Universal laws and architectures:
Theory and lessons from nets, grids, brains, bugs, planes, docs, fire, fashion, art, turbulence, music, buildings, cities, earthquakes, bodies, running, throwing, Synesthesia, spacecraft, statistical mechanics.
Understand this more deeply?

\[
\exp \left( \int \ln |T| \right) \leq \exp (p\tau) \left| \frac{z + p}{z - p} \right|
\]

Mechanics +
Gravity +
Light +
Control theory

+ Neuroscience

\[
|T(j\omega)| = \left| \frac{E}{N} \right|
\]

error
noise

C

P

eye
vision
delay
Control

Act
Understand this more deeply?

+ Neuroscience

Motion

Vision

error

eye

noise

vision

delay

Control

Act
Robust vision w/motion
- Object motion
- Self motion

Motion
Vision

eye

error
noise

vision
delay

Control
Act
Layering Feedback

Explain this amazing system.

Vision
Robust vision with
• Hand motion
• Head motion

Experiment
• Motion/vision control without blurring
• Which is easier and faster?
Why?
- Mechanism
- Tradeoff

Slow vision

Fast VOR
Mechanism
Vestibular
Ocular
Reflex (VOR)

Slow

Fast

Flexible

Inflexible

Vision

Tradeoff
It works in the dark or with your eyes closed, but you can’t tell.
Layering Feedback

Highly evolved (hidden) architecture

Vision

Delay

Flexible

Inflexible

Fast

Slow

Illusion
Layering Feedback

- Eye
- Fast
- Act
- Slow
- VOR
- Delay
- Vision
Architecture
layered/
distributed

slow
delay

Fast

Illusion

Flexible

Inflexible

Vision

Act

VOR

Fast

slow

vision
delay
vision
eye

Architecture
layered/
distributed

Act

fast

slow
delay

vision

Robust or fine-tuned? Both Modular or plastic? Both

Fast

Flexible

Inflexible

Illusion

VOR
Very rough cartoon
Object motion → + → eye → vision
Head motion → + → eye → vision

VOR → gain → Act → AOS
Tune gain

Error → Cortex → slow 
Cerebellum

Slightly better
AOS = Accessory Optical system
Object motion
Head motion

$VOR$

This fast “forward” path

Slightly better

$AOS = \text{Accessory Optical system}$

Error

$\text{vision}$

Cortex

Needs “feedback” tuning

Via $AOS$ and cerebellum (not cortex)

$\text{Tune gain}$

$\text{Act}$

$\text{Cerebellum}$
Highly evolved (hidden) architecture
Object motion

Head motion

VOR

gain

Act

Distributed control

Error

Cerebellum

Cortex

slow delay

delays everywhere

AOS = Accessory Optical system
Object motion

Head motion

VOR

Gain

Tune gain

Act

AOS

Error

Cerebellum

Heterogeneous delays everywhere

slowest

fast

noise

Vision

Cortex

slow

delay

Act

slowest delays everywhere
Slow Jylexible Vision

Act

VOR

Fast

3D + motion

Color?

vision

delay

See Marge Livingstone
Slow motion

3D + motion

Slowest

3D + motion

Slowest

Slow

Fast

Flexible

Inflexible

VOR

Fast

Slow

Act

eye

vision

color vision

See Marge Livingstone
Stare at the intersection
Stare at the intersection.
Stare at the intersection.
Seeing is dreaming
• is simulation
• requiring “internal model”
Robust perfect adaptation in bacterial chemotaxis through integral feedback control

Tau-Mu Yi\textsuperscript{*,†}, Yun Huang\textsuperscript{††}, Melvin I. Simon\textsuperscript{*,§}, and John Doyle\textsuperscript{‡}
Bacterial chemotaxis

- Internal model *necessary* for robust chemotaxis
- Reality is 3d, but…
- Internal model *virtual* and 1d
Universal laws and architectures (Turing)

- Slow
- Fast
- Flexible
- General
- Inflexible
- Special

Architecture (constraints that deconstrain)

Architecture

Impossible (law)

ideal

Turing's ideal architecture
Compute

Research progress

Slow

Fast

Insight

Flexible

Inflexible

Decidable

Pspace

NP

P

analytic

From toys to “real” systems

Control, OR
Compute

Research progress

Slow

Fast Insight

Flexible

Inflexible

Decidable

Pspace

NP

P

analytic

Improved algorithms

Control, OR
Layering Distributed Feedback

- Slow
- Fast

- Flexible
- Inflexible

- vision
- color vision

- VOR
This fast “forward” path

VOR

Object motion

Head motion

Vision

Cortex

Needs “feedback” tuning

Act

AOS

Slightly better

AOS = Accessory Optical system

Error

Tune gain

Cerebellum

Via AOS and cerebellum (not cortex)
AOS = Accessory Optical system
\[
\sup_\Delta |T(\Delta)|?
\]
Scale with dimension?
Uncertainty everywhere

- Real (NP hard)
- Complex = LTI (??)
- Operator valued or Noncomm (P)
Layering Distributed Feedback

Highly evolved (hidden) architecture

Fast

Flexible

Inflexible

Vision
eye \quad vision

delay \approx .3s

error \quad noise

p \propto \sqrt{\frac{1}{l}}
Model?

- 1 dimension, 4 states?
- Other 2 dimensions?
- New issues arise
error

noise

\[ |T(j\omega)| = \left| \frac{E}{N} \right| \]
\[ |T(j\omega)| = \left| \frac{E}{N} \right| \]
error

\[ |T(j\omega)| = \left| \frac{E}{N} \right| \]

vision
delay
Control
Act
Close one eye?

\[ |T(j\omega)| = \left| \frac{E}{N} \right| \]
Universal laws?

\[ \exp \left( \int \ln |T| \right) \geq \exp \left( p \tau \frac{z + p}{z - p} \right) \]

too fragile

complex

No tradeoff

\[ \text{Length, m} \]

\[ \text{expensive} \]

\[ k \]

\[ 10^0 \]

\[ 10^{-1} \]
How do these fit together?

\[
\exp\left(\int \ln|T|\right) \geq \exp(p\tau) \left|\frac{z + p}{z - p}\right|
\]
How do these fit together?

- **Fragile** vs. **Robust**
- **Slow** vs. **Fast**
- **Delay** vs. **Efficient** vs. **Waste**

- **Vision**
- **VOR**
Why such extreme diversity in *axon* size and delay?
Why such extreme diversity in *axon* size and delay?

Speed costs

Resolution and bandwidth are cheap

No diversity in VOR?

Retinal ganglion axons?

Other myelinated
Double the area (and cost)?

\[ \text{delay} \propto \frac{1}{\text{speed}} \]

\[ \sqrt{2} \times \text{speed (less delay)} \]

2 x resolution (less noise)

Resolution and bandwidth are cheap

Same area = same “cost”
speed doubly expensive but necessary

\[ \text{Speed} \propto \frac{1}{\tau} \]

\[ \exp(\beta \tau) \]

\[ \tau = 0.3 \text{s} \]

2 x resolution (less noise)
Object motion

Head motion

VOR

Gain

Tune gain

Eye

noise

Act

Fast

AOS

Error

Cerebellum

Heterogeneous delays everywhere

Vision

Cortex

Slow

Delay

Slowest
speed doubly expensive but necessary

\[ E \propto \exp(\rho \tau)N \]
How do these fit together?

- Robust vs. Fragile
- Fast vs. Slow
- Efficient vs. Waste

- Vision
- Speed Costs
In general?

- Robust vs. fragile
- Fast vs. slow
- Efficient vs. wasteful
- Flexible vs. inflexible
Cyber-physical

- Robust
- Flexible
- Inflexible
- Fast
- Slow
- Efficient
- Waste
PCA ≈ Principal Concept Analysis 😊
Compute, Communicate, Compute

Gödel, Shannon, Turing, Von Neumann

Turing, Theory?

Deep, but fragmented, incoherent, incomplete

Nash, Bode, Bode

Control, OR

Physics, Carnot, Boltzmann, Heisenberg, Einstein
Priorities

• Functionality (behavior, semantics)

• Robustness
  – Uncertain environment and components
  – Fast (sense, decide, act)
  – Flexible (adaptable, evolvable)

• Efficiency
  – Energy
  – Other resources (make and maintain)
Compute

Function, delay, robustness, most important

• Functionality (behavior, semantics)
• Robustness
  – Uncertain environment and components
  – Fast (sense, decide, act)
  – Flexible (adaptable, evolvable)
• Efficiency
  – Energy
  – Other resources (make and maintain)

Control, OR
• **Functionality** (behavior, semantics)

• **Robustness**
  - Uncertain environment and components
  - Fast (sense, decide, act)
  - Flexible (adaptable, evolvable)

• **Efficiency**
  - Energy
  - Other resources (make and maintain)

Physics
• Functionality (behavior, semantics)
• Robustness
  – Uncertain environment and components
  – Fast (sense, decide, act)
  – Flexible (adaptable, evolvable)
• Efficiency
  – Energy
  – Other resources (make and maintain)

[Highlighted text: Noise, average, asymptotic]

[Highlighted text: Info theory]

[Highlighted text: Physics]
Control, OR

Info theory

Physics

Function, delay, robustness

most important

least important

Compute

Func+on,
Dominate "high impact science" literature

Compute
  Turing

Function, delay, robustness
  most important

Control, OR

Bode

Info theory
  Shannon

Function, delay, robustness
  least important

Boltzmann

Physics
  Einstein

Carnot

Heisenberg
Improved algorithms
Compute
  Turing

Function, delay, robustness
  most important
  Bode

Control, OR

Info theory
  Shannon

Function, delay, robustness
  least important
  Carnot

Boltzmann

Heisenberg

Physics

Einstein
Control, OR

Function, delay, robustness
most important

Compute
Turing

Function, delay, robustness
least important

Communicate
Shannon

Physics

New progress!
Compute
Turing

Control, OR

Bode

New progress!

Function, delay, robustness
least important

Coherent structures and turbulent drag
Physics
**Shear flow turbulence**

• Exhaustively studied
  – Extensive experiments and **big** data
  – Detailed models and **big** simulations
  – Great! But all just deepen the mystery

• Perfectly illustrates robust/fragile

• Without which? Bewilderment.
Amplification and nonlinear mechanisms in plane Couette flow

Dennice F. Gayme, Beverley J. McKeon, Bassam Bamieh, Antonis Papachristodoulou, and John C. Doyle

Coherent structures and turbulent drag

high-speed region | upflow | 3D coupling | low speed streak

Blunted turbulent velocity profile

Turbulent

Laminar
Compute

Turing

Bode

Control, OR

Communications for control, computing, biology

Function, delay, robustness, least important

New progress!
New theory: Distributed control with delays everywhere.

Sense/Act

Physical

Internal delays

Compute/communicate
Compute  Comms for Comp/Cntrl/Bio  Info Thry

Optimization  Statistics  Theory

Control, OR  Orthophysics (Eng/Bio/Math)  Physics
Laminar

Turbulent

Control?

Orthophysics (Eng/Bio/Math)
Architecture, constraints, and behavior

John C. Doyle\textsuperscript{a,1} and Marie Csete\textsuperscript{b,1}

\textsuperscript{a}Control and Dynamical Systems, California Institute of Technology, Pasadena, CA 91125; and \textsuperscript{b}Department of Anesthesiology, University of California, San Diego, CA 92103

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.

For more info
Most accessible
No math

References
Universal laws and architectures

Fragile

Robust

Efficient

Wasteful

Architecture

Flexibly achieves what’s possible

Impossible (law)
Efficiency/instability/layers/feedback

Evolvability?

- Sustainable infrastructure? (e.g. smartgrids)
- Money/finance/lobbyists/etc
- Industrialization
- Society/agriculture/weapons/etc
- Bipedalism
- Maternal care
- Warm blood
- Flight
- Mitochondria
- Oxygen
- Translation (ribosomes)
- Glycolysis (2011 Science)
Accelerating evolution

RNA

mRNA

RNA polymerase (RNAP)

Horizontal Gene Transfer

Horizontal App Transfer

New gene

DNA

Sensory

Learning

Striatum

Prefrontal

Reflex

Software

Hardware

Digital

Analog

Horizontal Meme Transfer

Metabolism

Signal transduction

ATP

Transfer
tccelerating evolution

Requires shared “OS”
Sequence ~100 E Coli (*not* chosen randomly)
- ~4K genes per cell
- ~20K *different* genes in total (pangenome)
- ~1K universally shared genes
- ~300 essential (minimal) genes
Horizontal Meme Transfer

Horizontal App Transfer

DNA
New gene
Transcription
RNA
mRNA
Amino Acids
Ribosomes
Products
ATP
control feedback
Signal transduction

Software
Hardware

Digital Analog

Reflex
Sensory
prefrontal
striatum

What can go wrong?
Exploiting layered architecture

Meme

Horizontal Bad Meme Transfer

Fragility?

Virus

Horizontal Bad App Transfer

Parasites & Hijacking

Horizontal Bad Gene Transfer
Many human beliefs are:
- False
- Unhealthy
Object motion

Head motion

VOR

gain

Act

Distributed control

Vision

Cortex

slow

delay

Error

Cerebellum

Delays everywhere

AOS = Accessory Optical system
Redraw
(not anatomical)

Slow

Fast

slower

Vision

slow

Mixed

Flexible

Inflexible

VOR
Redraw
(not anatomical)

Objects

3d+motion
B&W

Vision

mixed

Flexible

Slow

Fast

slower

Fast

Inflexible

slow

Vision
Not sure how to draw this…
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)
Specific brain lesions can cause “blindness” to

- Faces
- Fruit or Animals or Tools or ??
- Left side of body
- Movement
- Nonmovement
- ??
Not sure how to draw this…

- Slower
- Objects
- Faces
- Learning + evolution
Specialized Face Learning Is Associated with Individual Recognition in Paper Wasps

Michael J. Sheehan* and Elizabeth A. Tibbetts

We demonstrate that the evolution of facial recognition in wasps is associated with specialized face-learning abilities. *Polistes fuscatus* can differentiate among normal wasp face images more rapidly and accurately than nonface images or manipulated faces. A close relative lacking facial recognition, *Polistes metricus*, however, lacks specialized face learning. Similar specializations for face learning are found in primates and other mammals, although *P. fuscatus* represents an independent evolution of specialization. Convergence toward face specialization in distant taxa as well as divergence among closely related taxa with different recognition behavior suggests that specialized cognition is surprisingly labile and may be adaptively shaped by species-specific selective pressures such as face recognition.

When needed, even wasps can do it.
• *Polistes fuscatus* can differentiate among normal wasp face images more rapidly and accurately than nonface images or manipulated faces.
• *Polistes metricus* is a close relative lacking facial recognition and specialized face learning.
• Similar specializations for face learning are found in primates and other mammals, although *P. fuscatus* represents an independent evolution of specialization.
• Convergence toward face specialization in distant taxa as well as divergence among closely related taxa with different recognition behavior suggests that specialized cognition is surprisingly labile and may be adaptively shaped by species-specific selective pressures such as face recognition.
Fig. 1 Images used for training wasps.

<table>
<thead>
<tr>
<th>P. fuscatus faces</th>
<th>Antenna-less faces</th>
<th>Rearranged faces</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Images" /></td>
<td><img src="image2.png" alt="Images" /></td>
<td><img src="image3.png" alt="Images" /></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Patterns</th>
<th>Caterpillars</th>
<th>P. metricus faces</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="pattern1.png" alt="Patterns" /></td>
<td><img src="caterpillar1.png" alt="Caterpillars" /></td>
<td><img src="image4.png" alt="Images" /></td>
</tr>
</tbody>
</table>

M J Sheehan, E A Tibbetts Science 2011;334:1272-1275
Seeing is dreaming

Highly evolved (hidden) architecture

Illusion

Slow

Fast

Flexible

Inflexible

vision
Objects

Slow

3d+motion B&W

Learning + evolution

Faces

Mixed

Flexible

VOR

Inflexible

Fast

Not sure how to draw this…
Universal tradeoffs?

Learning can be very slow.

Evolution is even slower.

- Prefrontal
- Motor
- Fast
- Sense
- Fast
- Evolve
- Reflex
- Inflexible
- Flexible
- Slow
- Fast
Accelerating evolution

Horizontal Meme Transfer

Software

Hardware

Horizontal App Transfer

Digital Analog

Reflex

Sensory

Prefrontal

Striatum

Software

Hardware

Horizontal Gene Transfer

New gene

DNA

RNA

mRNA

RNAp

Amino Acids

Ribosomes

Proteins

Products

ATP

Requirements shared “OS”

Signal transduction

control feedback
Some genes, apps, ideas are “invented”

But most bacteria and people get most of them from others
Learning

fragile

robust

efficient

costly
Learning

bike

walk

crawl
VOR

Object motion

Head motion

Fast

Gain

Act

Error

Cerebellum

AOS

Gain

Tune gain

Cortex

Slow delay

Vision

Noise

Act
AOS = Accessory Optical system
Learning

- Slow Flexible
- Prefrontal
- Motor
- Slow
- Sensory
- Striatum

Reflex (Fastest, Least Flexible)

Extreme heterogeneity

Ashby & Crossley
Learning can be very slow.

Reflex (Fastest, Least Flexible)

Ashby & Crossley
HMT

Teach

Prefrontal

Learn

Motor

Fast Sense

Evolve

Reflex

Flexible

Inflexible

Fast

Slow
Layered Architecture

Any layer needs all lower layers.

Slow

Fast

Cheap

Costly

Apps

OS

Digital

Lumped

Distrib.

OS

Digital

Lumped

Distrib.

Digital

Lumped

Distrib.

Lumped

Distrib.

Inflexible

Flexible

General

Special
Tech implications/extensions

- Apps
- OS
- Hardware
- Digital
- Lumped
- Distributed

Slow

Fast

Flexible

Inflexible
Universal laws and architectures (Turing)

Architecture (constraints that deconstrain)

Architecture (law)

Ideal

Flexible

General

Inflexible

Special

Slow

Fast
Research progress

From toys to “real” systems
Slow \quad \text{Flexible} \quad \text{Decidable} \quad \text{Pspace} \quad \text{NP} \quad \text{P} \quad \text{analytic} \quad \text{Improved algorithms} \\
Fast \quad \text{Inflexible} \\
\text{Insight} \\
\text{Compute} \quad \text{Research progress} \\
\text{Control, OR}
Resource cost vs effectiveness

- **Resource cost** vs **effectiveness**

- **Talk** vs **Pspace**
  - **Talk** (memory, bandwidth)
  - **Pspace**

- **Strong** vs **Weak**
  - **Strong**
  - **Weak**

- **Cheap** vs **Costly**
  - **Cheap**
  - **Costly**

- **Energy** vs **P(time)** (delay)
  - **Energy**
  - **P(time)** (delay)
Pspace

In use

Strong

Cheap

To make

$??

$50

1 TB < $100

1 TB = 1e12B

(use)

d.euJoJ

Ohc

Orr
What dominates tradeoffs

- Strong (memory, bandwidth)
- Pspace
- Cheap
- To make

- Weak
- Talk
- Costly
- Energy

P(time)
What dominates tradeoffs

![Diagram showing tradeoffs between time and energy. The x-axis represents energy, with 'Cheap' on one end and 'Costly' on the other. The y-axis represents time, with 'Fast' at the bottom and 'Slow' at the top.}
What dominates tradeoffs

Slow

Flexible

Costly

Fast

Inflexible

Cheap

Energy

time
What dominates tradeoffs
Computation
(on and off-line)

Slow

Fast

Flexible

General

Inflexible

Special

Decidable

Pspace

NP(time)

P(time)

analytic
Universal architecture

- Decidable
- Pspace
- Universal TM
- NP(time)
- P(time)
- analytic

- Flexible
- Inflexible
- General
- Special

- Slow
- Fast
Exploiting layered architecture

- Fast
- Slow
- Flexible
- Inflexible
- General
- Special

Apps
OS
HW
Core protocols

• OS seems to confuse
• Replace with “core protocols”?
• Examples different than OS or translation:
  – Core metabolism
  – 2 component signal transduction
• Highly conserved/constrained core (knot)
• Highly diverse/deconstrained edges
The image depicts a 3D graph with axes labeled 'slow', 'fast', 'efficient', 'flexible', 'inflexible', 'robust', and 'fragile'. The graph illustrates the relationship between these attributes, with 'robust' and 'fragile' being opposite ends of a spectrum, and 'slow' and 'fast', 'efficient' and 'waste' being additional dimensions.
The diagram represents a classification of systems along two dimensions: speed and flexibility. The x-axis indicates flexibility from general to special, while the y-axis indicates speed from slow to fast. The categories include:

- Apps
- OS
- HW
- Dig.
- Lump.
- Distrib.

Each category is situated in the appropriate quadrant according to the dimensions of speed and flexibility.
Horizontal Transfer

Deconstrained

Constrained

Deconstrained

Horizontal Transfer
Efficient
Robust
Evolvable

food

Blood
Glucose
Oxygen

Universal metabolic system

Organs
Tissues
Cells
Molecules
Efficient
Robust
Evolvable

Deconstrained

food

Constrained

Blood
Glucose
Oxygen

Deconstrained

Organs
Tissues
Cells
Molecules
Efficient
Robust
Evolvable

Deconstrained (Applications)

Constrained OS

Deconstrained (Hardware)

universal architectures

Deconstrained

Constrained

Diverse

Diverse

Diverse
Control feedback

Signal transduction

Metabolism

Products

ATP

DNA

New gene

Transcription

RNA

mRNA

Amino Acids

Ribosomes

Other Control

Proteins

Other Control

Metabolism

Fast Costly

Slow Cheap

Flexible

Metabolism
New gene

Transcription

mRNA

Translation

Amino Acids

Ribosomes

Proteins

Metabolism

Products

DNA

RNA

RNA polymerase (RNAP)

Signal transduction

Control feedback

Signal Transduction

ATP

Slow

Fast

Cheap

Costly

Flexible
Signal Transduction

DNA
New gene
Transcription
mRNA
Amino Acids
Ribosomes
Proteins
Metabolism
Products
ATP

control feedback

Slow
Cheap
Fast
Costly
Flexible
• ≈50 such “two component” systems in *E. Coli*
• All use the same protocol
  - Histidine autokinase transmitter
  - Aspartyl phospho-acceptor receiver
• Huge variety of receptors and responses
• Also multistage (phosphorelay) versions

**Signal transduction**
• “Name resolution” within signal transduction
• Transmitter must locate “cognate” receiver and avoid non-cognate receivers
• Global search by rapid, local diffusion
• Limited to very small volumes
Flow of “signal”

Ligands & Receptors

Recognition, specificity

Shared protocols

Ligands & Receptors

Transmitter

Receiver

Responses

Responses

Responses
Huge variety
- Combinatorial
- Almost digital
- Easily reprogrammed
- Located by diffusion

Recognition, specificity
Flow of “signal”

Limited variety
- Fast, analog (via #)
- Hard to change

Reusable in different pathways
Flow of “signal”

Ligands & Receptors

Shared protocols

Recognition, specificity

Flow of packets

Users

Internet sites

Note: Any wireless system and the Internet to which it is connected work the same way.
Layered Architecture

New gene

DNA

RNA

mRNA

Other Control

Amino Acids

Ribosomes

Proteins

Metabolism

Products

Signal transduction

ATP

HGT

DNA repair

Mutation

DNA replication

Transcription

Translation

Metabolism

Control

Fast
Costly

Flexible

Inflexible

Slow
Cheap
Biased random walk

Robust perfect adaptation in bacterial chemotaxis through integral feedback control

Tau-Mu Yi*, Yun Huang††, Melvin I. Simon*§, and John Doyle‡

PNAS | April 25, 2000 | vol. 97 | no. 9 | 4649–4653
More necessity and robustness

- Integral feedback and signal transduction (bacterial chemotaxis, G protein) (Yi, Huang, Simon)
- Example of “exploratory process”
Bacterial chemotaxis

Ligand → Motion → Motor

Random walk
Biased random walk

Ligand → Motion → Motor

Signal Transduction → CheY

gradient
Ligand

Motion

Motor

Signal Transduction

CheY
Ligand

Signal Transduction

Component of feedback controller

CheY

Motor

Motion
Ligand

Motion

Motor

CheY

Receptor

Transmitter

Receiver

Response

Component of feedback controller
From Taylor, Zhulin, Johnson

Variety of receptors/ligands

Common cytoplasmic domains

Common signal carrier

Common energy carrier

ENERGY TAXIS

C H E M O T A X I S

Aspartate

Ribose

PTS T A X I S

From Taylor, Zhulin, Johnson
Ligand

Motion

Motor

CheY

Variety of receptors & ligands

Transmitter

Receiver

Motor
Integral feedback internal to signaling network
Main feedback control loop

Integral feedback internal to signaling network
Biased random walk

Gradient

Ligand → Motion → Motor

Signal Transduction → CheY

Biased random walk

Gradient
Perfect adaptation is necessary …

Tumbling bias

Signal Transduction

CheYₚ

Motor

ligand
Perfect adaptation is necessary …

…to keep CheYp in the responsive range of the motor.
Tumbling bias
Integral feedback

\[ F(s) = \frac{\hat{F}(s)}{s}, \quad \hat{F}(0) < 0 \]

\[ F(0) = -\infty \]

\[ S(0) = 0 \]

\[ S \equiv \frac{y}{d} = \frac{1}{1 - F} \]
Variety of Ligands & Receptors

Transmitter

Receiver

Response

Aspartate
Ribose
Dipeptide

ENERGY TAXIS

CHROMATAXIS

PTS TAXIS

Enz1
Enz2
Man-6-P
Mannose
HPr
PEP

Aer
W
Trg
Tap
Layered architectures

Deconstrained (Applications) Diverse

Core Protocols

Constrained But hidden

Diverse Deconstrained (Hardware)

Apps

OS

HW
Next layered architectures (SDN)

Deconstrained (Applications)
Few global variables
Don’t cross layers

Constrained
Optimize & control, share, virtualize, manage resources

Deconstrained (Hardware)

Comms
Memory, storage
Latency
Processing
Cyber-physical
The essence of layering

Applications

Optimize & control, share, virtualize, manage resources

Optimize & control, share, virtualize, manage resources

Optimize & control, share, virtualize, manage resources

Physical resources
The essence of networking

Apps

Control

Control

Control

Physical

Physical

Physical

Virtual
Horizontal App Transfer

Apps

OS

Horizontal Hardware Transfer

HW

Fast

Flexible

General

Inflexible

Special

Slow
Layered Architecture

Any layer needs all lower layers.

Slow  Cheap

Fast  Costly

Flexible  Inflexible

General  Special

Apps          OS          OS          Digital
OS            HW          HW          Digital
HW            Digital     Lumped     Digital
Lumped        Lumped     Lumped     Lumped
0. **HGT**
1. DNA repair
2. Mutation
3. DNA replication
4. Transcription
5. Translation
6. Metabolism
7. Signal transduction
8. ...

Any layer needs all lower layers.
Sequence ~100 E Coli (not chosen randomly)
- ~4K genes per cell
- ~20K different genes in total (pangenome)
- ~1K universally shared genes
- ~300 essential (minimal) genes
Many systems/organisms only use lower layers.

Prefrontal

Learn

Motor

Fast Sense

Evolve

Reflex

Translation Metabolism

Signal

Lumped Distrib.

Distrib.

Flexible General

Inflexible Special

Slow

Fast

DNA repair

Mutation

HGT

DNA replication

Transcription

Apps

OS

OS

HW

HW

Dig.

Dig.

Digital

Lump.

Lump.

Lump.

Lump.

Distrib.

Distrib.

Distrib.

Distrib.

Many systems/organisms only use lower layers.
Many systems/organisms only use lower layers

- Motor
- Fast Sense
- Evolve
- Reflex

Most metazoans

Red blood cells
Normocephalic anucleosis

Metabolism
Signal

Analog

Lumped Distrib.  Distrib.
Most metazoans

Motor → Fast → Sense

Evolve → Reflex

Analog?
Many systems/organisms only use lower layers.

- Motor
- Fast Sense
- Evolve
- Reflex
- Metabolism
- Signal
- Analog
- Lumped Distrib. Distrib.

Most metazoans

Red blood cells

Normocephalic anucleosis
Normocephalic anucleosis

Denucleated neurons

*Megaphragma mymaripenne*

5 day lifespan
7,400 neurons
vs
housefly 340,000
honeybee 850,000.
Exploiting layered architecture

Meme

Horizontal Bad Meme Transfer

Fragility?

Virus

Horizontal Bad App Transfer

Parasites & Hijacking

Horizontal Bad Gene Transfer

Virus
Many human beliefs are:
- False
- Unhealthy
Many human beliefs are:
- False
- Unhealthy

Our greatest fragility?

- Masculinity
- Compassion