Universal laws and architectures

John Doyle
John G Braun Professor
Control and Dynamical Systems, EE, BE
Caltech
Turing on layering

The 'skin of an onion' analogy is also helpful. In considering the functions of the mind or the brain we find certain operations which we can explain in purely mechanical terms. This we say does not correspond to the real mind: it is a sort of skin which we must strip off if we are to find the real mind. But then in what remains we find a further skin to be stripped off, and so on. Proceeding in this way do we ever come to the 'real' mind, or do we eventually come to the skin which has nothing in it? In the latter case the whole mind is mechanical.

1950, Computing Machinery and Intelligence, Mind
“Universal laws and architectures?”

- Universal “conservation laws” (constraints)
- Universal architectures (constraints that deconstrain)
- Mention recent papers*
- Focus on broader context not in papers
- Lots of case studies for motivation

*try to get you to read them?
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.

Architecture, constraints, and behavior

John C. Doyle and Marie Csete

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.

Doyle, Csete, Proc Nat Acad Sci USA, JULY 25 2011
• Lots from cell biology
  – glycolytic oscillations for hard limits
  – bacterial layering for architecture
• Networking and “clean slate” architectures
  – wireless end systems
  – info or content centric application layer
  – integrate routing, control, scheduling, coding, caching
  – control of cyber-physical
  – PC, OS, VLSI, antennas, etc (IT components)
• Neuroscience
  – brains
  – neuroendocrine control
• Medical and exercise physiology
• Cell biology
• Networking & “clean slate” architectures
• Neuroscience
• Medical physiology
• Smartgrid, cyber-phys
• Wildfire ecology
• Earthquakes
• Lots of aerospace
• Physics:
  – turbulence,
  – stat mech (QM?)
• “Toy”:
  – Lego,
  – clothing,
  – buildings, ...
• Synesthesia
Existing design frameworks
- Sophisticated components
- Poor integration
- Limited theoretical framework

Fix?
Happy families are all alike; every unhappy family is unhappy in its own way.

Leo Tolstoy,
Anna Karenina,
Chapter 1, first line

• What could this mean? Given incredible diversity of people and environments?
• It has to be a statement about organization, and specifically architecture.
• Happy = empathy + cooperation + simple rules?

• Constraints on components and architecture
Requirements on systems and architectures

accessible accountable
accurate adaptable administrable
affordable audible autonomy
available credible process
capability compatible
configurable correctness
customizable debugable degradable
determinable demonstrable

dependable deployable discoverable
distributable durable effective
efficient evolvable extensible
failure transparent fault-tolerant
fidelity flexible inspectable
installable Integrity
interchangeable interoperable
reproducible resilient
responsive reusable
robust

manageable mobile modifiable
modular nomadic operable
orthogonality portable
precision predictable producible
provable recoverable
reliable repeatable
reproducible sustainable

reliable recoverable reusable
robust

safety scalable seamless
self-sustainable serviceable
supportable securable
simplicity stable
standards compliant
survivable sustainable
tailorabe testable timely
traceable ubiquitous
understandable usable
Simplified, minimal requirements

accessible  accountable  accurate  adaptable  administrable  affordable  auditable  autonomy  available  credible  process  capable  compatible  composable  configurable  correctness  customizable  debugable  degradable  determinable  demonstrable  dependable  deployable  discoverable  distributable  durable  effective  efficient  evolvable  extensible  failure  transparent  fault-tolerant  fidelity  flexible  inspectable  installable  Integrity  interoperable  interchangeable  interoperable  responsive  reusable  resilient  robust  manageble  mobile  modifiable  modular  nomadic  operable  orthogonality  portable  precision  predictable  producible  provable  recoverable  relevant  reliable  repeatable  reproducible  safety  scalable  seamless  self-sustainable  serviceable  supportable  securable  sustainable  simple  stable  standards  compliant  survivable  sustainable  tailorable  testable  timely  traceable  ubiquitous  understandable  usable  upgradable  usable
Requirements on systems and architectures

accessible accountable accurate adaptable administrable affordable auditable autonomy available credible process capable compatible composable configurable correctness customizable debugable degradable determinable demonstrable dependable deployable discoverable distributable durable effective manageable mobile modifiable modular nomadic operable orthogonality portable precision predictable producible provable recoverable relevant reliable repeatable reproducible resilient responsive reusable robust safety scalable seamless self-sustainable serviceable supportable securable sustainable standards compliant survivable tailorable testable timely traceable ubiquitous understandable understandable usable
Requirements on systems and architectures

- efficient
- simple
- sustainable
- resilient
- robust
Requirements on systems and architectures

- Efficient
- Robust
- Sustainable
- Simple

Diagram: 3D space with axes labeled "efficient", "robust", and "sustainable".
Requirements on systems and architectures

- Efficient
- Robust
- Simple
- Sustainable
- Fragile
- Resilient
- Wasteful
- Complex

Diagram showing the trade-offs between sustainability and resilience on one axis, efficiency and wastefulness on another, and simplicity and complexity on the third axis.
Requirements on systems and architectures

- Efficient
- Robust
- Simple
- Sustainable
- Fragile
- Wasteful

Diagram:

- Fragile vs. Robust
- Efficient vs. Wasteful
- Complex vs. Simple
Want to understand the space of systems/architectures

Want robust and efficient systems and architectures?

Case studies?

Strategies?

Architectures?

Hard limits on robust efficiency?
Resilient architectures are all alike; every brittle system is brittle in its own way.

Apologies to Tolstoy

- Resilience includes robustness, efficiency, sustainability, scalability, etc etc
- Effective architectures provide flexible tradeoffs across all these dimensions
- Subject to “laws” which are hard constraints on what is achievable
- Defer resolving terminology, focus on…
- Theorems and concrete case studies
Resilient architectures are all alike; every brittle system is brittle in its own way.

Good architecture =
“constrains that deconstrain”
(Gerhart and Kirschner)
The dangers of naïve biomemetics

Feathers and flapping?

Or lift, drag, propulsion, and \textit{control}?
“We know how to construct airplanes...” (lift and drag)
“... also know how to build engines.” (propulsion)
“When... balance and steer[ing]... has been worked out, the age of flying will have arrived, for all other difficulties are of minor importance.” (control)
Feathers and flapping? X

Lift, drag, propulsion, and *control*?
Universals?

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

Both

Accident or necessity?
Fire in the Earth System


Fire is a worldwide phenomenon that appears in the geological record soon after the appearance of terrestrial plants. Fire influences global ecosystem patterns and processes, including vegetation distribution and structure, the carbon cycle, and climate. Although humans and fire have always coexisted, our capacity to manage fire remains imperfect and may become more difficult in the future as climate change alters fire regimes. This risk is difficult to assess, however, because fires are still poorly represented in global models. Here, we discuss some of the most important issues involved in developing a better understanding of the role of fire in the Earth system.
Wildfires, complexity, and highly optimized tolerance

Max A. Moritz*, Marco E. Morais†, Lora A. Summerell‡, J. M. Carlson§, and John Doyle‖

*Department of Environmental Science, Policy, and Management, University of California, Berkeley, CA 94720; Departments of †Geography and §Physics, University of California, Santa Barbara, CA 93106; ‡Department of Earth Sciences, California Polytechnic State University, San Luis Obispo, CA 93407; and ‖Department of Control and Dynamical Systems, California Institute of Technology, Pasadena, CA 91125

Communicated by James S. Langer, University of California, Santa Barbara, CA, October 19, 2005 (received for review July 26, 2004)

Recent, large fires in the western United States have rekindled debates about fire management and the role of natural fire regimes in the resilience of terrestrial ecosystems. This real-world experience parallels debates involving abstract models of forest fires, a central metaphor in complex systems theory. Both real and modeled fire-prone landscapes exhibit roughly power law statistics in fire size versus frequency. Here, we examine historical fire catalogs and a detailed fire simulation model; both are in agreement with a highly optimized tolerance model. Highly optimized tolerance suggests robustness tradeoffs underlie resilience in different fire-prone ecosystems. Understanding these mechanisms may provide new insights into the structure of ecological systems and be key in evaluating fire management strategies and sensitivities to climate change.

Highly optimized tolerance (HOT) is a conceptual framework for examining organization and structure in complex systems (18). Theoretically, HOT builds on models and mathematics from physics and engineering, and identifies robustness tradeoffs as a principle underlying mechanism for complexity and power law statistics. HOT has been discussed in the context of a variety of technological and natural systems, including wildfires (18, 22). A quantitative prediction for the distribution of fire sizes has come from an extremely simple analytical HOT model, referred to as the PLR (probability–loss–resource) model (22). As a precursor to results presented later in this article, Fig. 2 demonstrates the PLR prediction and truncated power law statistics (23) for several fire history catalogs. This plot represents the raw data as rank or cumulative frequency of fires PLR greater than 1.
Wildfire ecosystem as ideal example

- Cycles on years to decades timescale
- Regime shifts: grass vs shrub vs tree
- Fire = keystone “specie”
  - Metabolism: consumes vegetation
  - Doesn’t (co-)evolve
  - Simplifies co-evolution spirals and metabolisms
- 4 ecosystems globally with convergent evo
  - So Cal, Australia, S Africa, E Mediterranean
  - Similar vegetation mix
  - Invasive species
At best we get one

Current Technology?
Often neither
Bad architectures?

- Fragile
- Robust
- Efficient
- Wasteful

- Gap?
- ?
- ?
- ?
Universal law?
Exponential improvement in efficiency $F$

$F = \text{Efficiency}$

http://phe.rockefeller.edu/Daedalus/Elektron/
When will lamps be 200% efficient?

Exponential improvement

Solving all energy problems?

\[ \log(F) \]

\[ F = \text{Efficiency} \]

Note: this is real data!

http://phe.rockefeller.edu/Daedalus/Elektron/
When will lamps be 200% efficient?

Oops… never.

\[
\frac{F}{1 - F}
\]

\[F = \text{Efficiency}\]

Note: need to plot it right.

http://phe.rockefeller.edu/Daedalus/Elektron/
$F \, \text{Efficiency}$

Doyle's law?

Exponential improvement

Steam Engines

$\log(F)$

$Lamps$

$F = \text{Efficiency}$

http://phe.rockefeller.edu/Daedalus/Elektron/
Universal law

\[ F = \text{Efficiency} \]
Universal law?

efficient

wasteful

100%
Some features robust to some perturbations

Other features or other perturbations
Case studies

Sharpen hard bounds

laws and architectures?

Hard limit

efficient

wasteful

fragile

robust
Control, OR Comms

Bode
Pontryagin
Kalman
Shannon

Nash
Von Neumann

Kalman

Theory?
Deep, but fragmented, incoherent, incomplete

Carnot
Boltzmann
Heisenberg
Einstein

Compute
Physics
Bad theory?

Bad architectures?

fragile

robust

efficient

wasteful

gap?
Find and fix bugs

Bad architectures?

Case studies

Sharpen hard bounds

fragile

wasteful
Compute

Turing (1912-1954)

• Turing 100\textsuperscript{th} birthday in 2012
• Turing
  – machine (math, CS)
  – test (AI, neuroscience)
  – pattern (biology)
• Arguably greatest*
  – all time math/engineering combination
  – WW2 hero
  – “invented” software

*Also world-class runner.
Key papers/results

• Theory (1936): Turing machine (TM), computability, (un)decidability, universal machine (UTM)
• Practical design (early 1940s): code-breaking, including the design of code-breaking machines
• Practical design (late 1940s): general purpose digital computers and software, layered architecture
• Theory (1950): Turing test for machine intelligence
• Theory (1952): Reaction diffusion model of morphogenesis, plus practical use of digital computers to simulate biochemical reactions
Fast and flexible

- Solve problems
- Make decisions
- Take actions

Fast vs. Slow
Flexible vs. Inflexible
Laws and architectures

- Fast
- Slow
- Flexible
- Inflexible

Architecture (constraints that deconstrain)

Laws (constraints)
Each theory \( \approx \) one dimension

- Tradeoffs *across* dimensions
- Assume architectures a priori
- Progress is encouraging, but...
- Stovepipes are an obstacle...
Control, OR

Compute
- Turing

Delay is most important
- Bode

Communicate
- Shannon

Delay is least important
- Carnot, Boltzmann, Heisenberg, Einstein

Physics
Control, OR

Compute

Turing

Delay is most important

Bode

Control, OR
Control, OR

Bode

important

most

Delay is

Turing

Compute
Turing as “new” starting point?

Control, OR Compute

Delay is *most* important

Bode

Software

Hardware

Digital

Analog

Turing
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

Turing as “new” starting point?
Who/what
Flexible

Solve problems
Make decisions
Take actions

General purpose
Large uncertainties
Diverse problems

Low latency/delay

Fast
Some features robust to some perturbations

Other features or other perturbations
Some features robust to some perturbations

Other features or other perturbations

Increased complexity?
<table>
<thead>
<tr>
<th>Robust</th>
<th>Modular</th>
<th>Simple</th>
<th>Plastic</th>
<th>Evolvable</th>
<th>and</th>
<th>Fragile</th>
<th>Distributed</th>
<th>Complex</th>
<th>Frozen</th>
<th>Frozen</th>
</tr>
</thead>
</table>

**Tradeoffs**
Modern technology gives lots of intermediate alternatives.
Want to emphasize the differences between these two types of layering.

Control, share, virtualize, and manage resources
What matters is the OS.
• Some people write apps and build hardware
• But most software and hardware is acquired by “horizontal” transfer from others
• Similarly, most new ideas (humans) and new genes (bacteria) are acquired horizontally
Why Necessity Compute Turing
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
• …being digital should be of greater interest than that of being electronic. That it is electronic is certainly important because these machines owe their high speed to this… But this is virtually all that there is to be said on that subject.
• That the machine is digital however has more subtle significance. … One can therefore work to any desired degree of accuracy.

1947 Lecture to LMS
• ... digital ... of greater interest than that of being electronic ...
• ... any desired degree of accuracy ...
• This accuracy is not obtained by more careful machining of parts, control of temperature variations, and such means, but by a slight increase in the amount of equipment in the machine.

1947 Lecture to LMS
Summarizing Turing:

- Digital more important than electronic…
- Robustness: accuracy and repeatability.
- Achieved more by internal hidden complexity than precise components or environments.

Turing Machine (TM)
- Digital
- Symbolic
- Logical
- Repeatable
• ... quite small errors in the initial conditions can have an overwhelming effect at a later time. The displacement of a single electron by a billionth of a centimetre at one moment might make the difference between a man being killed by an avalanche a year later, or escaping.

1950, Computing Machinery and Intelligence, Mind
• … quite small errors in the initial conditions can have an overwhelming effect at a later time.…

• It is an essential property of the mechanical systems which we have called 'discrete state machines' that this phenomenon does not occur.
• Even when we consider the actual physical machines instead of the idealised machines, reasonably accurate knowledge of the state at one moment yields reasonably accurate knowledge any number of steps later.

1950, Computing Machinery and Intelligence, Mind
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?)
Logic

Slow

Fast

time

large space

TM has $\infty$ memory

$\infty$ memory
Logic

∞ memory

TM has ∞ memory

space is free

large space

slow

time

fast
Decidable problem = ∃ algorithm that solves it

Most naively posed problems are undecidable.
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?)
2. **Universal architecture achieving hard limits (UTM)**

- Software: A Turing machine (TM) can be data for another Turing machine
- A Universal Turing Machine can run any TM
- A UTM is a virtual machine.
- There are lots of UTMs, differ only (but greatly) in speed and programmability (space assumed free)
The halting problem

- Given a TM (i.e. a computer program)
- Does it halt (or run forever)?
- Or do more or less anything in particular.
- Undecidable! There does not exist a special TM that can tell if any other TM halts.
- i.e. the program HALT does not exist. 😞
**Thm:** TM $H=\text{HALT}$ does not exist.

That is, there does not exist a program like this:

$$\begin{align*}
H(TM, input) \triangleq & \begin{cases} 
1 & \text{if } TM(input) \text{ halts} \\
0 & \text{otherwise}
\end{cases}
\end{align*}$$

**Proof** is by contradiction. Sorry, don’t know any alternative. And Turing is a god.
Thm: No such H exists.

Proof: Suppose it does. Then define 2 more programs:

\[ H'(TM, input) \triangleq \begin{cases} 1 & \text{if } H(TM, input) = 0 \\ \text{loop forever} & \text{otherwise} \end{cases} \]

\[ H*(TM) \triangleq H'(TM, TM) \]

Run \( H*(H*) = H'(H*, H*) \)

\[ = \begin{cases} \text{halt if } H*(H*) \text{ loops forever} \\ \text{loop forever otherwise} \end{cases} \]

Contradiction!
Implications

• Large, thin, nonconvex everywhere...
• TMs and UTMs are perfectly repeatable
• But perfectly unpredictable
• Undecidable: Will a TM halt? Is a TM a UTM? Does a TM do X (for almost any X)?
• Easy to make UTMs, but hard to recognize them.
• Is anything decidable? Yes, questions NOT about TMs.
Fast

Flexible/General

Undecidable

Really slow

Inflexible/Specific

Slow

Decidable

Flexible/General

Inflexible/Specific

Fast

Decidable

Really slow

Undecidable

Computational complexity
Space is powerful and/or cheap.
These are hard limits on the *intrinsic* computational complexity of *problems*.

Must still seek algorithms that achieve the limits, and architectures that support this process.
Computational complexity of:
- *Designing* control algorithms
- *Implementing* control algorithms

Delay is even more important in control

Control

Sense

Plant

Act

Digital

Analog

Software

Hardware
Slow Flexible

Fast Inflexible

Most UTMs here

Hopeless fragility

Unachievable robustness

Fast Inflexible

hard limits
Most UTMs here

- **Slow** Flexible
- **Fast** Inflexible

- Easy

Good architectures

hard limits

Impossible

Fast Inflexible
Issues for engineering

- Turing remarkably relevant for 76 years
- UTMs are \( \approx \) implementable
  - Differ only (but greatly) in speed and programmability
  - Time/speed/delay is most critical resource
  - Space (memory) almost free for most purposes
- Read/write random access memory hierarchies
- Further gradations of decidable (P/NP/coNP)

**Most crucial:**
- UTMs differ vastly in speed, usability, and programmability
- You can fix bugs but it is hard to automate finding/avoiding them
Issues for engineering

• Turing remarkably relevant for 76 years
• UTMs are \(\approx\) implementable
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**Most crucial:**

– UTMs differ *vastly* in speed, usability, and programmability
– You can fix bugs but it is hard to automate finding/avoiding them
Conjectures, biology

• Memory potential $\approx \infty$

• Examples
  – Insects
  – Scrub jays
  – Autistic Savants

• But why so rare and/or accidental?
• Large memory, computation of limited value?
• Selection favors fast robust action?
• Brains are distributed (not studied by Gallistel)
Control, OR
Communicate
Compute

Turing
Delay is most important

Bode

Shannon
Delay is least important

Carnot

Boltzmann

Heisenberg

Einstein

Physics
• Suppose we only care about space?
• And time is free
• Bad news: compression undecidable.
• Shannon: change the problem!
Shannon’s brilliant insight
• Forget time
• Forget files, use *infinite random ensembles*

Good news
• Laws and architecture!
• Info theory most popular and accessible topic in systems engineering
• *Fantastic* for some engineering problems
Shannon’s brilliant insight
• Forget time
• Forget files, use *infinite random ensembles*

**Bad news**
• Laws and architecture very brittle

• Less than zero impact on internet architecture
• Almost useless for biology (But see Lestas et al, 2010)
• Misled, distracted generations of biologists (and neuroscientists)
New progress!

Delay is *most* important

Compute

Turing

Communicate

Shannon

Delay is *least* important

Lowering the barrier

Control, OR

Bode

Physics

Heisenberg

Boltzmann

Carnot

Einstein
"Emergent": "Nontrivial" consequences of other constraints

Architecture = Constraints

Components

System

Protocols

UTM

TM

data
Components and materials:
Automata + $\infty$ memory

Systems requirements:
Algorithm to solve problem

Constraints

(Un)decidable

(data

UTM

TM

UTM

UTM

Components and materials:
Automata + $\infty$ memory
Universal architectures

What can go wrong?
Want to emphasize the differences between these two types of layering.
Diverse applications (HMT)

Physical

TCP
IP
App

IPC

Global and direct access to physical address!

DNS

IP addresses interfaces (not nodes)

131.215.9.49

caltech.edu?
IP addresses interfaces (not nodes)

Robust?
• Secure
• Scalable
• Verifiable
• Evolvable
• Maintainable
• Designable
• …
Naming and addressing need to have **scope** and
- 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?

Deconstrained (Applications)

Deconstrained (Hardware)

Constrained

TCP/IP

Facilitated wild evolution

Created

• whole new ecosystem

• completely opposite

Networked OS

• Expensive mainframes

• Trusted end systems

• Homogeneous

• Sender centric

• Unreliable comms
Cross-layer control
- Highly organized
- Naming and addressing

Coming later: contrast with cells
Next layered architectures

Deconstrained (Applications)

Constrained

Deconstrained (Hardware)

- 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")

Every layer has different diverse graphs.

Architecture is least graph topology.

Architecture facilitates arbitrary graphs.

TCP

IP

Physical
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, Nago 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 networks with no self-loops or parallel edges having the same graph degree sequence, we will say that graphs g ∈ G(D) have scaling-degree sequences...
Mathematics and the Internet: A Source of Enormous Confusion and Great Potential

Walter Willinger, David Alderson, and John C. Doyle
Who and what
Sequence ~100 E Coli (not chosen randomly)
- ~ 4K genes per cell
- ~20K different genes in total
- ~ 1K universally shared genes
- ~ 300 essential (minimal) genes

See slides on bacterial biosphere
Neuro motivation

Reflex

Fast
Inflexible
• Acquire
• Translate/integrate
• Automate

Thanks to Bassett & Grafton
Ashby & Crossley

- Acquire
- Translate/integrate
- Automate
Acquire
Translate/integrate
Automate

Build on Turing to show what is necessary to make this work.

Slow Flexible

Prefrontal

Motor Learning Striatum

Sensory

Fast Inflexible

Reflex
Turing architecture

- Slow
  - Flexible
- Fast
  - Inflexible

Software

Hardware

Digital

Analog

Hard limits?
Flexible

General purpose
Large uncertainties
Diverse problems

Solve problems
Make decisions
Take actions

Low latency/delay

Fast

Flexible
Human complexity

Robust

😊 Metabolism
😊 Regeneration & repair
😊 Healing wound /infect

Fragile

😢 Obesity, diabetes
😢 Cancer
😢 AutoImmune/Inflame

Start with physiology

Lots of triage
Benefits

Robust

😊 Metabolism
😊 Regeneration & repair
😊 Healing wound /infect

😊 Efficient
😊 Mobility
😊 Survive uncertain food supply
😊 Recover from moderate trauma and infection
Mechanism?

Robust

😊 Metabolism
😊 Regeneration & repair
😊 Healing wound /infect

😊 Fat accumulation
😊 Insulin resistance
😊 Proliferation
😊 Inflammation

Fragile

不得转载

😊 Obesity, diabetes
😊 Cancer
😊 AutoImmune/Inflame

😊 Fat accumulation
😊 Insulin resistance
😊 Proliferation
😊 Inflammation
What’s the difference?

Robust

😊 Metabolism
😊 Regeneration & repair
😊 Healing wound / infect

Fragile

😊 Fat accumulation
😊 Insulin resistance
😊 Proliferation
😊 Inflammation

-Controlled
-Dynamic

-Uncontrolled
-Chronic
Controlled Dynamic
Low mean
High variability

Fat accumulation
Insulin resistance
Proliferation
Inflammation
Controlled Dynamic
Low mean
High variability

Uncontrolled Chronic
High mean
Low variability

Death
Fat accumulation
Insulin resistance
Proliferation
Inflammation
Restoring robustness?

Robust

😊 Metabolism
😊 Regeneration & repair
😊 Healing wound /infect

😊 Fat accumulation
😊 Insulin resistance
😊 Proliferation
😊 Inflammation

Fragile

😊 Obesity, diabetes
😊 Cancer
😊 AutoImmune/Inflame

😊 Fat accumulation
😊 Insulin resistance
😊 Proliferation
😊 Inflammation

Controlled

Dynamic

Low mean
High variability

Uncontrolled

Chronic

High mean
Low variability
Human complexity

Robust

😊 Metabolism
😊 Regeneration & repair
😊 Immune/inflammation
😊 Microbe symbionts
😊 Neuro-endocrine

ığ Complex societies
ığ Advanced technologies
ığ Risk “management”

Yet Fragile

😊 Obesity, diabetes
😊 Cancer
😊 Autoimmune/Inflame
😊 Parasites, infection
😊 Addiction, psychosis,…

☠ Epidemics, war,…
bigintx Disasters, global &!%$#
bigpadl Obfuscate, amplify,…

Accident or necessity?
Robust

- Metabolism
- Regeneration
- Healing wound

Fragile

- Obesity, diabetes
- 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?
Some features robust to some perturbations

Other features or other perturbations
Increased complexity?

fragile

robust

Some features robust to some perturbations

Other features or other perturbations
Robust
Modular
Simple
Plastic
Evolvable

and

Fragile
Distributed
Complex
Frozen
Frozen

tradeoffs
Cyber-physical: decentralized control with internal delays.
Decentralized, but initially assume computation is fast and memory is abundant.
Plant is also distributed with its own component dynamics
Internal delays between components, and their sensor and actuators, and also externally between plant components
Going beyond black box: control is decentralized with internal delays.

Huge theory progress in last decade, year, mo., ...
The best case study so far

Layered architecture of the bacterial biosphere

Not done here in detail, see slides elsewhere
How?

Universal architectures
Modern technology gives lots of intermediate alternatives.
Want to emphasize the differences between these two types of layering.
What matters is the OS.
- Some people write apps and build hardware
- But most software and hardware is acquired by “horizontal” transfer from others
- Similarly, most new ideas (humans) and new genes (bacteria) are acquired horizontally
Slow Flexible

Fast Inflexible

Software
Hardware

Digital
Analog

Technology Evolution

Fast Inflexible
• Acquire
• Translate/integrate
• Automate

- Horizontal Meme Transfer
- Very Slow Process
- “Vertical” App Migration
- Fast Inflexible

- Slow Flexible
- Prefrontal
- Motor
- Sensory
- Striatum

- Reflex

- Reflex
Horizontal Meme Transfer

Sensory Learning

Prefrontal

Striatum

Reflex

Depends crucially on layered architecture

Flexible/Adaptable/Evolvable

Software

Hardware

Horizontal App Transfer

Digital

Analog

Horizontal Gene Transfer

ATP

Ribosome

RNAp

DNAp

Horizontal Meme Transfer

Gene

Replication

precursors

ATP

Depends crucially on layered architecture
Most
• software and hardware
• new ideas (humans)
• new genes (bacteria)

is acquired by “horizontal” transfer, though sometimes it is evolved locally
Exploiting layered architecture

Hijacking Parasites &

Horizontal Bad Meme Transfer

Fragility?

Virus

Horizontal Bad App Transfer

Virus

Horizontal Bad Gene Transfer
Build on Turing to show what is *necessary* to make this work.

- Acquire
- Translate/integrate
- Automate

**Horizontal Gene Transfer**

**Horizontal App Transfer**

**Horizontal Meme Transfer**

**Amazingly Flexible/Adaptable**

Depends crucially on layered architecture
Bode
Control

Delay is even more important

Compute
Turing

Universal laws and architectures

Slow Flexible
Software
Hardware
Digital
Analog

Fast Inflexible

Control
Sense
Plant
Act
Why

Necessity
\[ x_{t+1} = px_t + w_t + u_{t-a} \]

\[ p > 1 \]
No delay or no uncertainty

\[ u_{t-a} = -\left( px_t + w_t \right) \]

\[ \Rightarrow \|x\| \approx 0 \quad \|u\| \approx \|w\| \]

\[ x_{t+1} = px_t + w_t + u_{t-a} \]

\[ p > 1 \]
No delay or no uncertainty

\[ u_{t-a} = -(px_t + w_t) \]

\[ \Rightarrow \|x\| \approx 0 \quad \|u\| \approx \|w\| \]

With delay and uncertainty

\[ x_{t+1} = px_t + w_t + u_{t-a} \]

\[ \Rightarrow \|x\| \approx \|u\| \approx p^a \|w\| \]
Linearized pendulum on a cart

\[
\begin{bmatrix}
\dot{x} \\
\dot{\theta}
\end{bmatrix}
= \begin{bmatrix}
0 & 0 & \frac{1}{q} & 0 \\
0 & \frac{m^2 gl^2}{q} & 0 & 1 \\
0 & \frac{mgl(M + m)}{q} & \frac{-(J + ml^2)b}{q} & 0 \\
0 & \frac{ml}{q} & \frac{-mlb}{q} & 0
\end{bmatrix}
\begin{bmatrix}
x \\
\theta \\
\dot{x} \\
\dot{\theta}
\end{bmatrix}
+ \begin{bmatrix}
0 \\
0 \\
\frac{J + ml^2}{q} \\
\frac{ml}{q}
\end{bmatrix}u
\]

\[q = J(M + m) + Mml^2\]
\[(M + m) \ddot{x} + ml(\ddot{\theta} \cos \theta - \dot{\theta}^2 \sin \theta) = u\]
\[\ddot{x} \cos \theta + l\dot{\theta} + g \sin \theta = 0\]
\[y = x + \alpha l \sin \theta\]

linearize

\[(M + m) \ddot{x} + ml \dot{\theta} = u\]
\[\ddot{x} + l\dot{\theta} \pm g \theta = 0\]
\[y = x + \alpha l \theta\]
Robust
= agile and balancing
Robust
= agile and balancing
Efficient = length of pendulum (artificial)
\[
\begin{bmatrix} x \\ \theta \end{bmatrix} = \frac{1}{D(s)} \left[ \begin{array}{c} ls^2 \pm g \\ -s^2 \end{array} \right] u
\]

\[D(s) = s^2 \left( Ml s^2 \pm (M + m) g \right)\]

\[y = x + \alpha l \theta = \frac{\varepsilon ls^2 \pm g}{D(s)}\]

\[\varepsilon = 1 - \alpha\]

\[p = \sqrt{\frac{g}{l}} \sqrt{1 + r} \quad r = \frac{m}{M}\]

\[z = \sqrt{\frac{g}{l}} \sqrt{\frac{1}{\varepsilon}}\]

\[\begin{bmatrix} (M + m) \ddot{x} + ml \ddot{\theta} = u \\ \ddot{x} + l \ddot{\theta} \pm g \theta = 0 \end{bmatrix}
\]

\[y = x + \alpha l \theta\]
Delay $\tau$

$p \propto \sqrt{\frac{1}{l}}$

$|T(j\omega)| = \left| \frac{E}{N} \right|$
\[
\frac{1}{\pi} \int_{0}^{\infty} \ln |T(j\omega)| d\omega \geq 0
\]

Easy, even with eyes closed
No matter what the length

Proof: Standard UG control theory:
Easy calculus, easier contour integral, easiest Poisson Integral formula
Harder if delayed or short
Also harder if sensed low

\[ r = \frac{m}{M} \]
Delay $\tau$

$p \propto \sqrt{\frac{1}{l}}$

$|T(j\omega)| = \left| \frac{E}{N} \right|$
Delay $\tau$ is hard

\[
\frac{1}{\pi} \int_0^\infty \ln |T(j\omega)| \frac{2p}{p^2 + \omega^2} d\omega \geq \ln |T_{mp}(p)| = p\tau \propto \tau \sqrt{\frac{1}{l}}
\]
Delay $\tau$ is hard.

Any control problem is constrained by this inequality:

$$\frac{1}{\pi} \int_0^\infty \ln |T(j\omega)| \frac{2p}{p^2 + \omega^2} d\omega \geq \ln |T_{mp}(p)| = p\tau \propto \tau \sqrt{\frac{1}{l}}$$

This holds for any controller so is an intrinsic constraint on the difficulty of the problem.

The error in the system's output is given by:

$$|E| = \frac{E}{N}$$
\[
\frac{1}{\pi} \int_{0}^{\infty} \ln |T(j\omega)| \frac{2p}{p^2 + \omega^2} d\omega \geq p\tau \propto \tau \sqrt{\frac{1}{l}}
\]
\[
\frac{1}{\pi} \int_0^\infty \ln |T(j\omega)| \frac{2p}{p^2 + \omega^2} d\omega \geq p\tau \propto \tau \sqrt{\frac{1}{l}}
\]

We would like to tolerate large delays (and small lengths), but large delays severely constrain the achievable robustness.

large $\tau$  \hspace{1cm} small $\tau$

small $1/\tau$  \hspace{1cm} large $1/\tau$
Short is hard

\[
\frac{1}{\pi} \int_{0}^{\infty} \ln |T(j\omega)| \frac{2p}{p^2 + \omega^2} d\omega \geq \ln |T_{mp}(p)| = p\tau \propto \tau \sqrt{\frac{1}{l}}
\]
\[
\frac{1}{\pi} \int_0^\infty \ln |T(j\omega)| \frac{2p}{p^2 + \omega^2} d\omega \geq \ln |T_{mp}(p)| = p\tau \propto \tau \sqrt{\frac{1}{l}}
\]

Fragility

\[\tau \propto \frac{1}{\sqrt{l}}\]

Too fragile

Why oscillations?

Side effects of hard tradeoffs

For fixed delay

length L
The ratio of delay between people is proportional to the lengths they can stabilize.

\[
\frac{1}{\pi} \int_0^\infty \ln |T(j\omega)| \frac{2p}{p^2 + \omega^2} d\omega \geq \ln |T_{mp}(p)| = p\tau \propto \tau \sqrt{\frac{1}{l}}
\]
Eyes moved down is harder (RHP zero)
Similar to delay
Suppose \( r = \frac{m}{M} \ll 1 \)

Units \( \Rightarrow M = g = 1 \)

\[
y = x + \alpha l\theta = \frac{\varepsilon ls^2 \pm g}{s^2(\pm ls^2 \pm g)} \quad \varepsilon = 1 - \alpha
\]

\[
p \approx \sqrt{\frac{g}{l}} \quad z = \sqrt{\frac{g}{l}} \sqrt{\frac{1}{\varepsilon}} \Rightarrow \frac{z + p}{z - p} = \frac{1 + \sqrt{\varepsilon}}{1 - \sqrt{\varepsilon}}
\]
Compare
\[ p = \sqrt{\frac{g}{l(1-\varepsilon)}} \sqrt{1+r} = p_0 \sqrt{\frac{1}{1-\varepsilon}} \approx p_0 \left(1 + \frac{\varepsilon}{2}\right) \]

Move eyes
\[ p = \sqrt{\frac{g}{l}} \sqrt{1+r} \quad r = \frac{m}{M} \quad z = \sqrt{\frac{g}{l}} \sqrt{\frac{1}{\varepsilon}} \]
\[ p = z \Rightarrow 1+r = \frac{1}{\varepsilon} \Rightarrow \varepsilon = \frac{1}{1+r} \]
\[ p \left(1 + \frac{1}{3} p^2 \right) = \sqrt{\frac{g}{l}} \sqrt{1+r} \left(1 + \frac{1}{3} \varepsilon \right) = p \left(1 + \frac{\varepsilon}{3}\right) \]
\[ = p \left(1 + \frac{1-\alpha}{3}\right) \]
This is a cartoon, but can be made precise.
Hard limits on the *intrinsic* robustness of control problems.

Must (and do) have algorithms that achieve the limits, and architectures that support this process.

This is a cartoon, but can be made precise.
How do these two constraints (laws) relate?

\[ \frac{1}{\pi} \int_{0}^{\infty} \ln |S(j\omega)| \left( \frac{2z}{z^2 + \omega^2} \right) d\omega \geq \ln \left| \frac{z + p}{z - p} \right| \]
Delay comes from sensing, communications, computing, and actuation. Delay limits robust performance.

\[
\frac{1}{\pi} \int_0^\infty \ln |T(j\omega)| \frac{2p}{p^2 + \omega^2} d\omega \geq \ln |T_{mp}(p)| = p\tau \propto \tau \sqrt{\frac{1}{l}}
\]
How do these two constraints (laws) relate?

Computation delay adds to total delay.

Computation is a component in control.

This is about speed and flexibility of computation.
Delay makes control hard.

Computation delay adds to total delay.

Computation is a component in control.

\[
\frac{1}{\pi} \int_0^\infty \ln |T(j\omega)| \frac{2p}{p^2 + \omega^2} d\omega \geq p\tau \propto \tau \sqrt{\frac{1}{l}}
\]

Flexible

Inflexible

large \( \tau \)

small \( \tau \)

large delay

small delay

hard limits

computation
How general is this picture?

Bacteria

Phage

Bacteria
Phage lifecycle

- Multiply
- Survive
- Lyse
- Infect
Survive

fragile

fast

Robust

thick

big

Good architectures?

Hard limits?

Multiply

slow

thick small

Capsid Genome
Glycolytic Oscillations and Limits on Robust Efficiency

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

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

Chandra, Buzi, and Doyle

Most important paper so far.
Theorem!

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

\( z \) and \( p \) functions of enzyme complexity and amount

Fragility

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

Savageaumics

Enzyme amount

simple enzyme

complex enzyme
Hard tradeoff in glycolysis is
• robustness vs efficiency
• absent without autocatalysis
• too fragile with simple control
• plausibly robust with complex control

\[
\frac{1}{\pi} \int_0^\infty \ln |S(j\omega)| \left(\frac{z}{z^2 + \omega^2}\right) d\omega \\
\geq \ln \left|\frac{z + p}{z - p}\right|
\]
“Emergent”: “Nontrivial” consequences of other constraints

Architecture = Constraints

System

Protocols

Components
Systems requirements:
Survive in hostile environments

Components and materials:
“Chemistry”

Constraints
Components and materials:

“Chemistry”

Constraints

Constrained ("conserved"):
Moieties
1. NAD
2. Adenylate
3. Carbon
4. phosphate
5. oxygen
6. Oxidized state of metabolites
7. Reduced state of metabolites
8. High energy potential release
Bacterial biosphere
- carriers: ATP, NADH, etc
- Precursors, ...
- Enzymes
- Translation
- Transcription
- Replication
- ...

Architecture = protocols
= “constraints that deconstrain”
Catabolism

Genes

Co-factors

Proteins

Precursors

DNA replication

Trans*

Carriers

Components and materials:
Energy, moieties

Systems requirements:
functional, efficient, robust, evolvable

Hard constraints:
Thermo (Carnot)
Info (Shannon)
Control (Bode)
Compute (Turing)

Constraints

Protocols

Diverse

Universal Control

Diverse

Diverse

Components and materials:
Energy, moieties
Systems requirements: functional, efficient, robust, evolvable

**Constrained ("conserved"):**

Moieties
1. NAD
2. Adenylate
3. Carbon
4. phosphate
5. oxygen
6. Oxidized state of metabolites
7. Reduced state of metabolites
8. High energy potential release

Components and materials: Energy, moieties

Protocols

\[
\frac{1}{\pi} \int_{0}^{\infty} \ln |S(j\omega)| \left(\frac{z}{z^2 + \omega^2}\right) d\omega \\
\geq \ln \left| \frac{z + p}{z - p} \right|
\]
Inside every cell... almost

Catabolism

Precursors

Building Blocks

Crosslayer autocatalysis

ATP

AA

RNA

DNA

Enzymes

Proteins

Ribosome

RNAp

DNAP

Repl.

transc.

transl.

Gene

Macro-layers

ATP

Crosslayer autocatalysis
Yeast anaerobic glycolysis

Catabolism

Precursors → ATP

Energy

ATP

Rest of cell

energy

Minimal model
ATP

Autocatalytic feedback

Rest of cell

Minimal model

Yeast anaerobic glycolysis

Catabolism

Precursors

ATP

Reactions

Reaction 1 ("PFK")

Reaction 2 ("PK")

Intermediate metabolite

Energy
Robust = Maintain energy (ATP concentration) despite demand fluctuation

Tight control creates “weak linkage” between power supply and demand
Constrained ("conserved"): Moieties

1. NAD
2. Adenylate
3. Carbon
4. phosphate
5. oxygen

6. Oxidized state of metabolites
7. Reduced state of metabolites
8. High energy potential release

\[
\frac{1}{\pi} \int_{0}^{\infty} \ln |S(j\omega)| \left( \frac{z}{z^2 + \omega^2} \right) d\omega \geq \ln \left| \frac{z + p}{z - p} \right|
\]
Hard tradeoff in glycolysis

Fragile

Robust

Robust = Maintain energy (ATP concentration) despite demand fluctuation

disturbance

energy

ATP

Rest of cell
What makes this hard?
1. Instability (autocatalysis)
2. Delay (enzyme amount)
What makes this hard?

1. Instability
2. Delay

The CNS must cope with both

Today’s important point
enzyrnes catalyze reactions

Reaction 1 ("PFK")

Energy

ATP

Reaction 2 ("PK")

Rest of cell
Efficient = low metabolic overhead ≈ low enzyme amount
reaction rates \( \propto \) enzyme amount

Can’t make too many enzymes here, need to supply rest of the cell.

Efficient = low metabolic overhead
\( \approx \) low enzyme amount
(\( \Rightarrow \) slow reactions)
Robust = Maintain ATP

Efficient = low enzyme amount
(⇒ slow reactions)
Hard tradeoff in glycolysis is
- robustness vs efficiency
- absent without autocatalysis
- too fragile with simple control
- plausibly robust with complex control

\[
\frac{1}{\pi} \int_{0}^{\infty} \ln |S(j\omega)| \left( \frac{z}{z^2 + \omega^2} \right) d\omega \geq \ln \left| \frac{z + p}{z - p} \right|
\]
What (some) reviewers say

• “...to establish universality for all biological and physiological systems is **simply wrong**. It cannot be done..."

• ... a mathematical scheme **without any real connections to biological or medical...**

• ...universality is well justified in physics... for biological and physiological systems **...a dream that will never be realized**, due to the vast diversity in such systems.

• ...**does not seem to understand or appreciate** the vast diversity of biological and physiological systems...

• ... **a high degree of abstraction, which ...make[s] the model useless ...**
This picture is very general

fragile

complex tech

robust

simple tech

cheap

large delay $\tau$

fast multiply

metabolic expensive

small $\tau$

slow

### Domain specific costs/tradeoffs

<table>
<thead>
<tr>
<th></th>
<th>cheap</th>
<th>→</th>
<th>metabolic expensive</th>
</tr>
</thead>
<tbody>
<tr>
<td>metabolic overhead</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CNS reaction</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>time $\tau$ (delay)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>phage multiplication</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>rate</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- metabolic overhead: cheap ↔ metabolic expensive
- CNS reaction time $\tau$: large $\tau$ ↔ small $\tau$
- phage multiplication rate: fast multiply ↔ slow
This picture is very general

- fragile
- robust
- simple tech
- complex tech

- metabolic cost
- reaction time $\tau$
- phage x rate
- cheap ↔ expensive
- large $\tau$ ↔ small $\tau$
- fast ↔ slow

Domain specific costs/tradeoffs
fragile

Survive

fast multiply

slow

thin
small

thick
big

Capsid thickness
Genome size

Good architectures?

Hard limits?

fast multiply

slow
For fixed length

\[
\frac{1}{\pi} \int_{0}^{\infty} \ln |T(j\omega)| \frac{2p}{p^2 + \omega^2} d\omega \geq p\tau \propto \tau \sqrt{\frac{1}{l}}
\]
This is a cartoon, but can be made precise.
Hard tradeoff in glycolysis is
• robustness vs efficiency
• absent without autocatalysis
• too fragile with simple control
• plausibly robust with complex control

\[
\frac{1}{\pi} \int_0^\infty \ln |S(j\omega)| \left( \frac{z}{z^2 + \omega^2} \right) d\omega \geq \ln \left| \frac{z + p}{z - p} \right|
\]
Turing has the original “universal law”
Delay makes control hard.

Computation delay adds to total delay.

Computation is a component in control.

Fragility

$$\frac{1}{\pi} \int_{0}^{\infty} \ln |T(j\omega)| \frac{2p}{p^2 + \omega^2} d\omega \geq p\tau \propto \tau \sqrt{\frac{1}{l}}$$

Delay makes control hard.

Computation delay adds to total delay.

Computation is a component in control.
This needs formalization:

What **flexibility** makes control hard?

Large, structured uncertainty?

\[ \frac{1}{\pi} \int_{0}^{\infty} \ln|T(j\omega)| \frac{2p}{p^2 + \omega^2} d\omega \geq p\tau \propto \tau \sqrt{\frac{1}{l}} \]
What about: Cyber-physical: decentralized control with internal delays?
\[ x_{t+1} = px_t + w_t + u_{t-a} \]
\[ p > 1 \]

No delay or no uncertainty
\[ u_{t-a} = -\left( px_t + w_t \right) \]
\[ \Rightarrow \| x \| \approx 0 \quad \| u \| \approx \| w \| \]

With delay \textit{and} uncertainty
\[ \Rightarrow \| x \| \approx \| u \| \approx p^a \| w \| \]
Focus on delays

Actuator delay

\[ x_{t+1} = px_t + w_t + u_{t-a} \]

\[ p > 1 \]
Focus on delays

\[ a = \text{act} \]

Actuator delay
Decentralized control

t = transmission

0

l = internal

s = sense

p = plant

0

r = internal

a = act
\[ l + \left( p + a + s \right) + r \]

- \( l = \text{internal} \)
- \( r = \text{internal} \)
- \( s = \text{sense} \)
- \( a = \text{act} \)
- \( p = \text{plant} \)

**Total remote + plant delay**
Communications delay

\[ t = \text{transmission} \]
Then decentralized control design can be made \textit{convex}
A primary driver of human brain evolution?

Want
\[ t \leq (p + a + s) \]
\[ (a + s) \text{ small} \]
Wolpert, Grafton, etc

Brain as optimal controller

- Acquire
- Translate/integrate
- Automate

Reflex
Going beyond black box: control is decentralized with internal delays.

Huge theory progress in last decade, year, mo., ...
Decision-making components in the brain

Decentralized, but initially assume computation is fast and memory is abundant.
Plant is also distributed with its own component dynamics
Internal delays between brain components, and their sensor and actuators, and also externally between plant components
Internal delays involve both computation and communication latencies
This progress is important.
Going beyond black box: control is decentralized with internal delays.

Huge theory progress in last decade, year, mo., ...
Going beyond black box: control is decentralized with internal delays.

Mammal NS seems organized to reduce delays in motor control.
Universal architectures

Implications

(Layered architectures discussed elsewhere)
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

Turing as “new” starting point?
What matters is the OS.
Flexible/Adaptable/Evolvable

Horizontal Meme Transfer

Sensory

Prefrontal

Striatum

Learning

Reflex

Horizontal App Transfer

Software

Hardware

Digital

Analog

ATP

RN

xRNA

trans

Precursors

Catabolism

Nuc.

AA

Ribosome

RNAp

DNAp

Depends crucially on layered architecture

Gene

Rep

D

Horizontal Gene Transfer
Sequence ~100 E Coli (*not* chosen randomly)
- ~4K genes per cell
- ~20K *different* genes in total
- ~1K universally shared genes

See slides on microbial biosphere laws and architectures.
selection + drift + mutation + gene flow + facilitated variation

large functional changes in genomes

plasmid(s)

Horizonal Gene Transfer

HGT

virus
natural selection + genetic drift + mutation + gene flow
+ facilitated variation

Genome can have large changes
natural selection + genetic drift + mutation + gene flow
+ facilitated variation

Small gene change can have large but functional phenotype change

Architecture

Phenotype

Genotype

Selection acts on phenome

Stress acts on phenome
natural selection + genetic drift + mutation + gene flow + facilitated variation

Only possible because of shared, layered, network architecture

Architecture
Standard theory:
natural selection + genetic drift
  + mutation + gene flow

Greatly abridged cartoon here

Shapiro explains well what this is and why it’s incomplete (but Koonin is more mainstream)
Standard theory:

selection + drift + mutation + gene flow
Standard theory:
selection + drift + mutation + gene flow

No new laws.
No architecture.
No biology.
selection + 
drift + 
mutation + 
gene flow

Phenotype

Gene alleles

All complexity is emergent from random ensembles with minimal tuning. 

No new laws. 

No architecture.
The battleground

Pheno-type

No gap.
Just physics.

Huge gap.
Need supernatural

Gene alleles

Genes?
What they agree on

No new laws.
No architecture.
No biology.

Phenotype

No gap.

Gene alleles

Huge gap.

Genes
Depends crucially on layered architecture.
Putting biology back into evolution
Universal architectures

What can go wrong?
Unfortunately, not intelligent design

Ouch.
Why?

left recurrent laryngeal nerve
Why? Building humans from fish parts.

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

take sense

take move

Spine
Flexor Reflex

Pain receptor

Sharp tack

Alpha motor neurons

Excitatory interneurons

SN
Vestibulo-ocular reflex

1. Detection of rotation

2. Inhibition of extraocular muscles on one side.

2. Excitation of extraocular muscles on the other side

3. Compensating eye movement
Same actuators
Delay is limiting
Versus standing on one leg
- Eyes open vs closed
- Contrast
  - young surfers
  - old football players
delay = death

sense

move

Spine

Control Loop
Feed-Back Differential

Descending Neural Radiations to the Hippocampus/Thalamus/hypothalamus
Cerebral Cortex
Anterior Thalamic Nucleus
Cerebral Hemisphere
Olfactory Bulb
Visual Impulses
Hypothalamus
Pituitary Gland
Mamillary Body of Hypothalamus
Amygdaloid Nucleus
Auditory Impulses
Projection to Spinal Cord
Ascending Sensory Tracts
Ascending Neural Radiations to the Cortex
Corpus Callosum
Thalamus
Pineal Gland
Hippocampus
Cerebellum
Reflect

Reflex

Spine
Reflex
Reflect

move
Layered architectures (cartoon)

Cortex

Neurons

Neurons

Neurons

Cells

Physiology

Organs

Cells
Visual Cortex

Why?

Visual Thalamus

10x
What are the consequences?

There are 10x feedback neurons

10x

Why?

Visual Cortex

Visual Thalamus

Prediction

Goals

Actions

Conscious perception

errors

Prediction

Goals

Actions

Why?
Seeing is *dreaming*

Conscious perception

3D + time Simulation

Conscious perception

Zzzzzz……
Same size?
Same size
Same size

Toggle between this slide and the ones before and after

Even when you “know” they are the same, they appear different
Same size?

Vision: evolved for complex simulation and control, not 2d static pictures

Even when you “know” they are the same, they appear different
Seeing is *dreaming*

Conscious perception

3D + time
Simulation + complex models ("priors")

Conscious perception

Zzzzzz…..
Seeing is *dreaming*

Conscious perception

3D + time
Simulation + complex models ("priors")

Prediction

Conscious perception

Errors
Inferring shape from shading
Which blue line is longer?
Which blue line is longer?
Which blue line is longer?
Which blue line is longer?
Which blue line is longer?
Which blue line is longer?
Which blue line is longer?

With social pressure, this one.

Standard social psychology experiment.
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)
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 fuscatu*s 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. fuscatu*s 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.

P. fuscatius faces | Antenna-less faces | Rearranged faces

Patterns | Caterpillars | P. metricus faces

M J Sheehan, E A Tibbetts Science 2011;334:1272-1275
Human evolution

All very different.

How is this progress?
This much seems pretty consistent among experts regarding circa 1.5-2Mya Homo Erectus?

So how did H. Erectus survive and expand globally?

Efficient (slow)  

Roughly modern

Very fragile

Weak fragile

Strong robust

Hands  

Feet  

Skeleton  

Muscle  

Skin  

Gut
inefficient
wasteful
weak
fragile
efficient
(slow)
strong
robust
(fast)
endurance

speed & strength
Apes

Biology
Human evolution

weak
fragile
(slow)

strong
robust
(fast)

efficient
(slow)

inefficient
wasteful

Apes

Biology

hands
feet
skeleton
muscle
skin
gut
inefficient wasteful weak fragile efficient (slow) strong robust

Architecture? Evolvable?

Hard tradeoffs?

Apes

Biology
Speculation? There is only evidence for crude stone tools. But sticks, fire, teams might not leave a record?
Speculation? With only evidence for crude stone tools. But sticks and fire might not leave a record?

From weak prey to invincible predator

Before much brain expansion?

Plausible but speculation?
Cranial capacity

Before much brain expansion?

Gap?

Greatest brain size increase

Today

2Mya
Key point: Our physiology, technology, and brains have co-evolved. Probably true no matter what.
From weak prey to invincible predator

Before much brain expansion?

Key point needing more discussion: The evolutionary challenge of big brains is *homeostasis*, not basal metabolic load.

Huge implications.
inefficient wasteful

Architecture?

weak fragile

strong robust

efficient (slow)
inefficient wasteful

+ sticks

+ stones

+ fire

+ Technology

Biology
From weak prey to invincible predator

Before much brain expansion?

weak

fragile

strong

robust

hand
feet
skeleton
muscle
skin
gut

+ sticks
stones
fire

efficient
(slow)
weak fragile

strong robust

efficient (slow)

inefficient wasteful

Architecture?

Biology

+ Technology

+ sticks stones fire
Human complexity?

Consequences of our evolutionary history?

- fragile
- robust
- sticks
- stones
- fire

Biology

± Technology
Constraints (that deconstrain)

- Fragile
- Robust

- Efficient
- Wasteful

Hard tradeoffs?

Architecture?
>90% of most bacterial genomes
Unfortunately, we’re not sure how this all works.
Horizontal App Transfer

Horizontal Meme Transfer

Digital Analog

Horizontal Gene Transfer

Depends crucially on layered architecture

Flexible/Adaptable/Evolvable

Software Hardware

Reflex

Catabolism

Sensory Striatum

Learning

Gene Transfer

RN xRNA

ATP

DNAp

RNAp

Ribosome

RNAp

xRNA transd RN

ATP

Nuel AA

Precursors

Flexible/Adaptable/Evolvable
“New sciences” of “complexity” and “networks”?  

Science as  
- Pure fashion  
- Ideology  
- Political  
- Evangelical  
- Nontech trumps tech

- Edge of chaos  
- Self-organized criticality  
- Scale-free “networks”  
- Creation “science”  
- Intelligent design  
- Financial engineering  
- Risk management  
- “Merchants of doubt”  
- …
Theorem! 

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

\[ z \text{ and } p \text{ functions of enzyme complexity and amount} \]

Savageaumics

Fragility

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

simple enzyme

complex enzyme

Enzyme amount

Catalytic sites

Allinetic sites
Fragility

- General
- Rigorous
- First principle

Overhead, waste

- Domain specific
- Ad hoc
- Phenomenological

Plugging in domain details
**Control**

- Wiener
- Bode
- Kalman

**Comms**

- Shannon

**Physics**

- Heisenberg
- Boltzmann
- Carnot

- *Fundamental multiscale physics*
- *Foundations, origins of*
  - noise
  - dissipation
  - amplification
  - catalysis

- *General*
- *Rigorous*
- *First principle*
What I’m not going to talk much about

- It’s true that most “really smart scientists” think almost everything in these talks is nonsense
- Why they think this
- Why they are wrong

- Time (not space) is our problem, as usual
- Don’t have enough time for what is true, so have to limit discussion of what isn’t
- No one ever changes a made up mind (almost)
- But here’s the overall landscape
"New sciences" of complexity and networks edge of chaos, self-organized criticality, scale-free,...

Wildly “successful”

Control

Comms

Complex networks

Compute

Stat physics

Carnot

Boltzmann

Heisenberg

Physics
Popular but wrong
Complex systems?

Even small amounts can create bewildering complexity

Fragile

- Scale
- Dynamics
- Nonlinearity
- Nonequilibrium
- Open
- Feedback
- Adaptation
- Intractability
- Emergence
- ...

...
### Complex systems?

<table>
<thead>
<tr>
<th>Robust</th>
<th>Fragile</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Scale</td>
<td>• Scale</td>
</tr>
<tr>
<td>• Dynamics</td>
<td>• Dynamics</td>
</tr>
<tr>
<td>• Nonlinearity</td>
<td>• Nonlinearity</td>
</tr>
<tr>
<td>• Nonequilibrium</td>
<td>• Nonequilibrium</td>
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<tr>
<td>• Open</td>
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<td>• Feedback</td>
<td>• Feedback</td>
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<tr>
<td>• Adaptation</td>
<td>• Adaptation</td>
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<tr>
<td>• Intractability</td>
<td>• Intractability</td>
</tr>
<tr>
<td>• Emergence</td>
<td>• Emergence</td>
</tr>
<tr>
<td>• …</td>
<td>• …</td>
</tr>
</tbody>
</table>
Complex systems?

Robust complexity

- Scale
- Dynamics
- Nonlinearity
- Nonequilibrium
- Open
- Feedback
- Adaptation
- Intractability
- Emergence
- ...

- Resources
- Controlled
- Organized
- Structured
- Extreme
- *Architected*
- ...

These words have lost much of their original meaning, and have become essentially meaningless synonyms.
• e.g. nonlinear ≠ not linear

Can we recover these words?

Idea: make up a new word to mean “I’m confused but don’t want to say that”
• Then hopefully we can take these words back (e.g. nonlinear = not linear)

Fragile complexity

• Scale
• Dynamics
• Nonlinearity
• Nonequilibrium
• Open
• Feedback
• Adaptation
• Intractability
• Emergence
• …
New words

Emergulent

Emergulence at the edge of chaocritiplexity

Fragile complexity

- Scale
- Dynamics
- Nonlinearity
- Nonequilibrium
- Open
- Feedback
- Adaptation
- Intractability
- Emergence
- ...

Complex networks

Alderson & Doyle, Contrasting Views of Complexity and Their Implications for Network-Centric Infrastructure, IEEE TRANS ON SMC, JULY 2010

"New sciences" of complexity and networks
edge of chaos, self-organized criticality, scale-free,...
Complex systems?

Control

Comms

Complex networks

Compute

Stat physics

Jean Carlson, UCSB Physics

Carnot

Boltzmann

Heisenberg

Physics
Complex networks

Alderson & Doyle, Contrasting Views of Complexity and Their Implications for Network-Centric Infrastructure, IEEE TRANS ON SMC, JULY 2010

Control

Sandberg, Delvenne, & Doyle, On Lossless Approximations, the Fluctuation-Dissipation Theorem, and Limitations of Measurement, IEEE TRANS ON AC, FEBRUARY, 2011

Stat physics

Carnot

Boltzmann

Heisenberg

Physics
“The last 70 years of the 20th century will be viewed as the dark ages of theoretical physics.” (Carver Mead)

Complex networks

“orthophysics”

From prediction to mechanism to control

Sandberg, Delvenne, & Doyle, On Lossless Approximations, the Fluctuation-Dissipation Theorem, and Limitations of Measurement, IEEE TRANS ON AC, FEBRUARY, 2011

Stat physics, fluids, QM

Carnot

Boltzmann

Heisenberg

Physics
A streamwise constant model of turbulence in plane Couette flow

D. F. GAYME\textsuperscript{1}\textdagger, B. J. M\textsc{c}KEON\textsuperscript{1},
A. PAPACHRISTODOULO\textsc{u}\textsuperscript{2}, B. BAMIEH\textsuperscript{3}
AND J. C. DOYLE\textsuperscript{1}

Streamlined Laminar Flow

Transition to Turbulence
Increasing Drag, Fuel/Energy Use and Cost

Flow

Turbulence and drag?
Amplification and nonlinear mechanisms in plane Couette flow

Dennice F. Gayme,¹ Beverley J. McKeon,¹ Bassam Bamieh,² Antonis Papachristodoulou,³ and John C. Doyle³

Dennice Gayme,
Beverley McKeon,
Bassam Bamieh (UCSB ME),
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John Doyle
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Coherent structures and turbulent drag

high-speed region

upflow

3D coupling

low speed streak

Blunted turbulent velocity profile

Turbulent

Laminar
A diagram showing a graph with axes labeled 'efficient' and 'wasteful'. The graph transitions from Laminar to Turbulent with a dashed line indicating a transition point labeled 'Control?'. The diagram also includes labeled axes 'fragile' and 'robust'. The term 'fundamentals!' is mentioned in the top left corner of the image.
Existing design frameworks
- Sophisticated components
- Poor integration
- Limited theoretical framework

Fix?