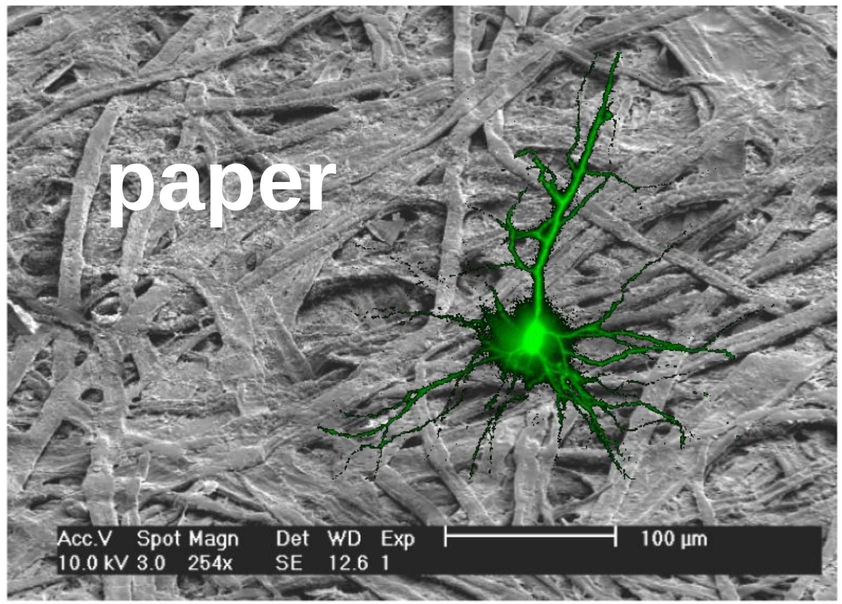
.5mm x .35 mm cotton paper

500μm

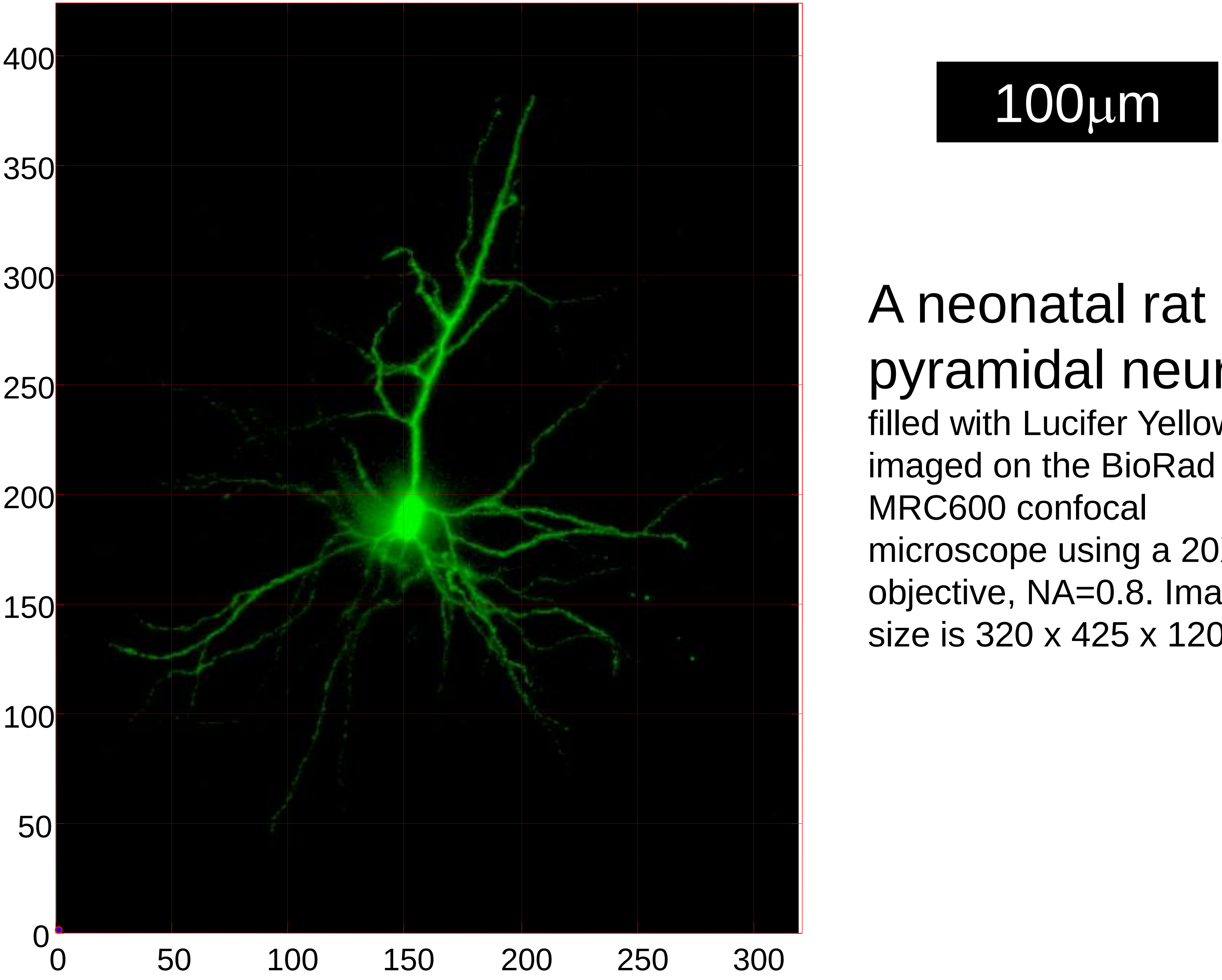




500μm

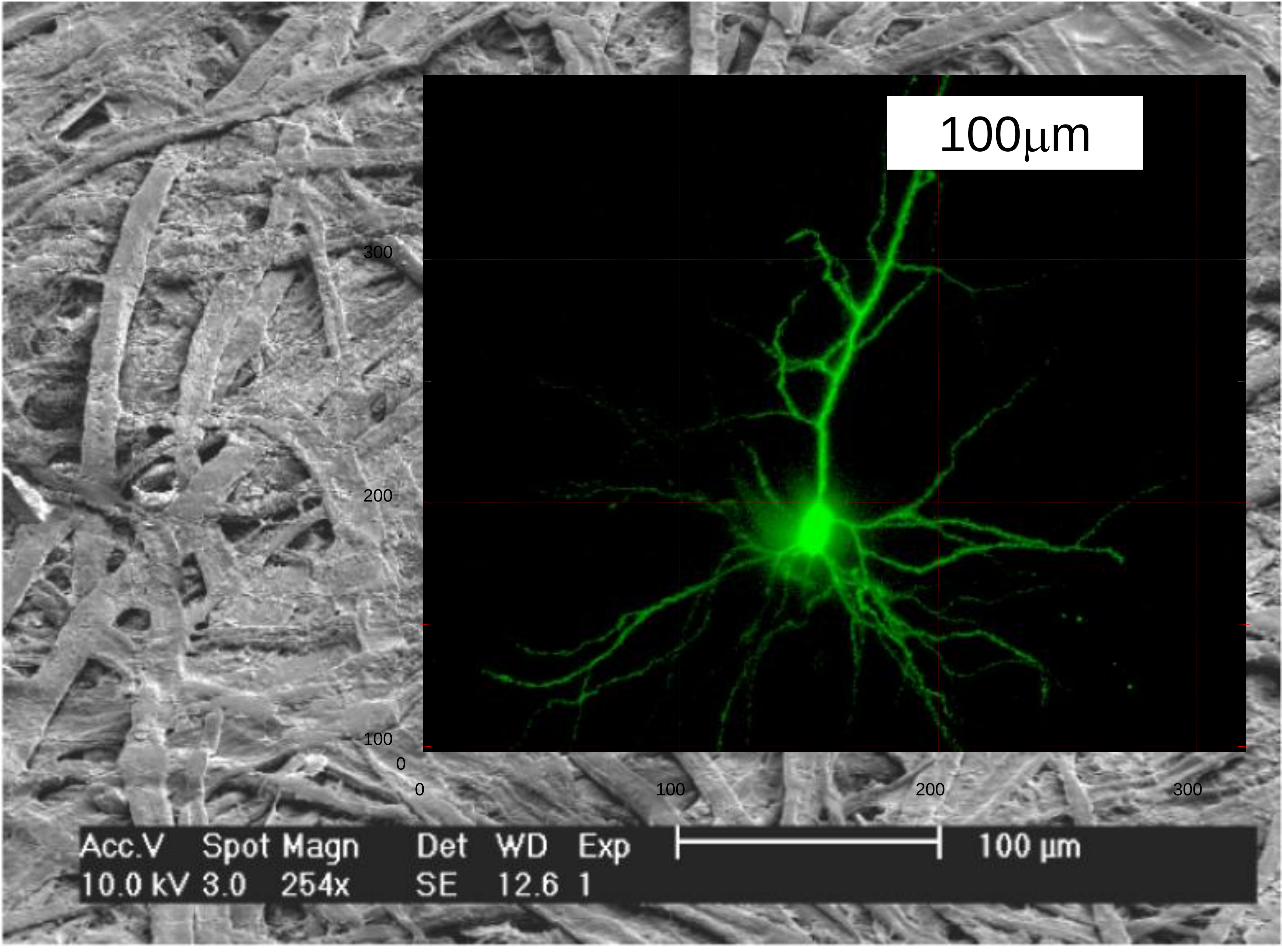


Minimal architecture



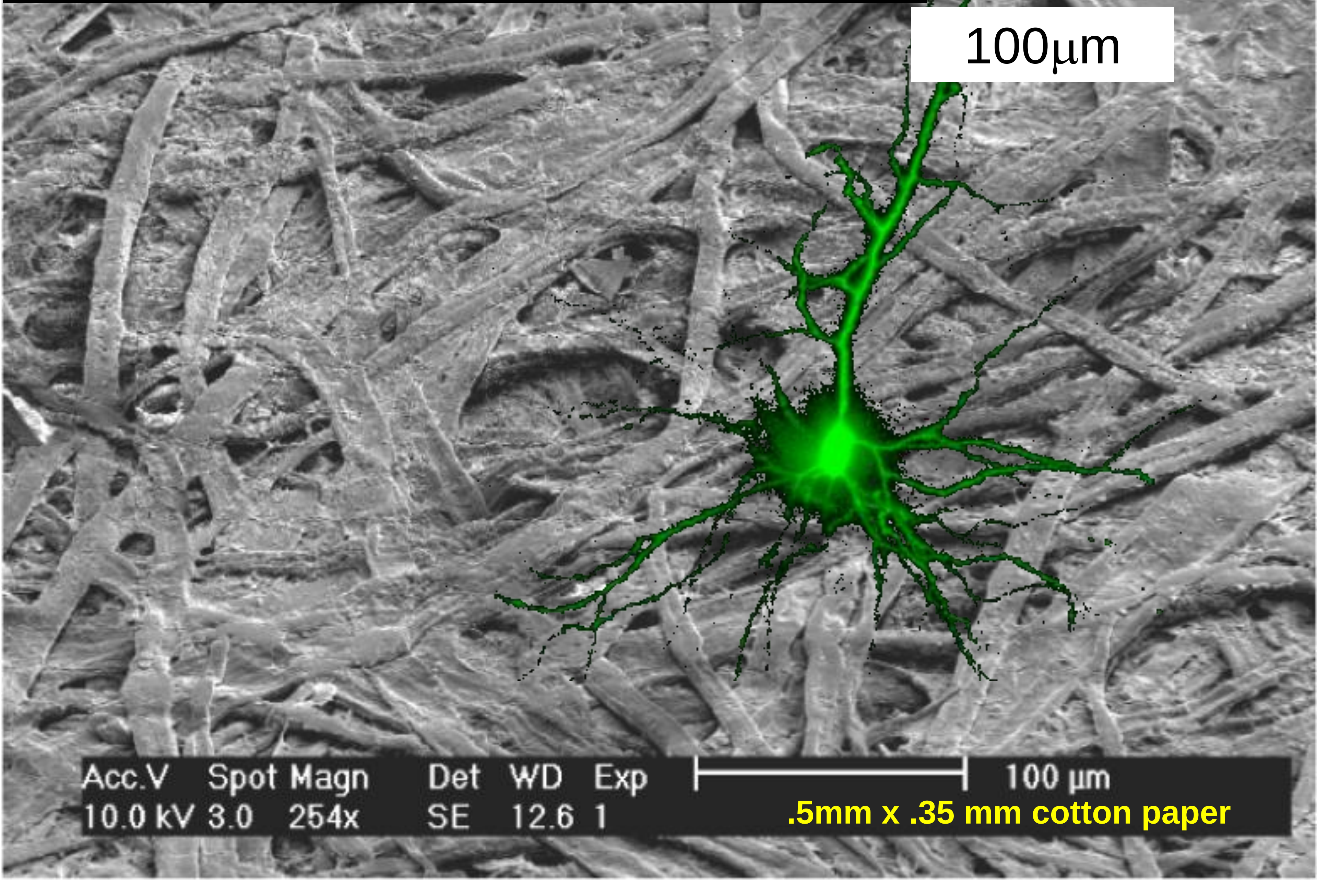
A neonatal rat pyramidal neuron

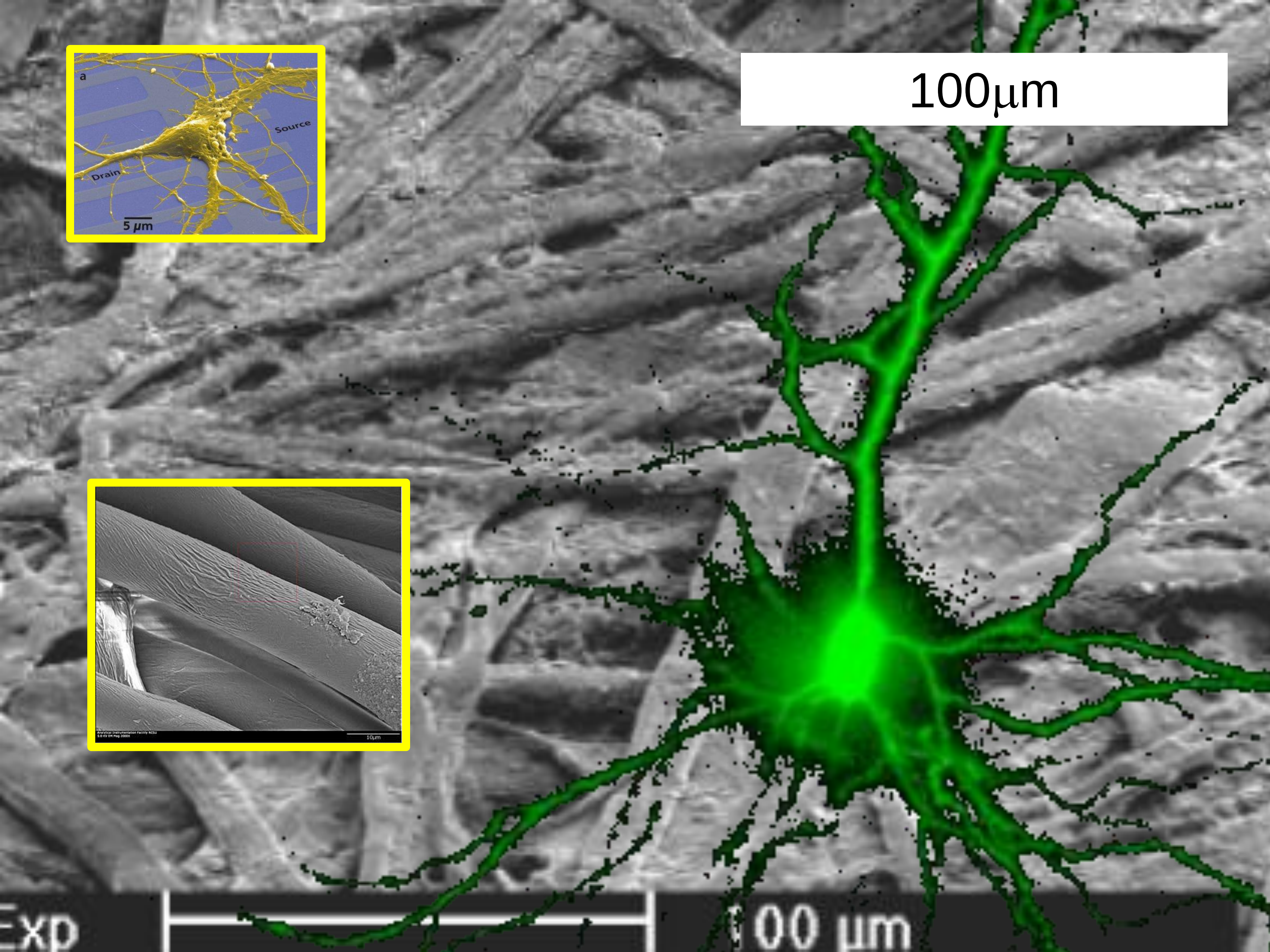
filled with Lucifer Yellow imaged on the BioRad MRC600 confocal microscope using a 20X oil objective, NA=0.8. Image size is 320 x 425 x 120 μm.

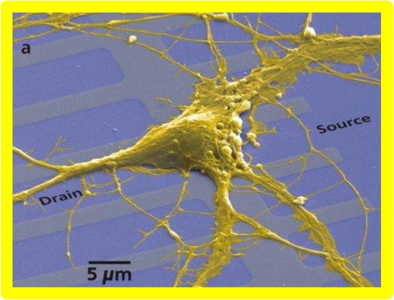


100μm
300
200
100
0
0
100
200
300
Acc.V Spot Magn Det WD Exp
10.0 kV 3.0 254x SE 12.6 1
100 μm

.5mm x .35 mm cotton paper



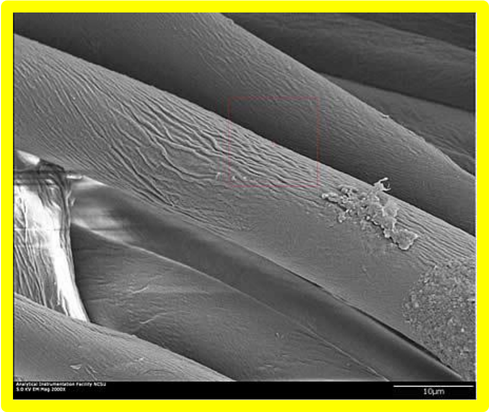

100μm
a
Source
Drain
5 μm
Exp
00 μm



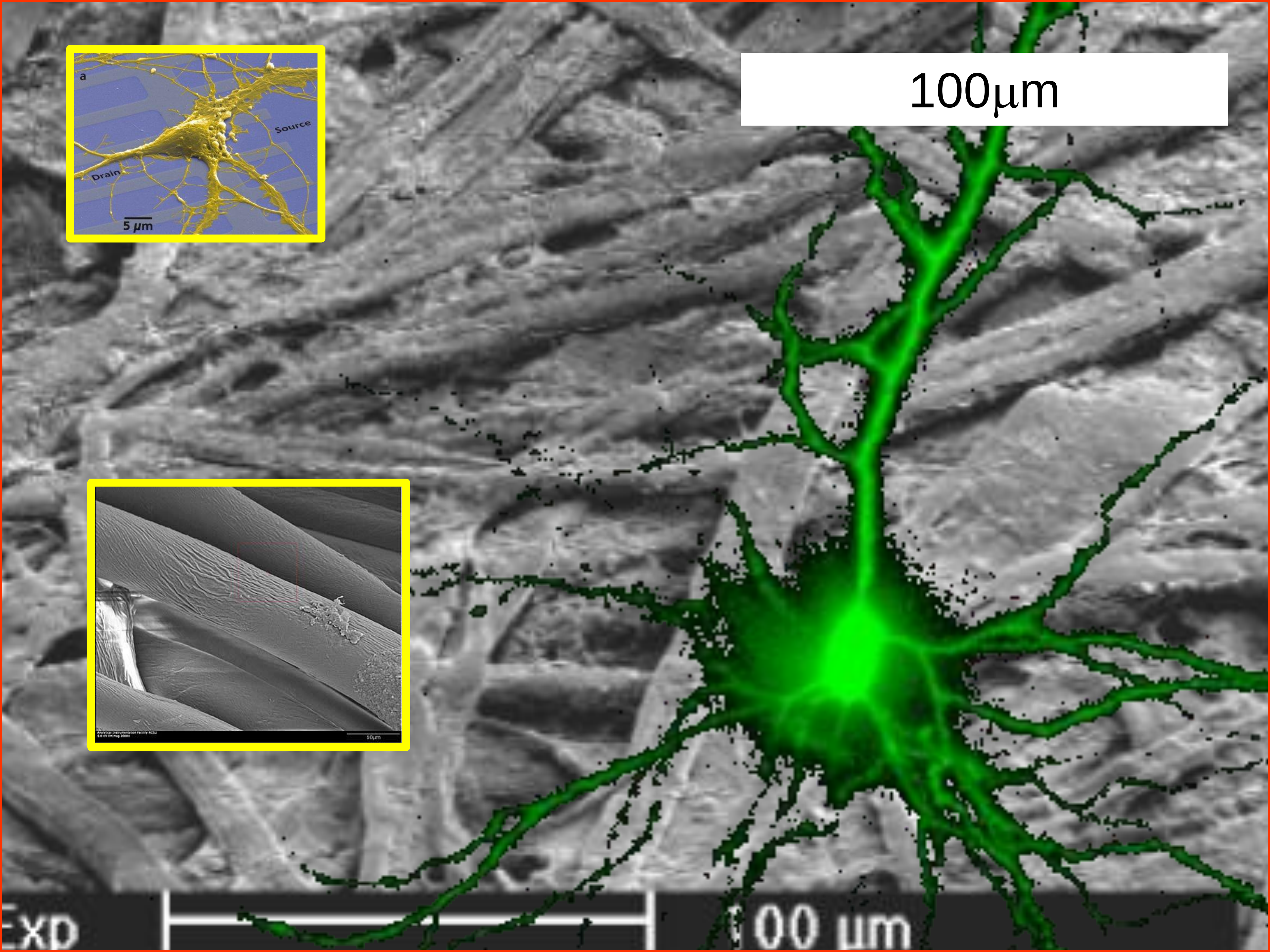
47x35 micron

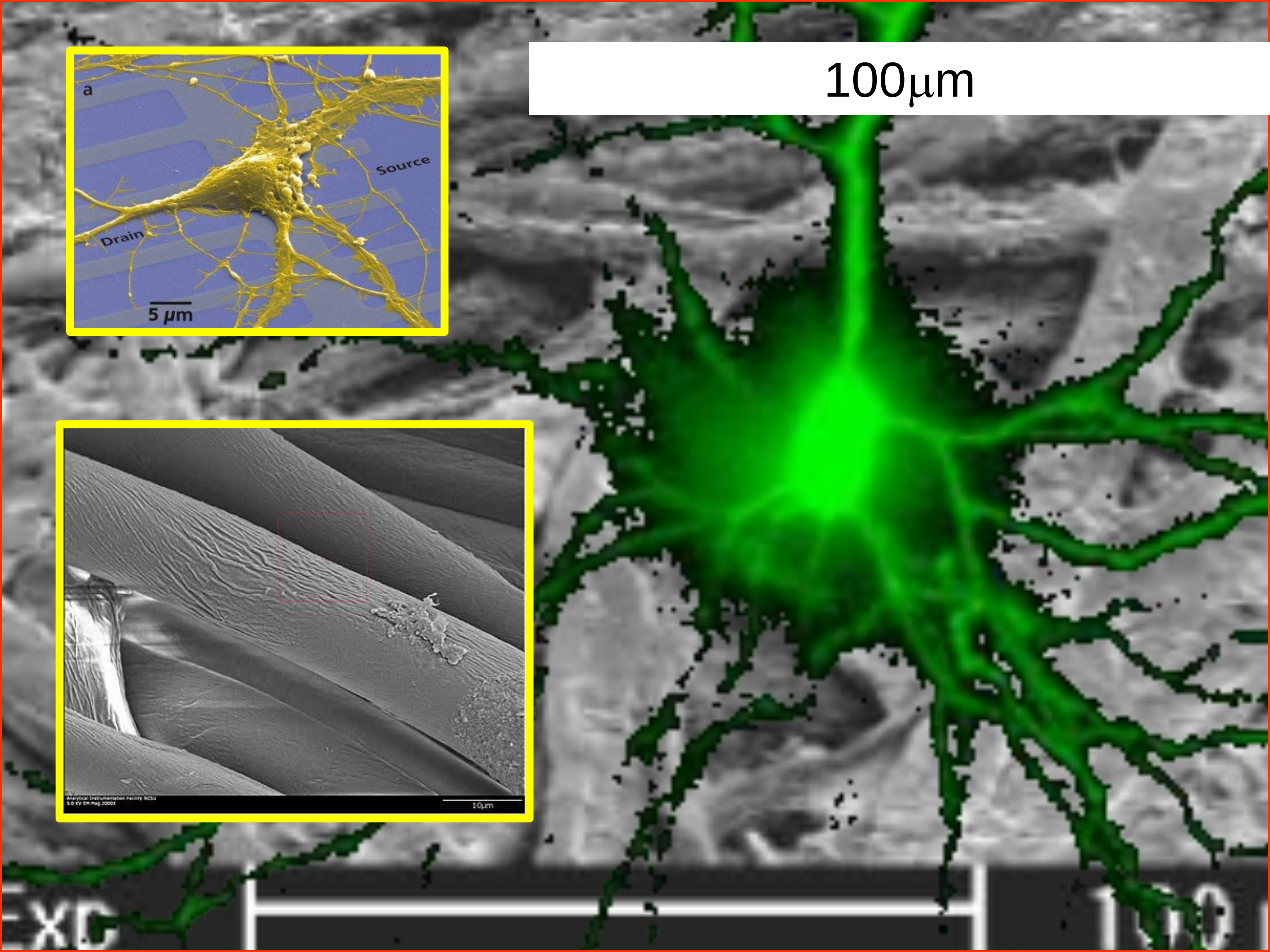
100μm

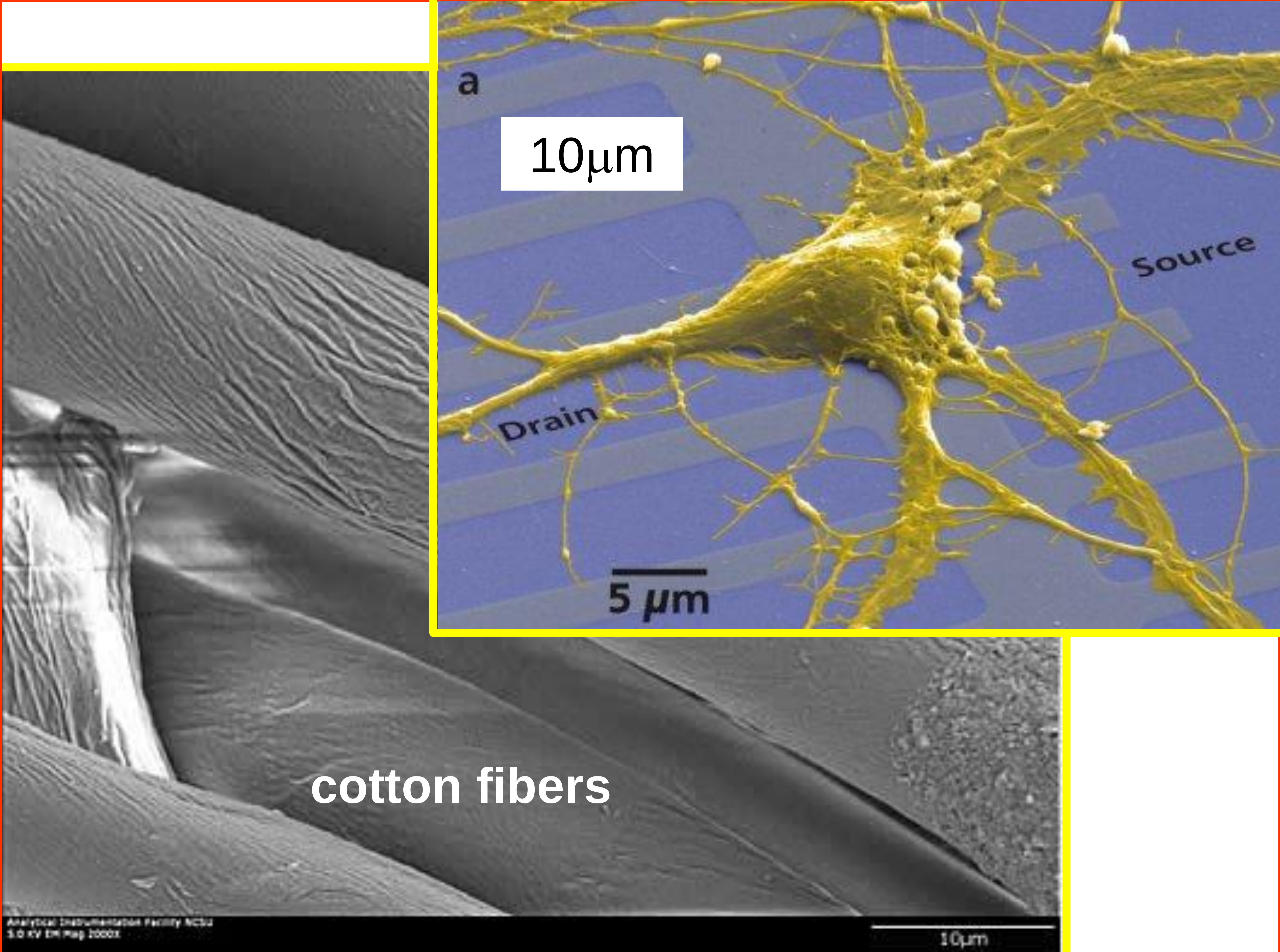
cotton fibers

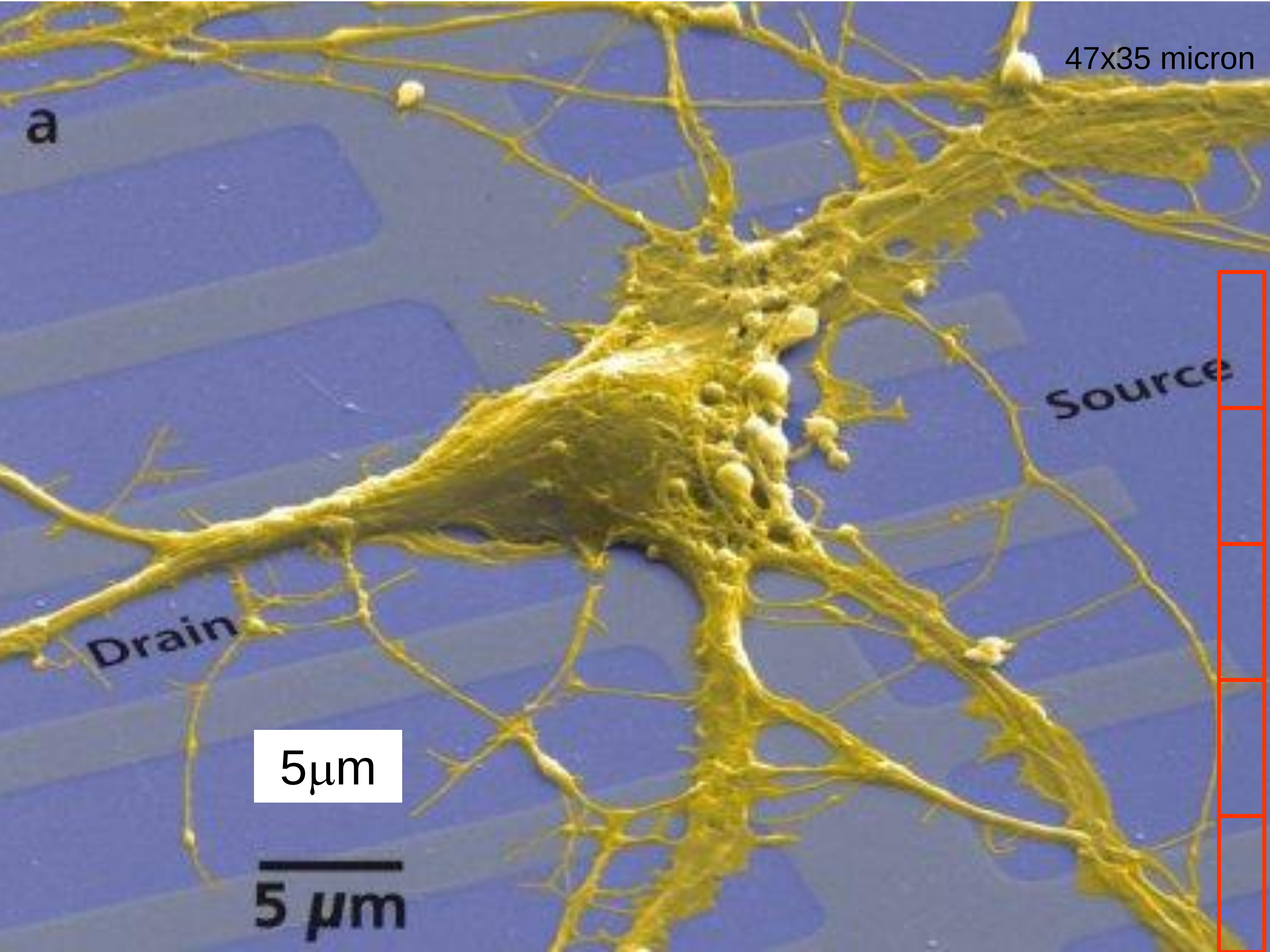


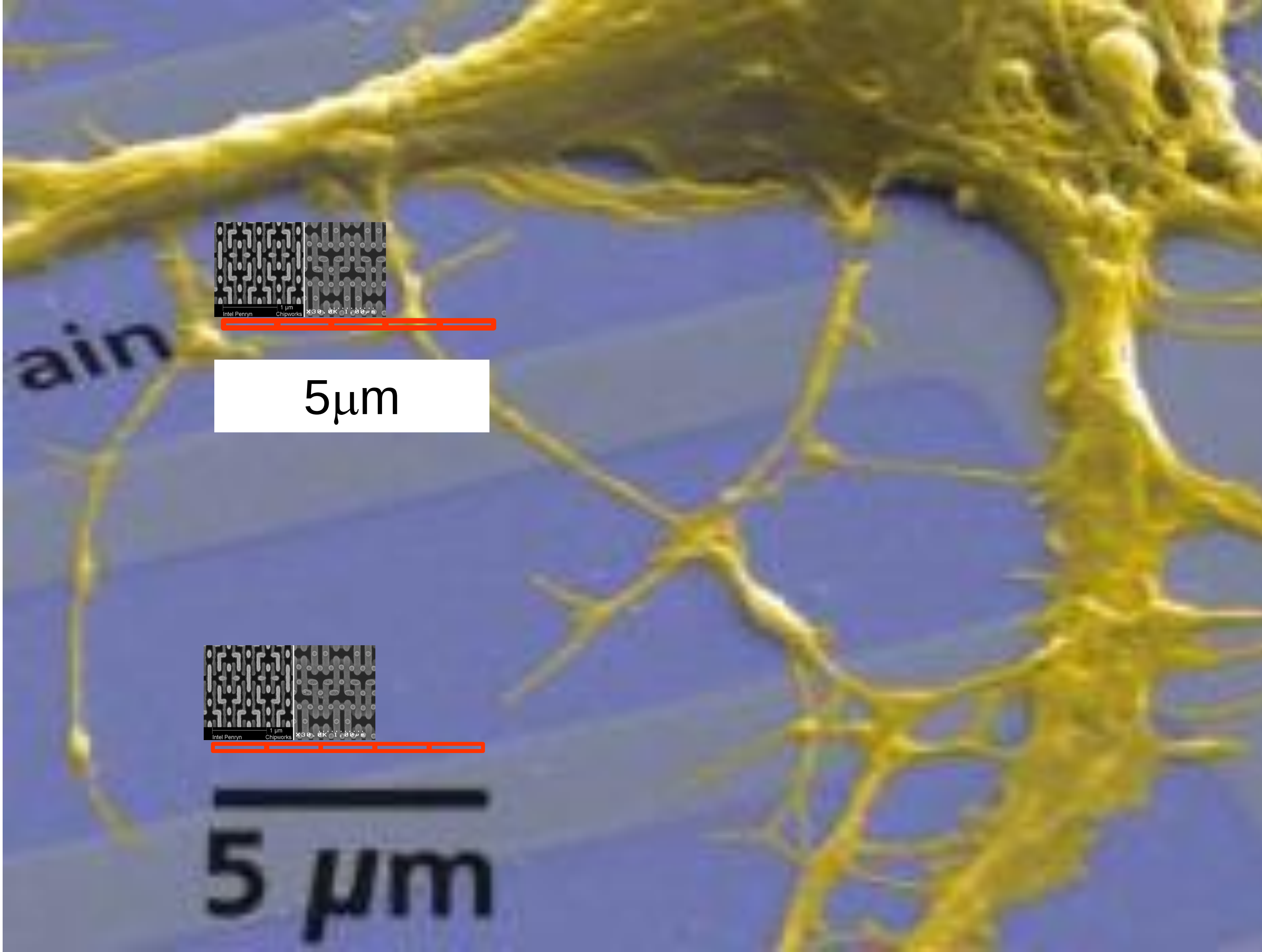
60x50 microns

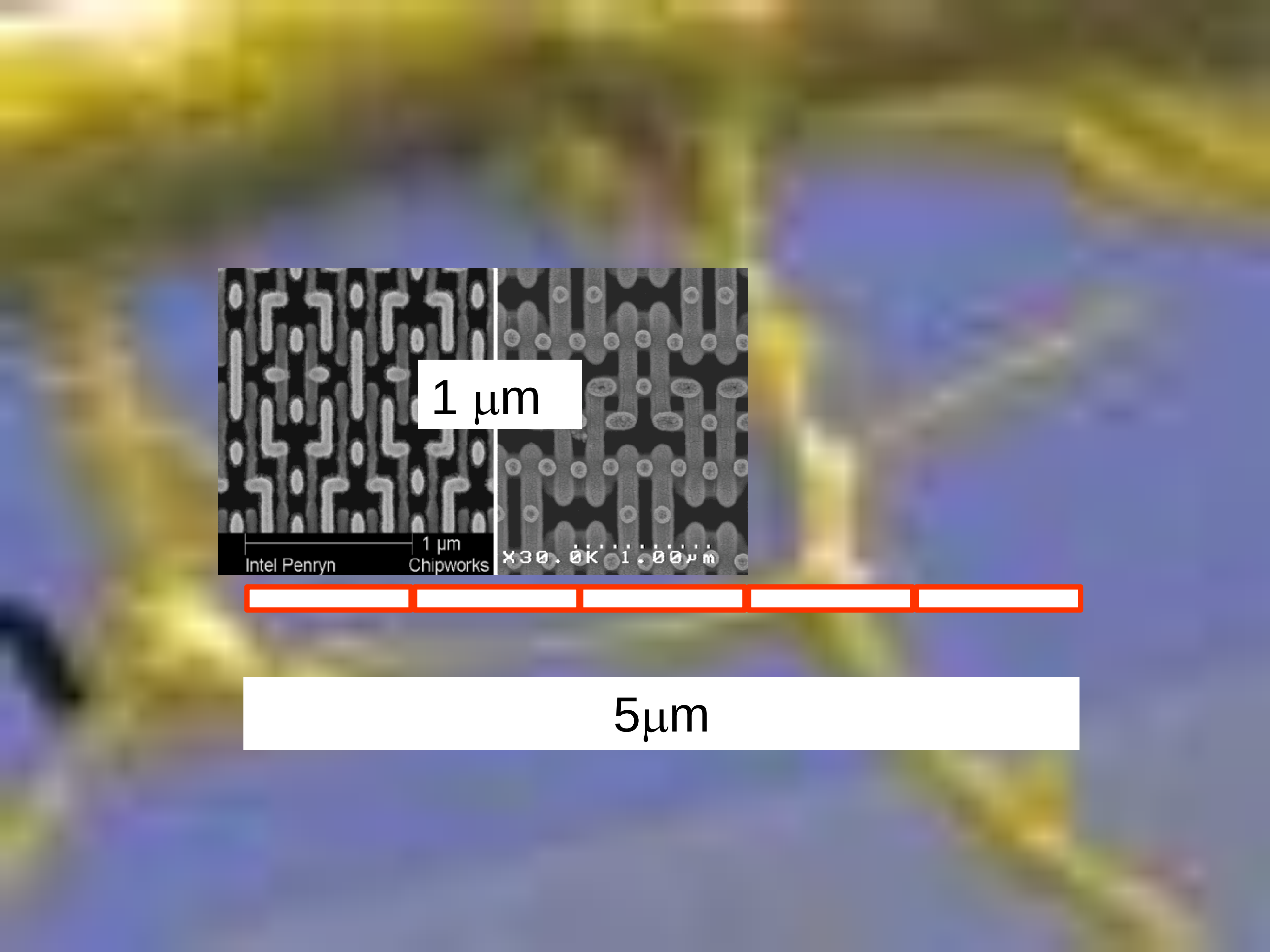

100μm
a
Source
Drain
5 μm
Exp
00 μm


100μm
a
Source
Drain
5 μm
10μm

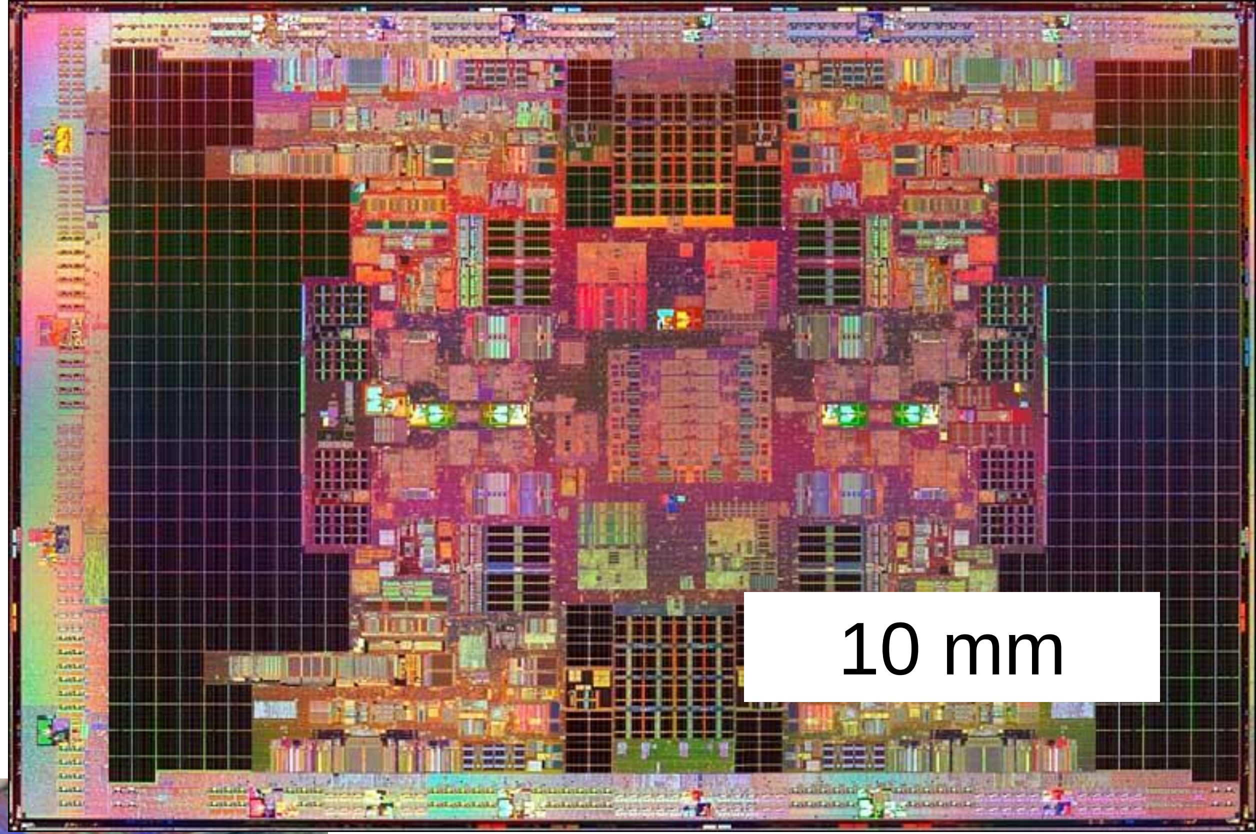

a
10µm
Source
Drain
5 µm
cotton fibers
10µm

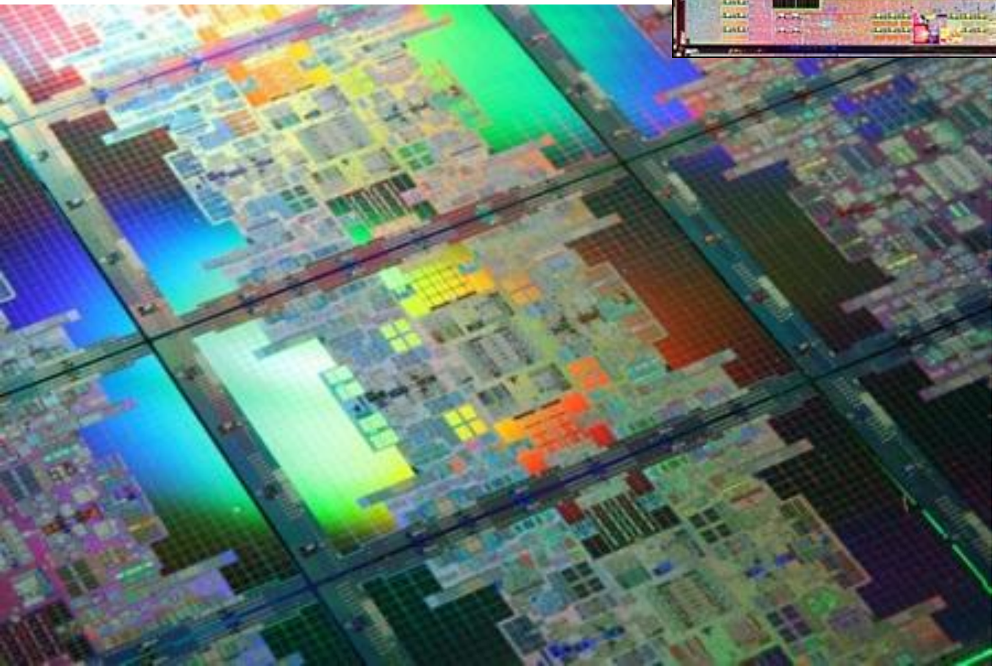

47x35 micron
a
Source
Drain
5μm
5 μm

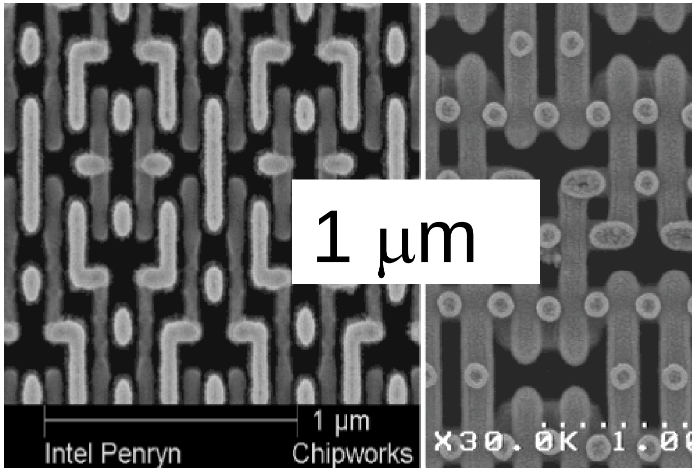

ain
1 µm
Intel Penryn
Chipworks
5µm
1 µm
Intel Penryn
Chipworks
5 µm

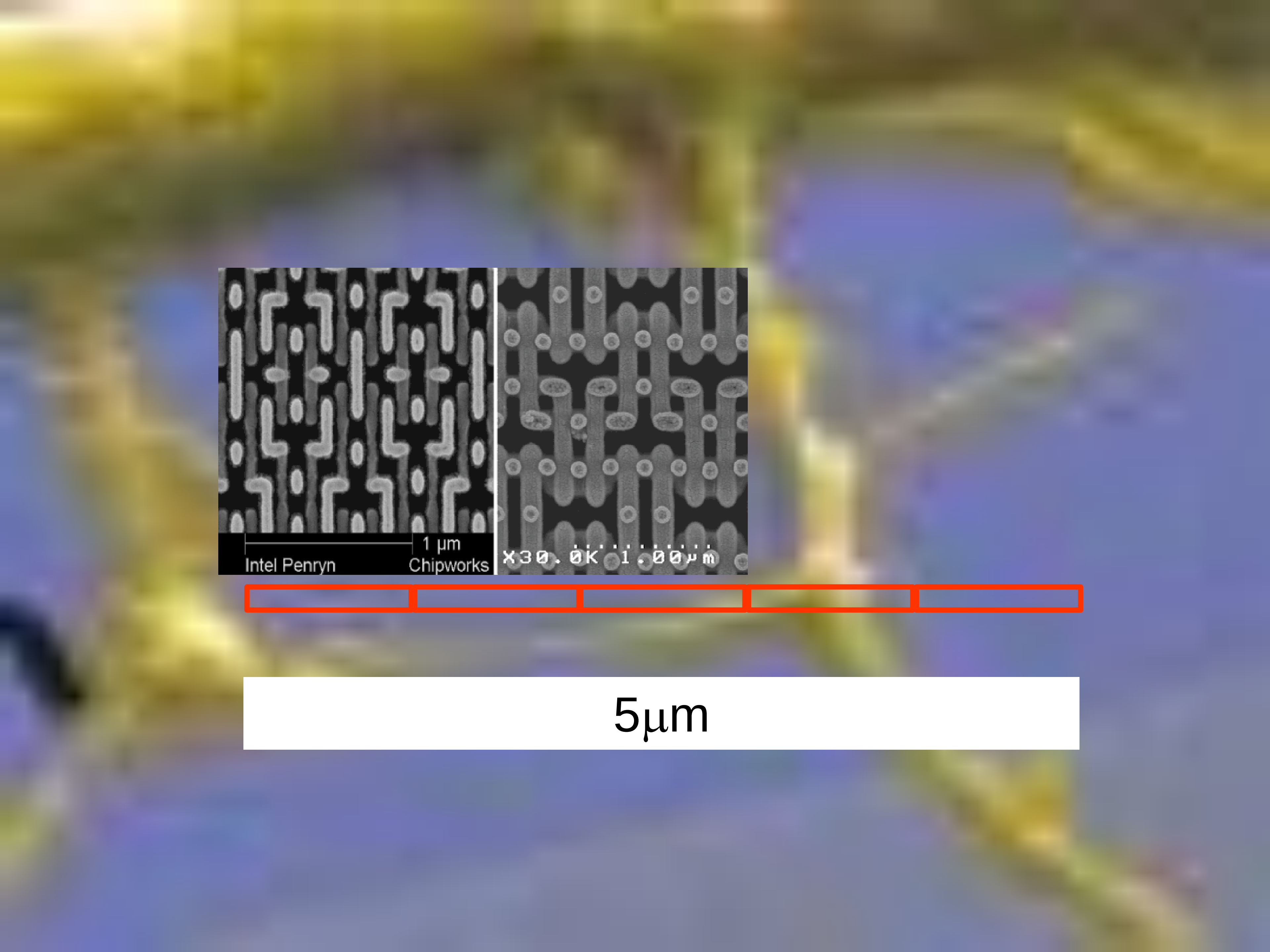

1 μm
1 μm
Intel Penryn
Chipworks
X30.0K 1.00μm
5μm

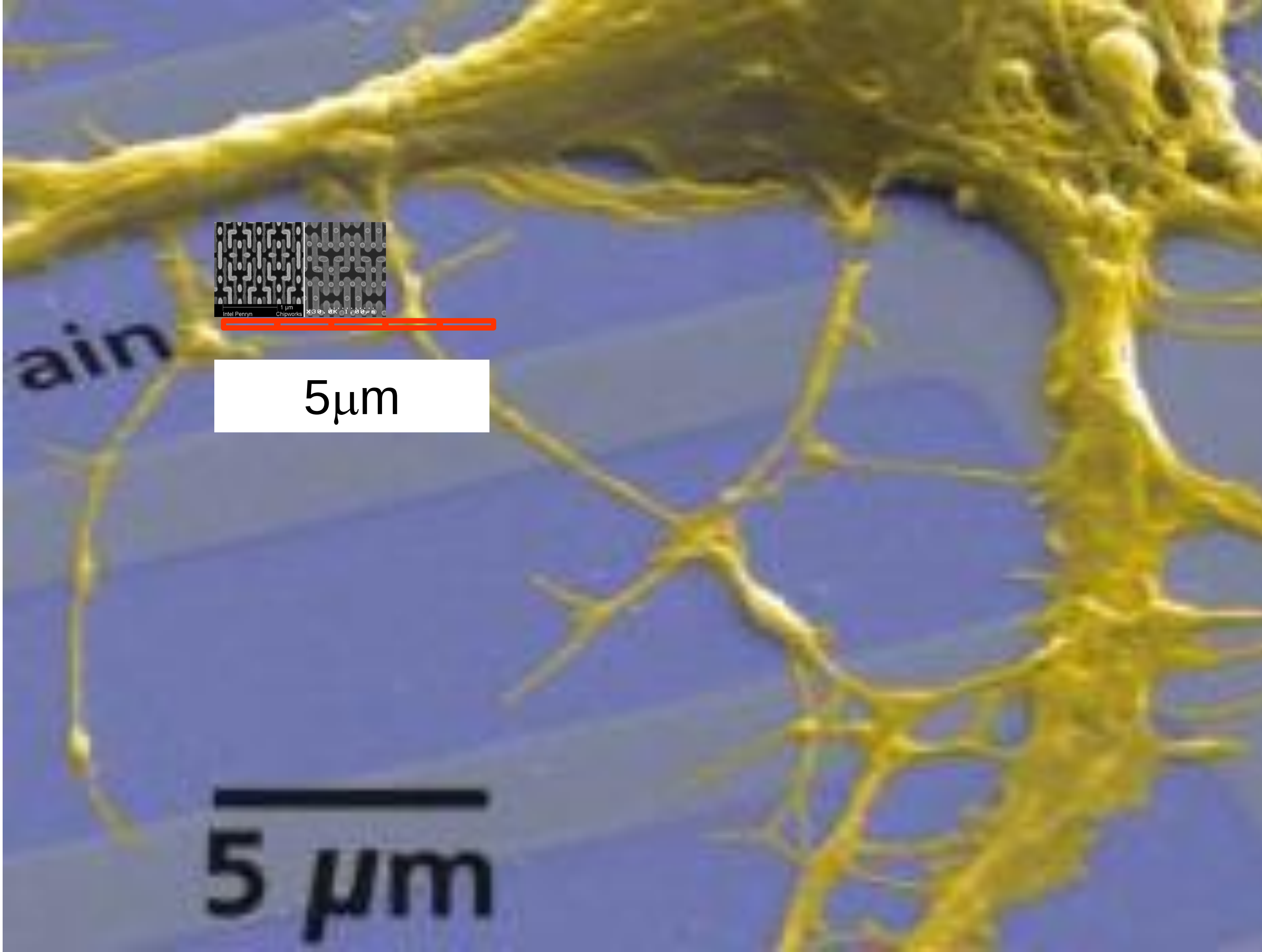
Intel Tukwila quad core chip with more than 2 billion transistors



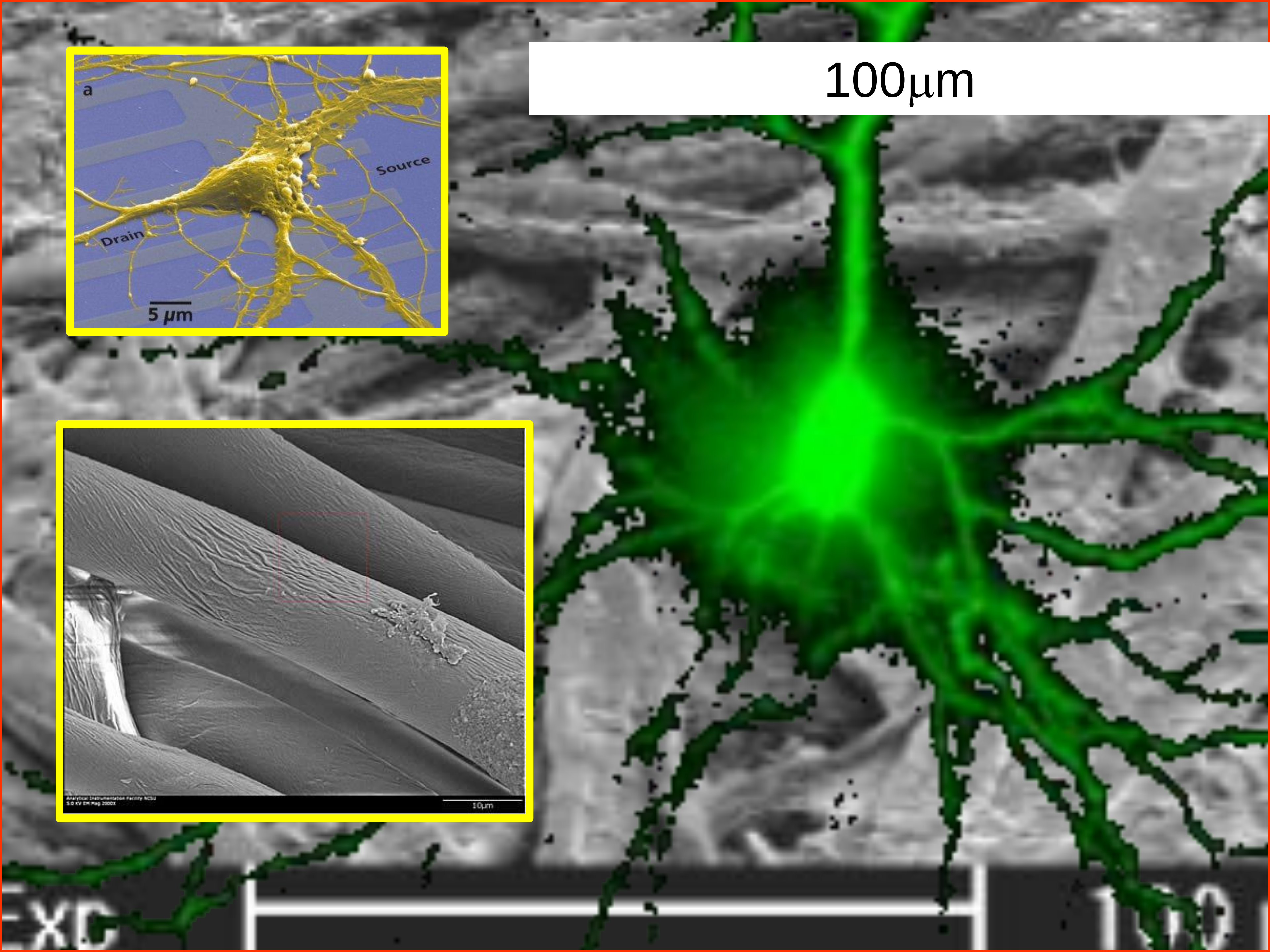




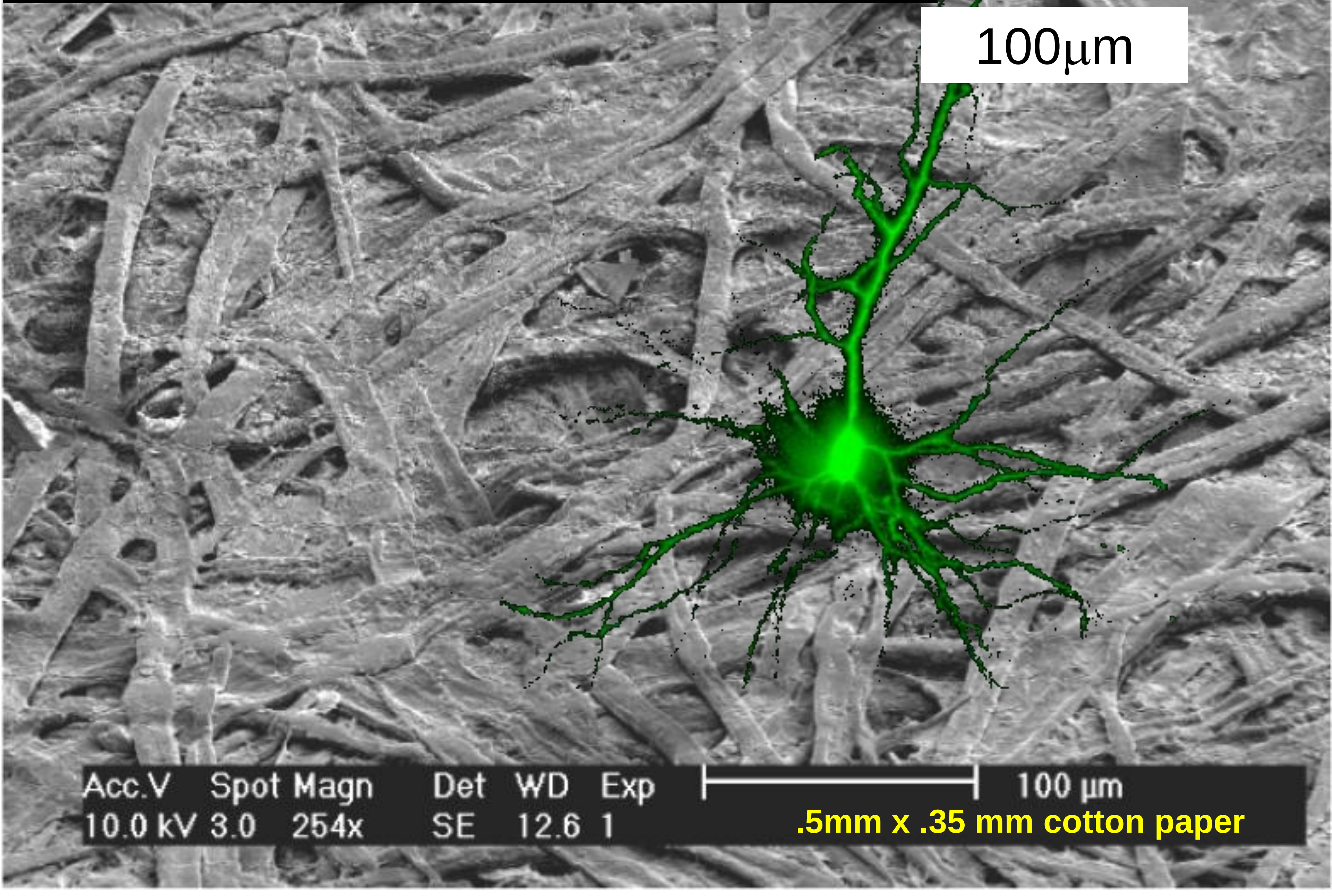

1 µm
Intel Penryn
Chipworks
X30.0K 1.00µm
5µm



ain
Intel Penryn
1 µm
Chipworks
5µm
5 µm

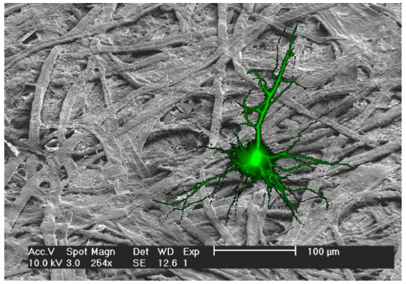

100μm
a
Source
Drain
5 μm
10μm

.5mm x .35 mm cotton paper



500μm

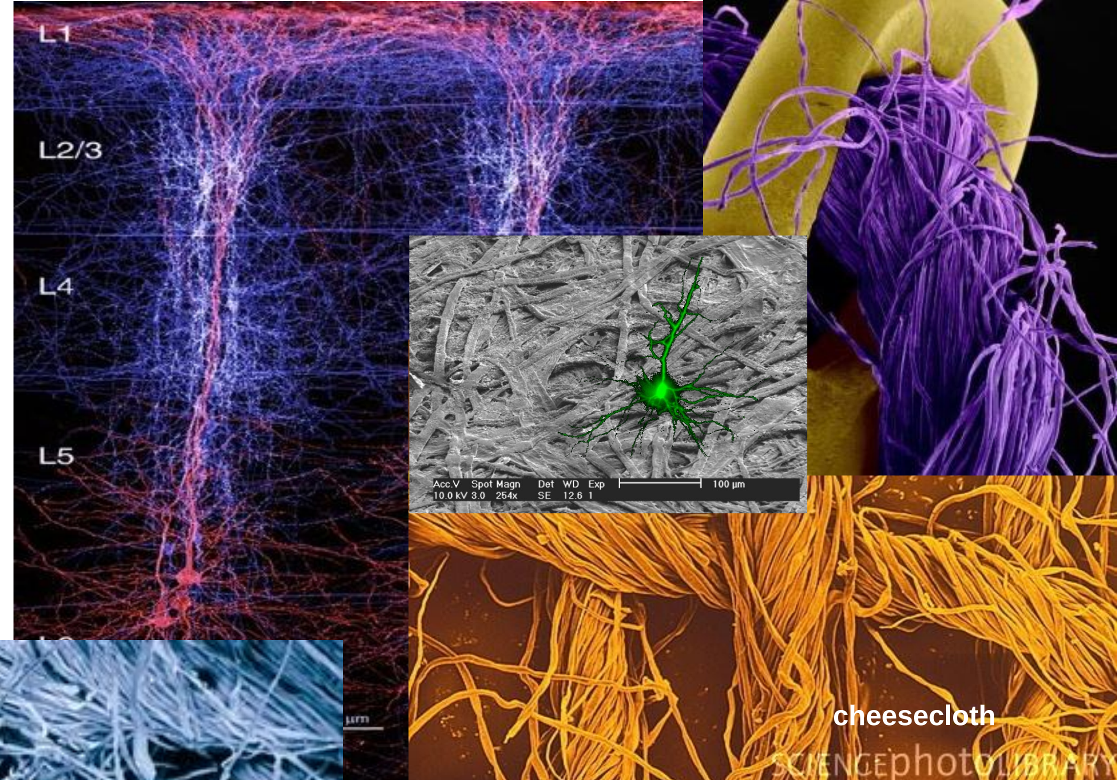
.5mm

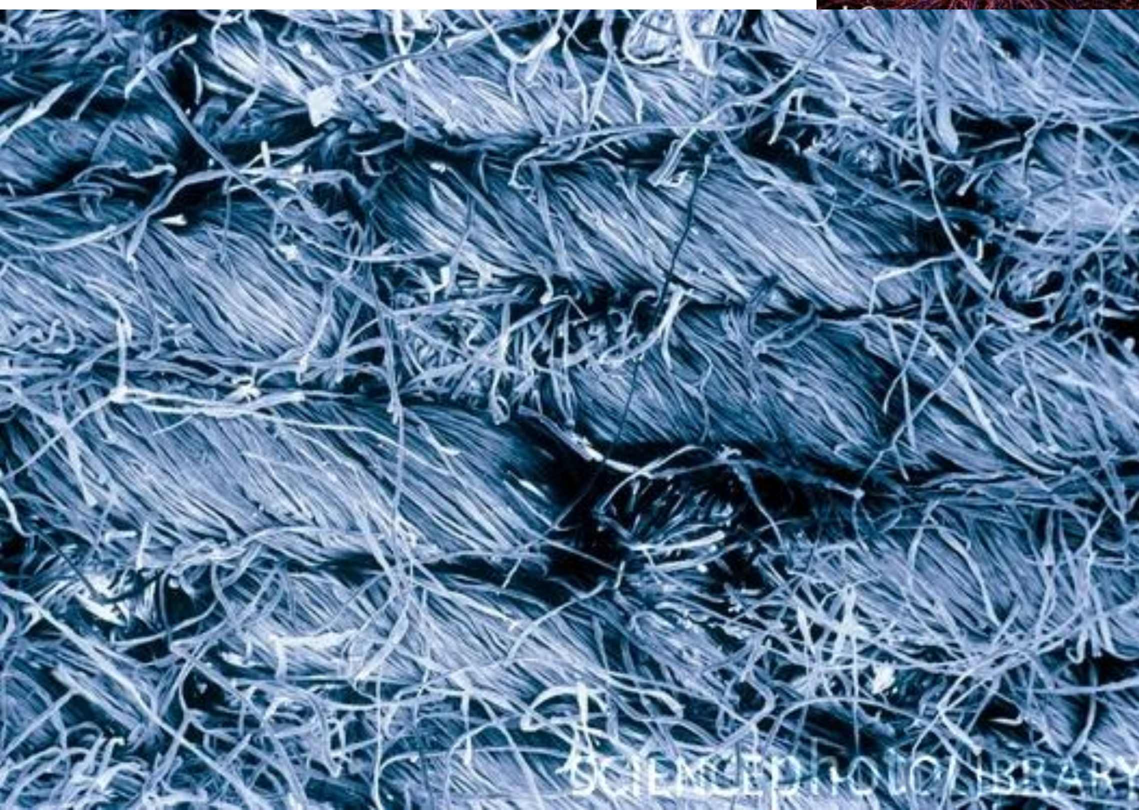


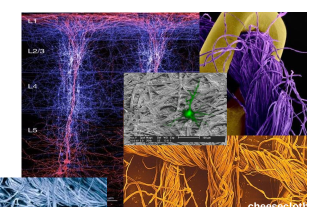
500µm

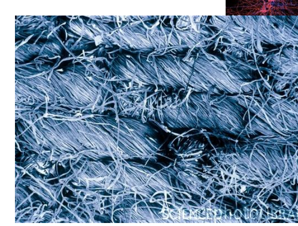
.5mm

denim





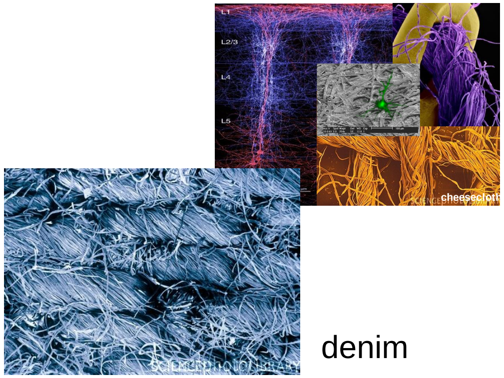




denim

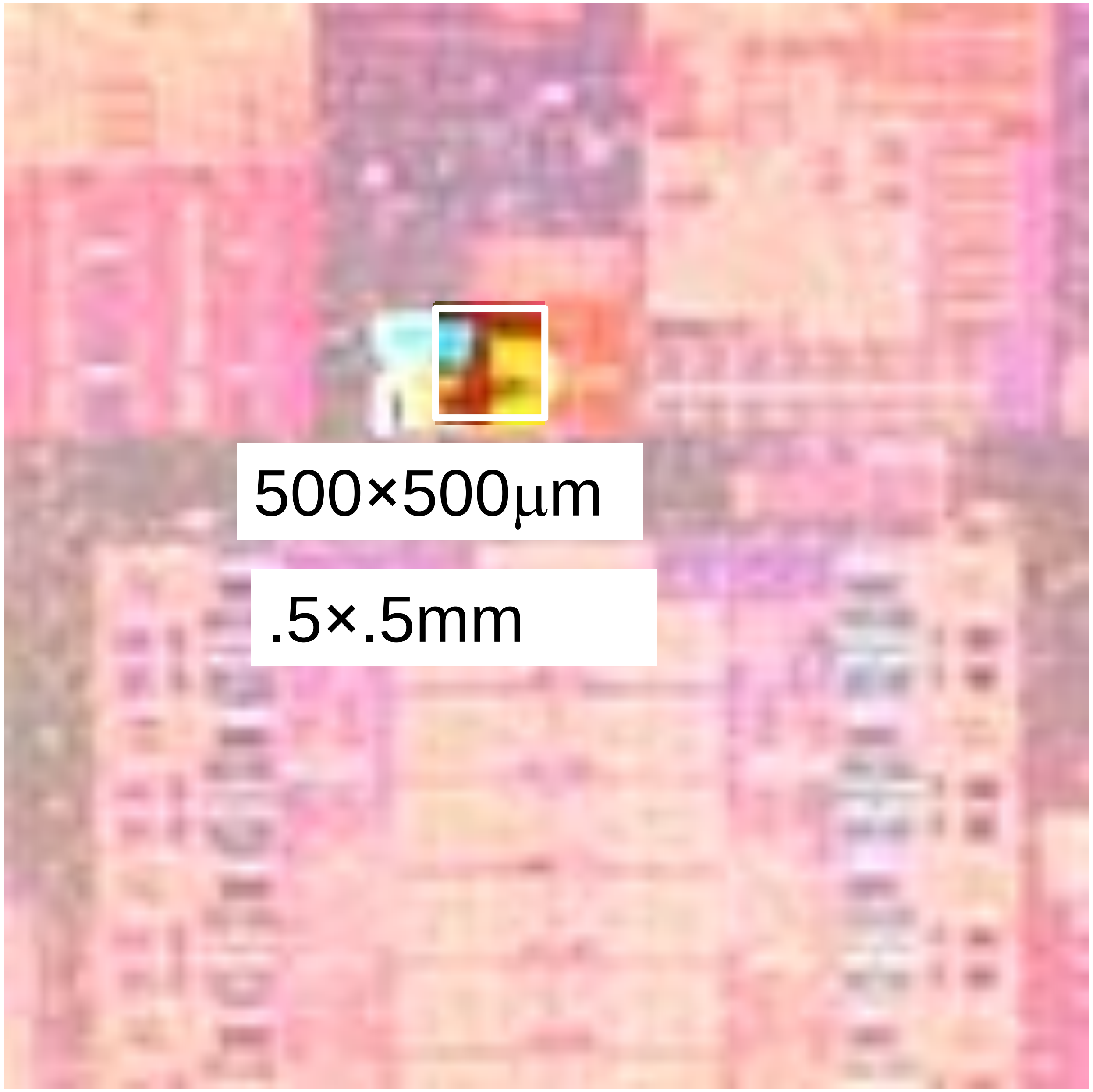
500×500μm

.5×.5mm

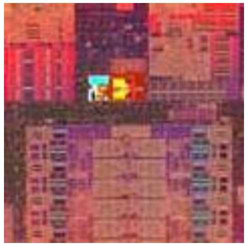


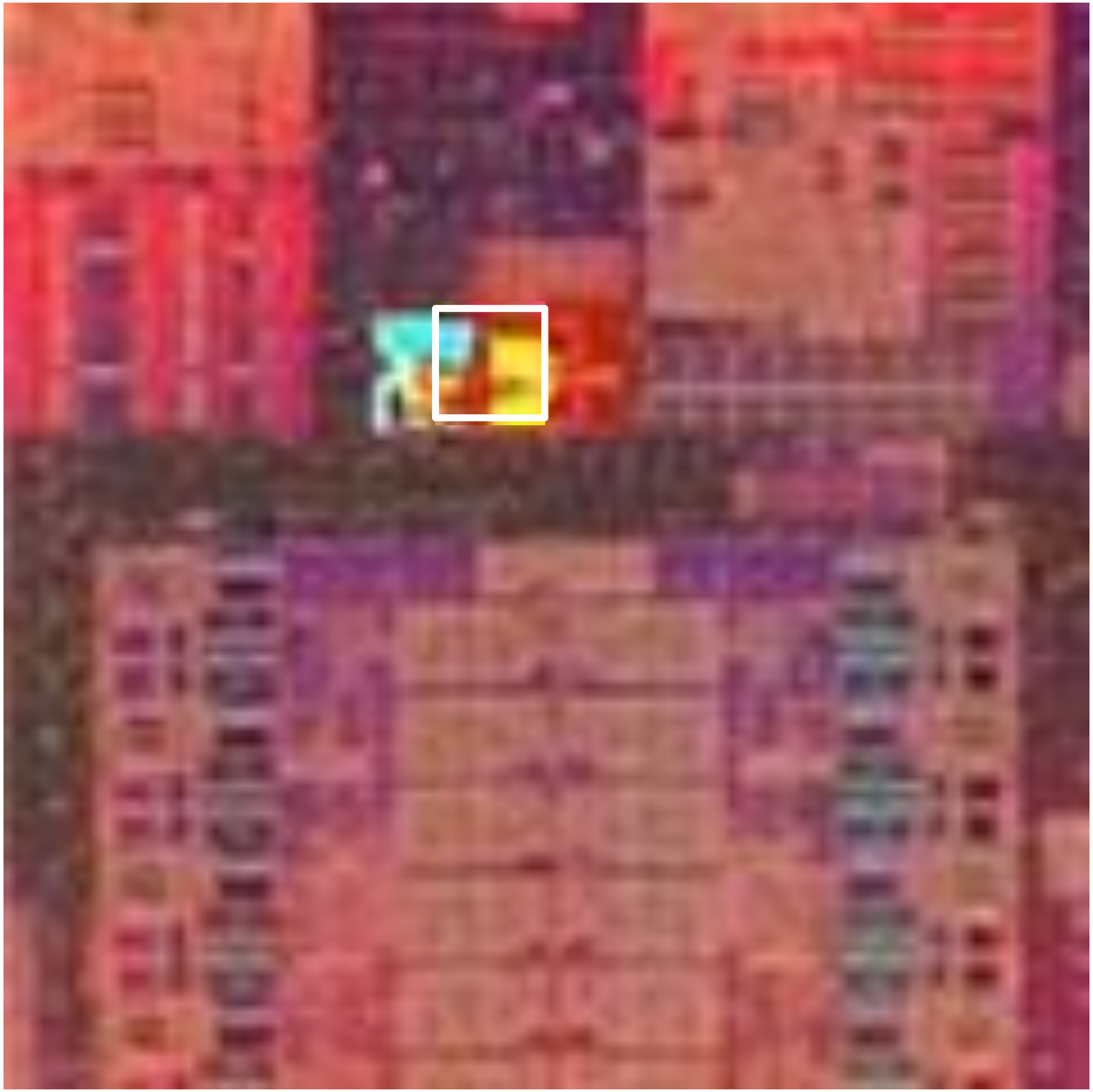
denim

5×5 mm

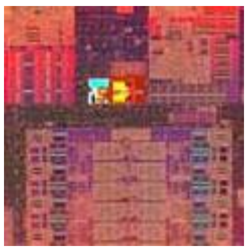


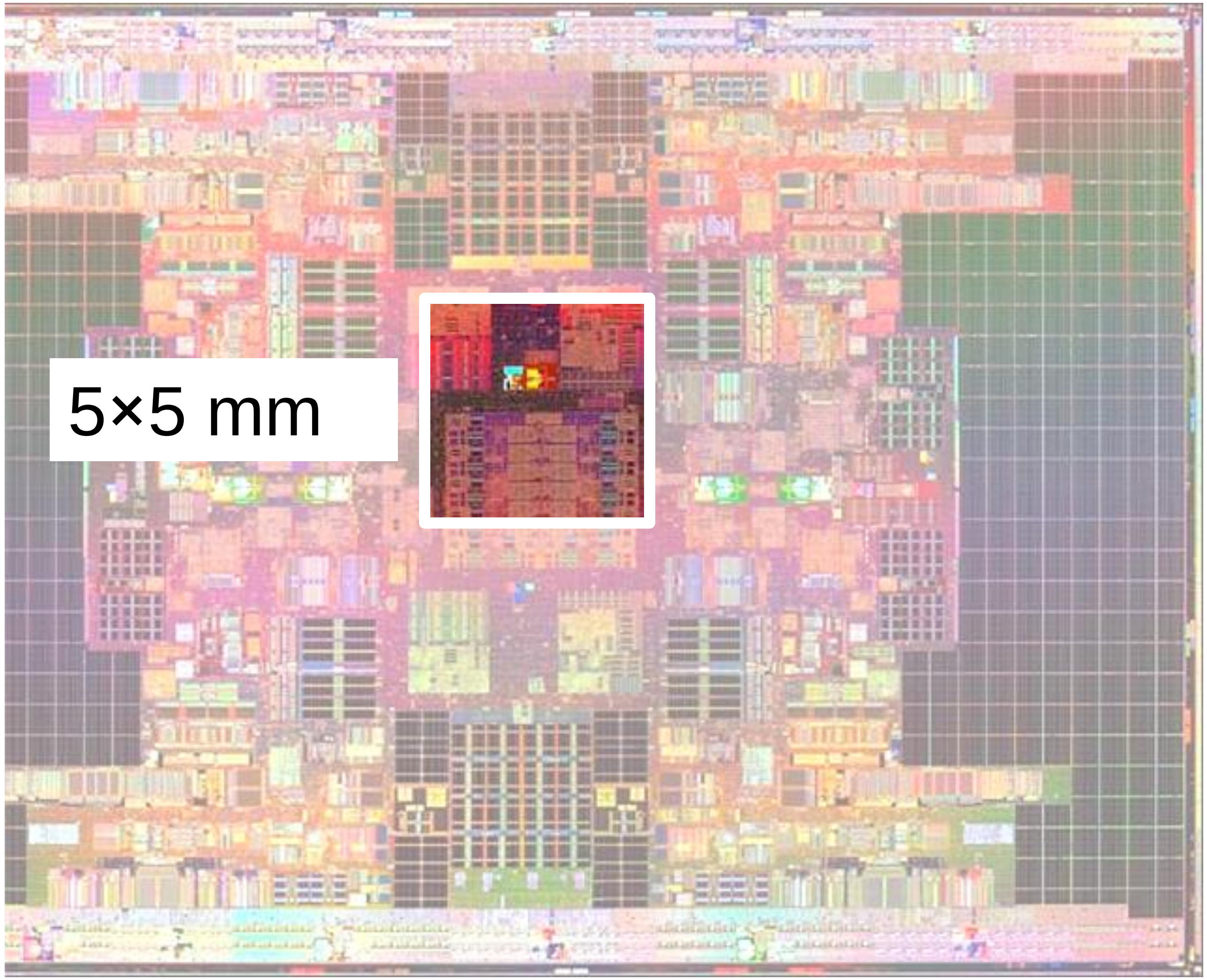
5×5 mm

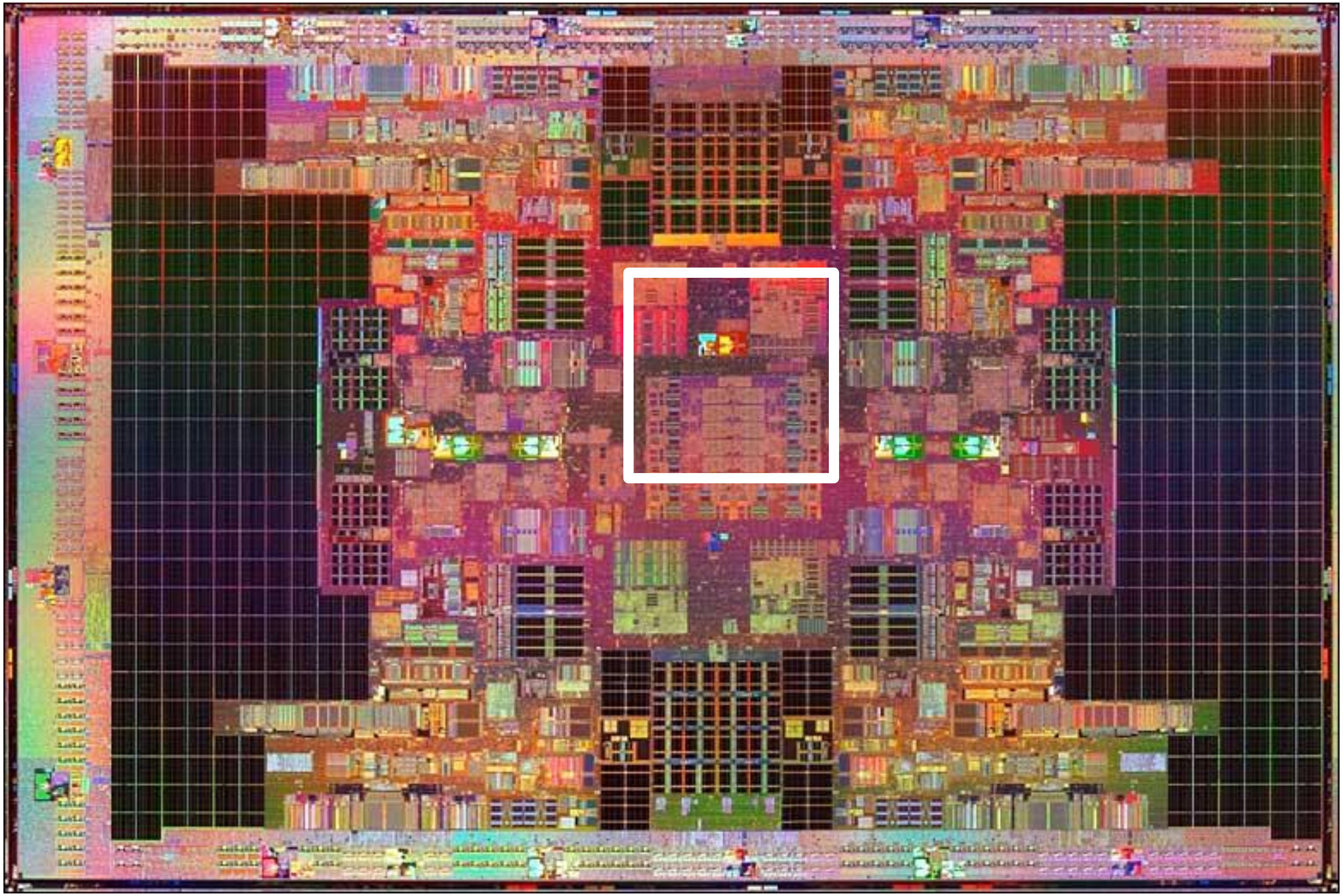


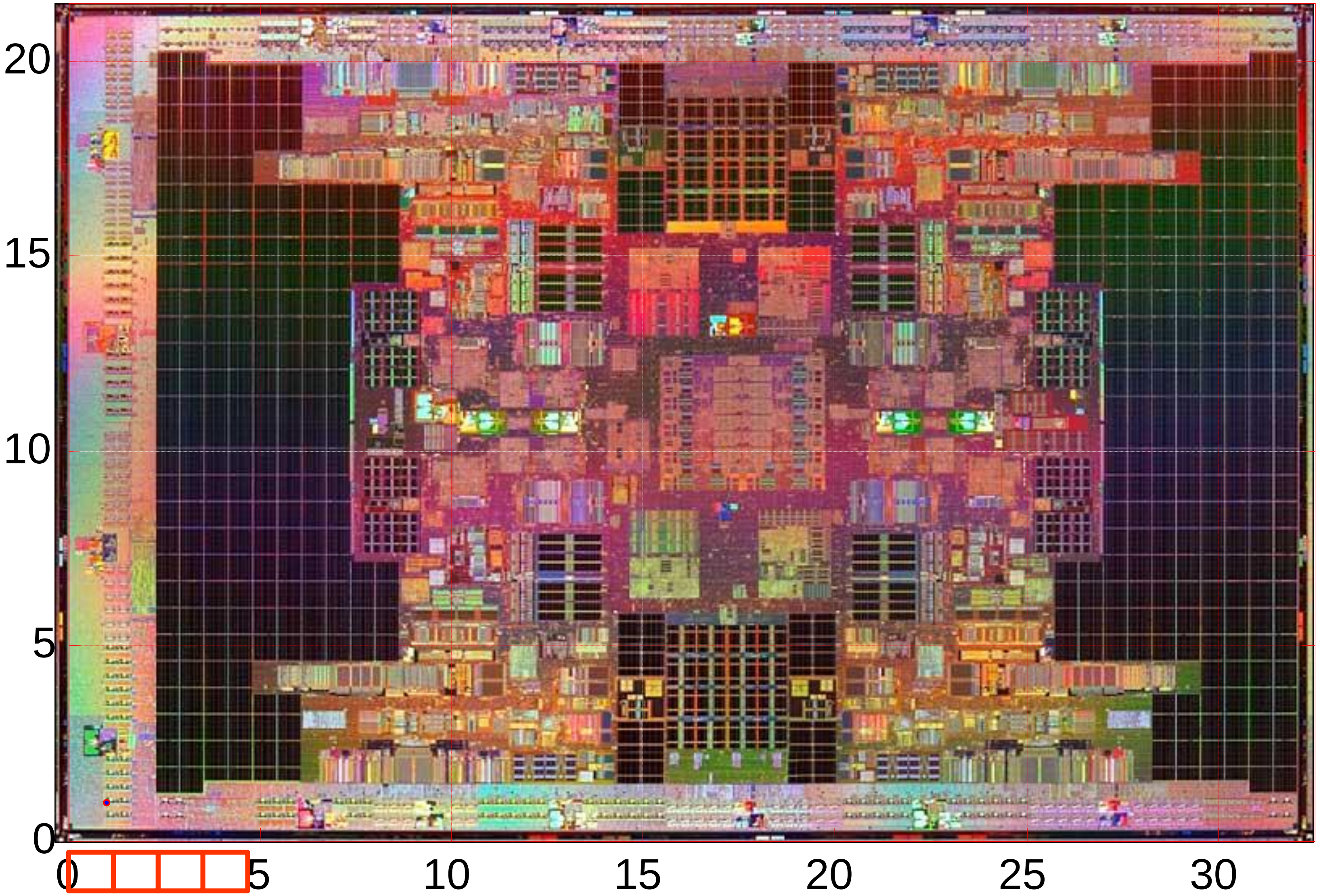


5×5 mm

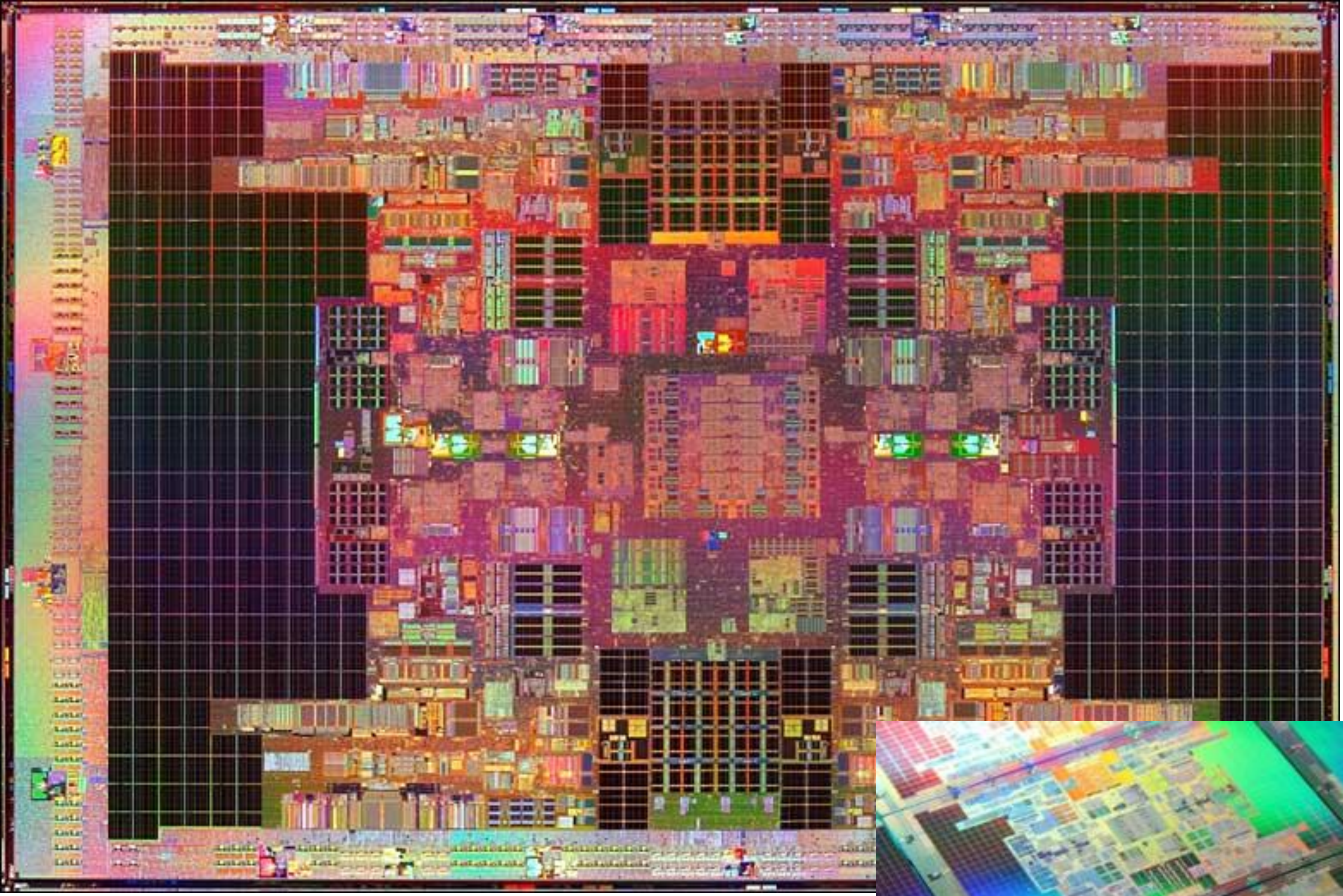


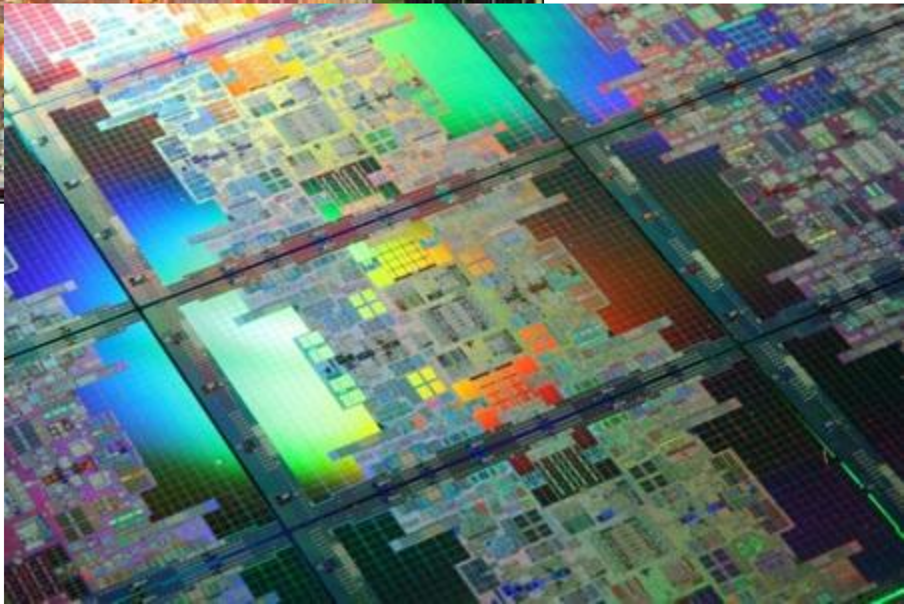






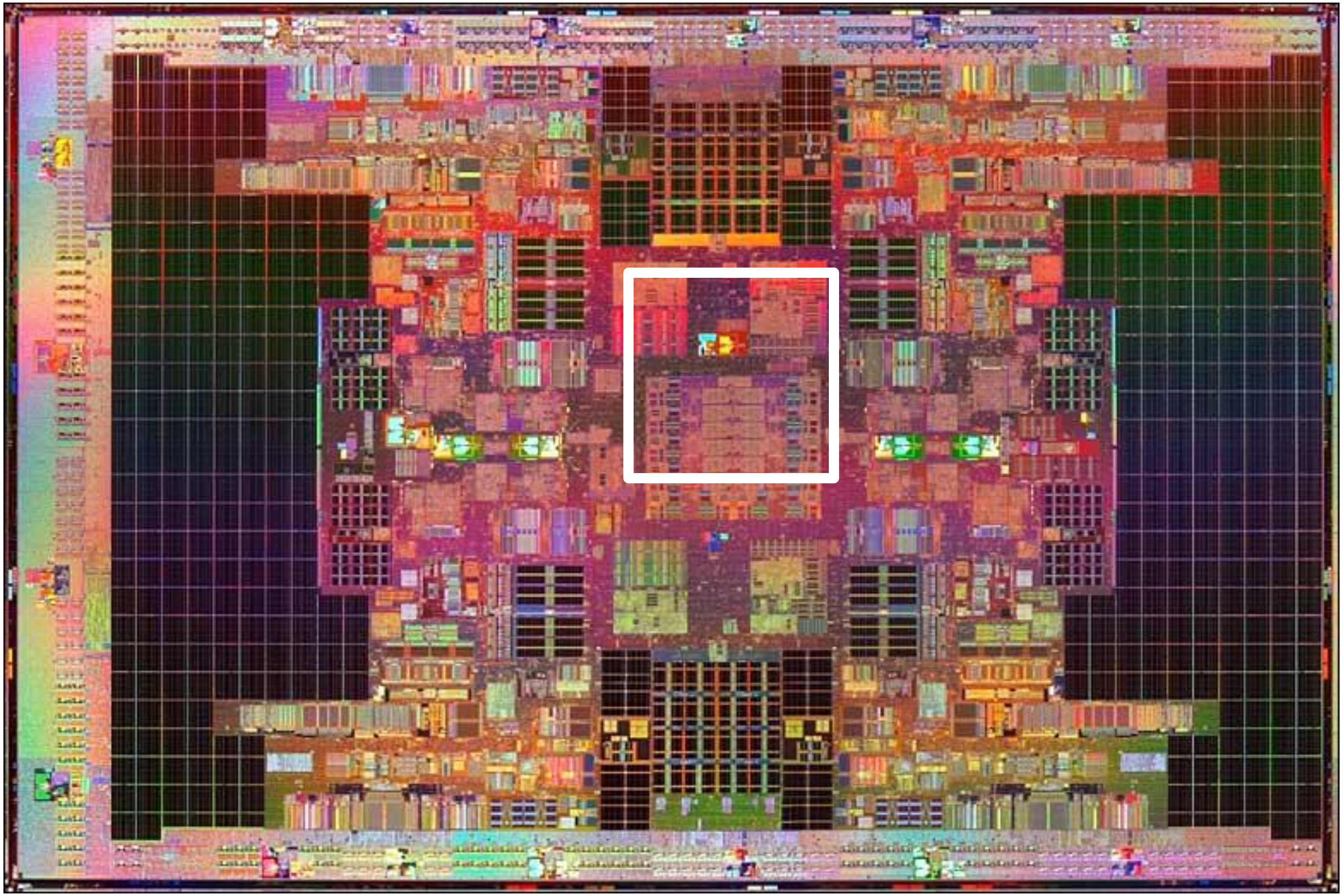
21.5×32.5 mm



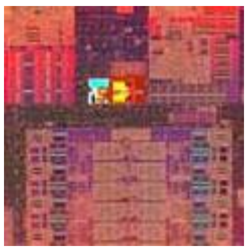


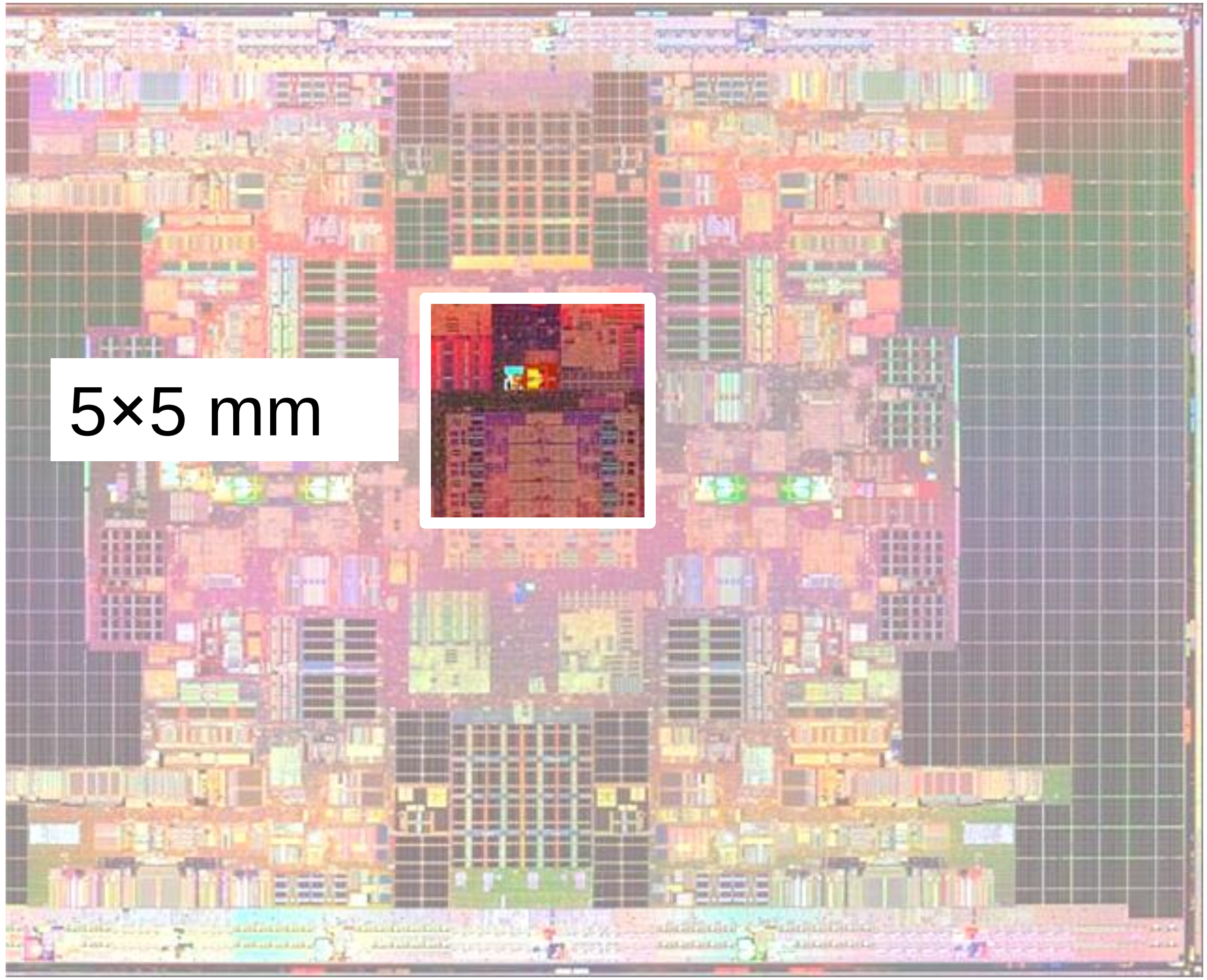
Intel Tukwila quad core chip with more than 2 billion transistors

21.5×32.5 mm

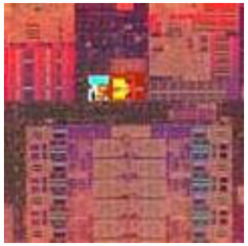


5×5 mm

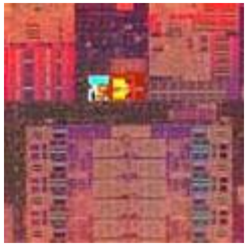


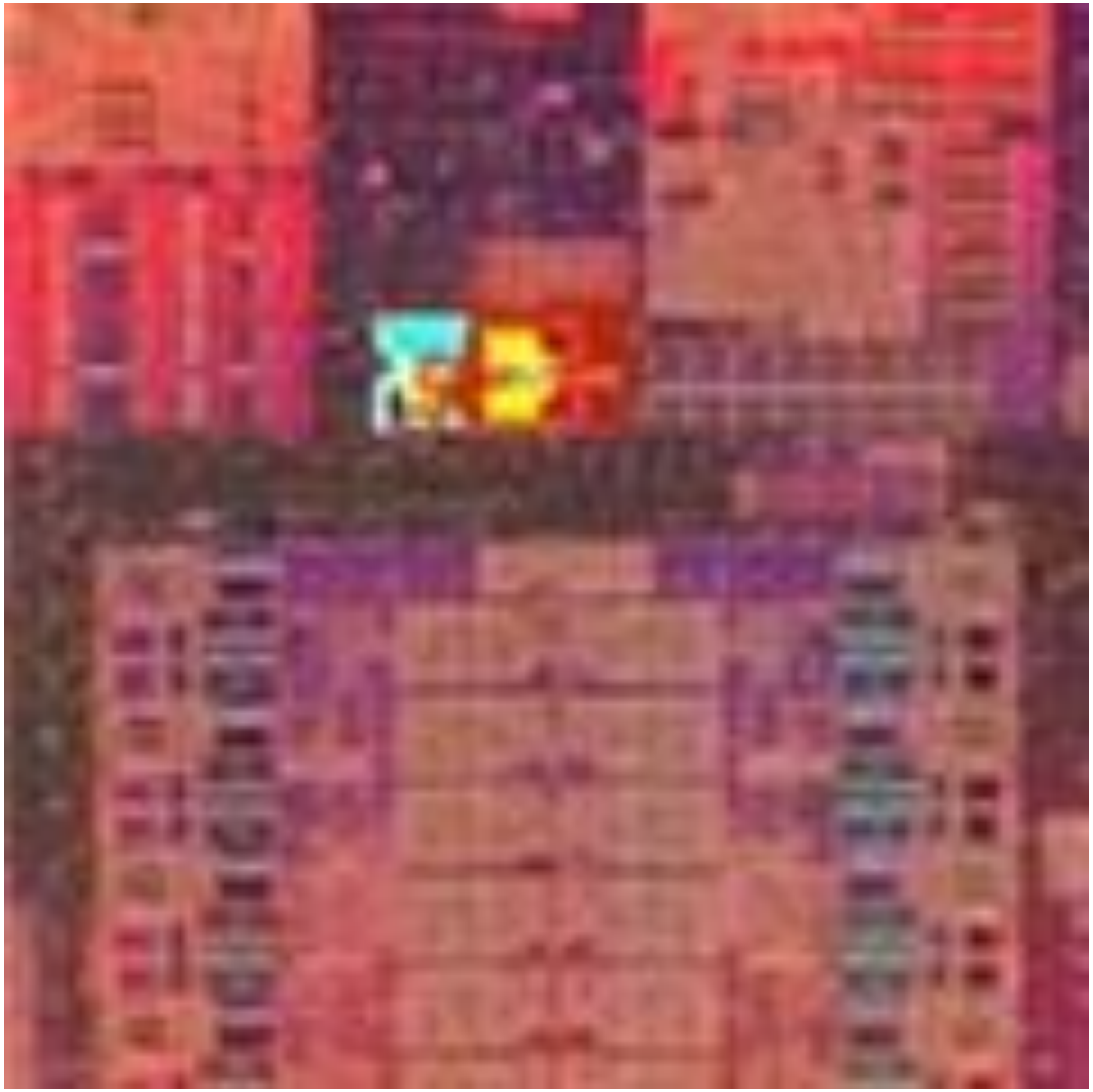


5×5 mm

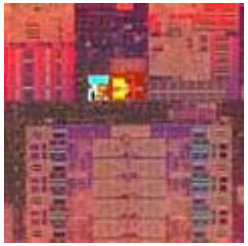


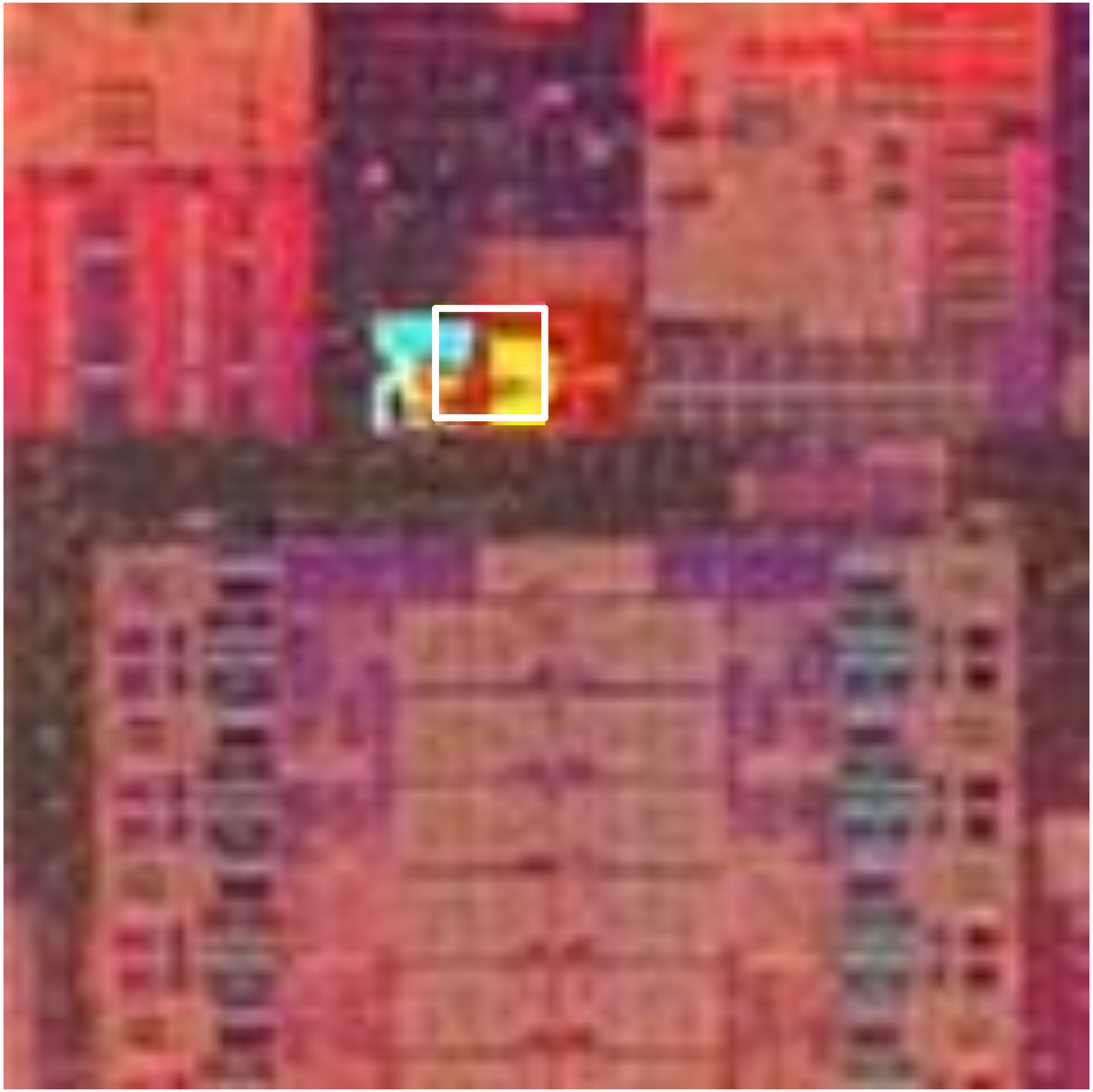
5×5 mm



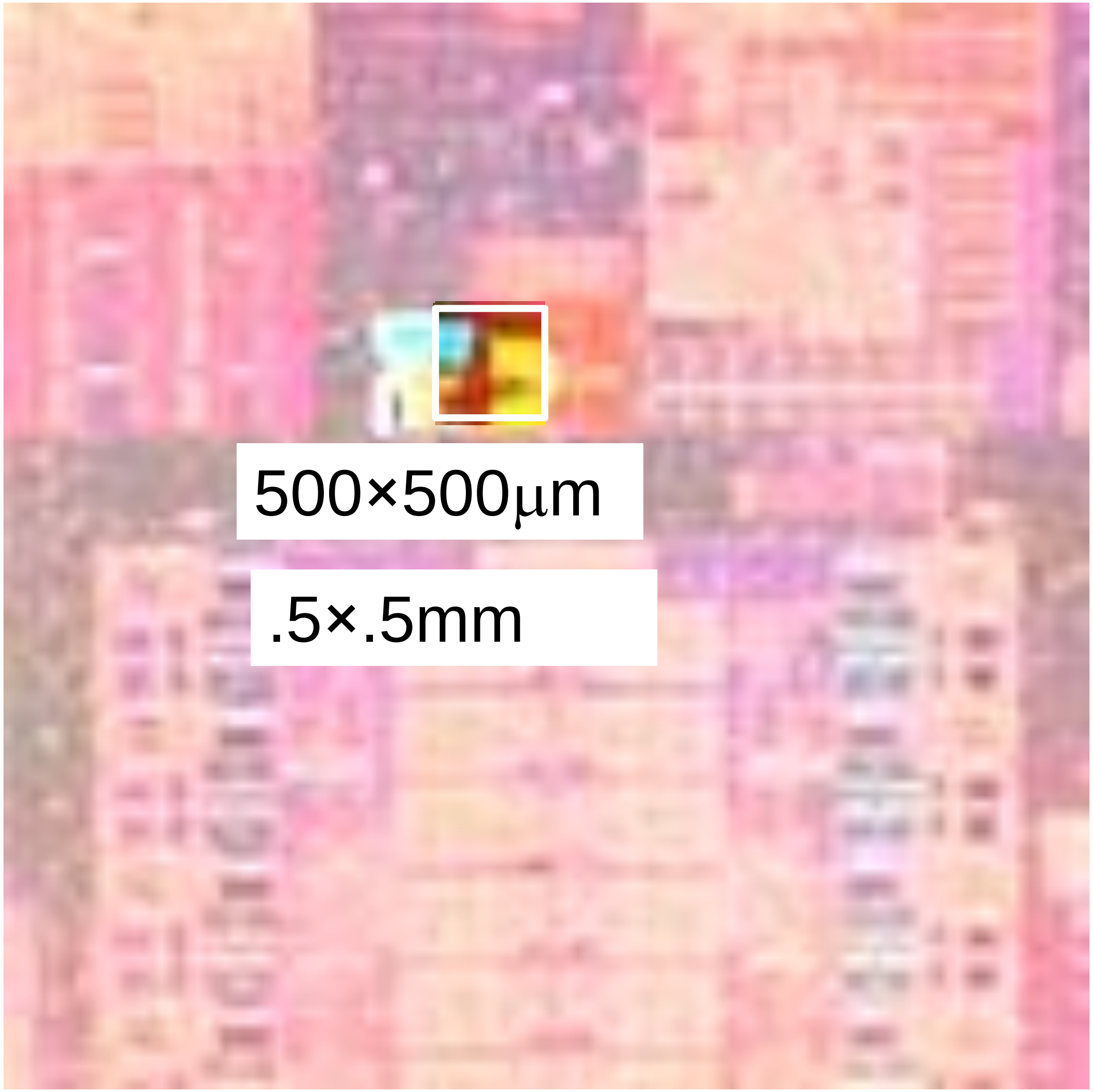


5×5 mm



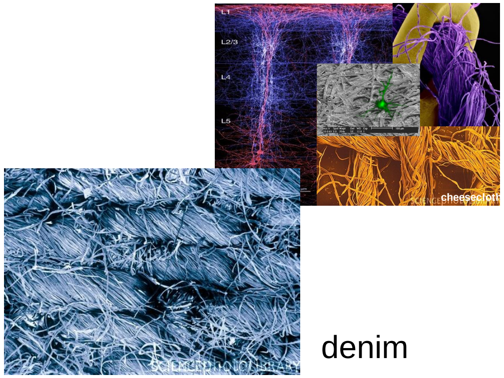


5×5 mm



500×500μm

.5×.5mm

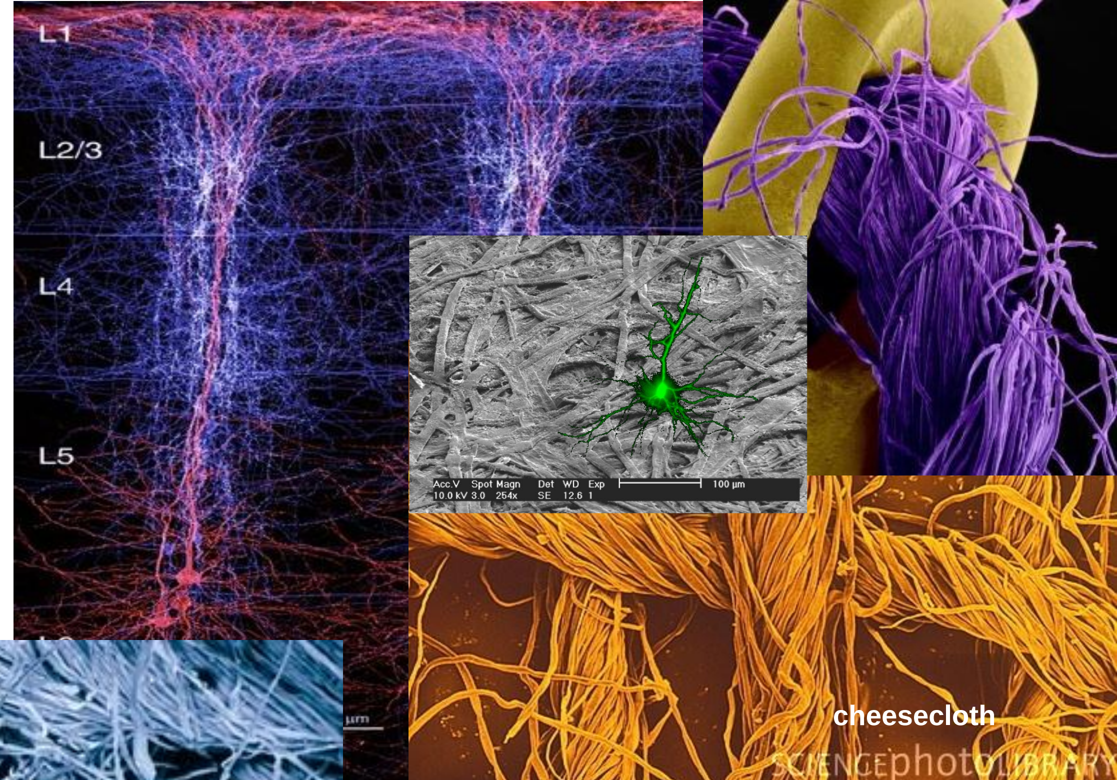


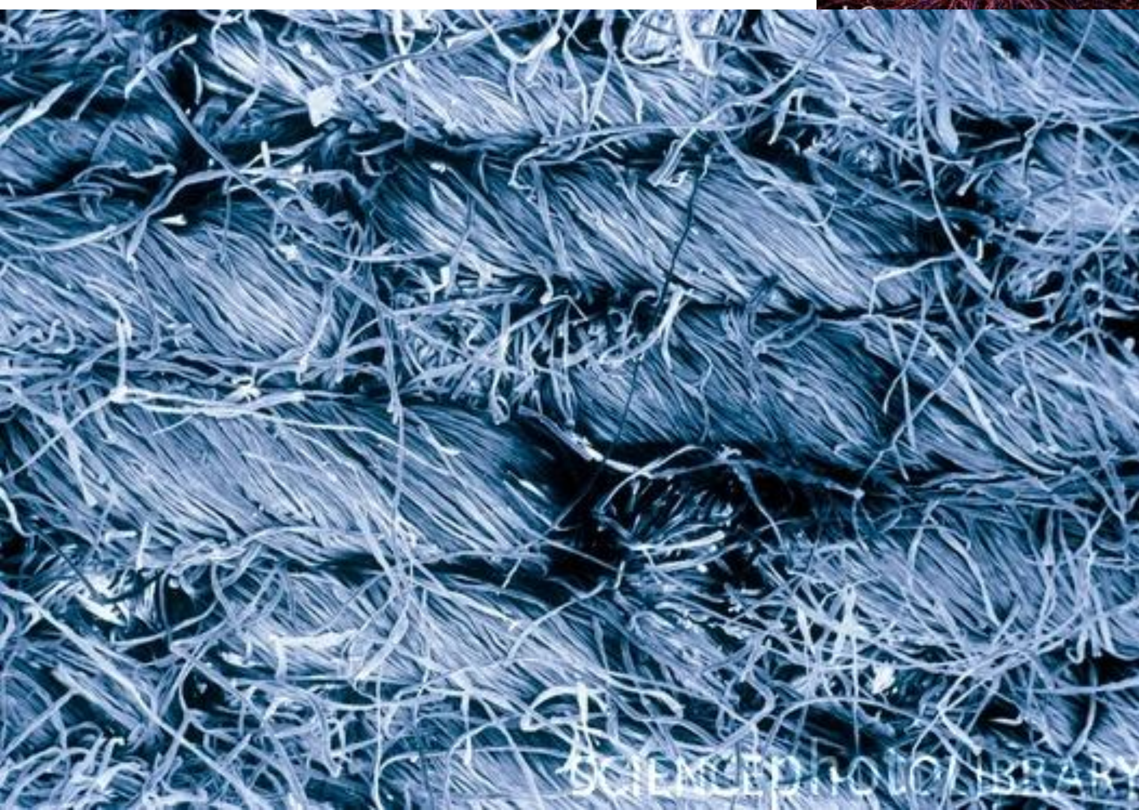
denim

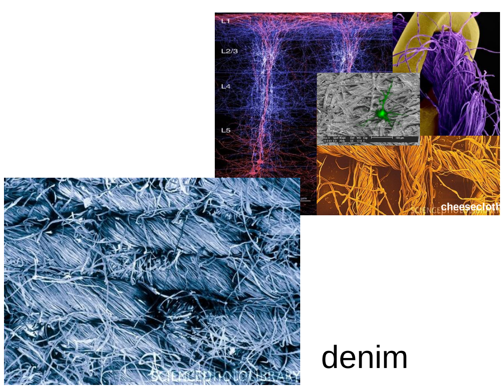
500μm

.5mm

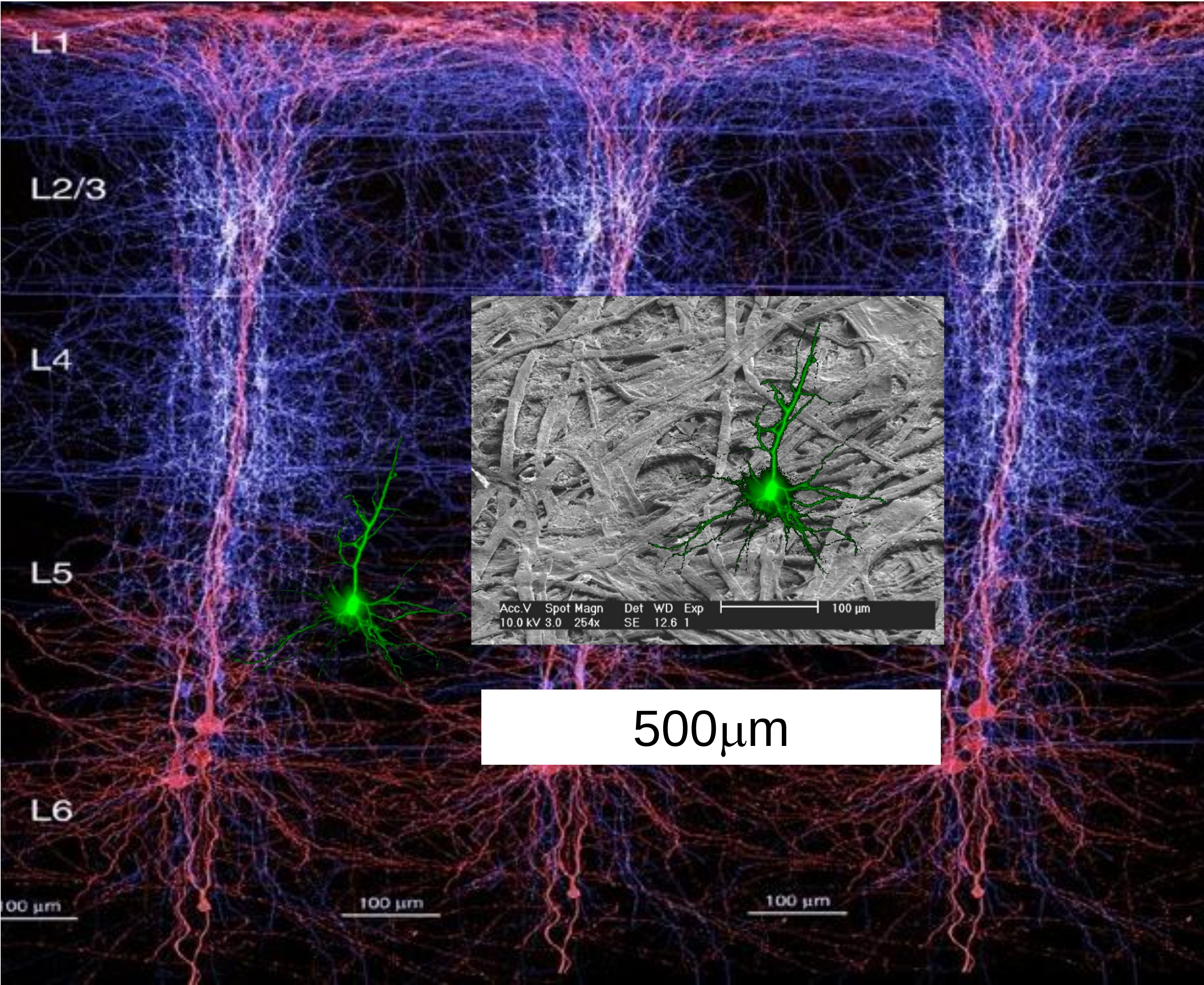
denim

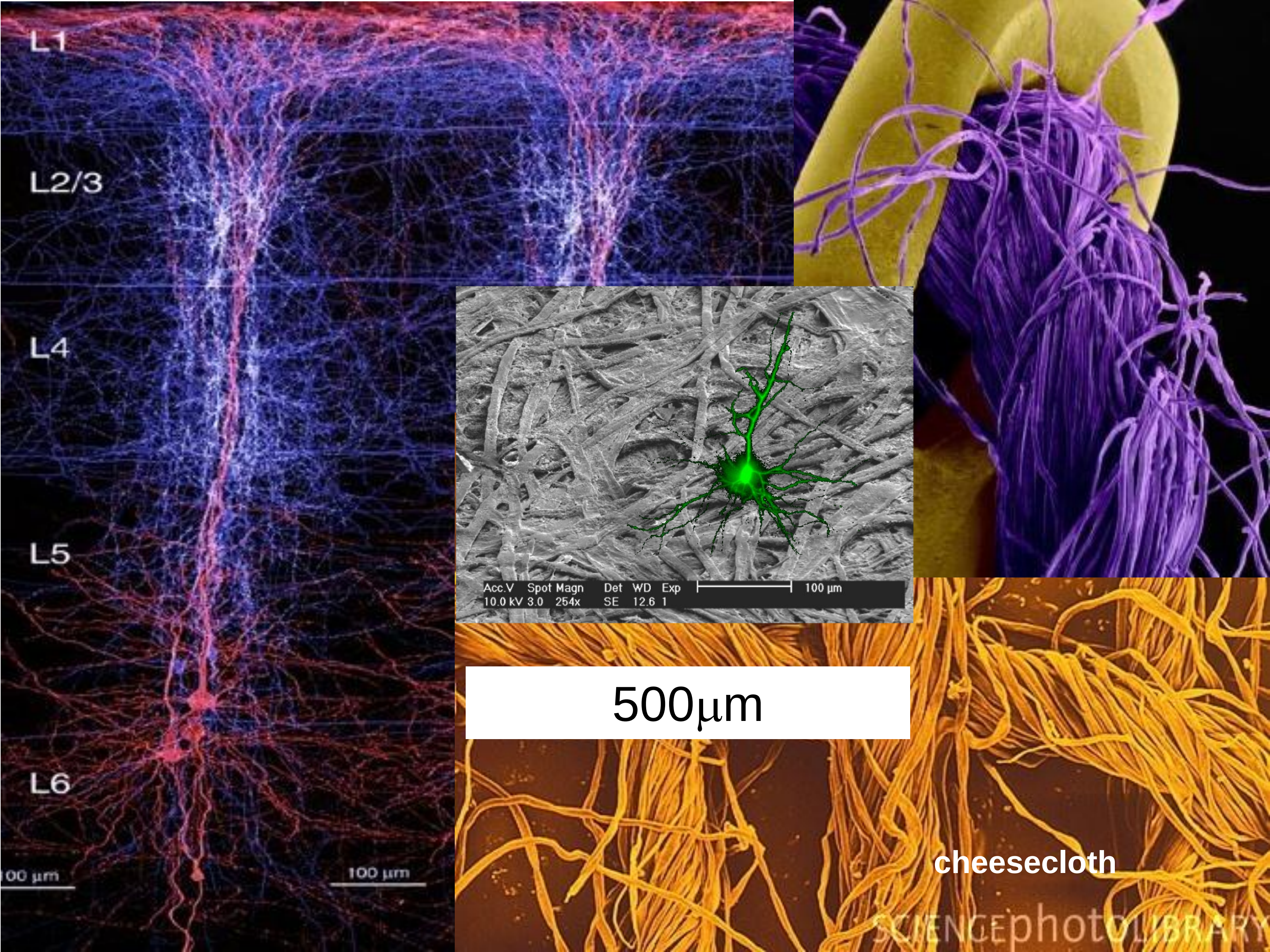


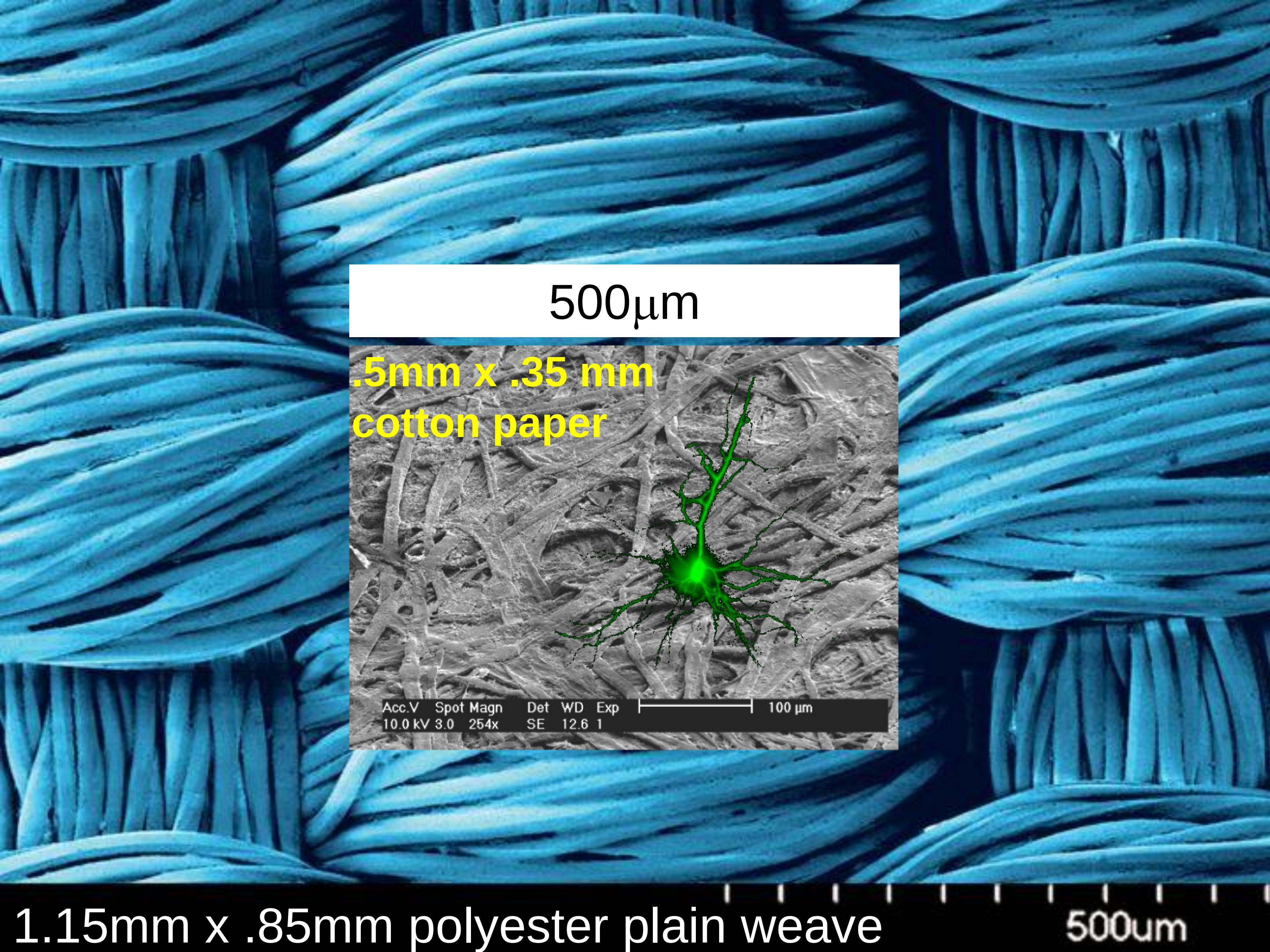


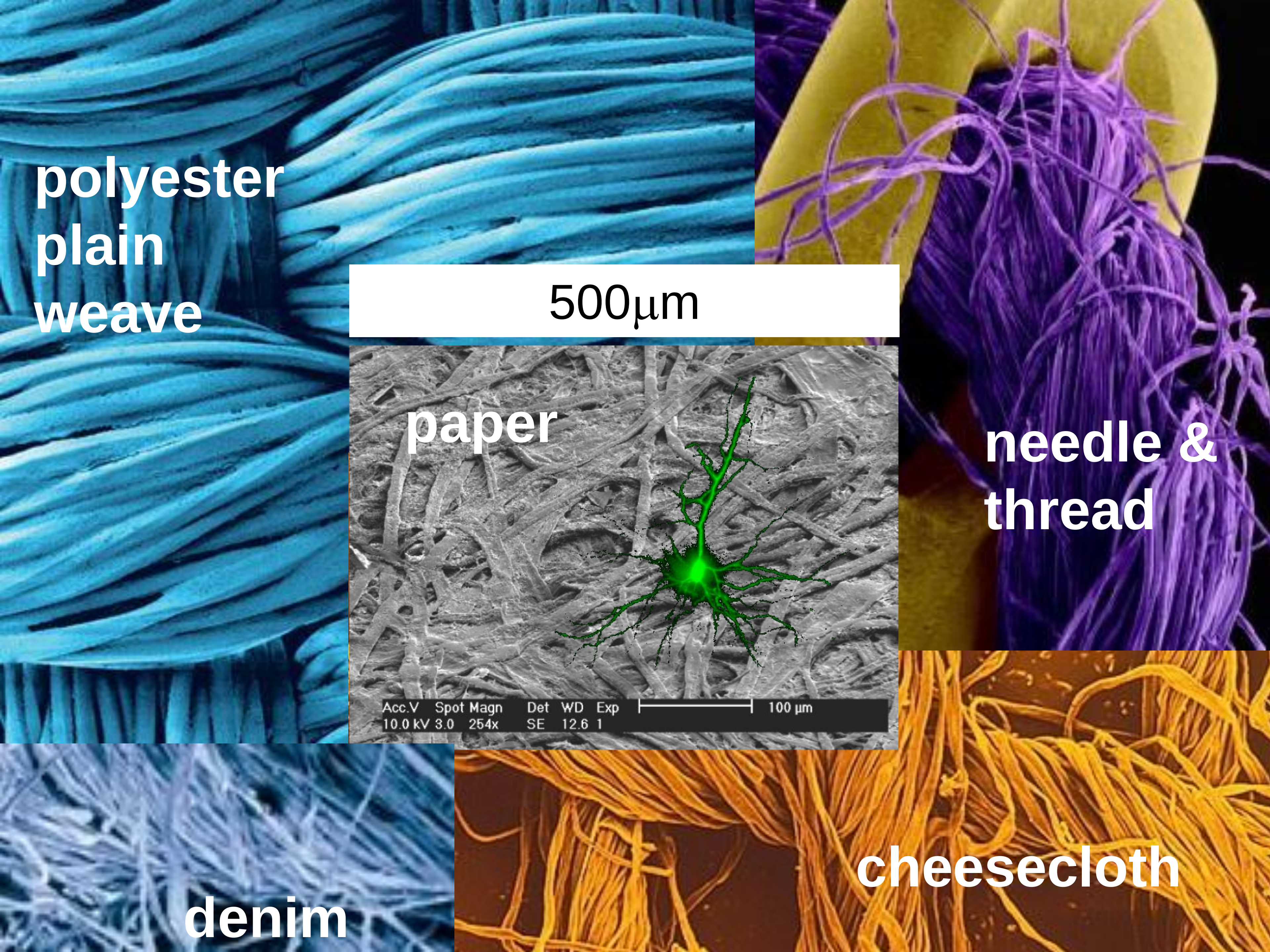


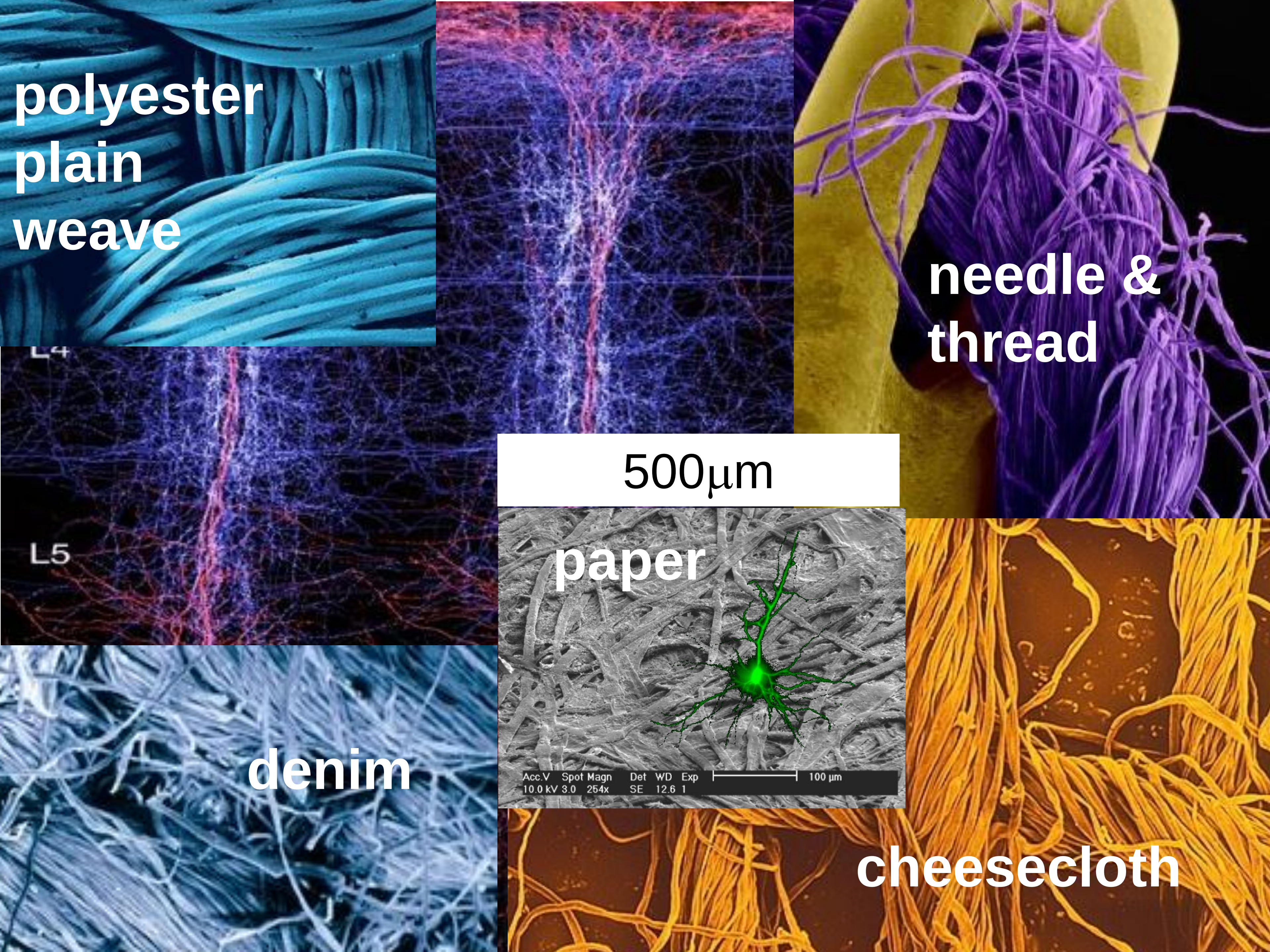
denim


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
10.0 kV 3.0 254x SE 12.6 1
100 µm
500µm
cheesecloth
SCIENCEPHOTOLIBRARY

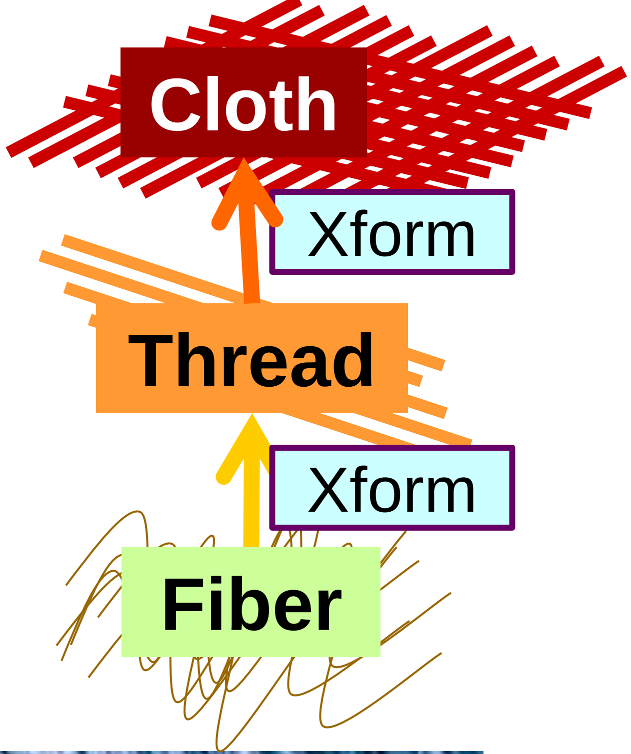

500μm
.5mm x .35 mm
cotton paper
Acc.V Spot Magn Det WD Exp 100 μm
10.0 kV 3.0 254x SE 12.6 1
1.15mm x .85mm polyester plain weave
500um

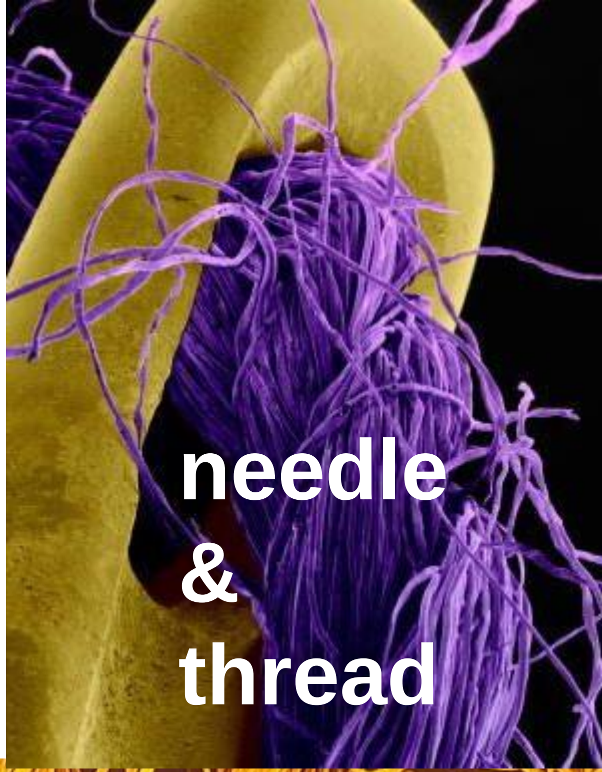

polyester
plain
weave
500µm
paper
Acc.V Spot Magn Det WD Exp 100 µm
10.0 kV 3.0 254x SE 12.6 1
needle &
thread
denim
cheesecloth

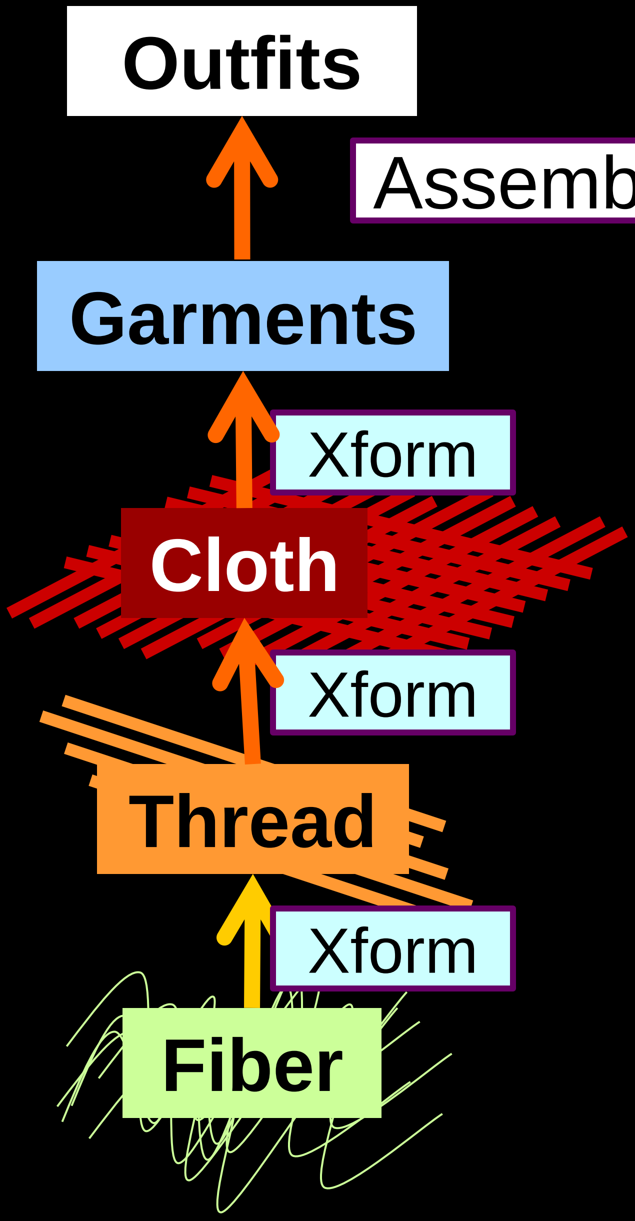

polyester
plain
weave
needle &
thread
500μm
L5
paper
Acc.V Spot Magn Det WD Exp
10.0 kV 3.0 254x SE 12.6 1
100 μm
denim
cheesecloth

Hidden, large, thin, nonconvex

are *necessary*







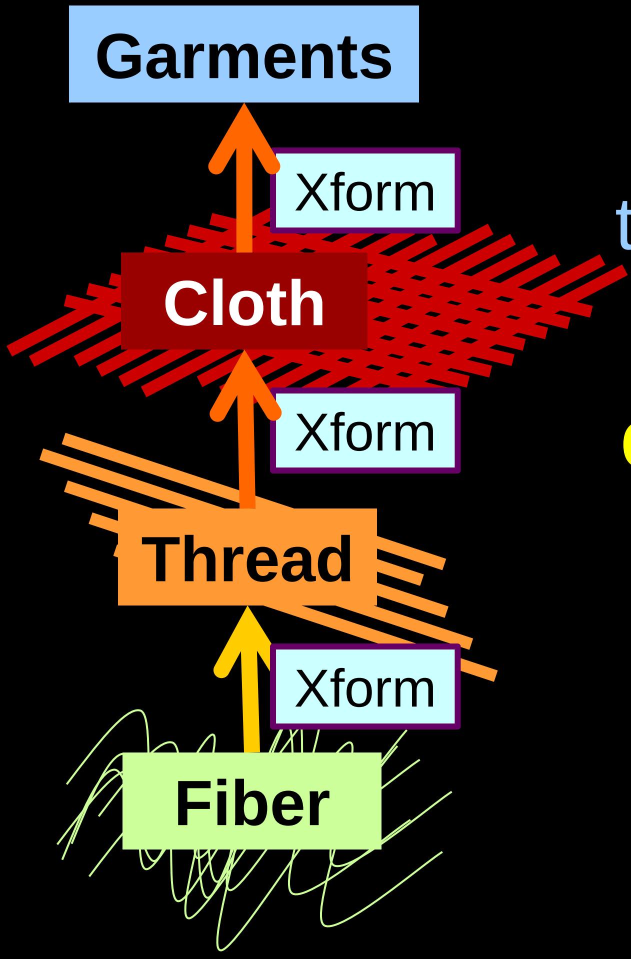
Hidden, large, thin, nonconvex

are *necessary*

Universal strategies?

Even though garments seem analog/continuous

Garments have limited access to threads and fibers



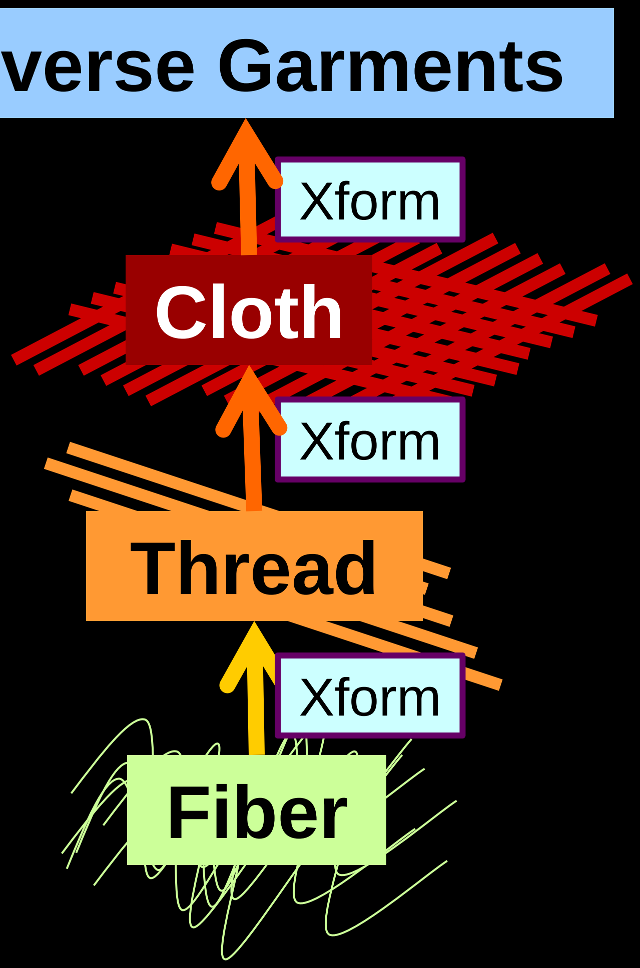
quantization for robustness

constraints on cross-layer interactions

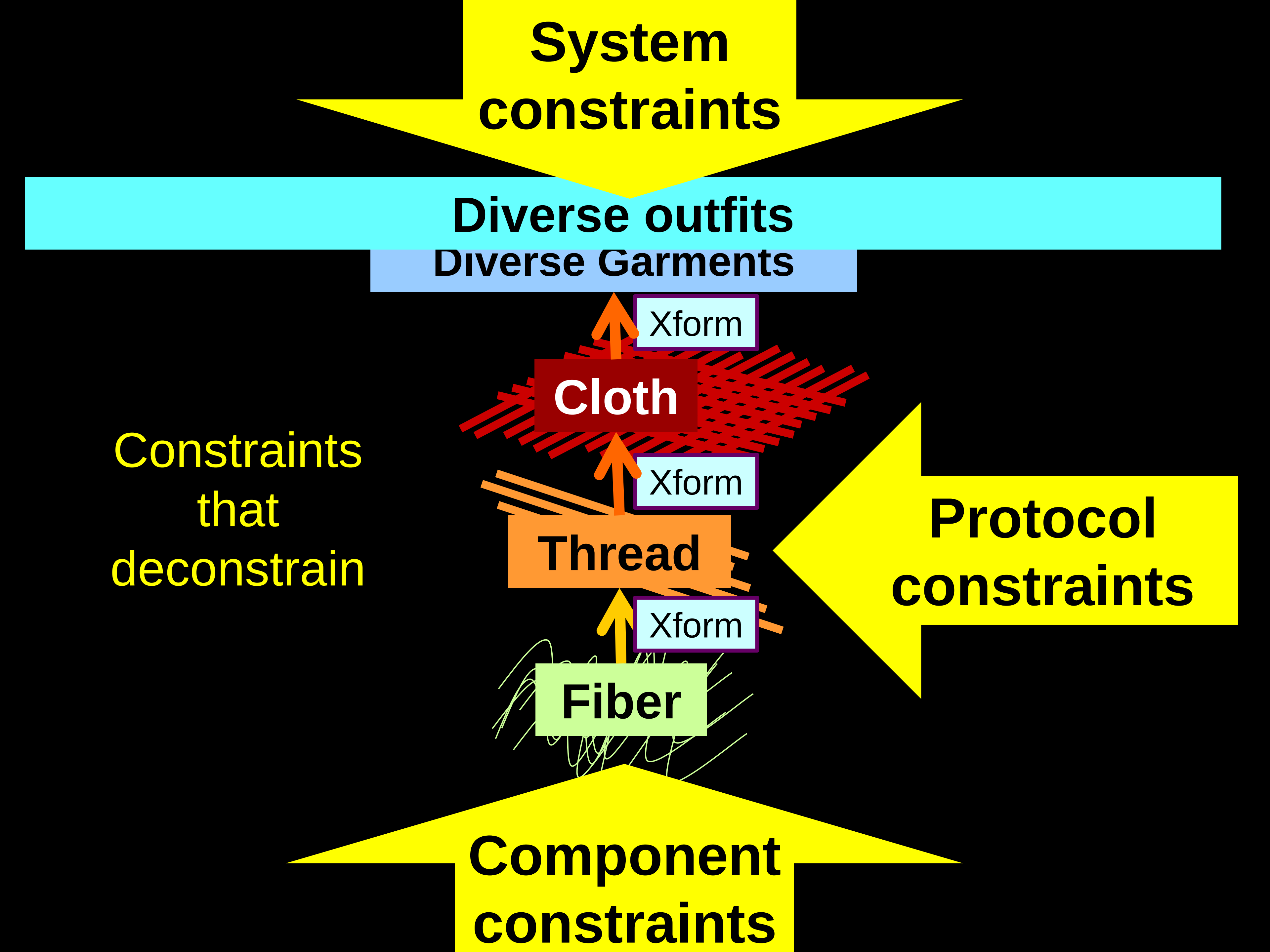
Prevents unraveling of lower layers

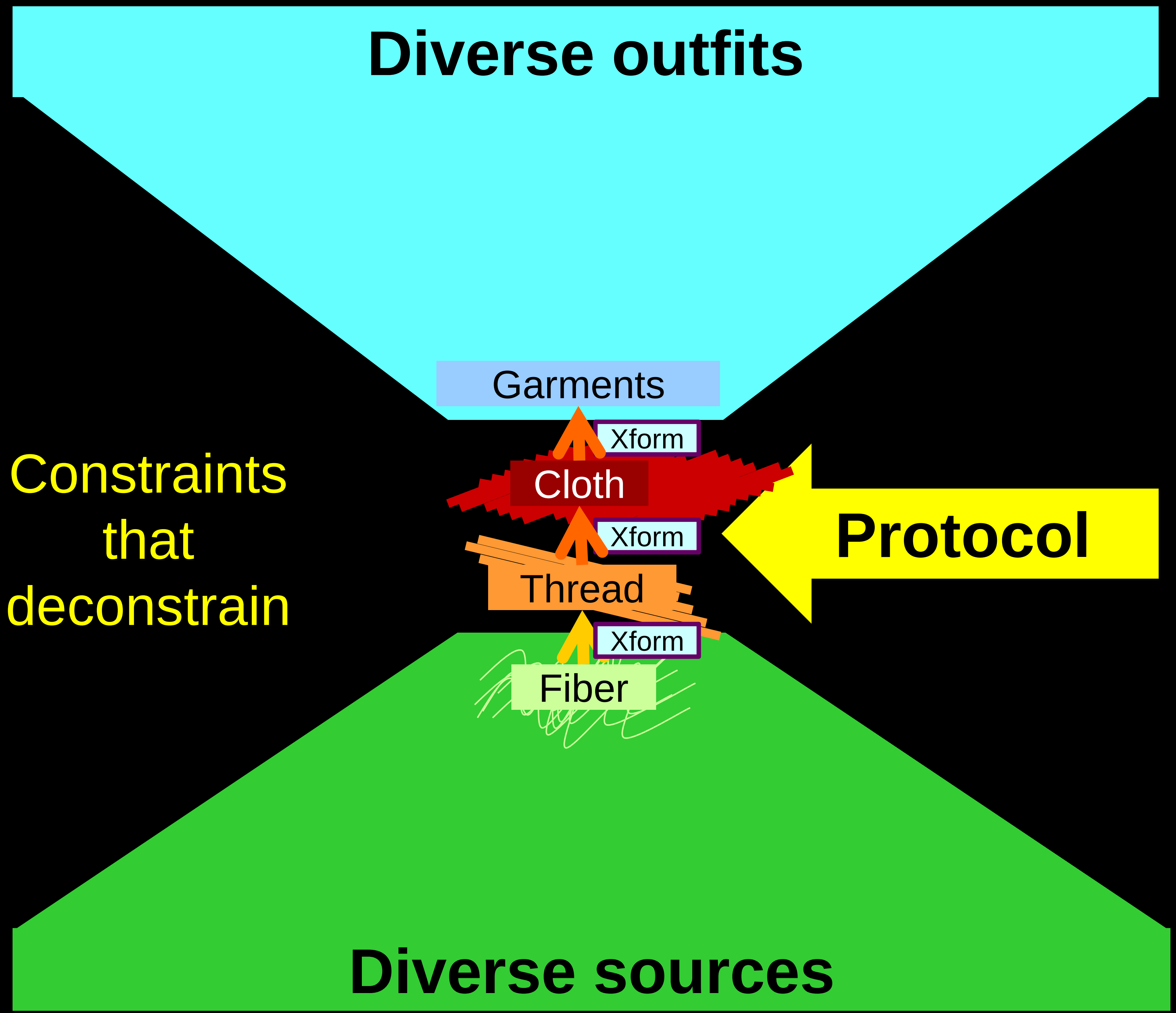
Diverse outfits

Constraints
that
deconstrain

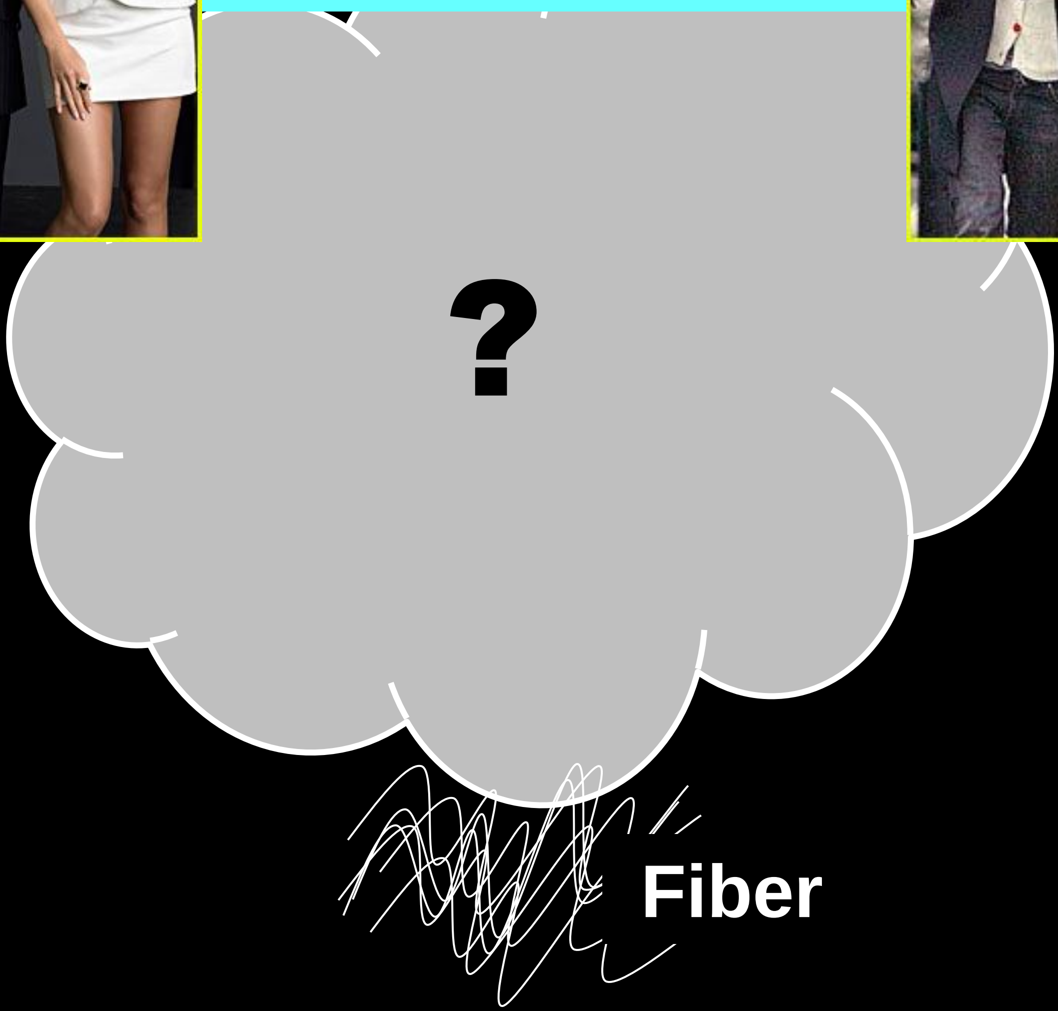


Geographically diverse sources

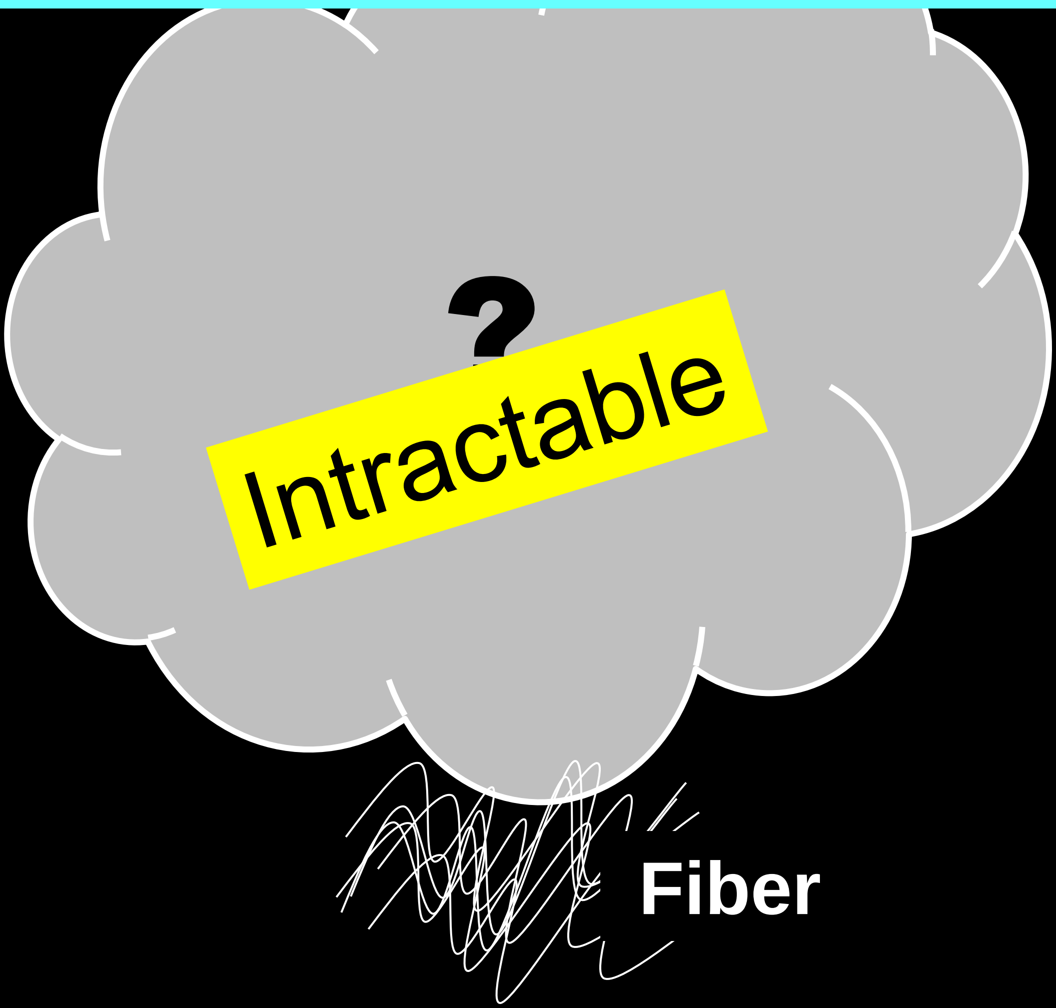

System constraints
Diverse outfits
Diverse Garments
Xform
Cloth
Xform
Thread
Xform
Fiber
Constraints that deconstrain
Protocol constraints
Component constraints


Diverse outfits
Garments
Xform
Cloth
Xform
Thread
Xform
Fiber
Constraints that deconstrain
Protocol
Diverse sources

Diverse outfits



Diverse outfits



SOC/EOC?

Self-Organized Clothing

Edge of Couture

Scale-Free Fashion

Standard error

Diverse outfits

Small gap

No architecture

Self-Organized Clothing

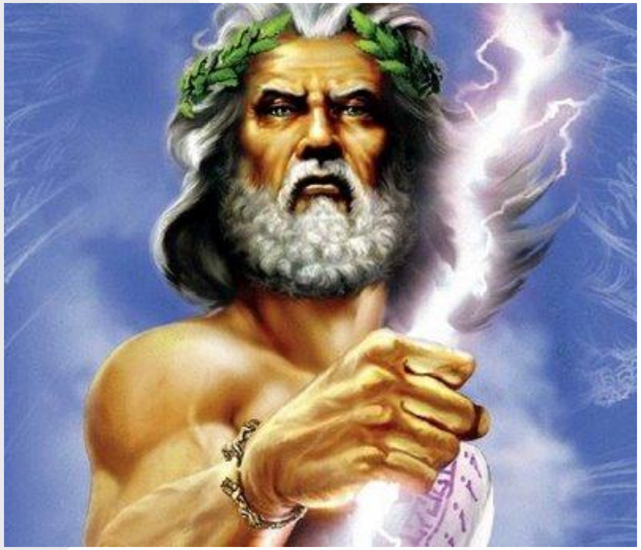
Edge of Couture

Scale-Free Fashion

Standard error

Diverse outfits

Huge gap
No architecture
Supernatural

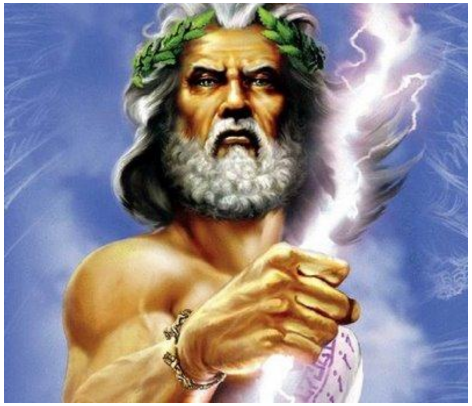


Fiber

Mysteries in the gaps
No architecture

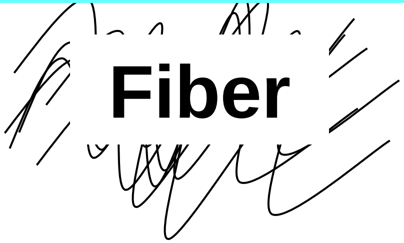
Diverse outfits

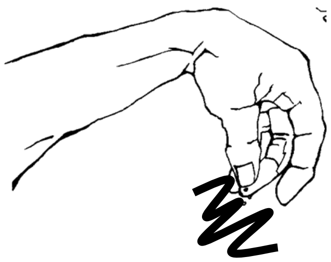
Small gap
Emergence
Self-organized
Phase transition
Edge-of
Scale-free



Huge gap
Supernatural

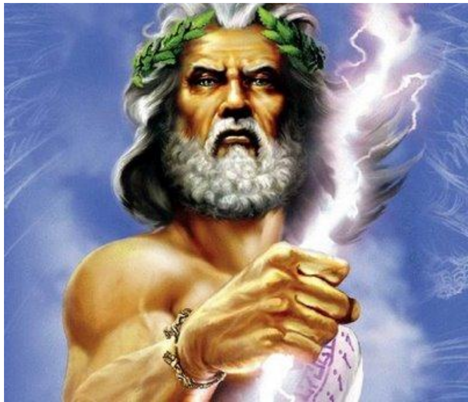
Diverse outfits





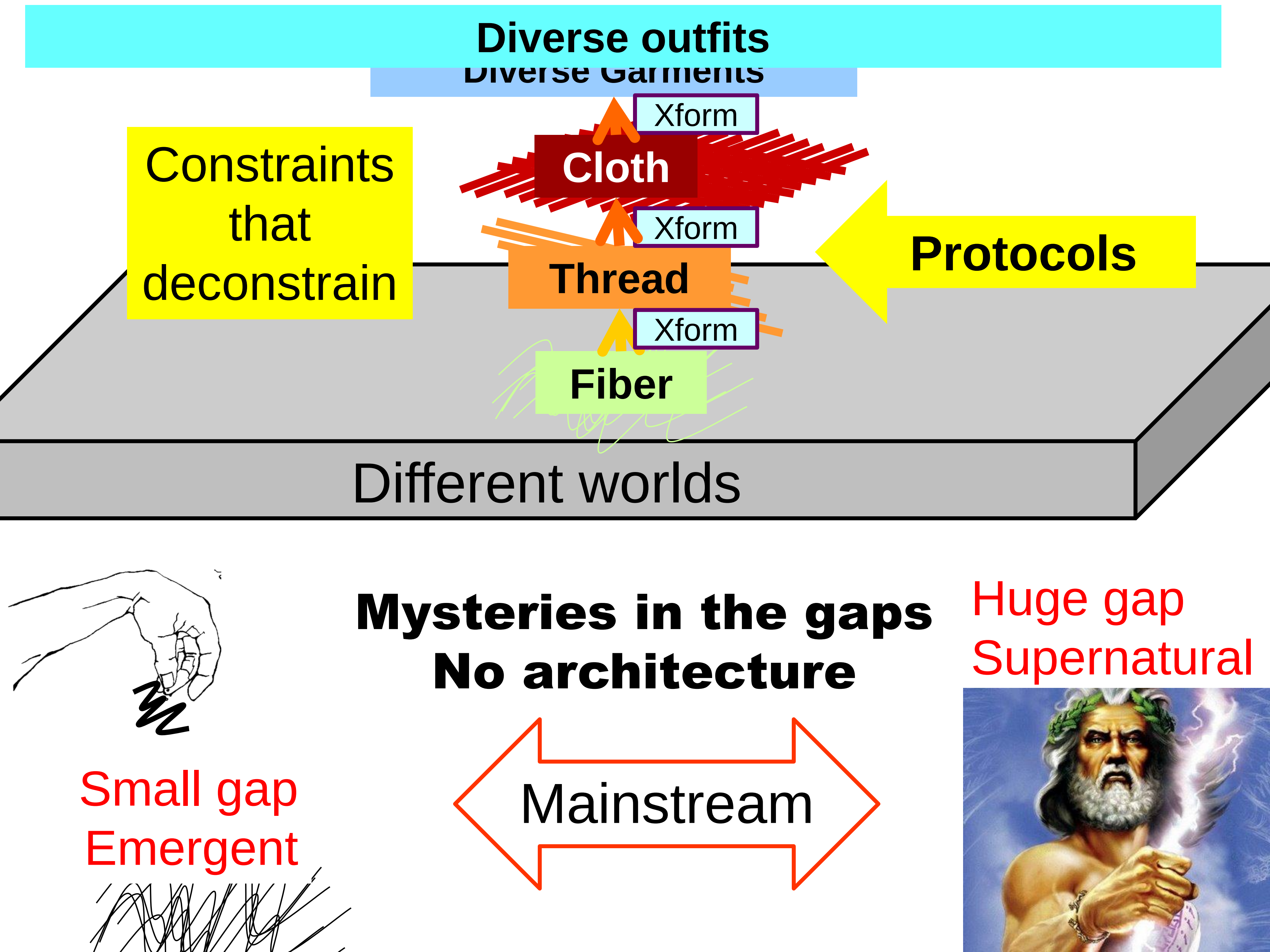
Mysteries in the gaps
No architecture

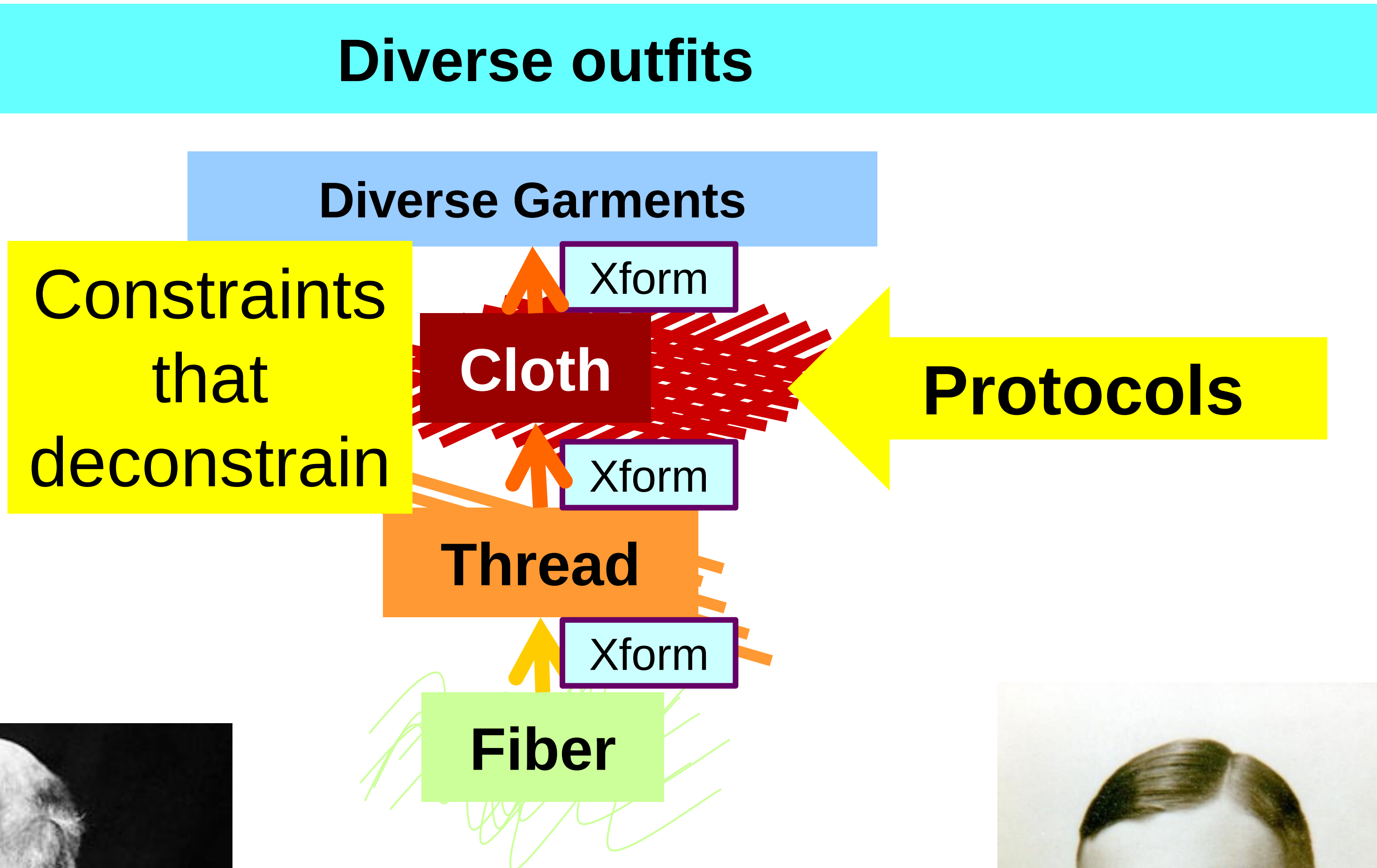
Huge gap
Supernatural

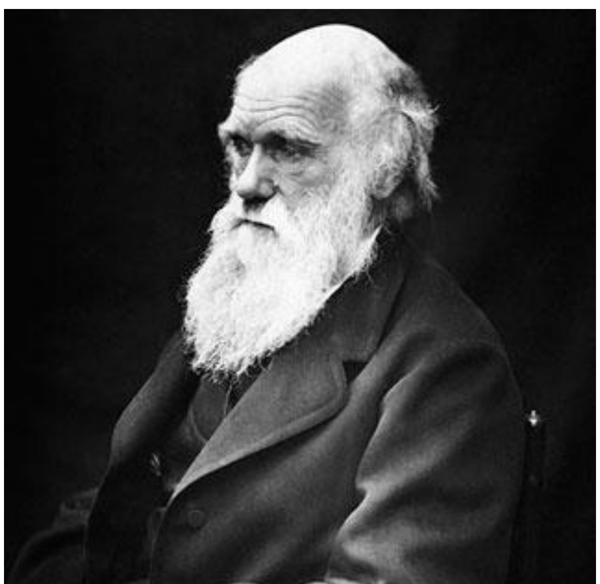


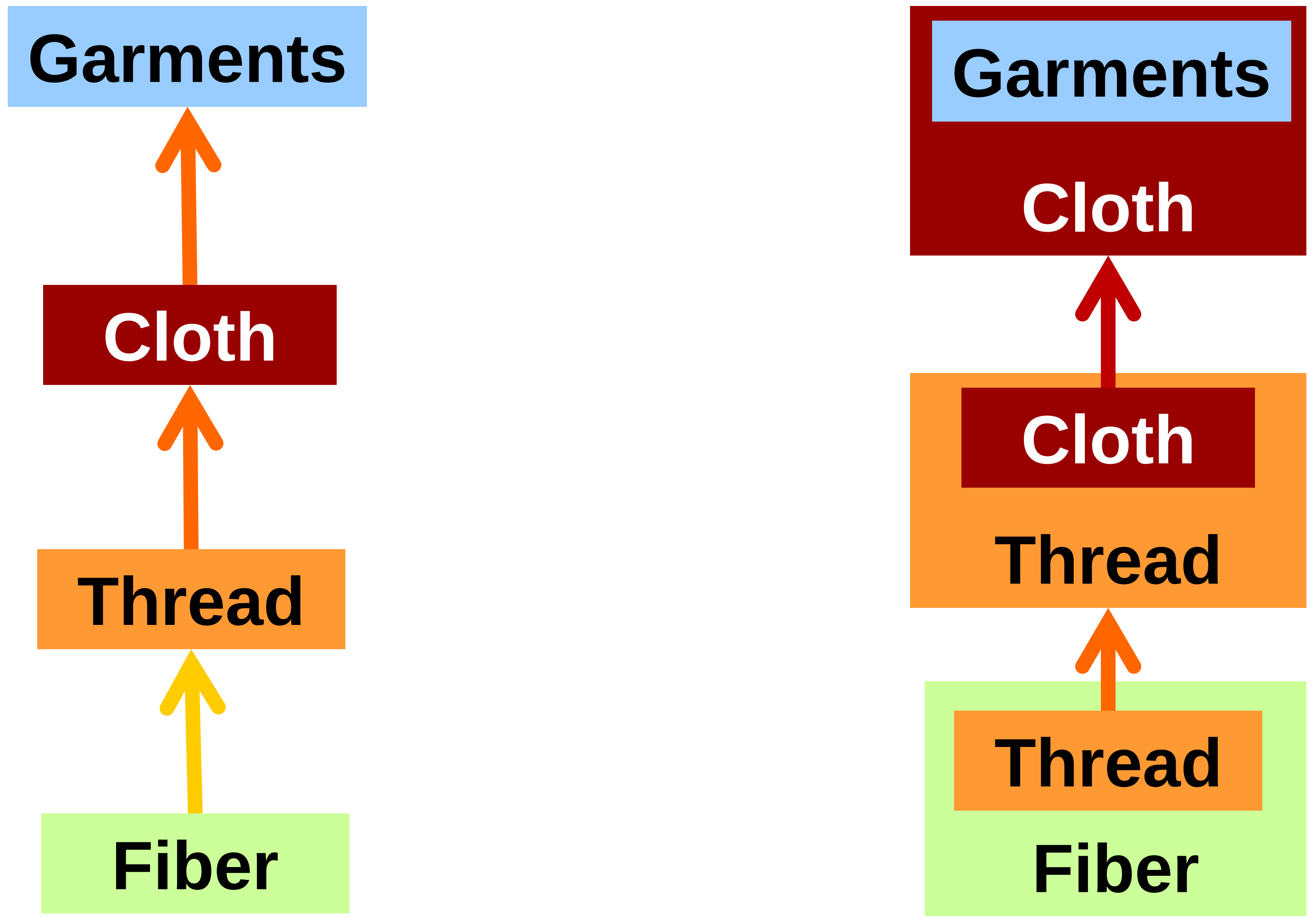
Small gap
Emergent

Mainstream

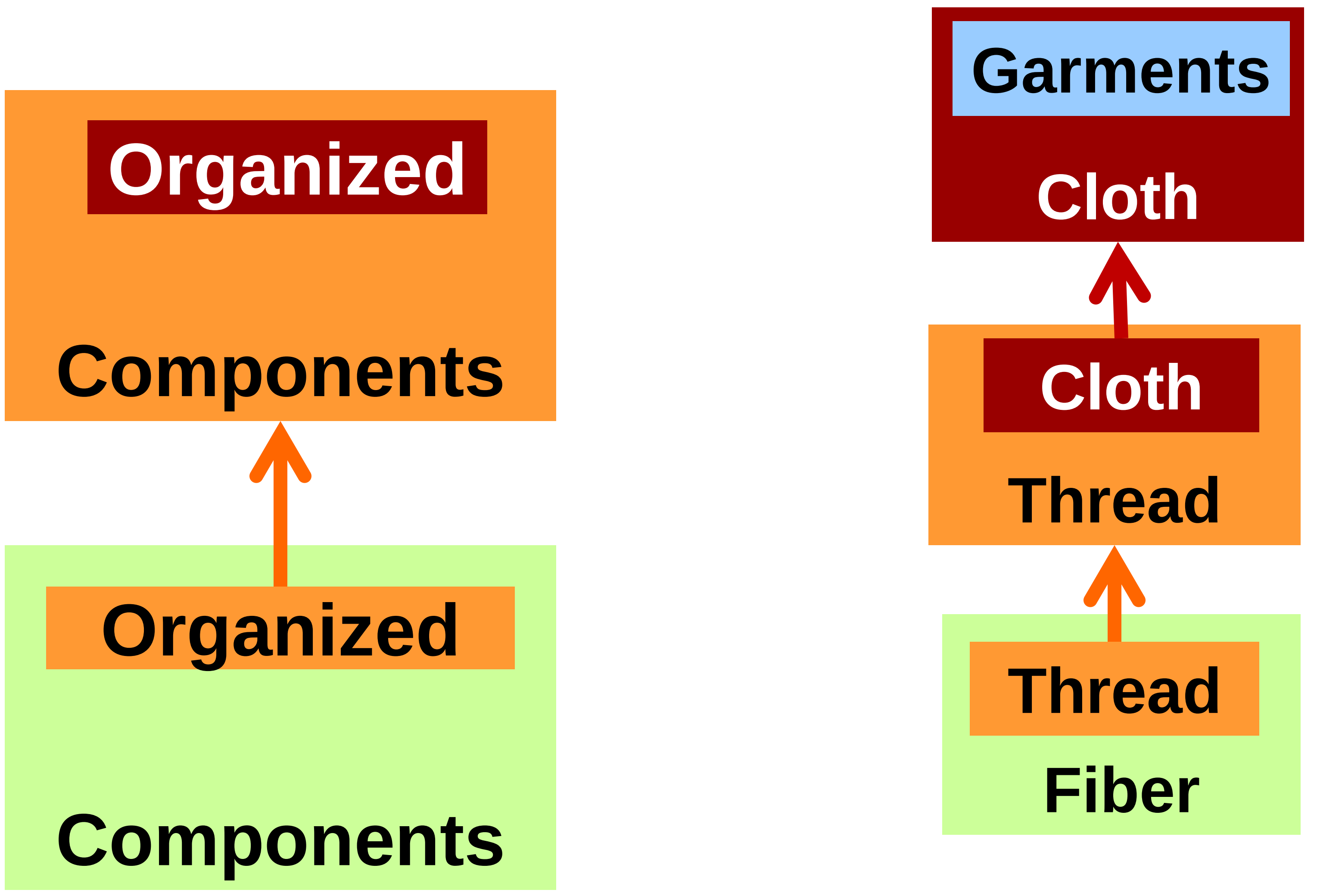

Diverse outfits
Diverse Garments
Xform
Cloth
Xform
Thread
Xform
Fiber
Constraints that deconstrain
Protocols
Different worlds
Mysteries in the gaps
No architecture
Huge gap
Supernatural
Small gap
Emergent
Mainstream


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

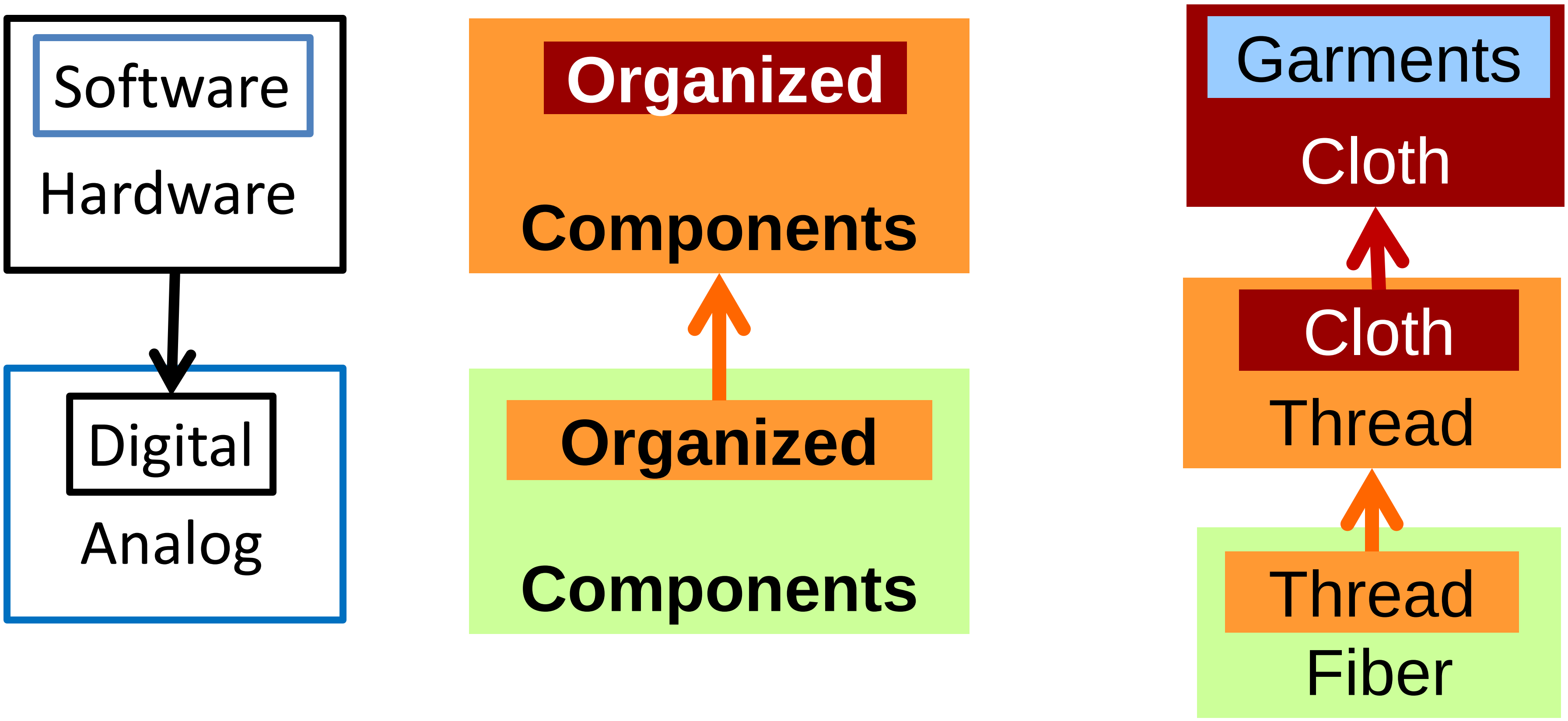
large **thin**

1 << # outfits << # heaps

Organized

Components

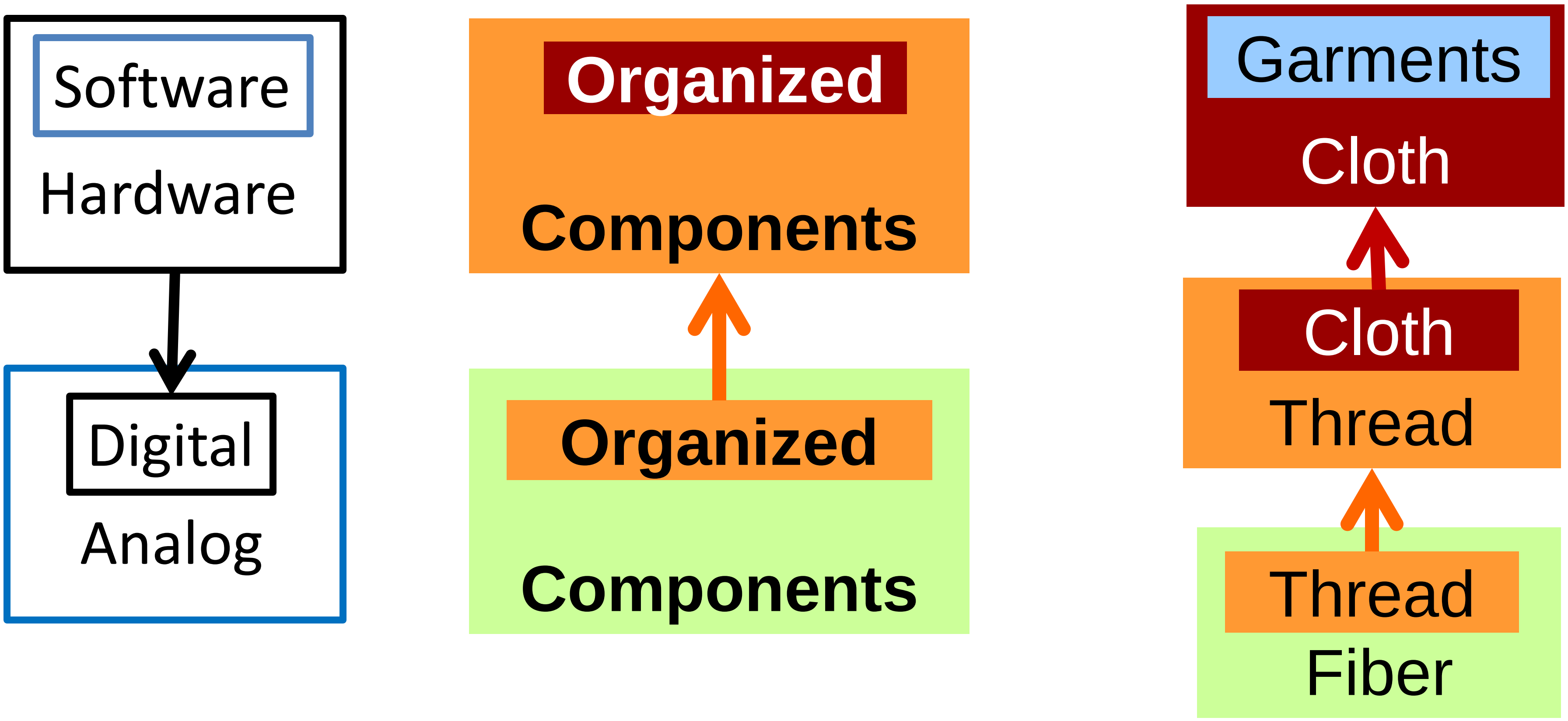
What is the "true functional ~~unit~~?" *Architecture*

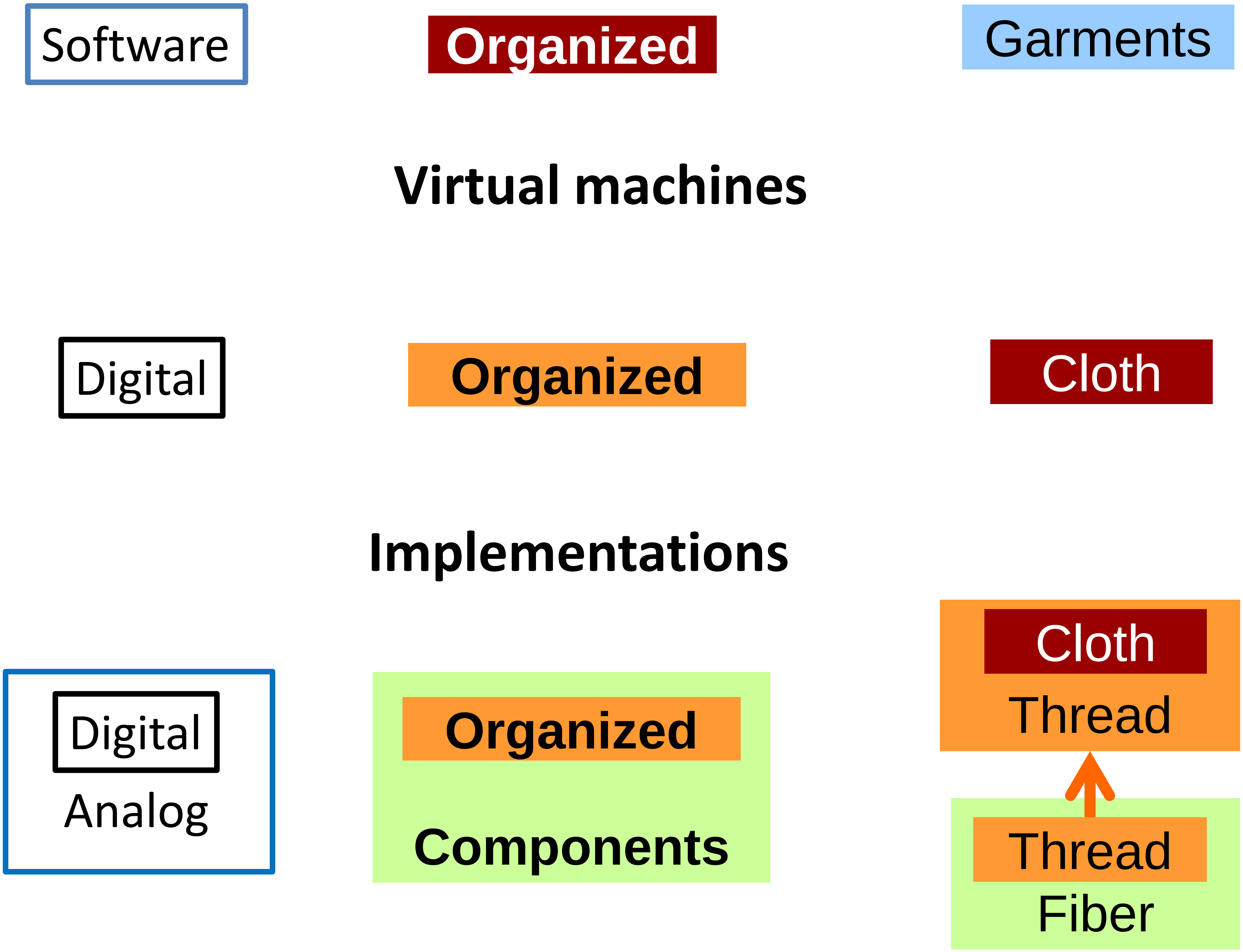


Virtual machines

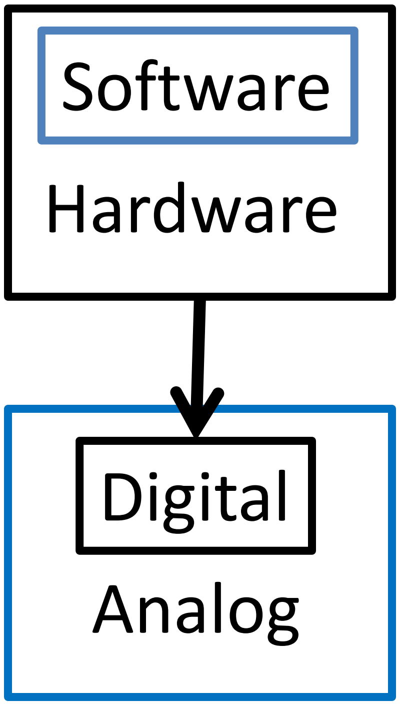
Software | Organized | Garments

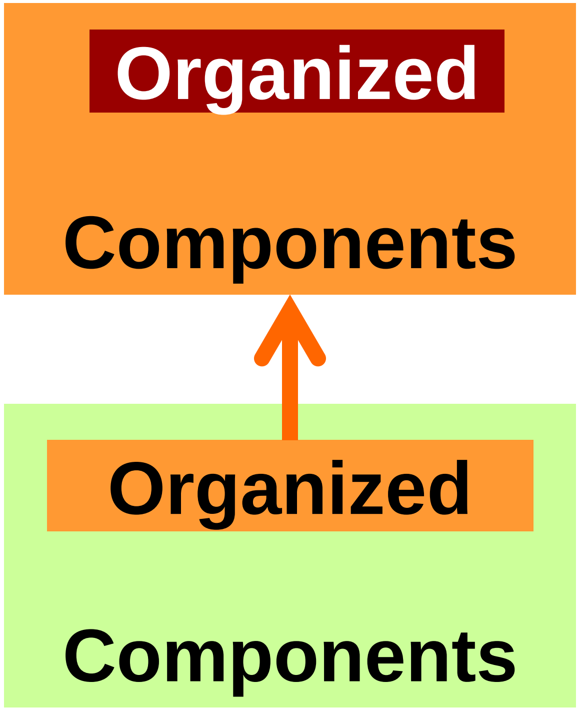
Implementations

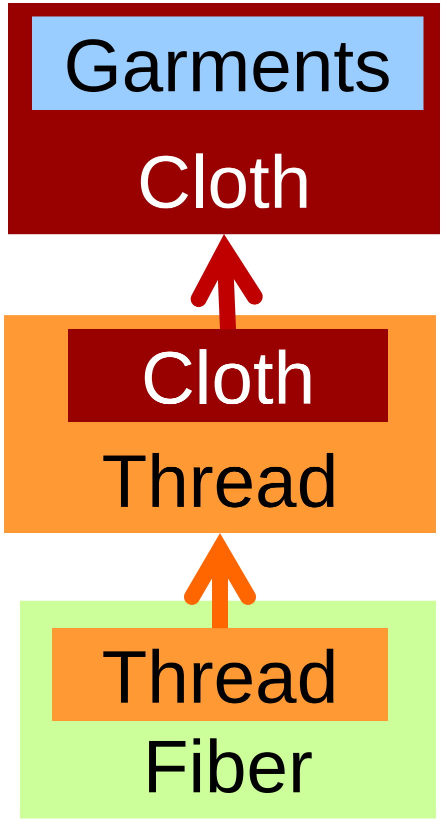


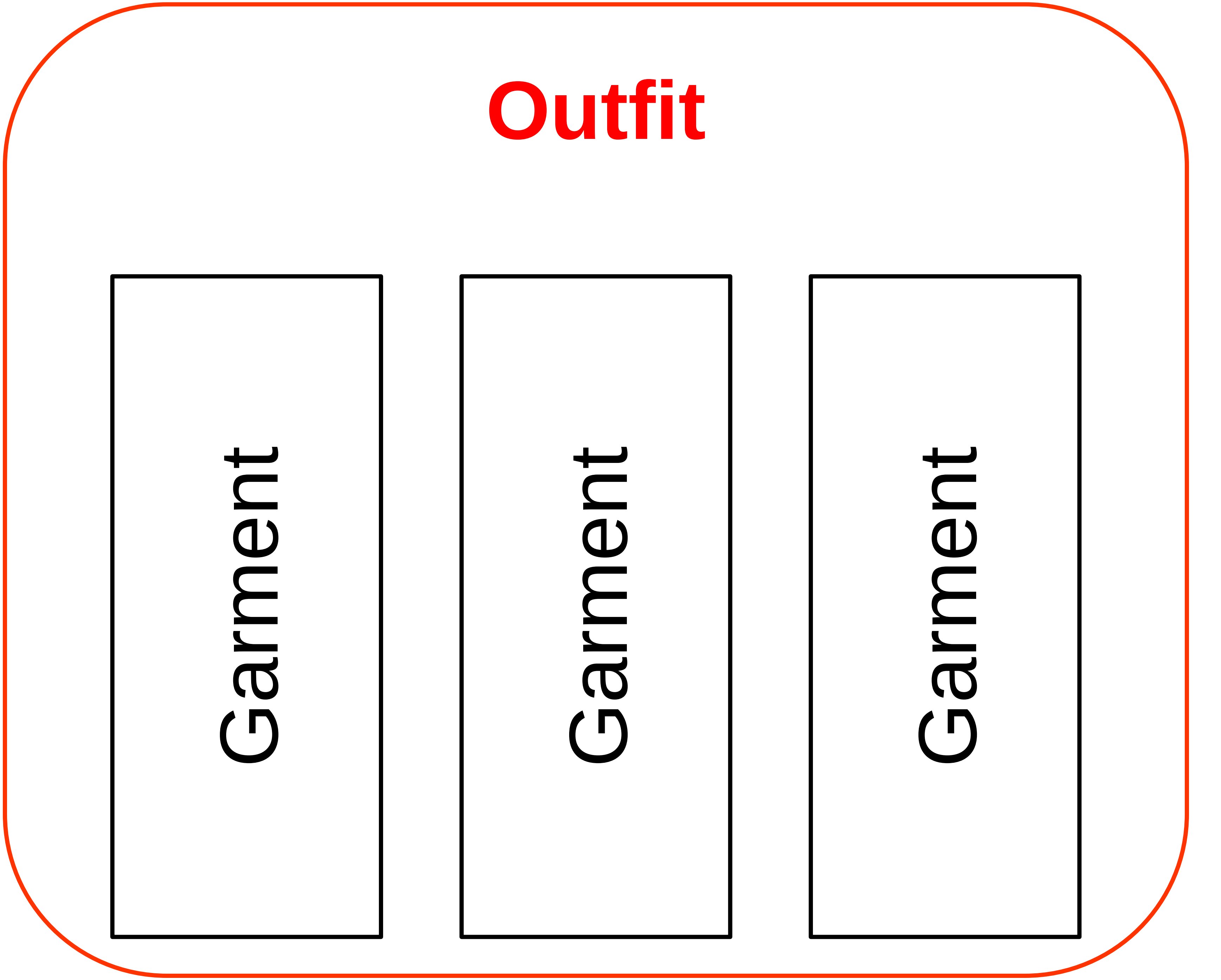

Software
Organized
Garments
Virtual machines
Digital
Organized
Cloth
Implementations
Cloth
Thread
Digital
Analog
Organized
Components
Thread
Fiber

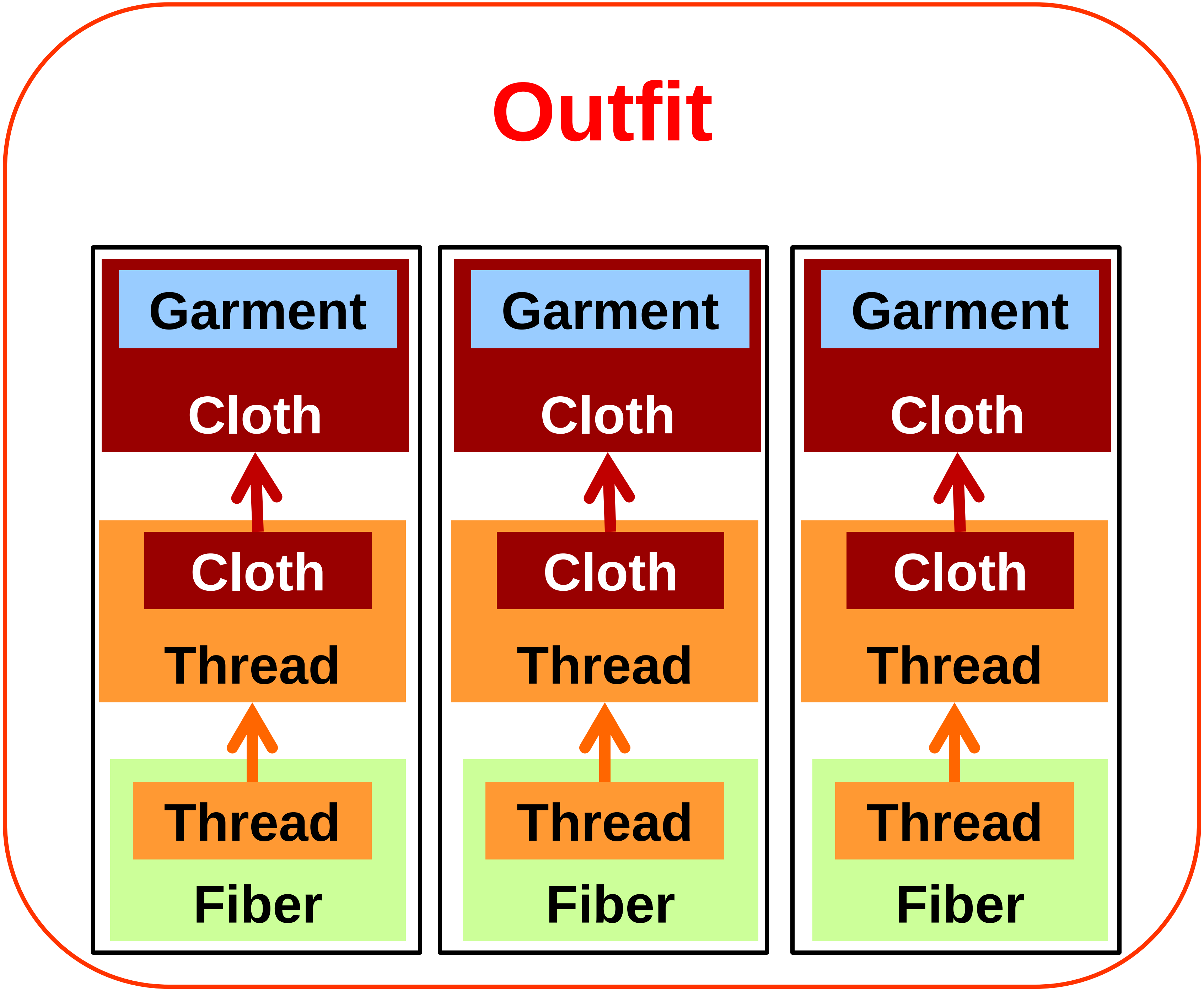
Layered, large, thin
Hidden
Virtualized



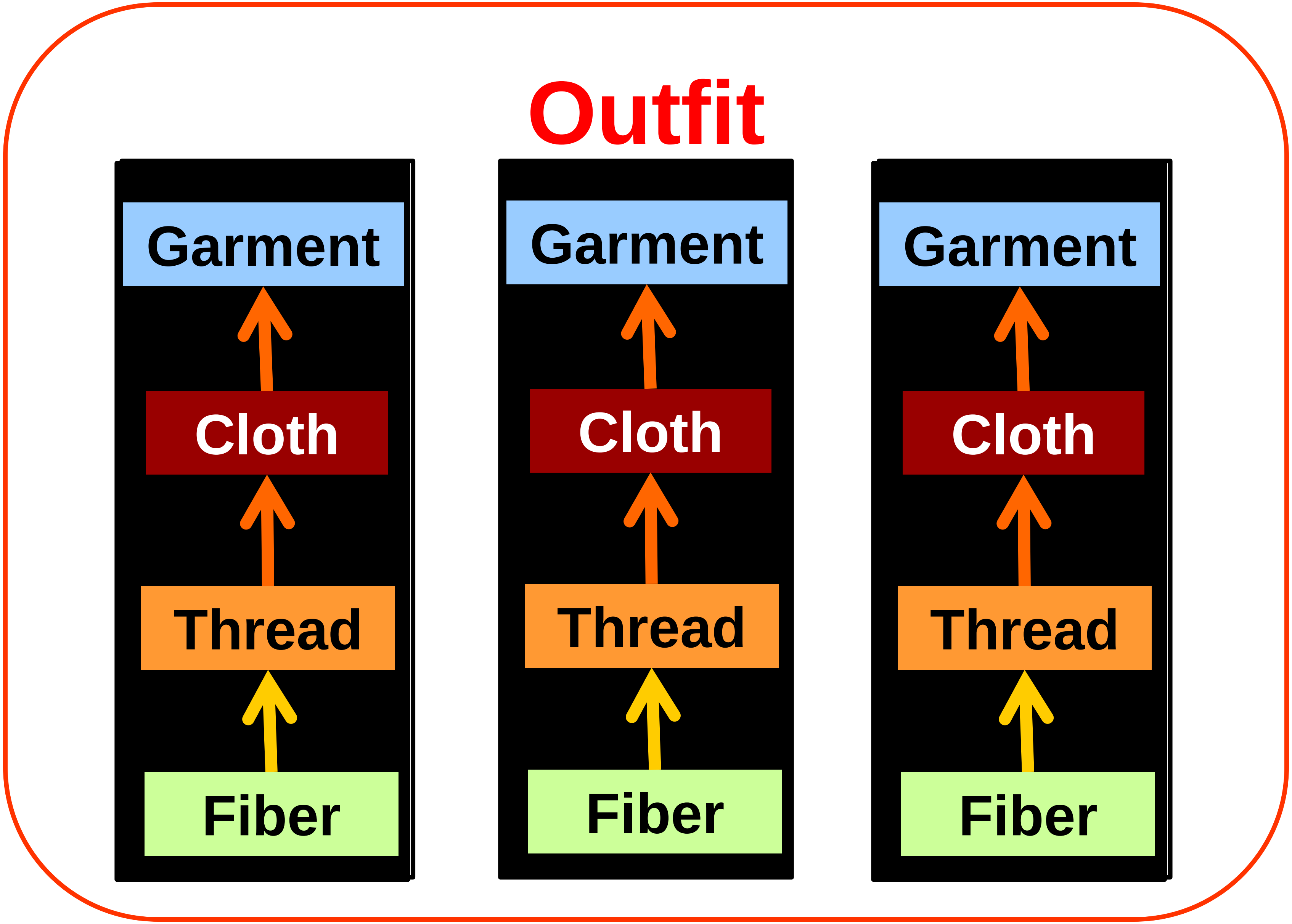


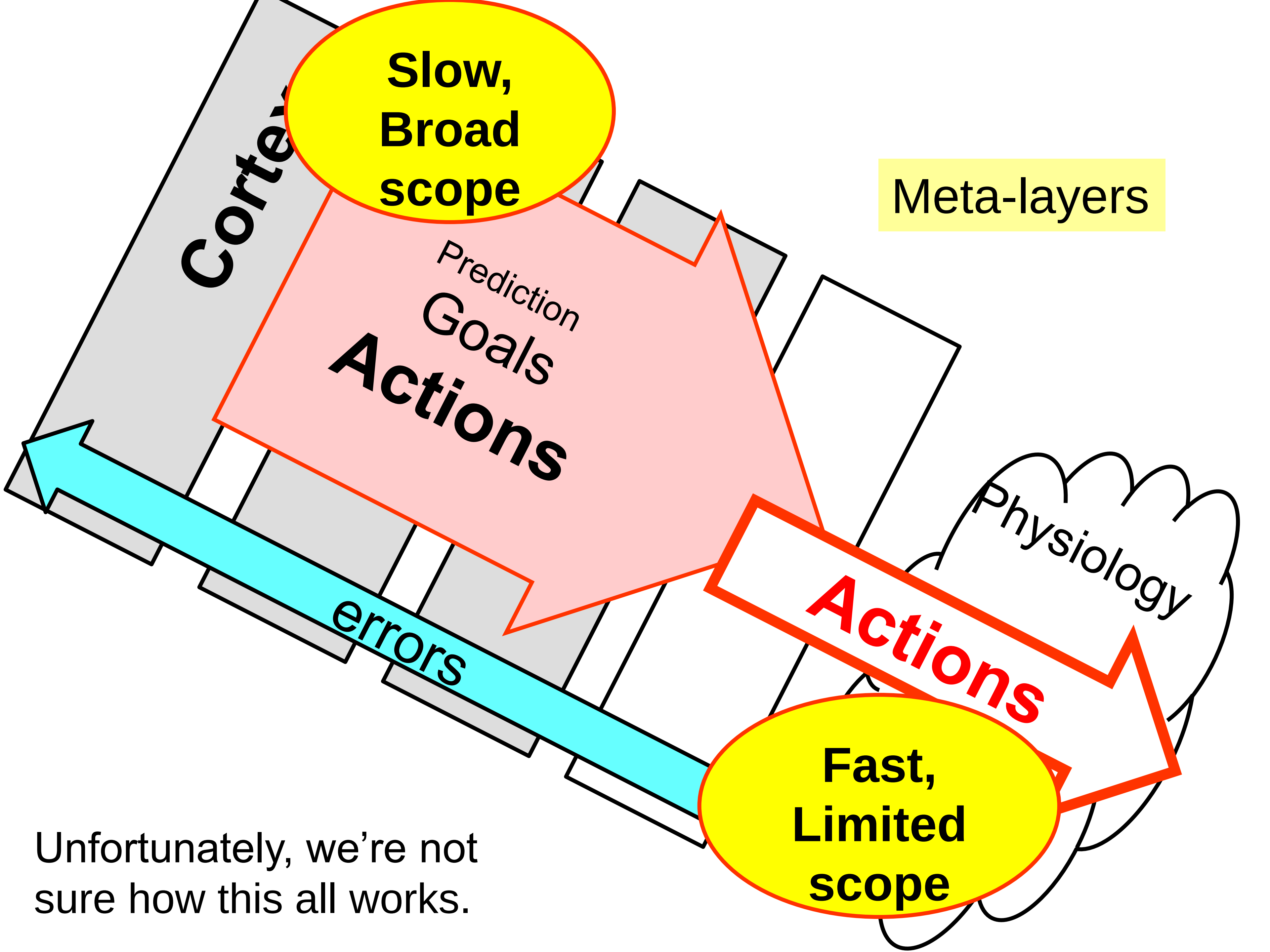



Outfit
Garment
Garment
Garment

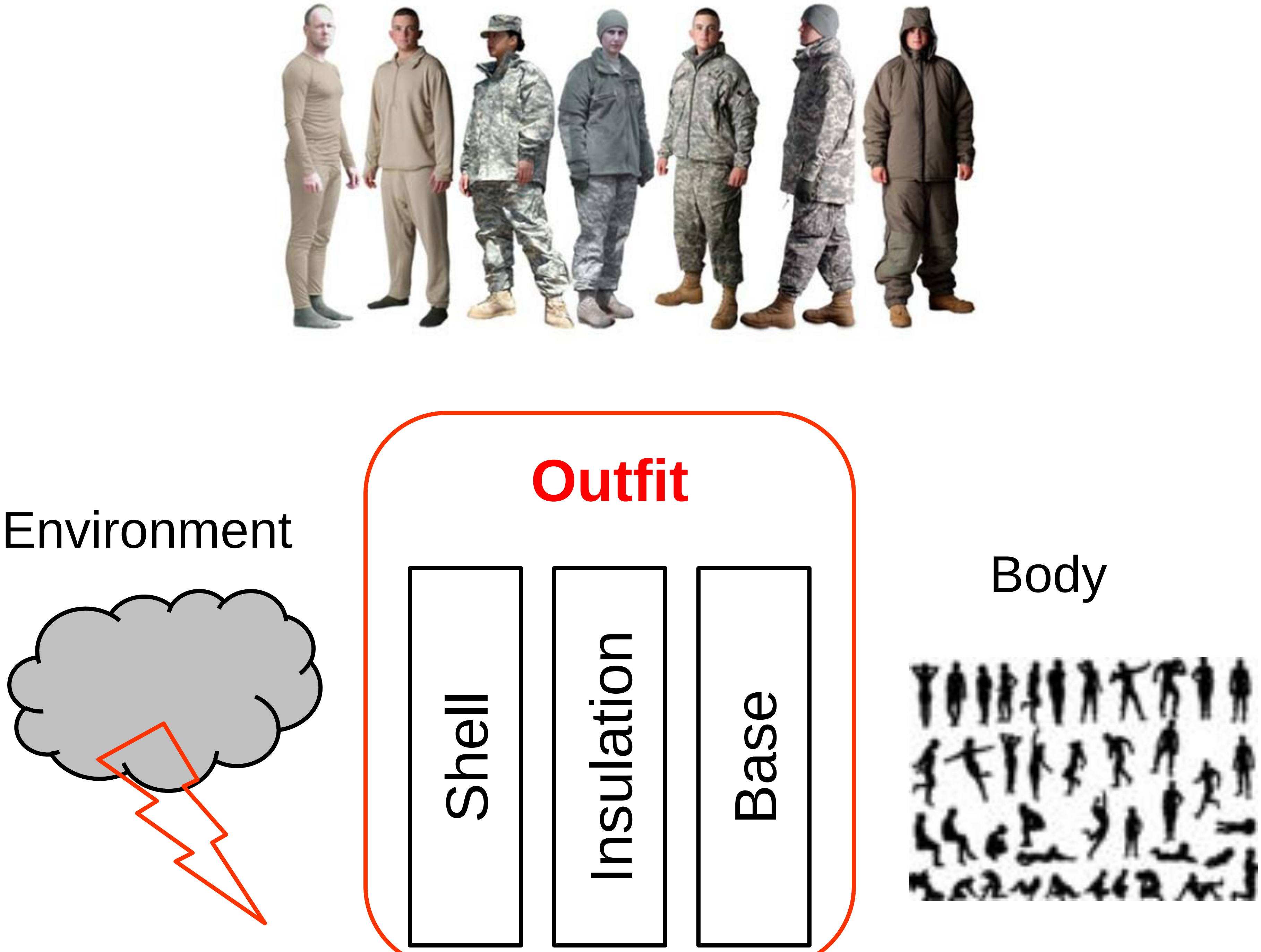

Outfit
Garment
Cloth
Cloth
Thread
Thread
Fiber
Garment
Cloth
Cloth
Thread
Thread
Fiber
Garment
Cloth
Cloth
Thread
Thread
Fiber

Layering within garments (textiles)

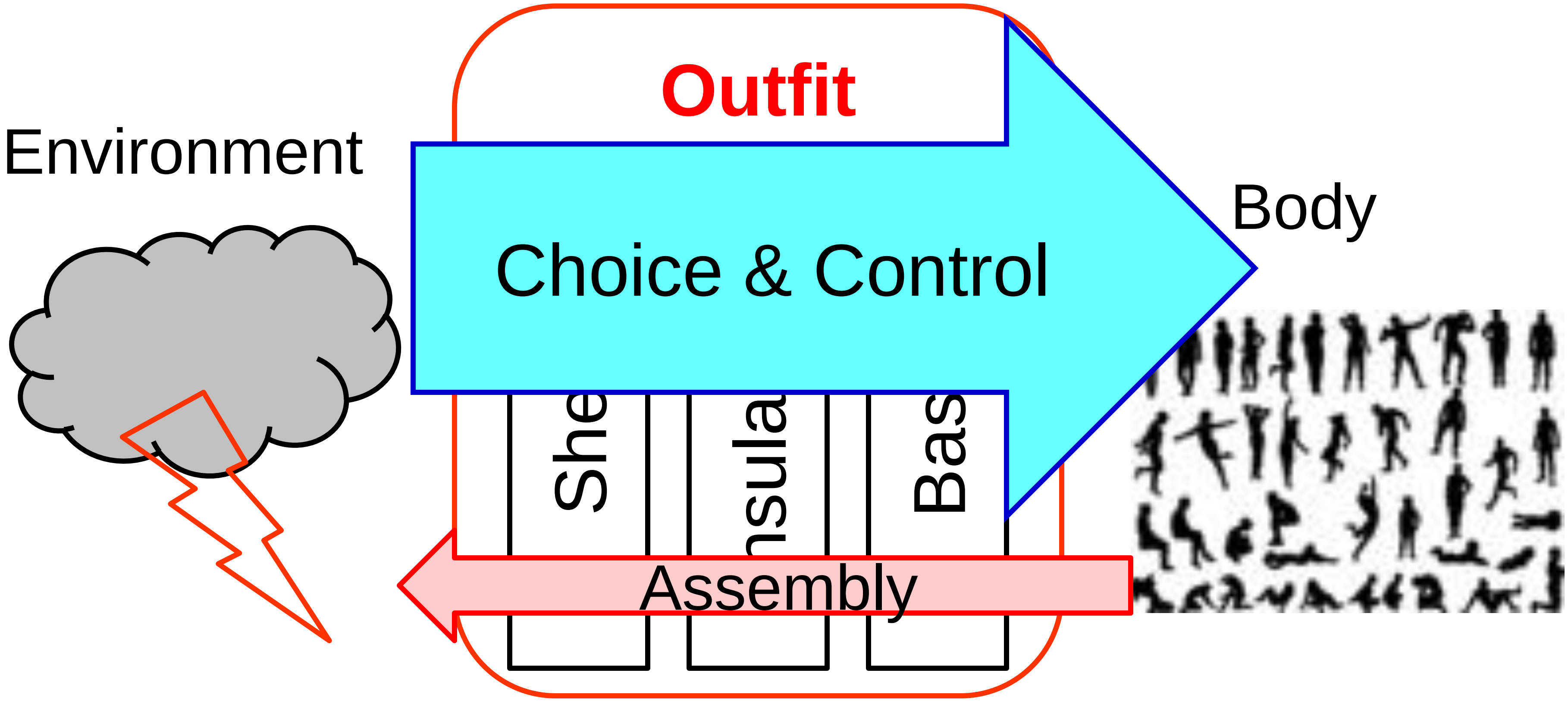


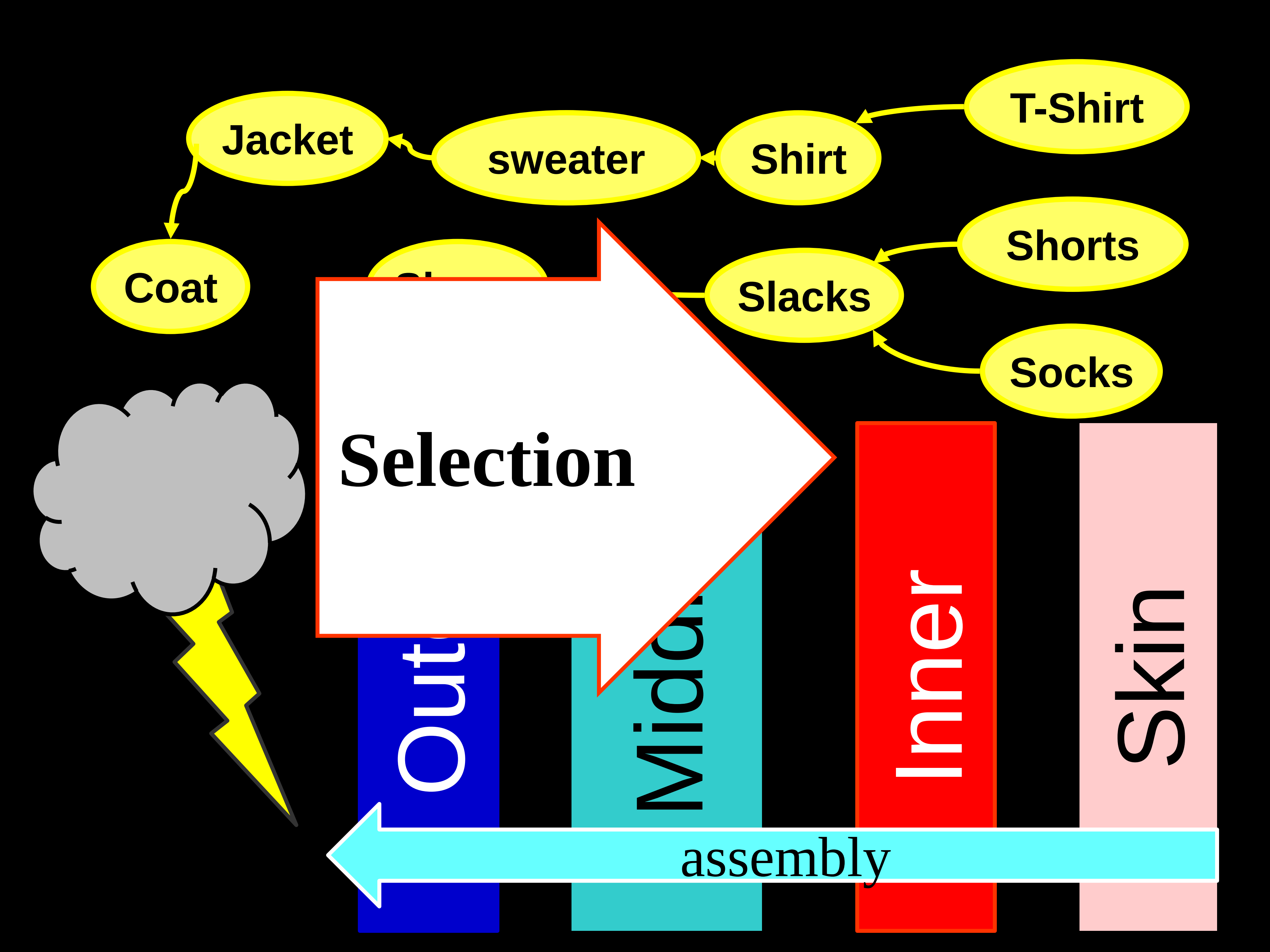


Unfortunately, we're not sure how this all works.

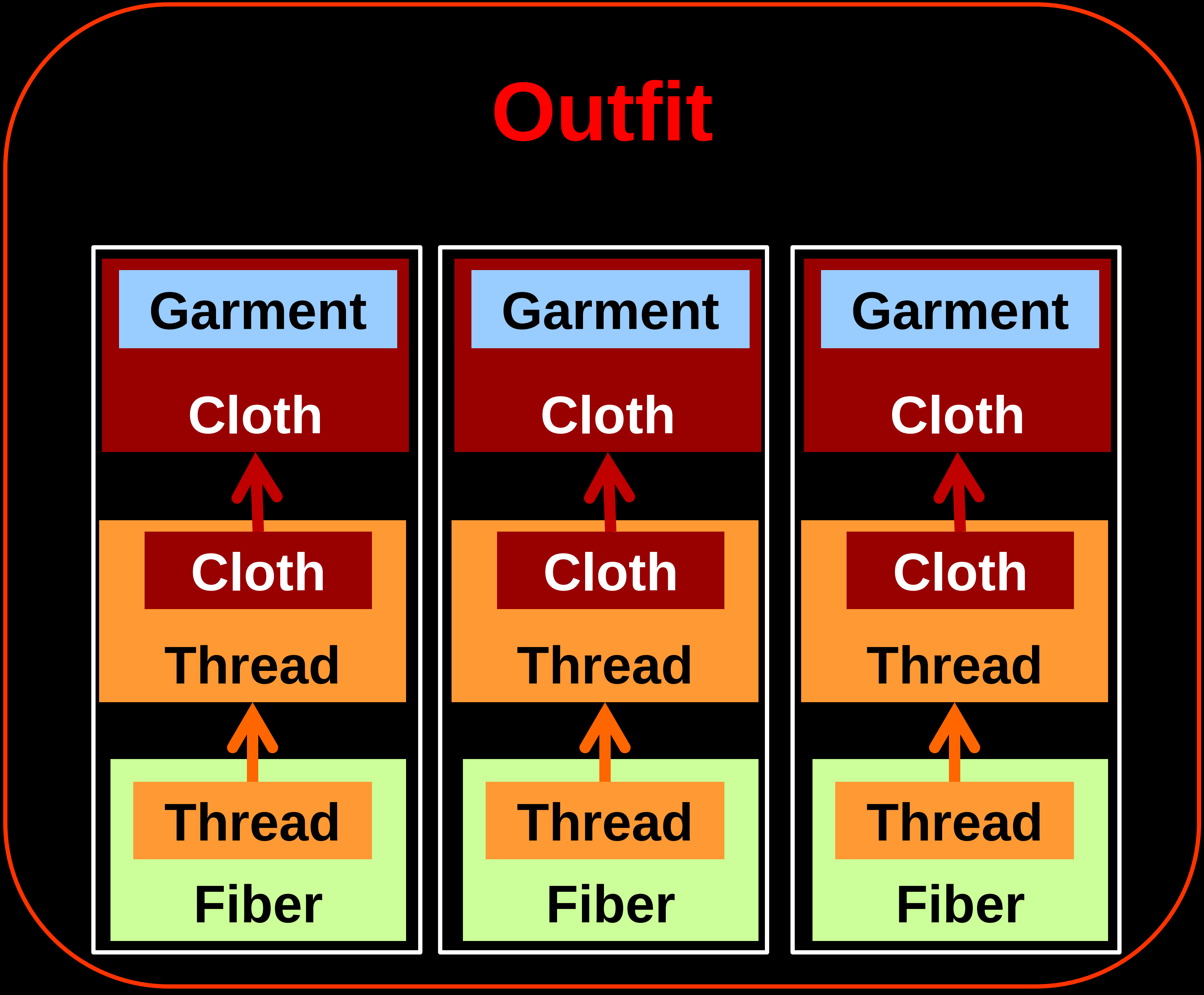

Environment
Outfit
Shell
Insulation
Base
Body

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

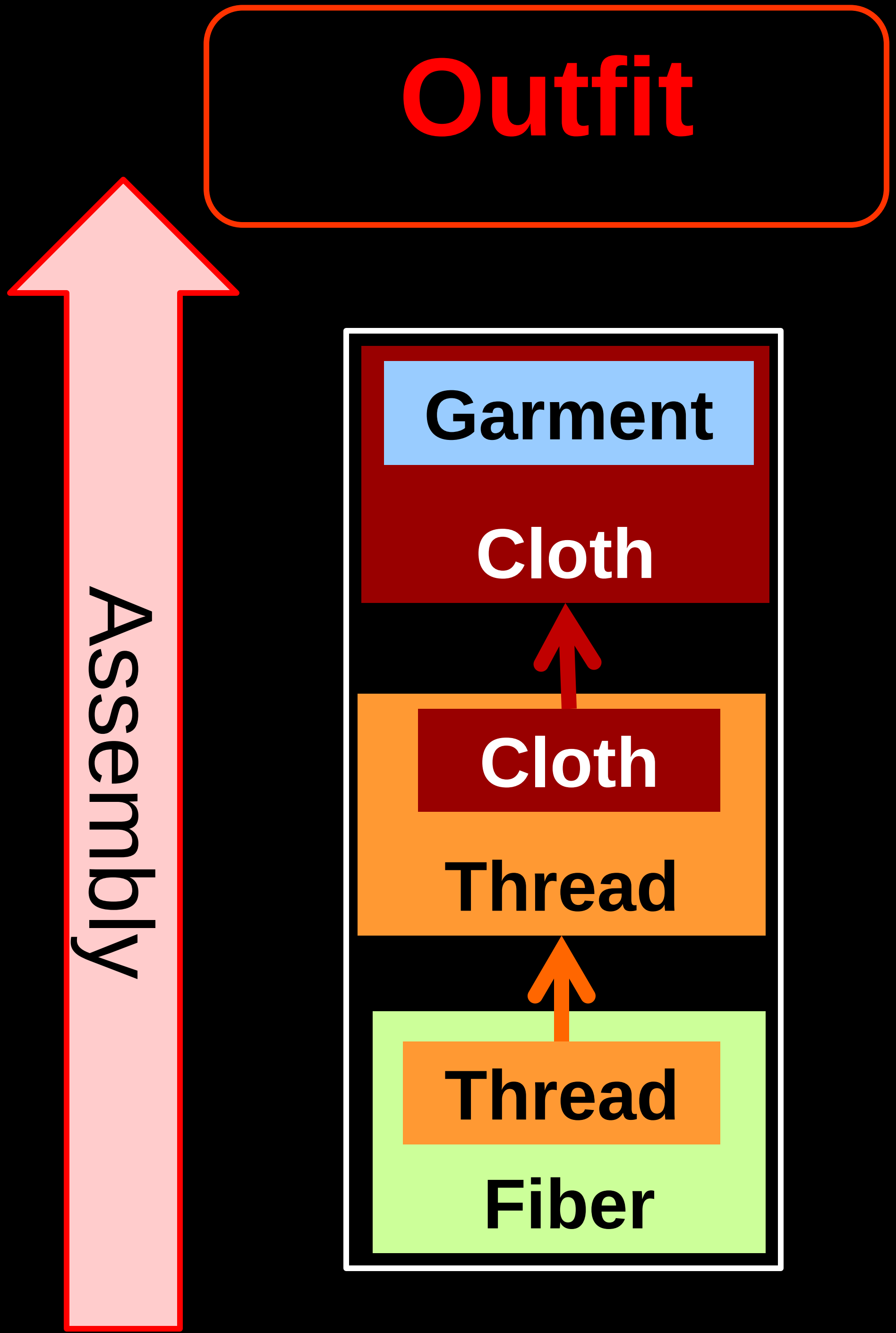




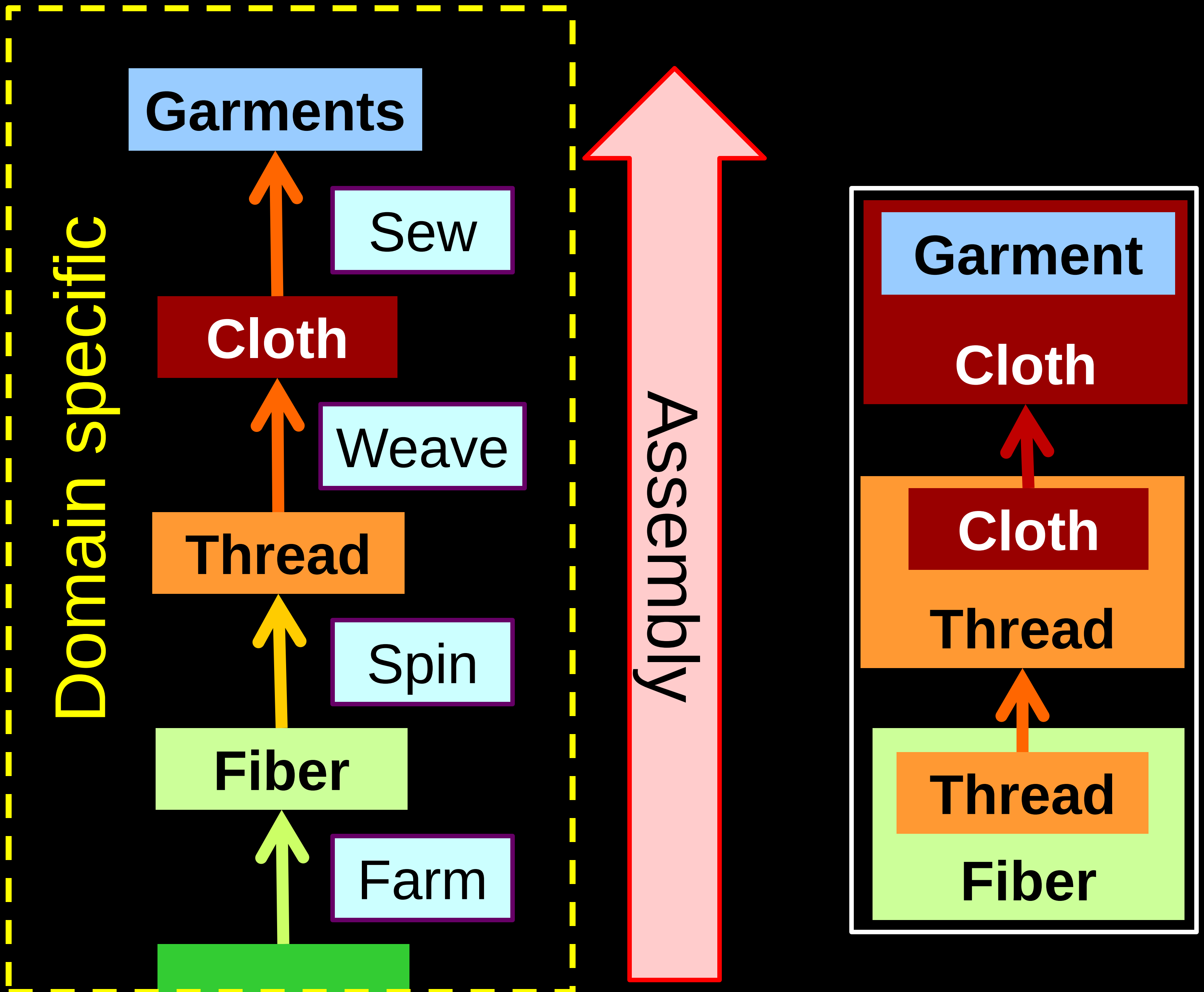
T-Shirt
Jacket
sweater
Shirt
Shorts
Coat
Slacks
Socks
Selection
Inner
Skin
assembly

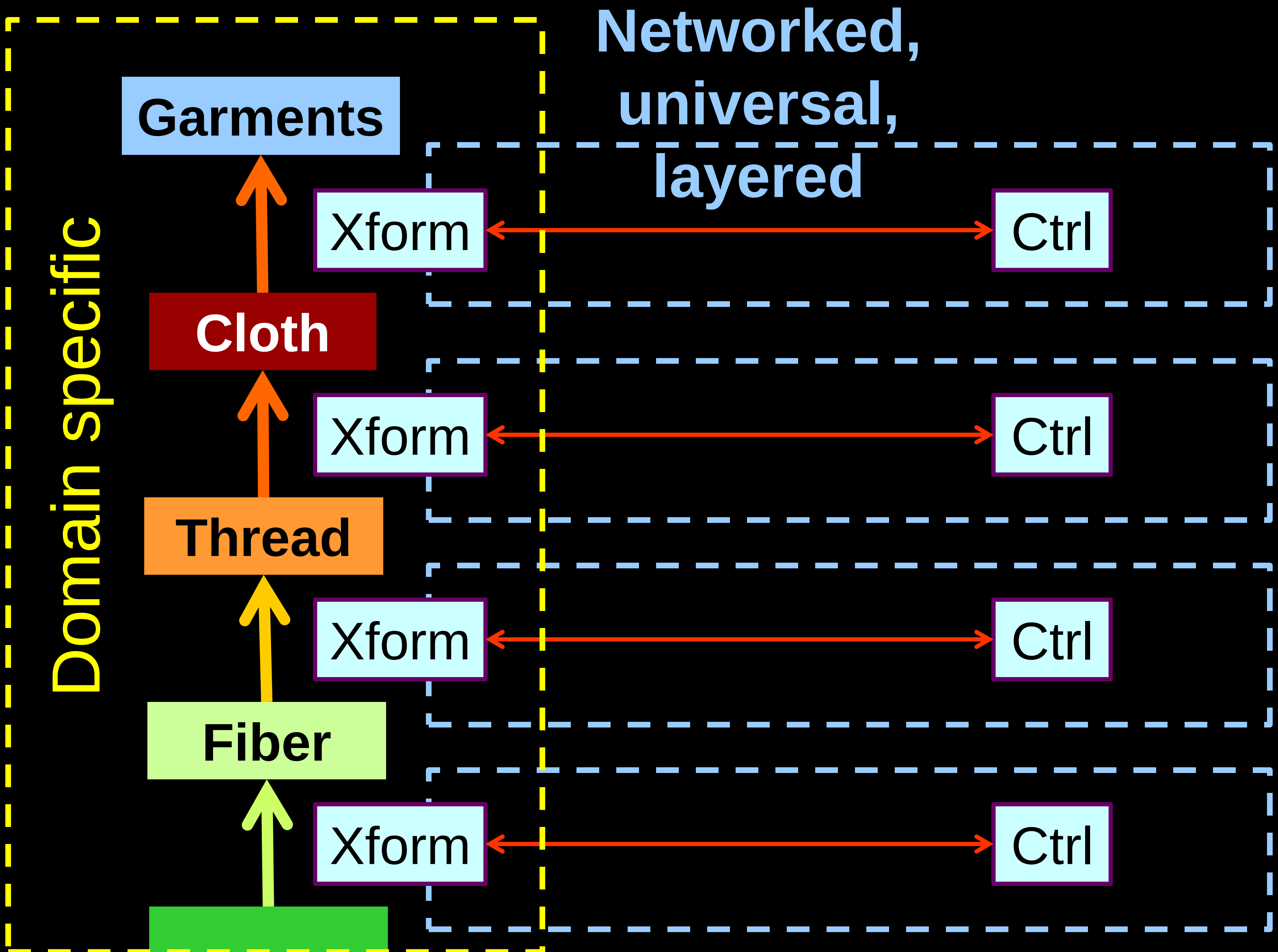


Outfit
Garment
Cloth
Cloth
Thread
Thread
Fiber
Garment
Cloth
Cloth
Thread
Thread
Fiber
Garment
Cloth
Cloth
Thread
Thread
Fiber

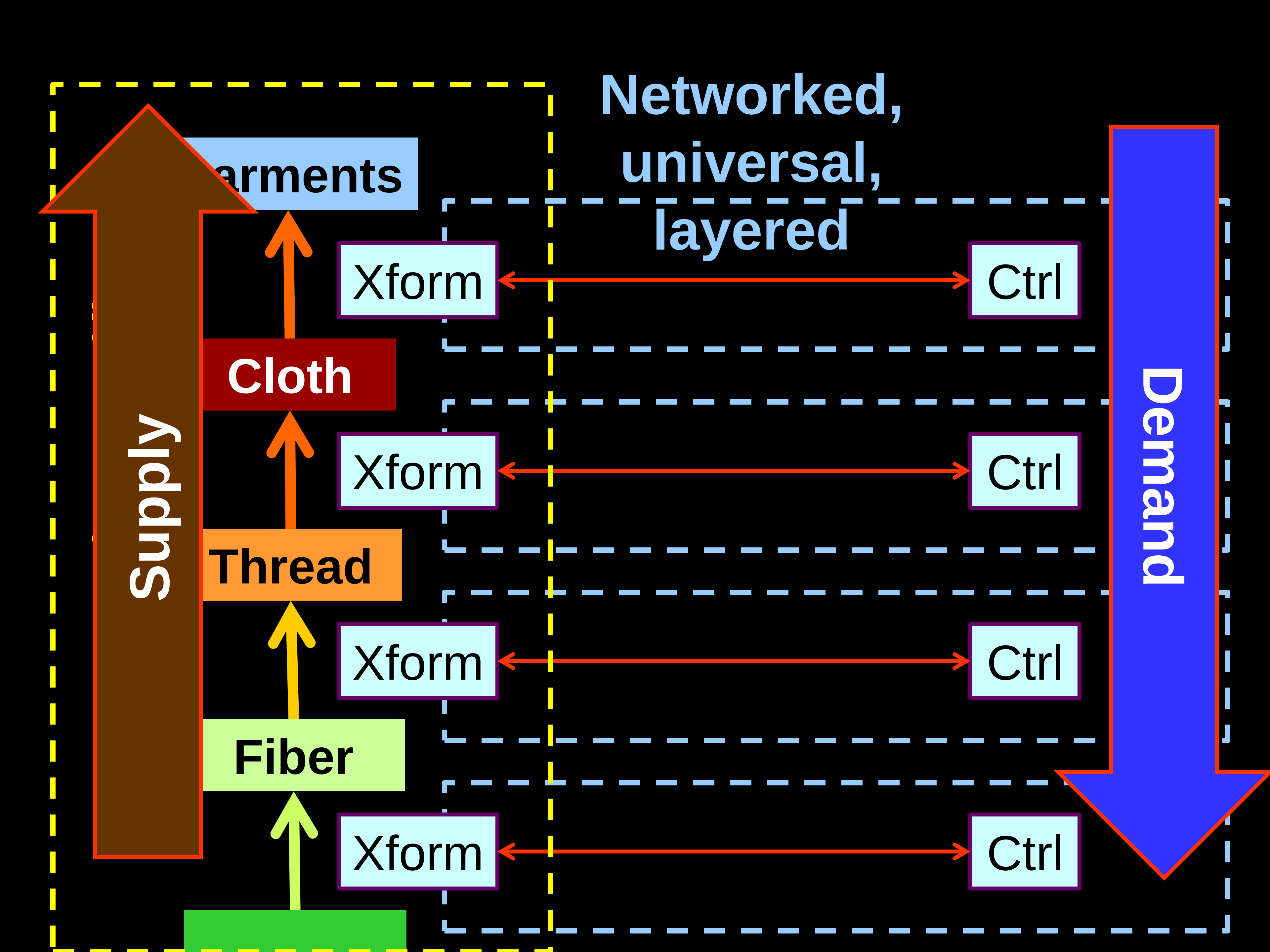


Outfit
Assembly
Garment
Cloth
Cloth
Thread
Thread
Fiber

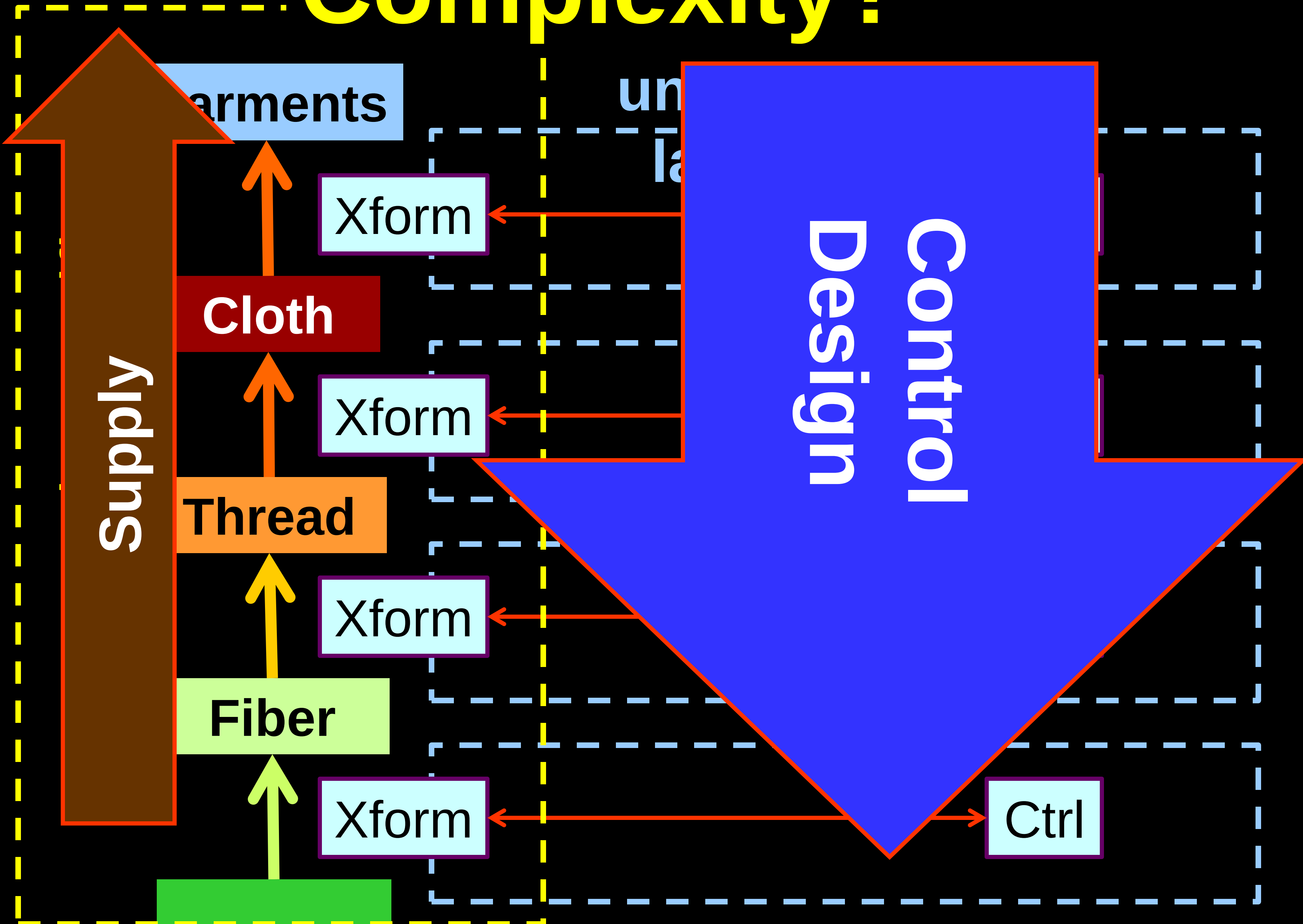

Domain specific
Garments
Sew
Cloth
Weave
Thread
Spin
Fiber
Farm
Assembly
Garment
Cloth
Cloth
Thread
Thread
Fiber



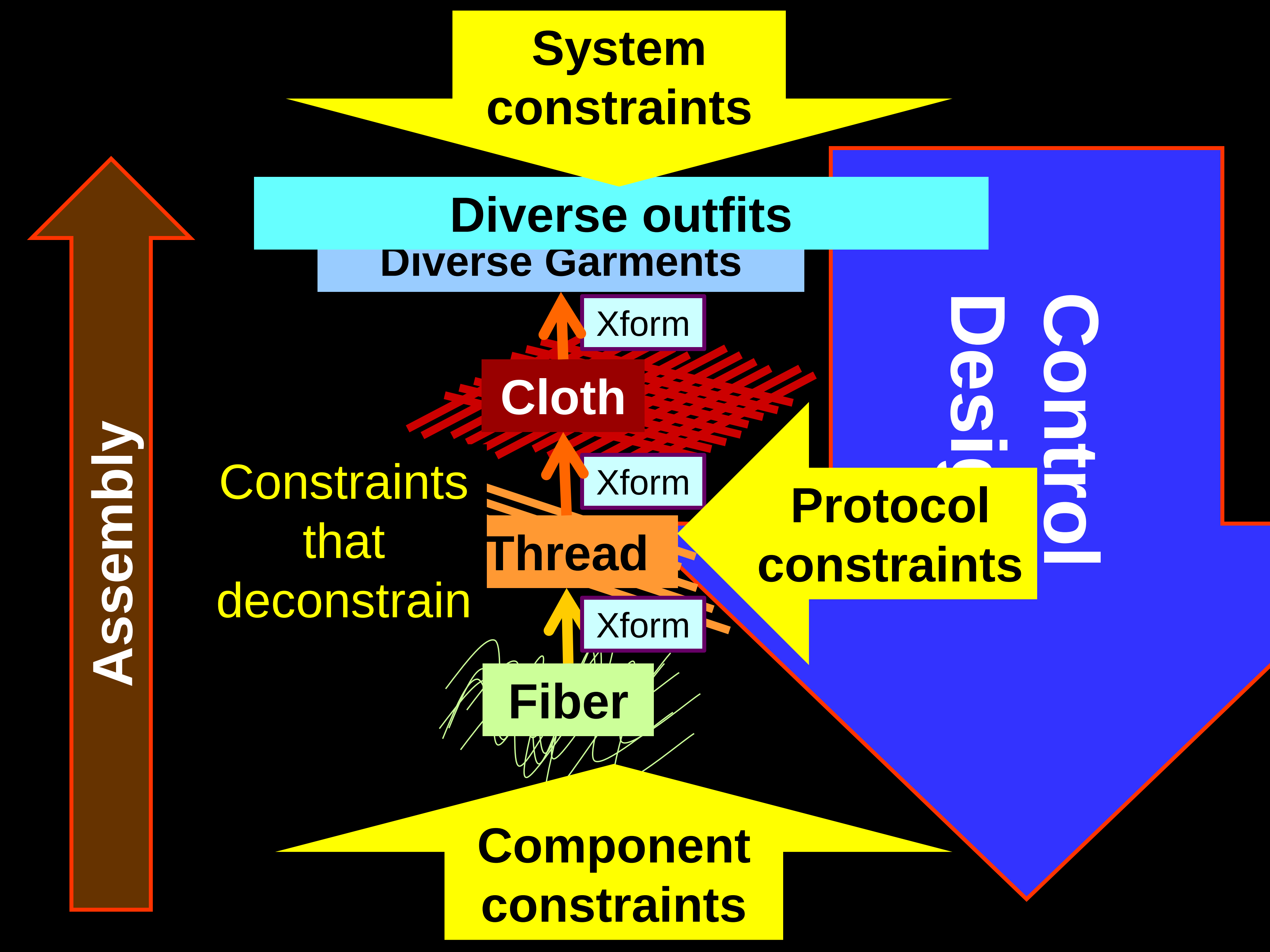
Networked, universal, layered
Domain specific
Garments
Cloth
Thread
Fiber
Xform
Ctrl
Xform
Ctrl
Xform
Ctrl
Xform
Ctrl

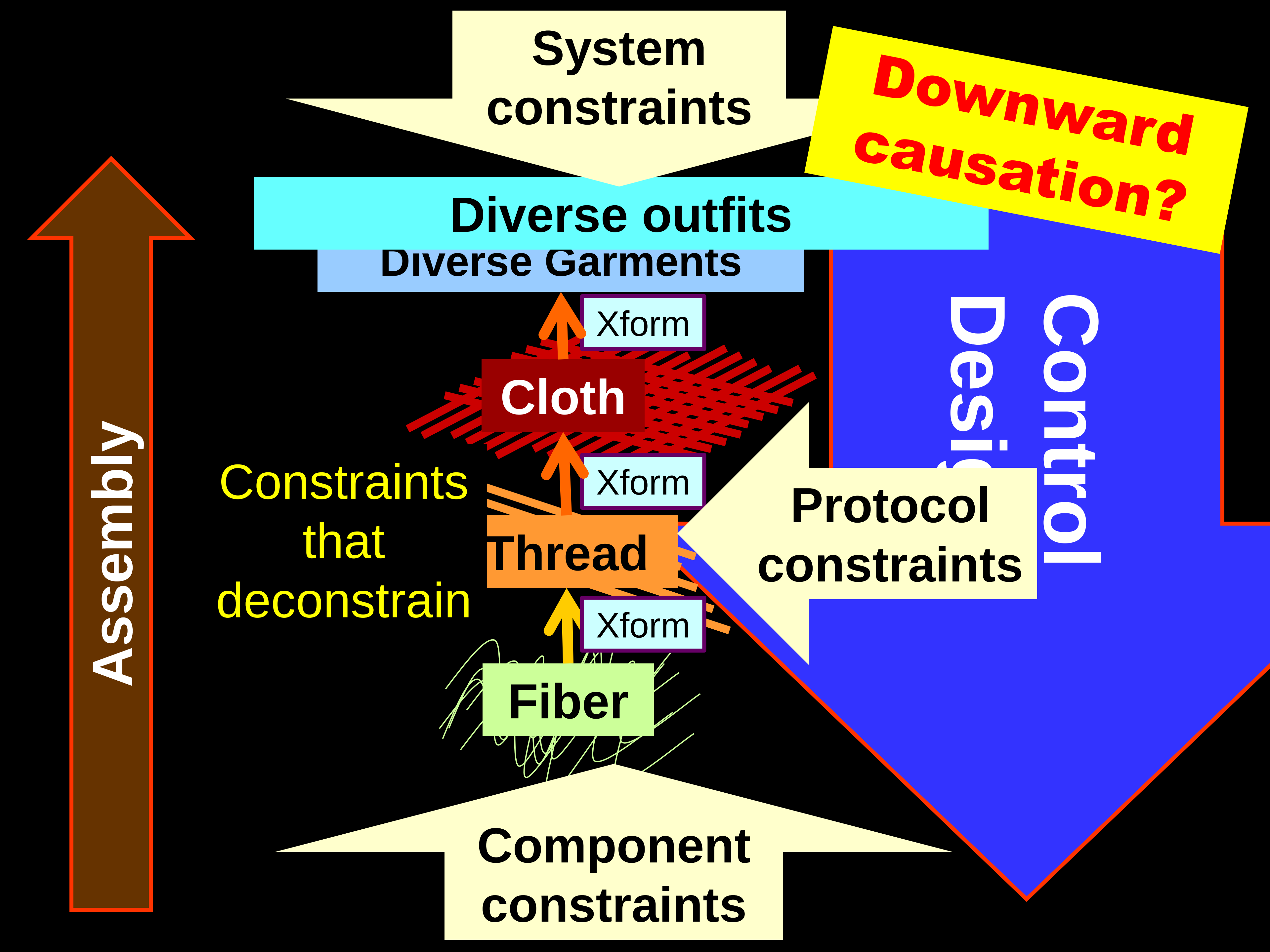

Networked,
universal,
layered
Garments
Xform
Ctrl
Cloth
Xform
Ctrl
Thread
Xform
Ctrl
Fiber
Xform
Ctrl
Supply
Demand

Complexity?

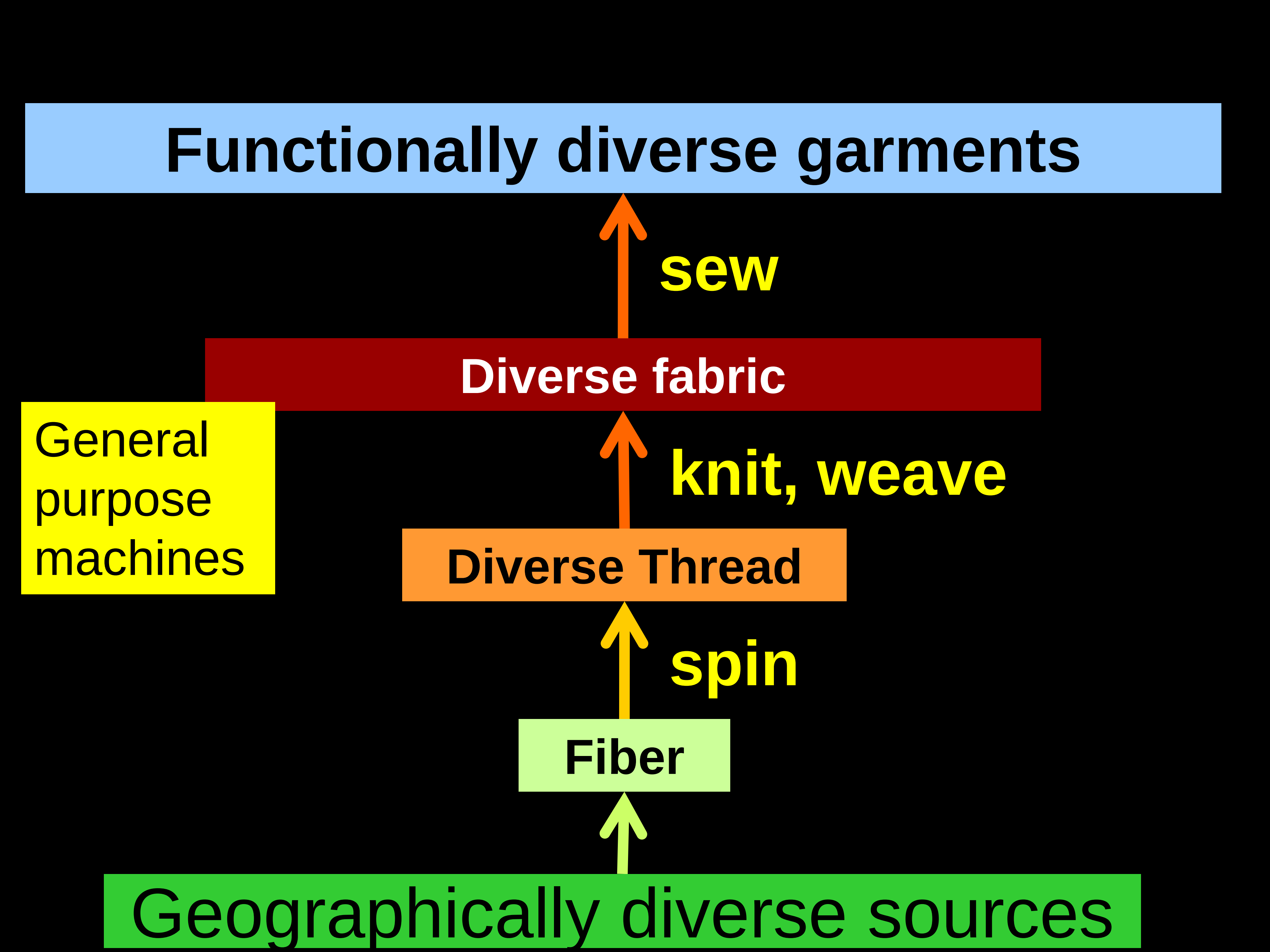


Supply
Xform
Cloth
Xform
Thread
Xform
Fiber
Xform
Ctrl
Control
Design


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

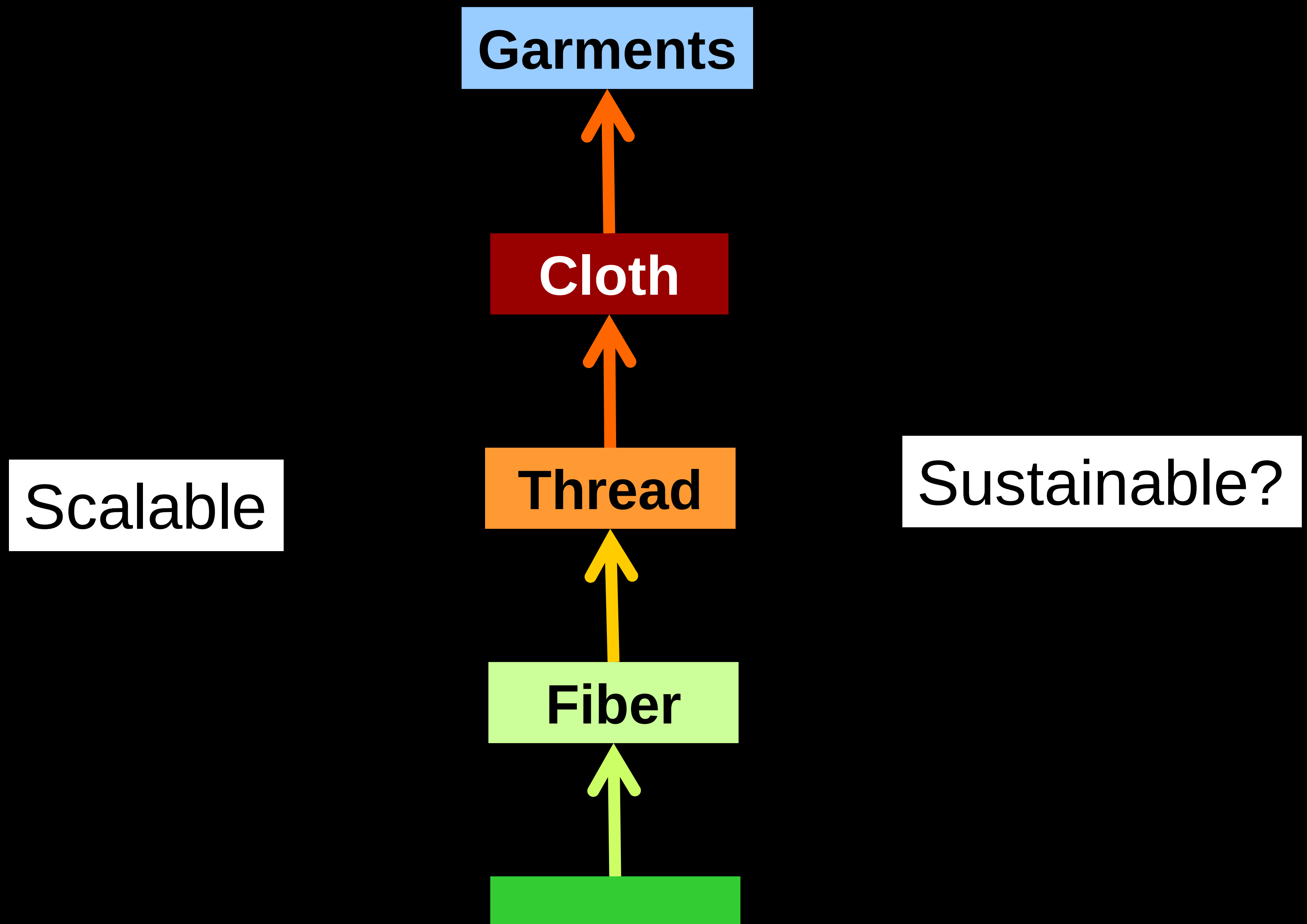


System constraints
Downward causation?
Diverse outfits
Diverse Garments
Xform
Cloth
Xform
Constraints that deconstrain
Thread
Protocol constraints
Control Design
Xform
Fiber
Assembly
Component constraints

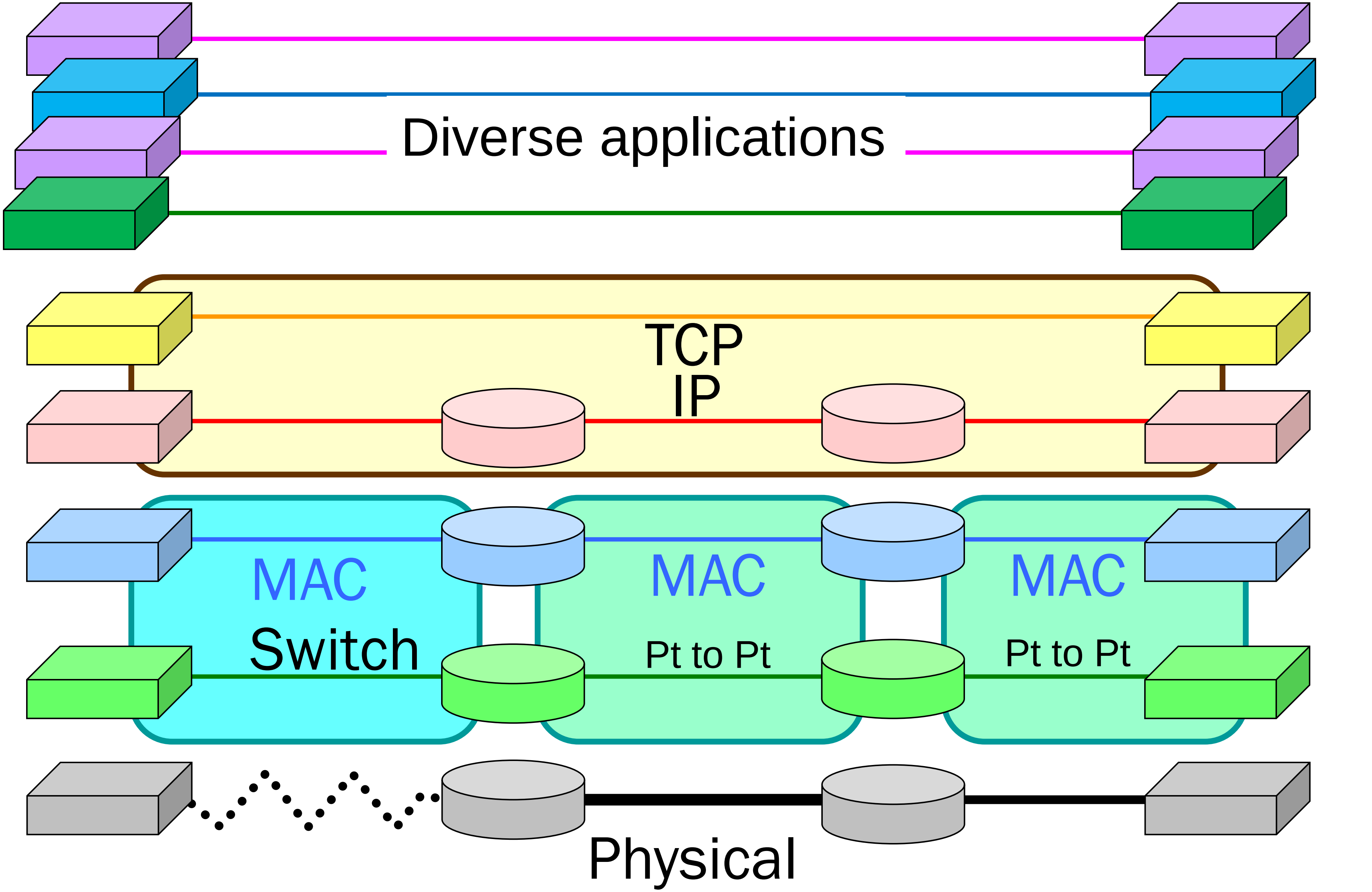

Functionally diverse garments
sew
Diverse fabric
knit, weave
General purpose machines
Diverse Thread
spin
Fiber
Geographically diverse sources

~~Functionally~~ diverse garments

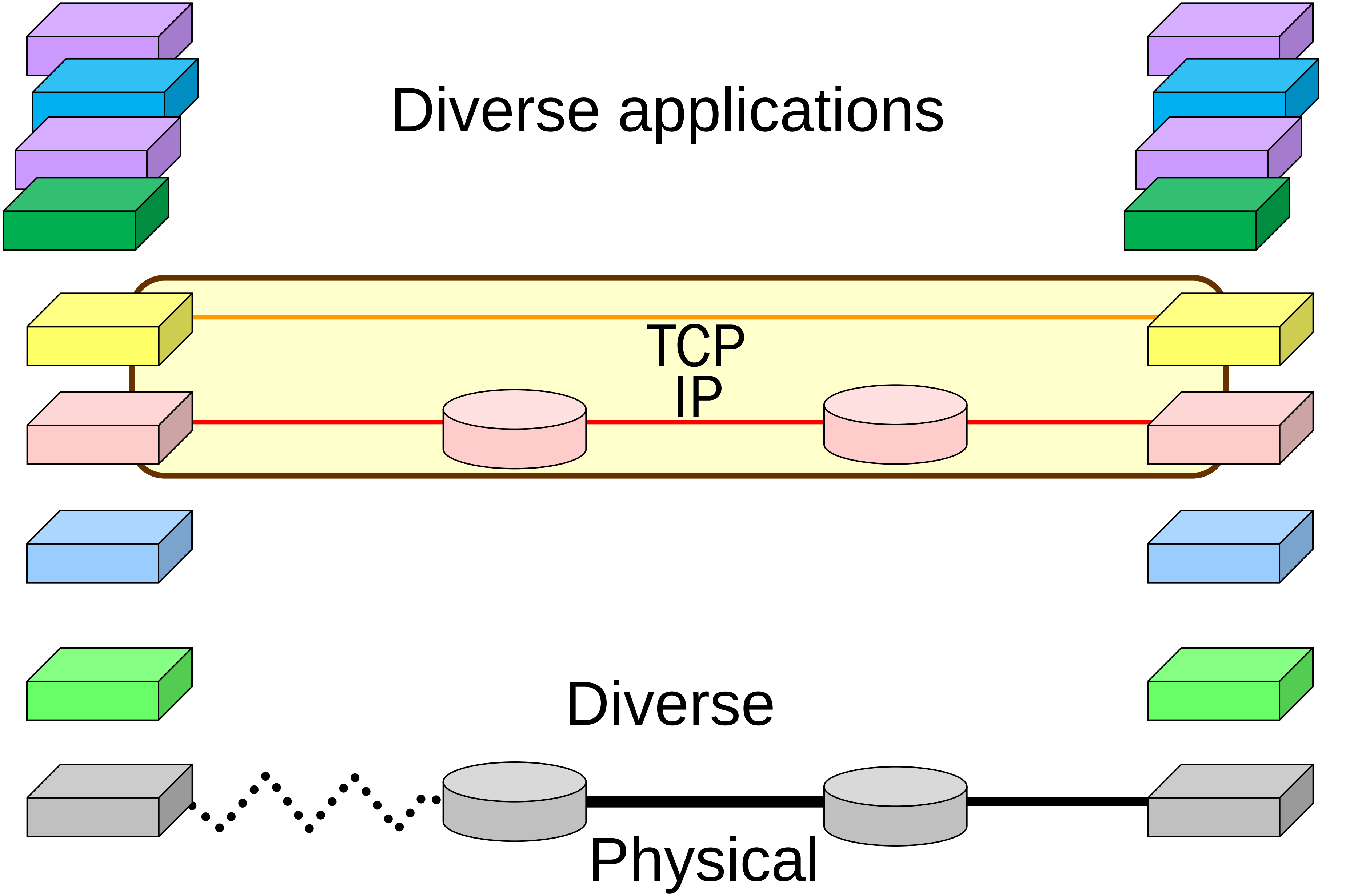

FASHION WARS
NEW YORK SPRING 2009
Garments
Fragilities?
Thread
Fiber


Garments
Cloth
Thread
Fiber
Scalable
Sustainable?

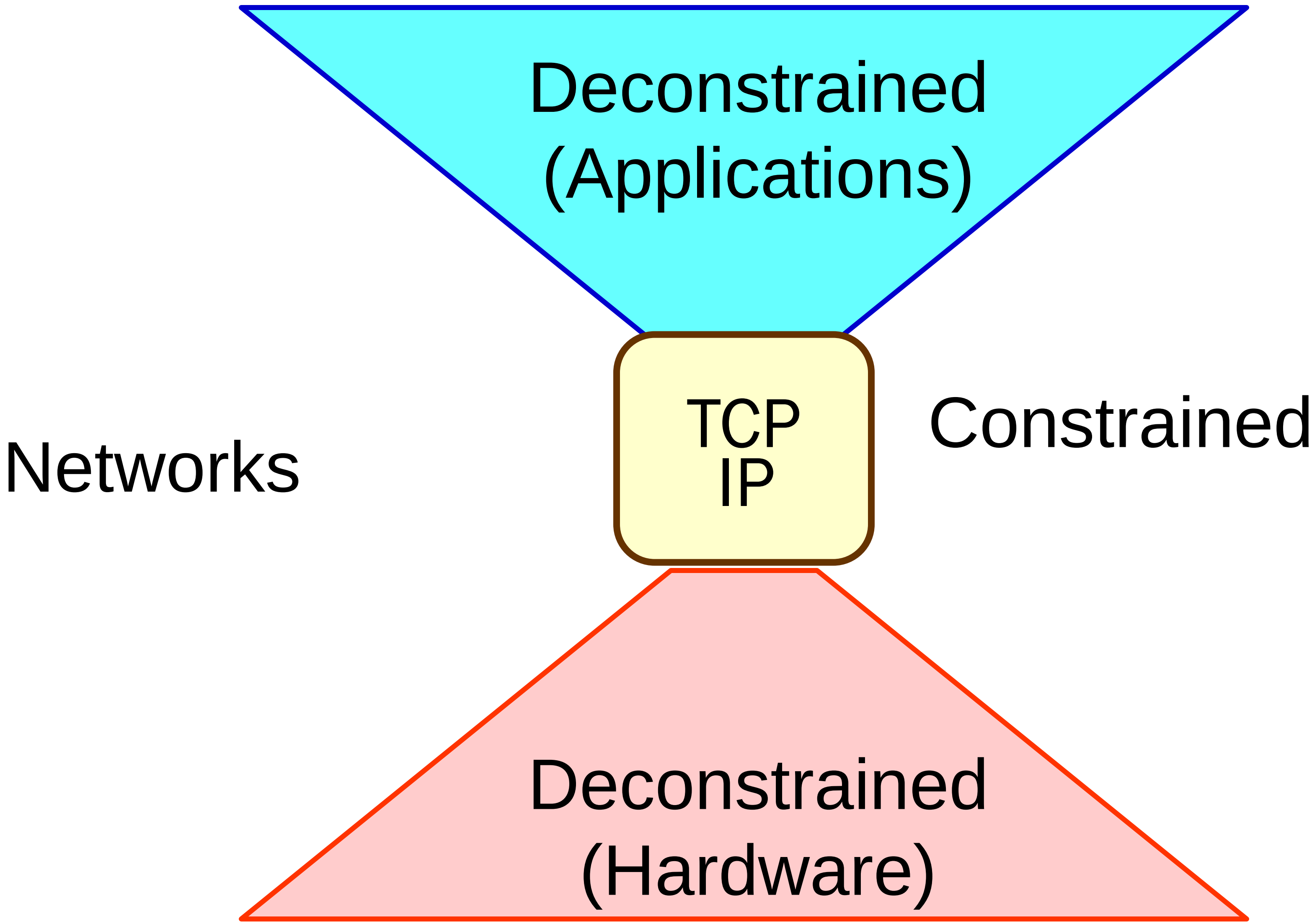
Layered architectures



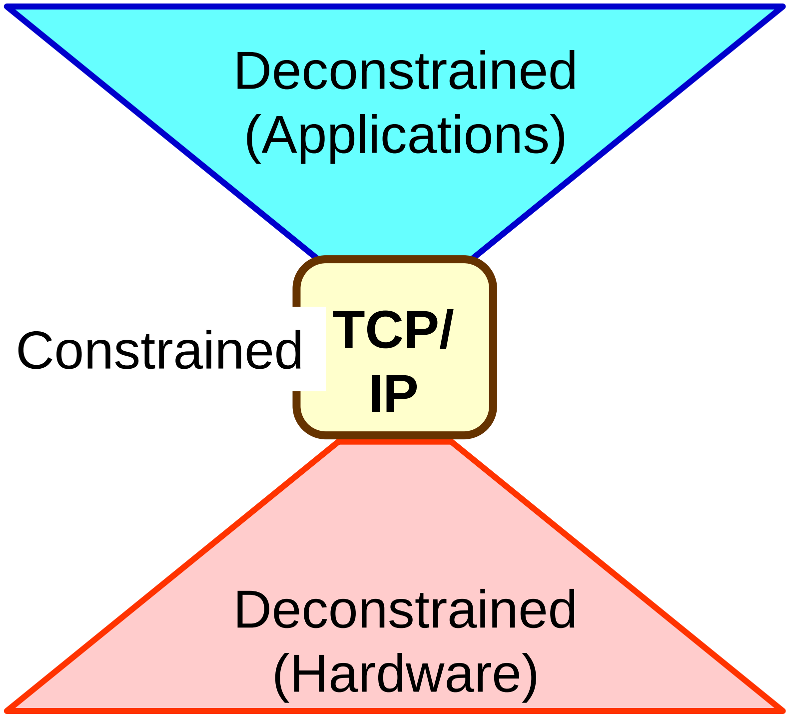
Too clever?



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

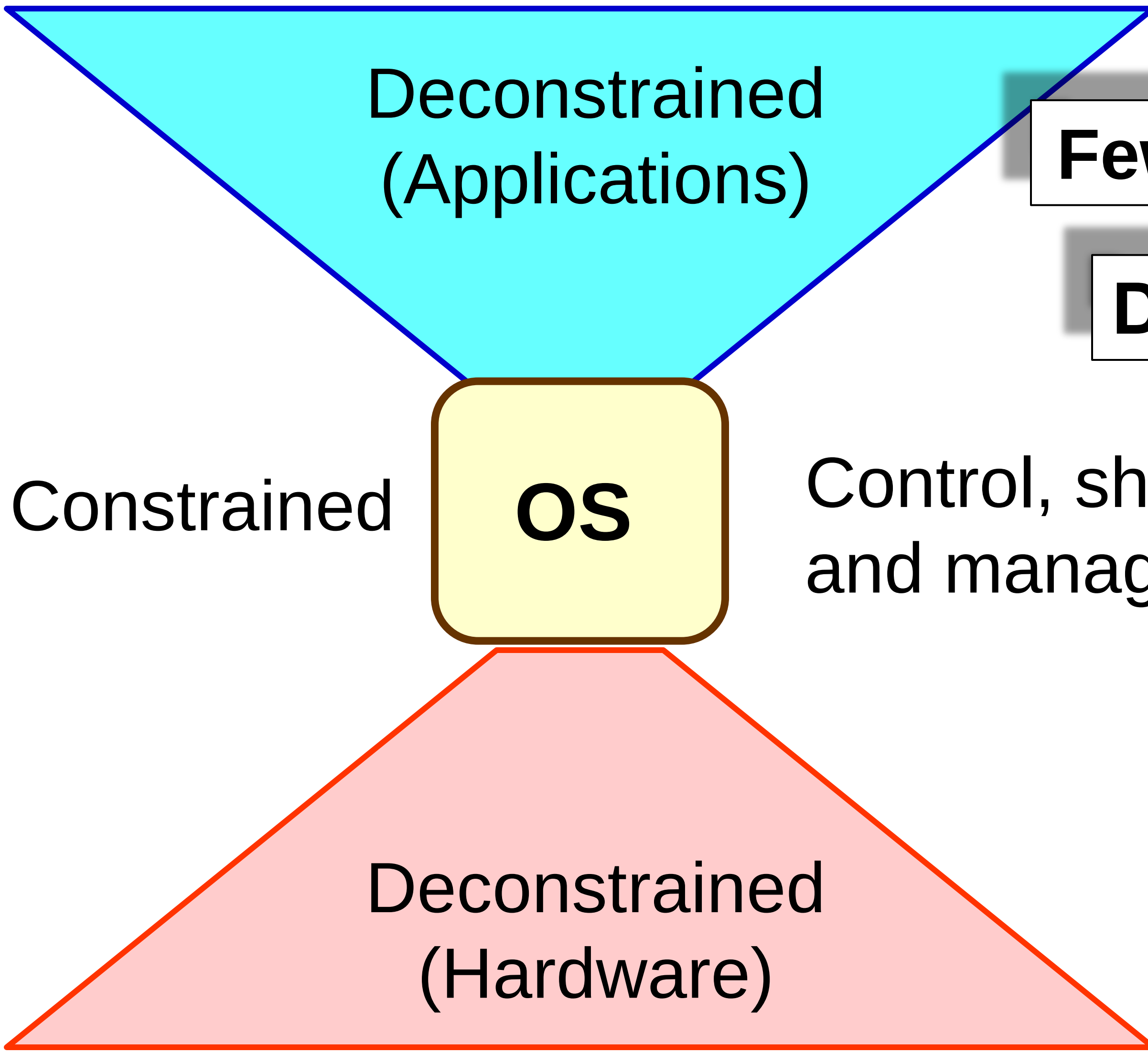
Created
- whole new ecosystem
- completely opposite

Why?

Architecture

Layered architectures

Essentials



Few global variables

Don’t cross layers

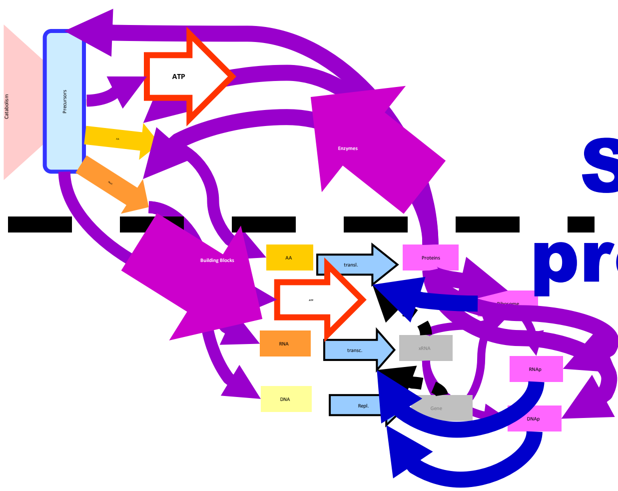
Control, share, virtualize, and manage resources

Processing
Memory
I/O

Layered architectures

Bacterial biosphere

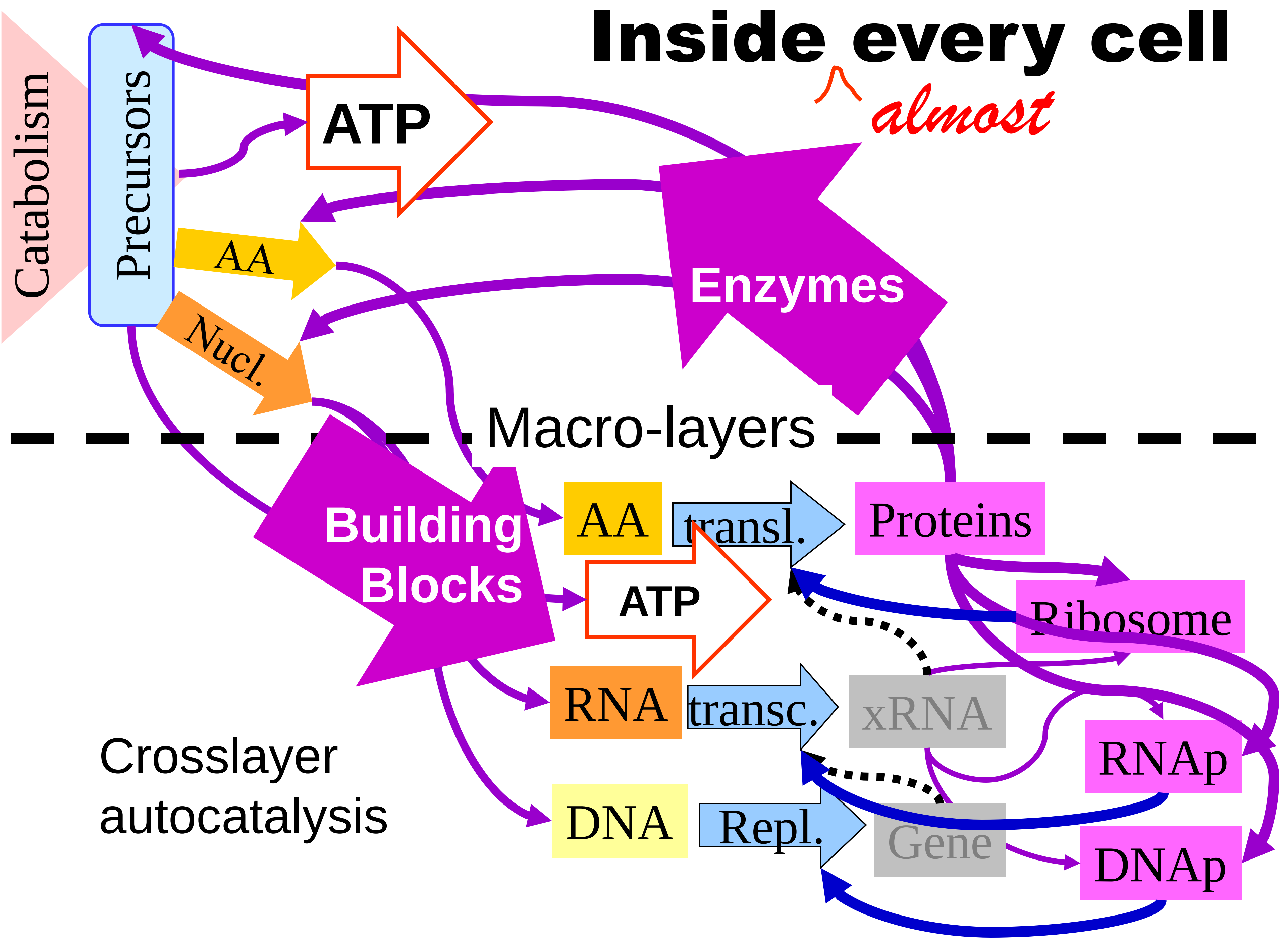
Deconstrained (diverse) Environments



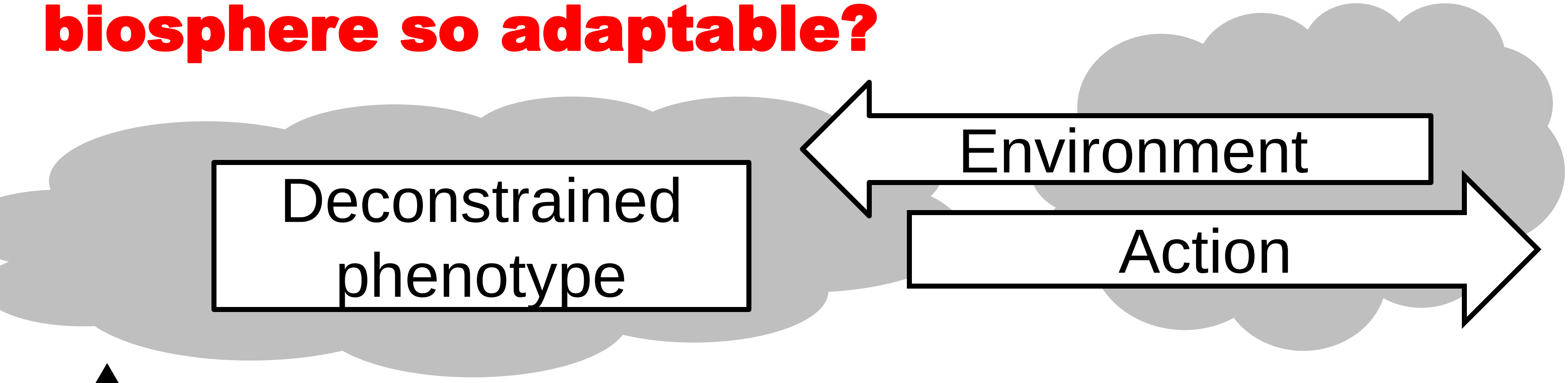
Shared protocols

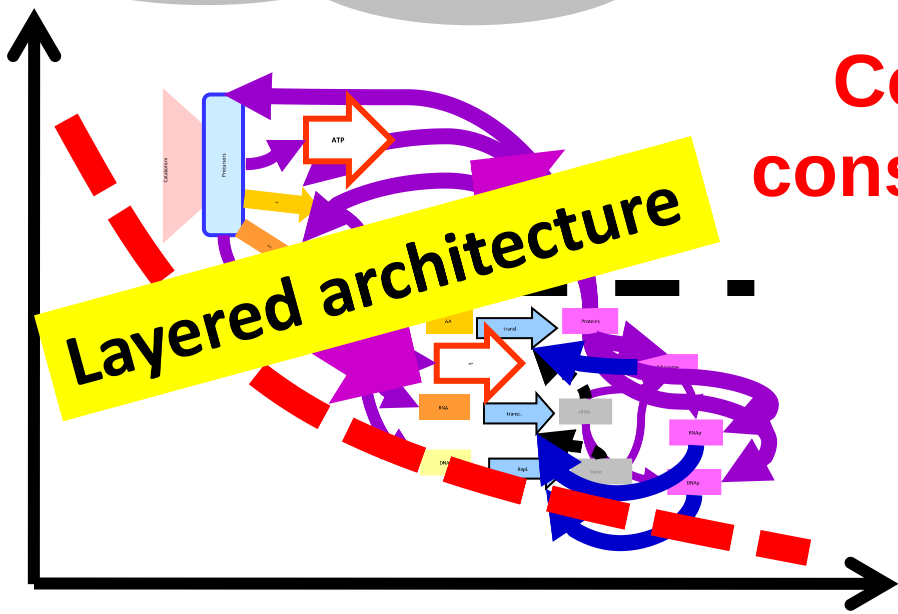
Architecture = Constraints that Deconstrain

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?





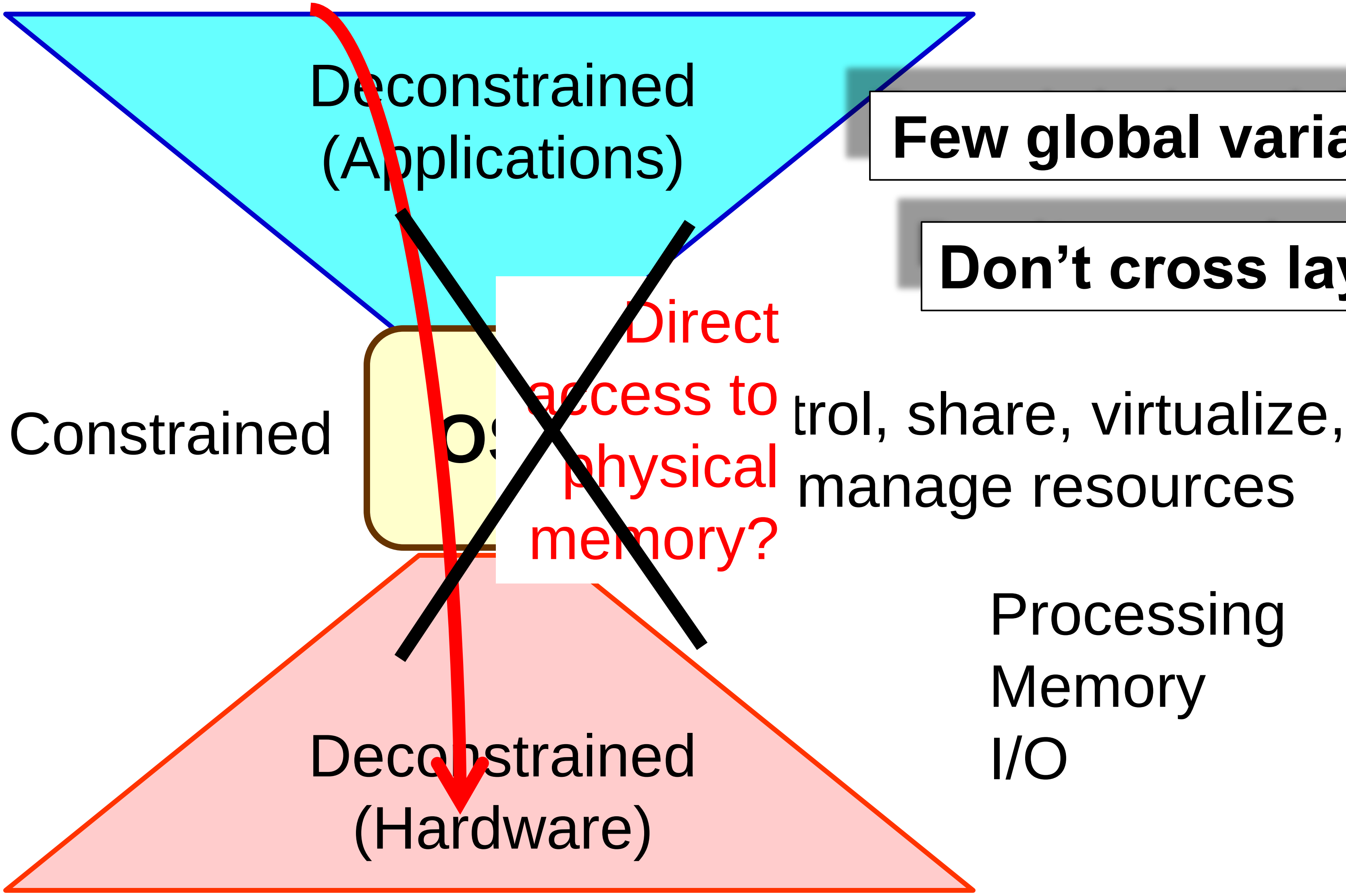
Core conserved constraints facilitate tradeoffs

+

Active control of the genome (facilitated variation)

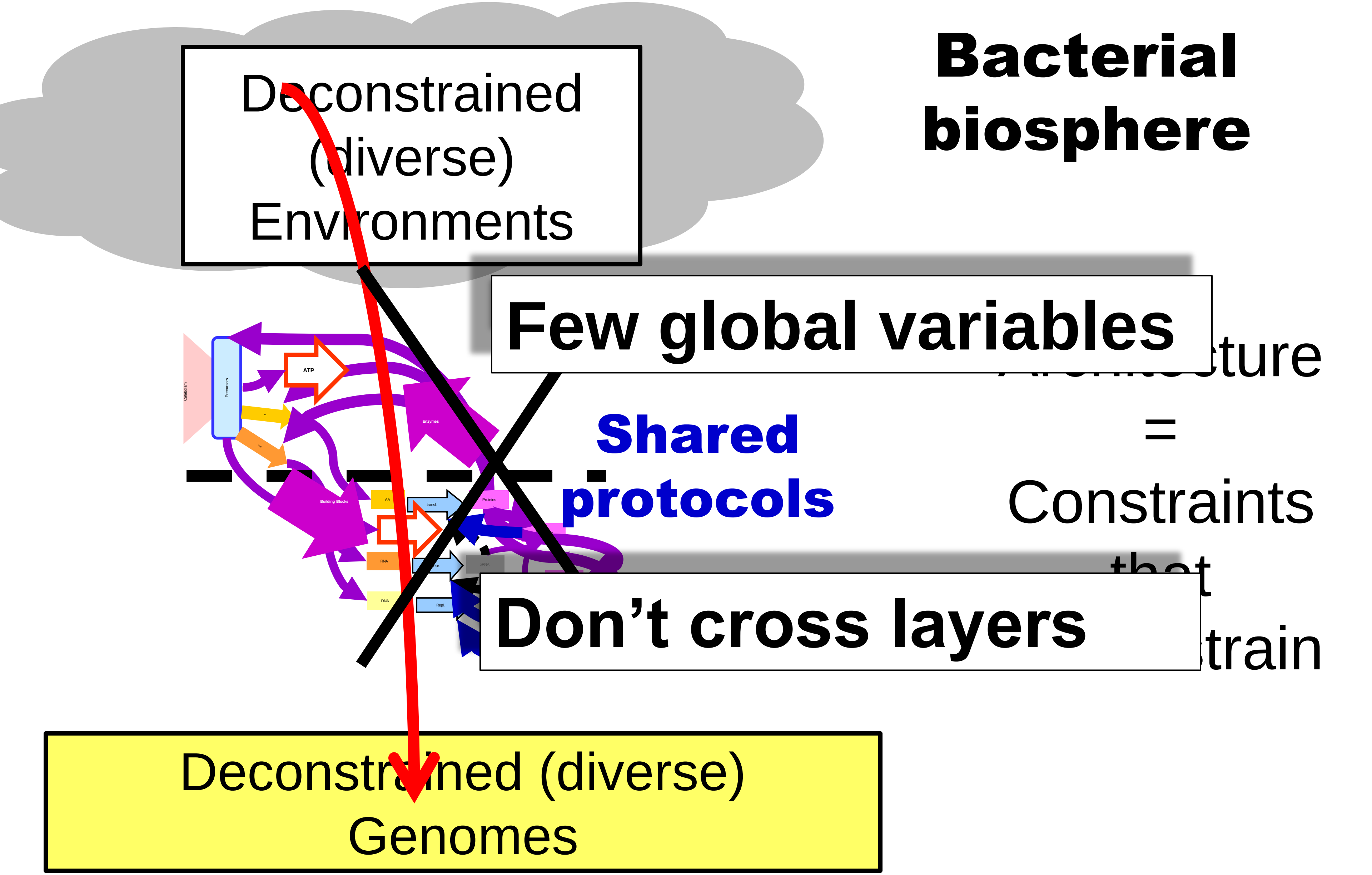
Deconstrained genome

Layered architectures



Few global variables

Don’t cross layers


Bacterial biosphere
Deconstrained (diverse) Environments
Few global variables
Shared protocols
=
Constraints
Don’t cross layers
ATP
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

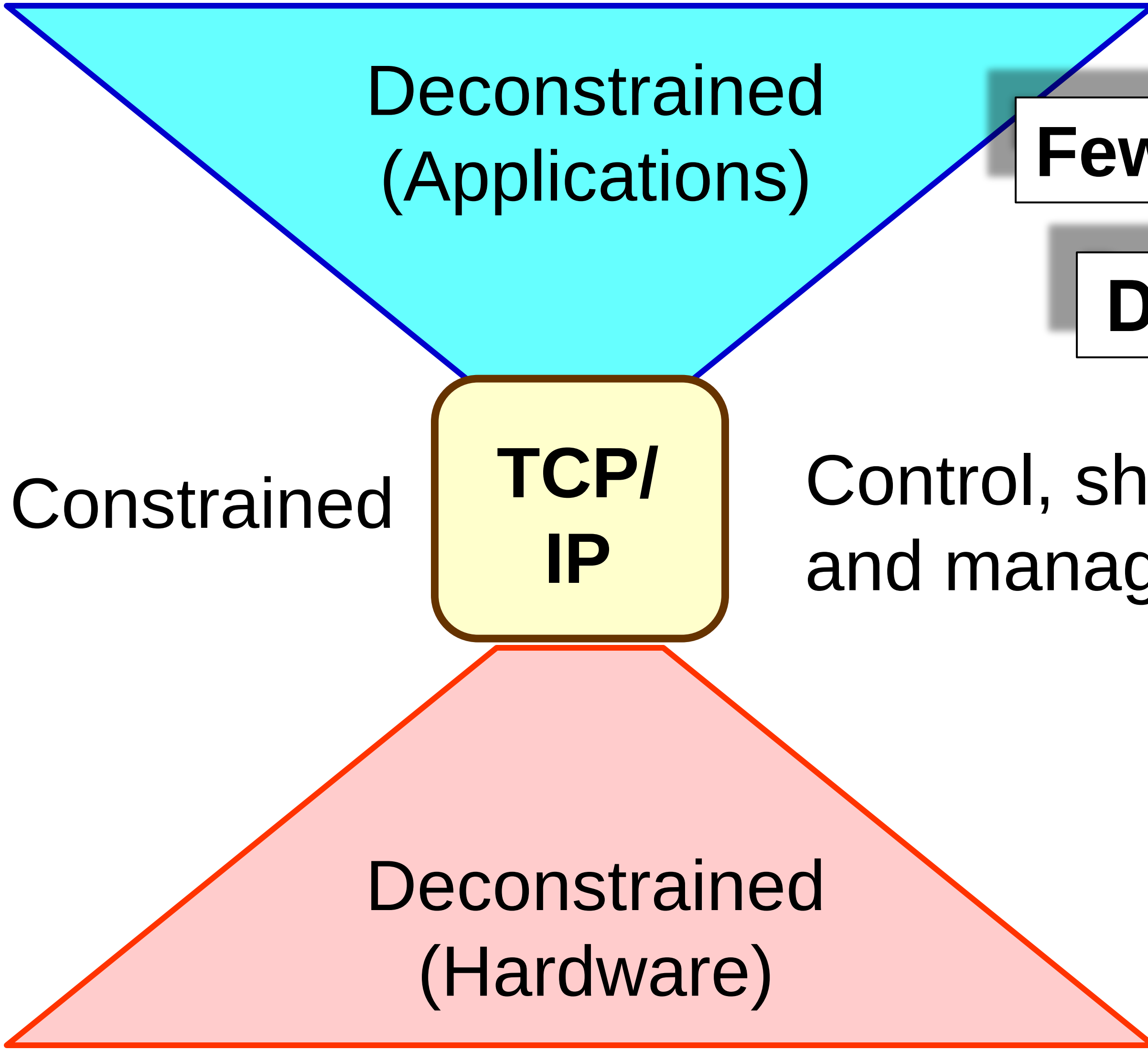
- Limits optimization/control by duality?

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

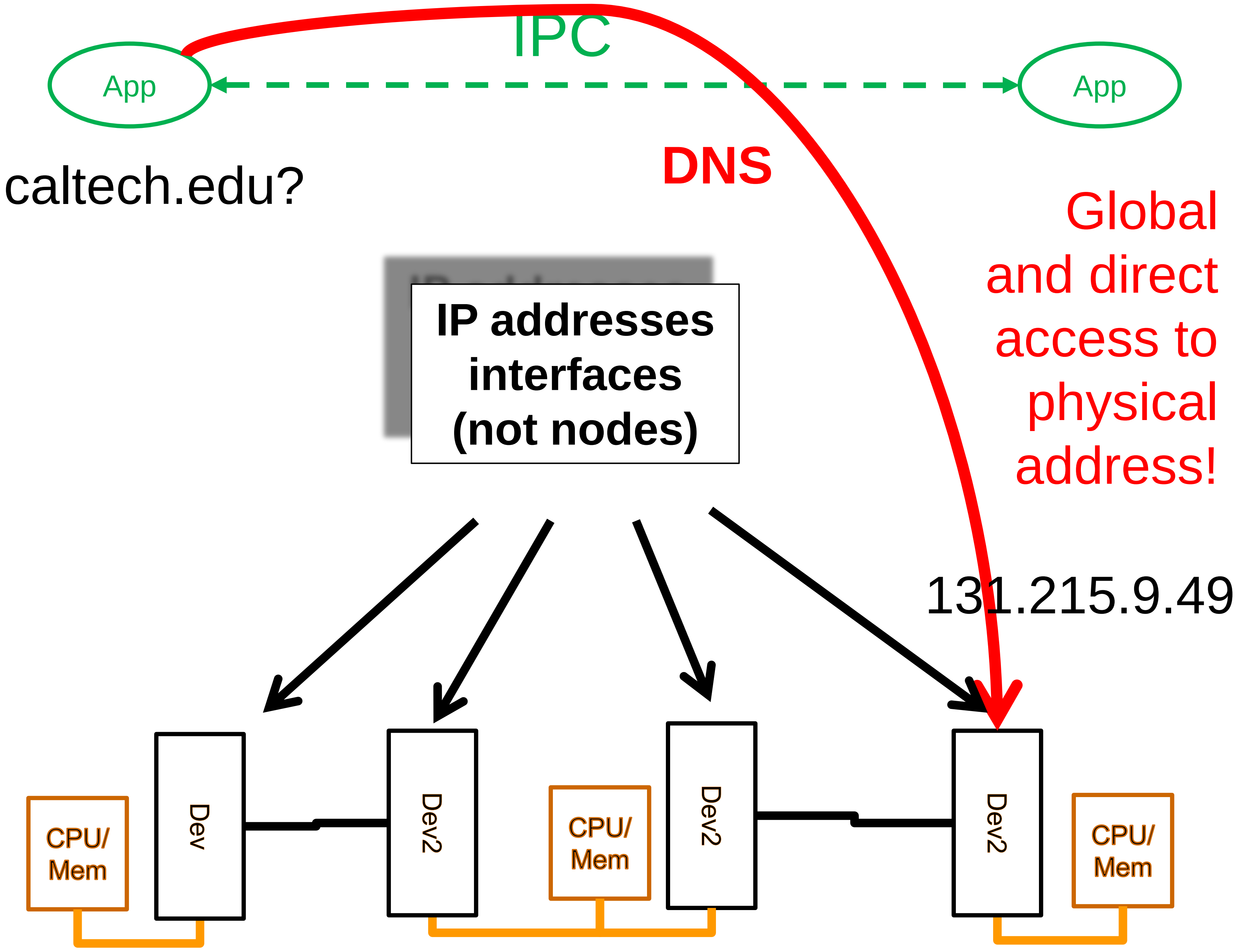


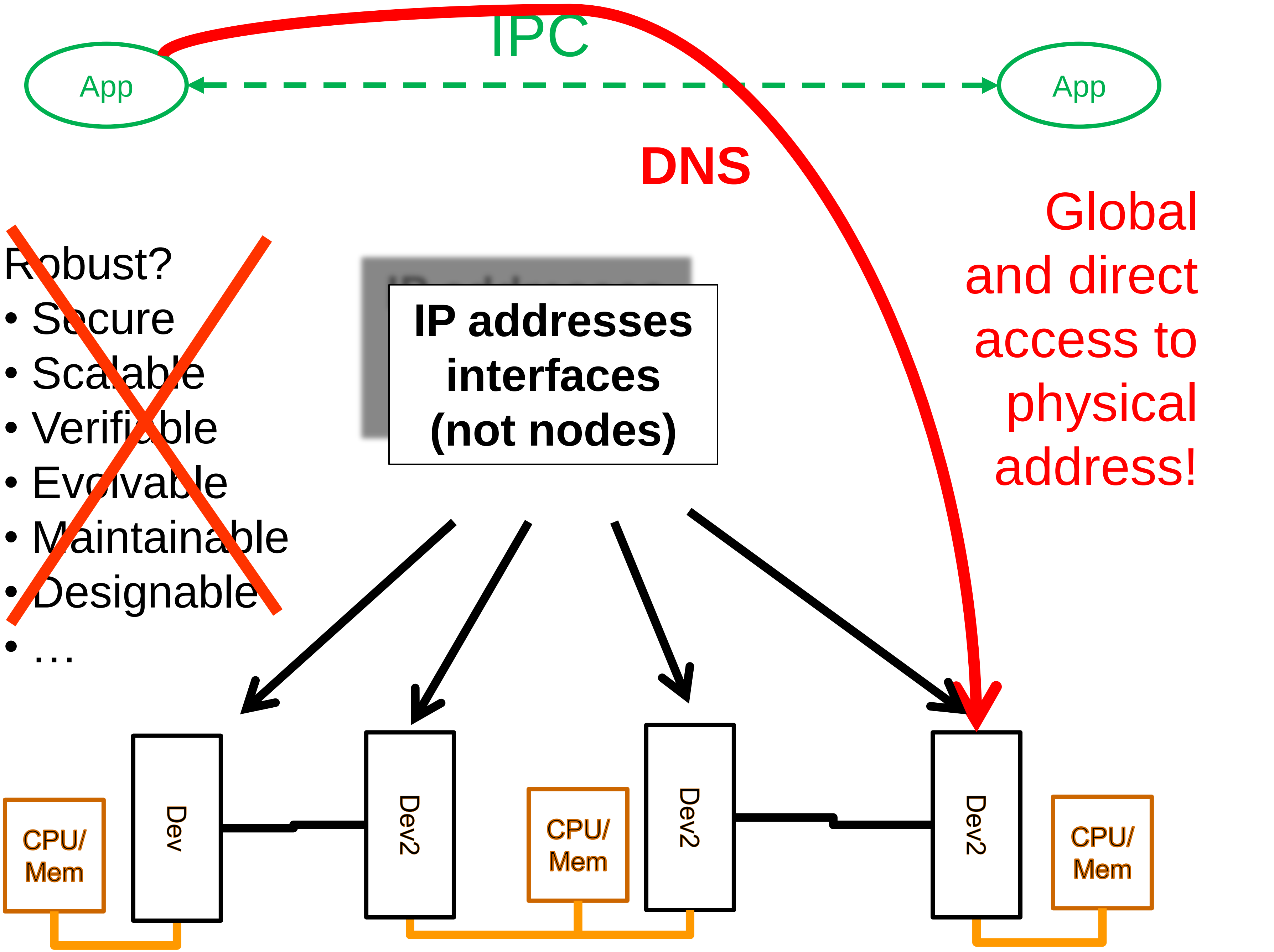
Few global variables?

Don’t cross layers?

Control, share, virtualize, and manage resources

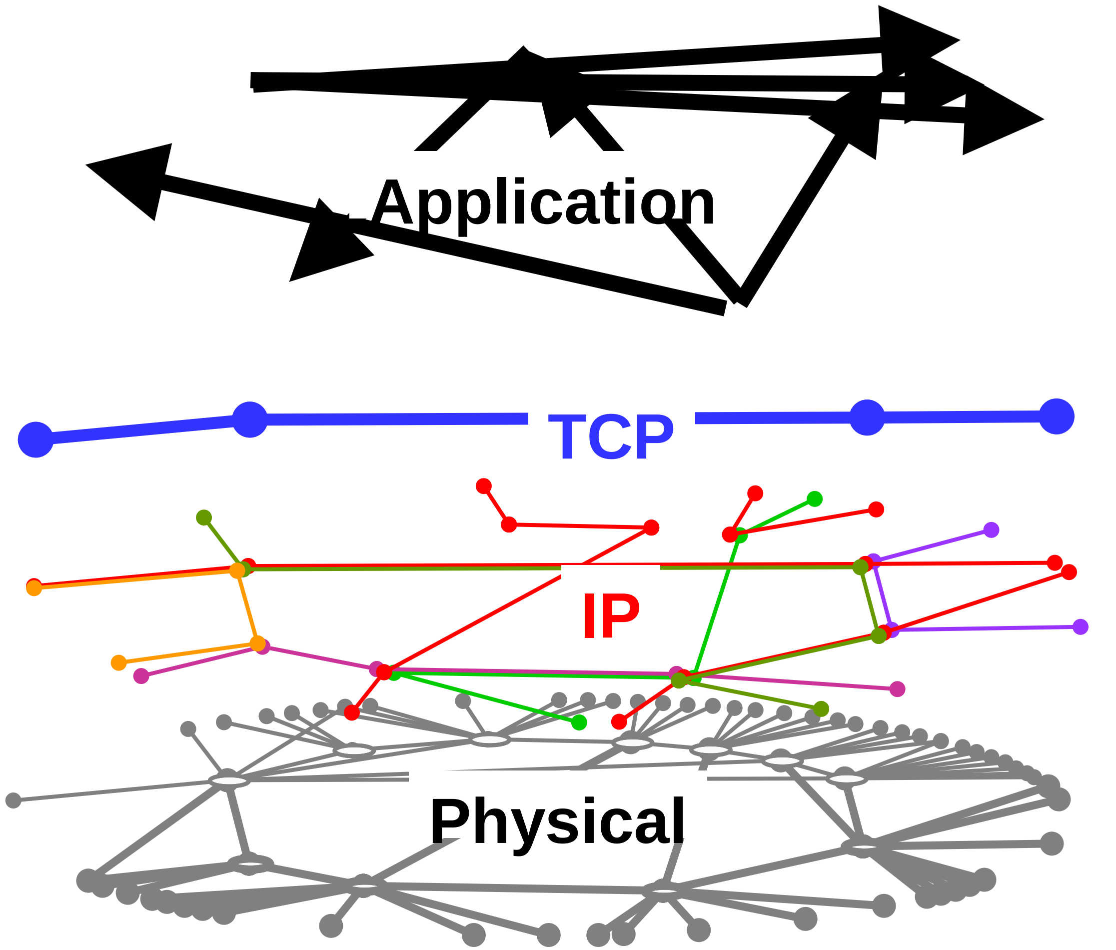
I/O
Comms
Latency?
Storage?
Processing?


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

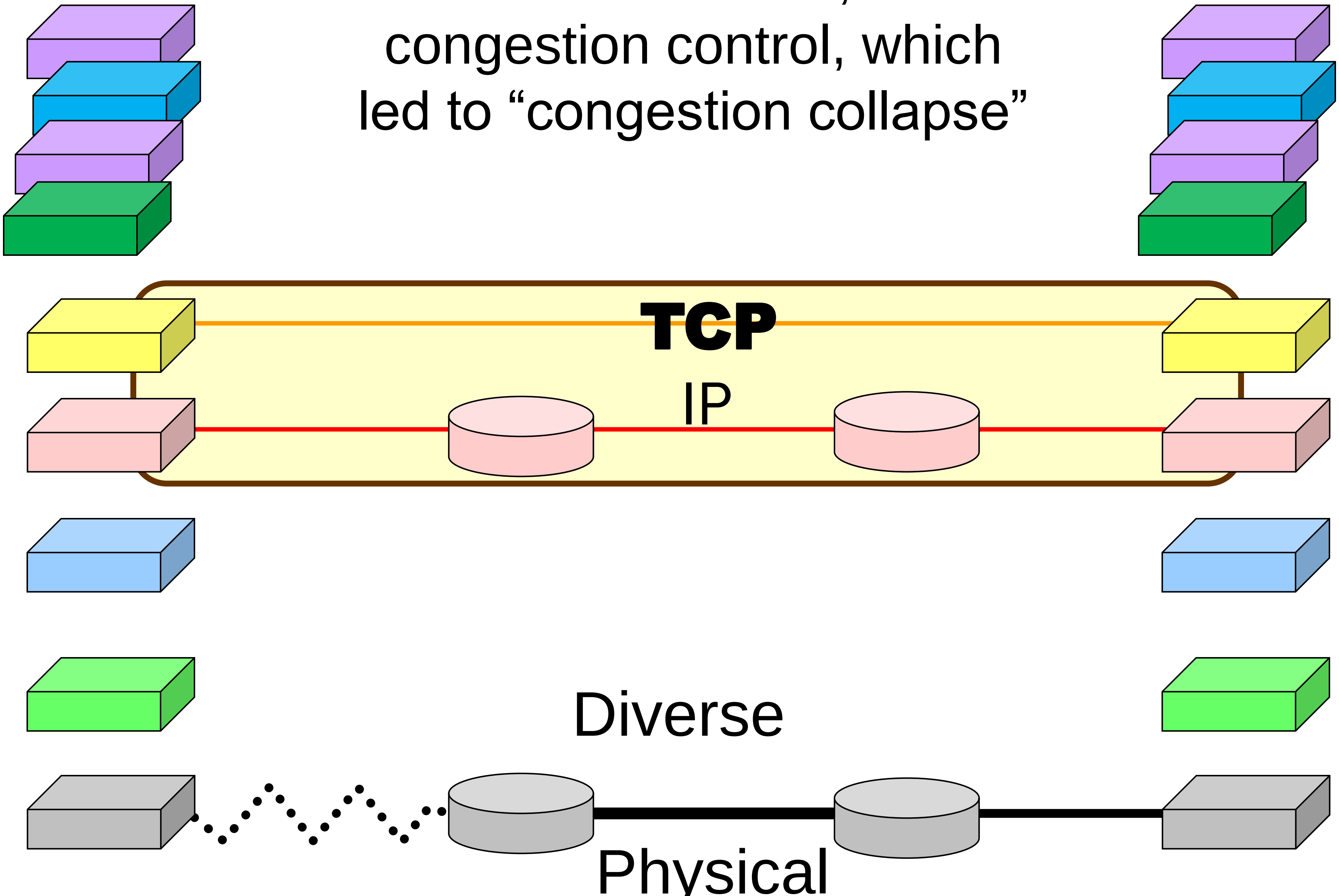

IPC
App
App
DNS
Global and direct access to physical address!
Robust?
• Secure
• Scalable
• Verifiable
• Evolvable
• Maintainable
• Designable
• …
IP addresses interfaces (not nodes)
CPU/ Mem
Dev
Dev2
CPU/ Mem
Dev2
Dev2
CPU/ Mem

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

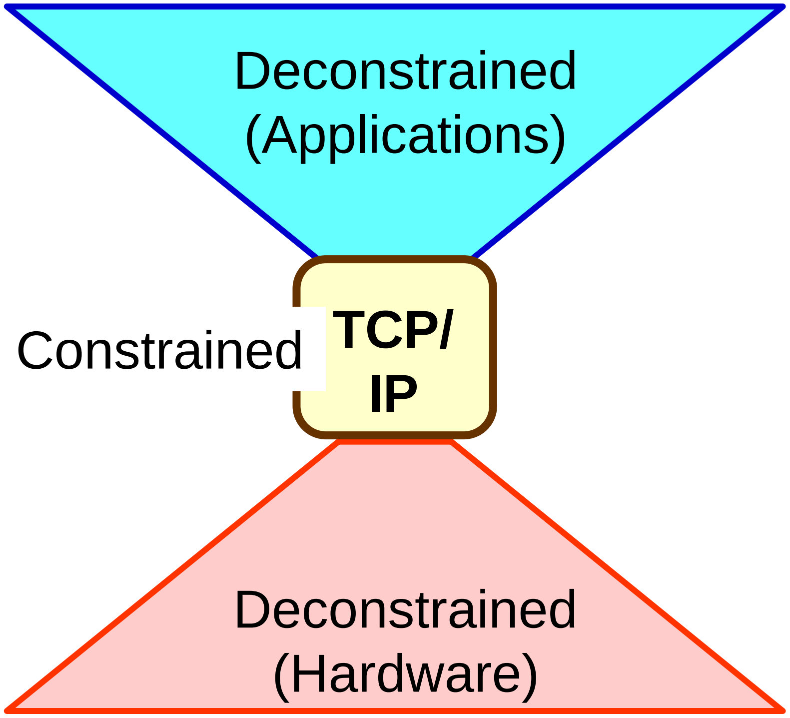
Related “issues”
- VPNs
- NATS
- Firewalls
- Multihoming
- Mobility
- Routing table size
- Overlays
- …



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



Original design challenge?



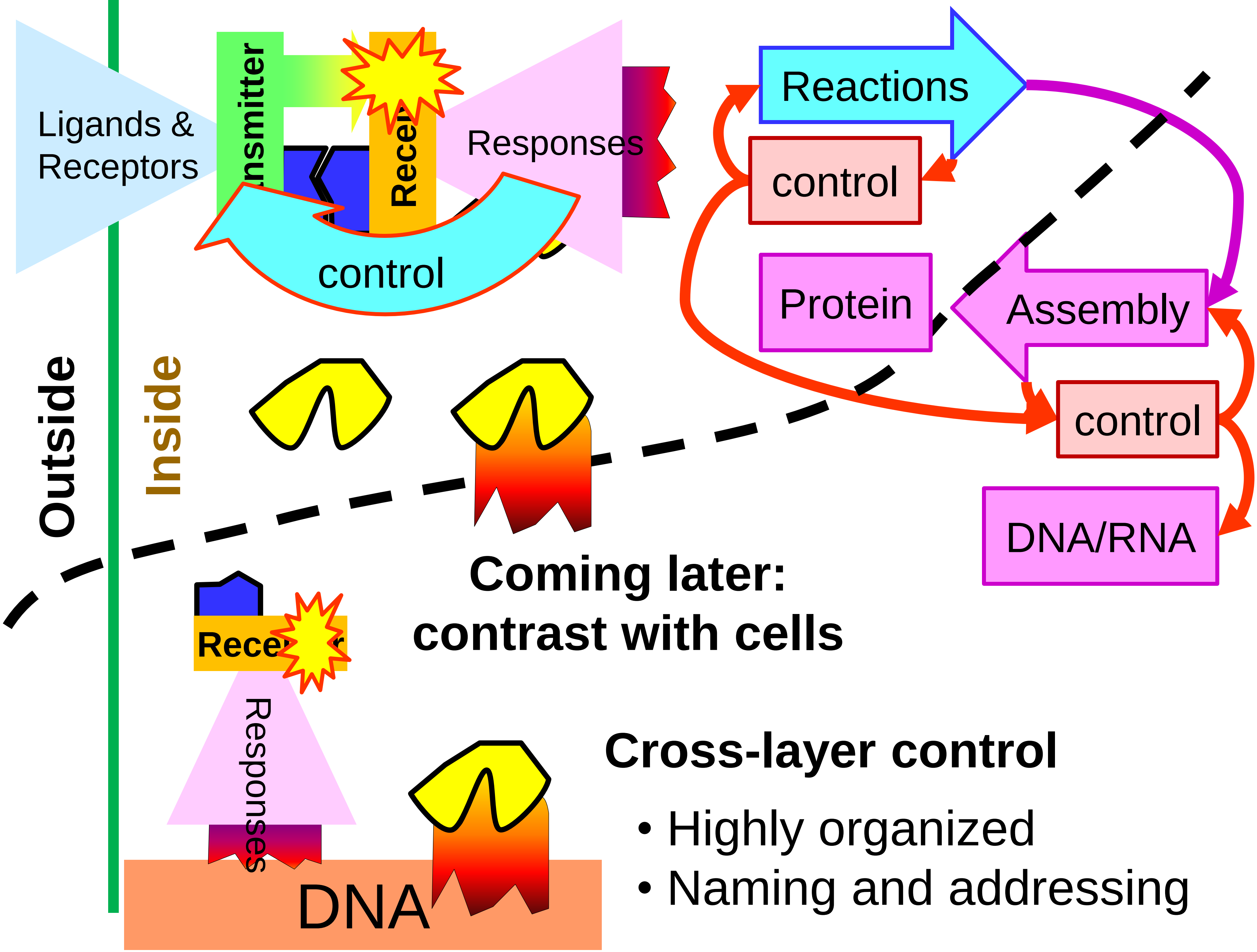
Networked OS

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

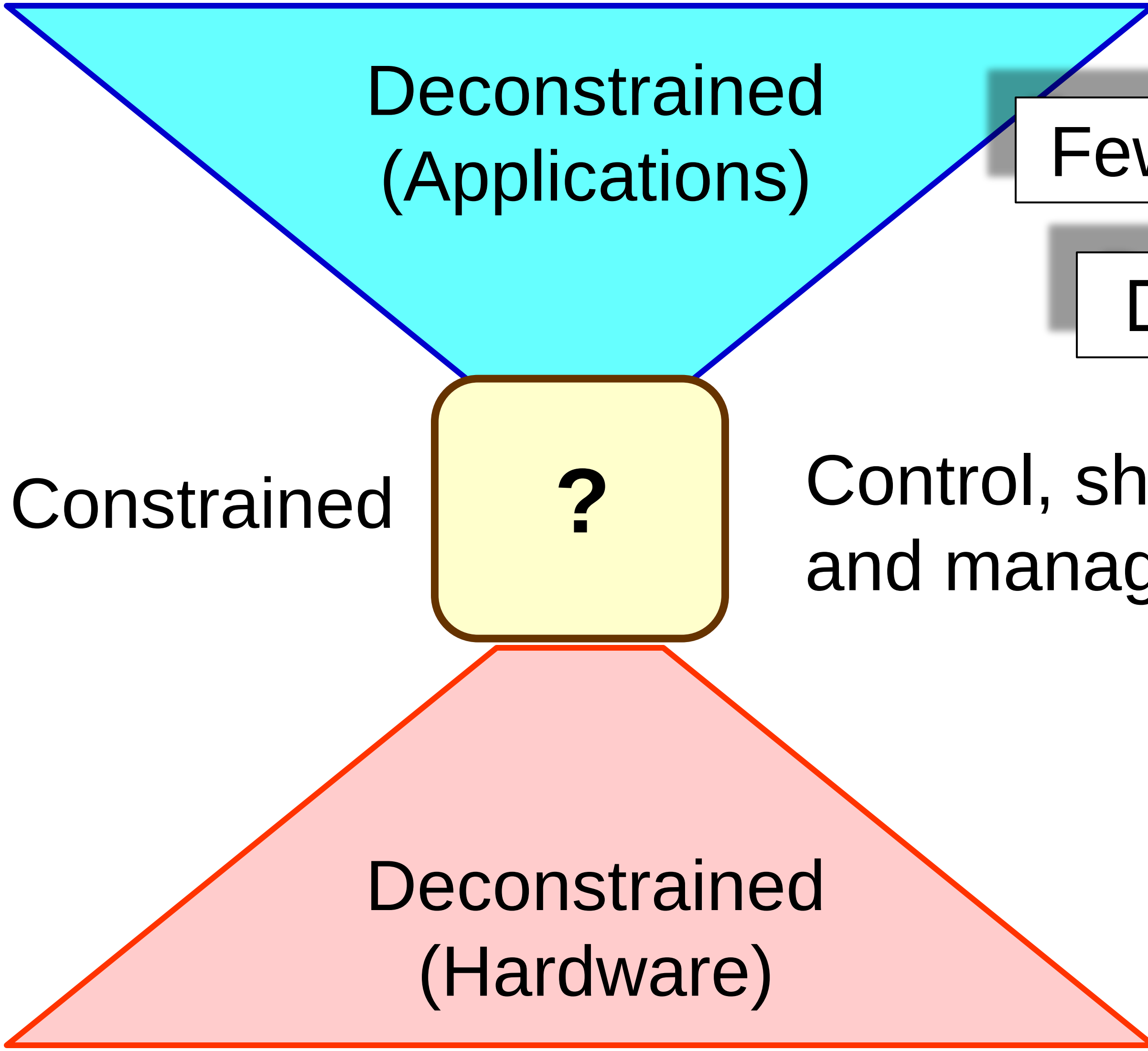
Facilitated wild evolution

Created

- whole new ecosystem
- completely opposite


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

Next layered architectures



Few global variables

Don’t cross layers

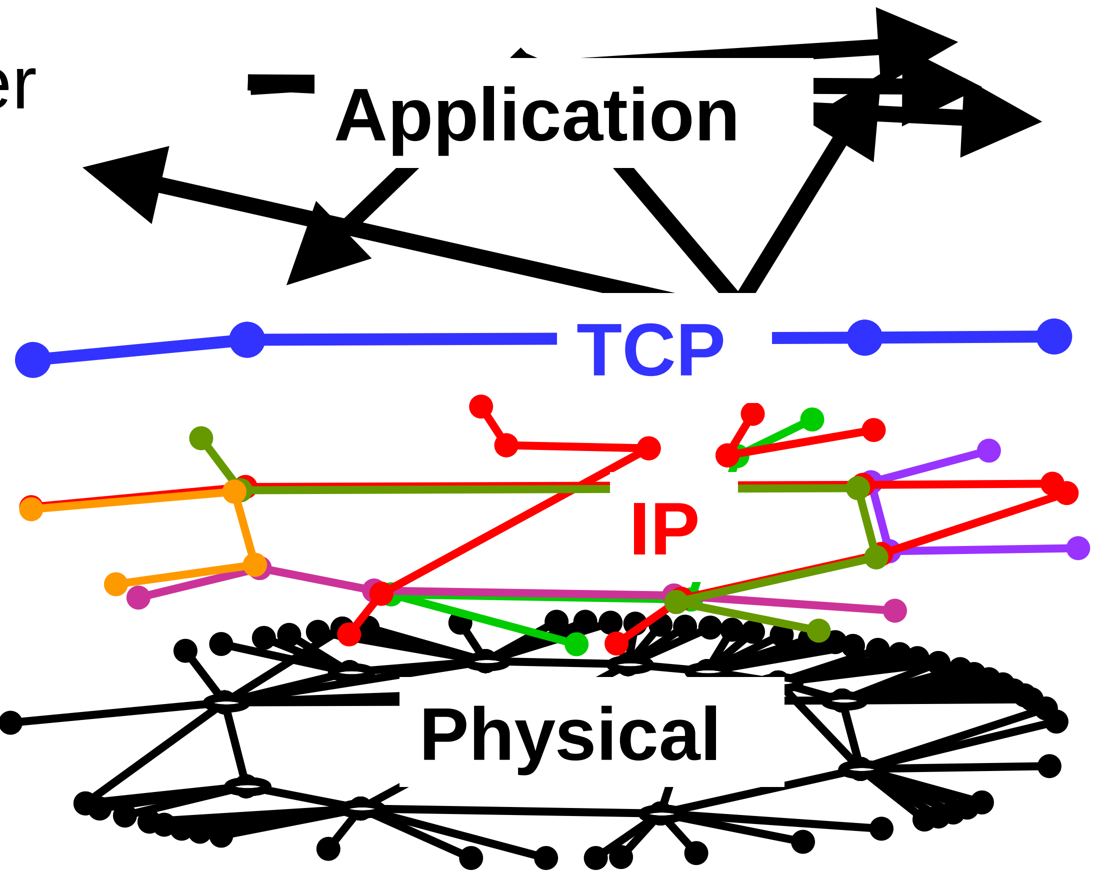
Control, share, virtualize, and manage resources

Comms
Memory, storage
Latency
Processing
Cyber-physical

Persistent errors and confusion ("network science")

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

Every layer has different diverse graphs.



Architecture facilitates arbitrary graphs.

The "robust yet fragile" nature of the Internet

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

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

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

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

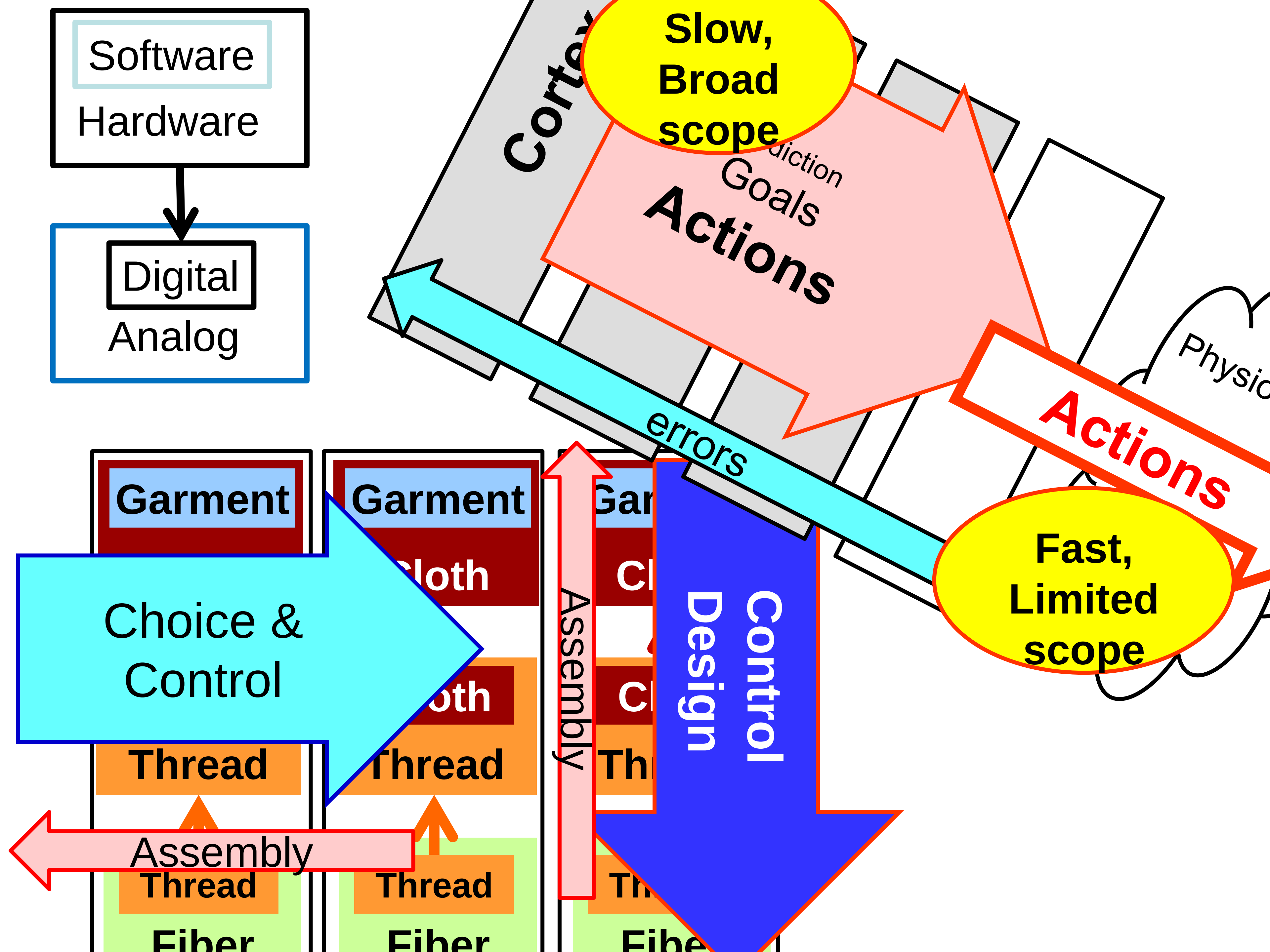
no self-loops or parallel edges) having the same graph degree
We will say that graphs $g \in G(D)$ have scaling-degree sequen

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

Notices of the AMS, 2009

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

Walter Willinger, David Alderson, and John C. Doyle



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