Universals in complex, robust networks

Today’s focus on fundamentals

- Concepts: Complexity, robustness, and fragility
- Theory: Fundamental laws, constraints, tradeoffs
- Network architecture
- Illustrate with “simple” and familiar case studies

- Warm up with some (hopefully familiar) examples

John Doyle
John G Braun Professor
Control and Dynamical System, Electrical Engineering, BioEngineering
Caltech
My interests

Multiscale Physics

Core theory challenges

Sustainability?

Network Centric, Pervasive, Embedded, Ubiquitous

Systems Biology & Medicine
“Architecture”

- Most persistent, ubiquitous, and global features of organization
- Constrains what is possible for good or bad
- Platform that enables (or prevents) innovation, sustainability, etc.
- Existing architectures are unsustainable
- Internet, biology, energy, manufacturing, transportation, water, food, waste, law, etc.
- Theoretical foundation is fragmented, incoherent, incomplete
Infrastructure networks?

- Power
- Transportation
- Water
- Waste
- Food
- Healthcare
- Finance

All examples of “bad” architectures:
- Unsustainable
- Hard to fix

Where do we look for “good” examples?
Informative case studies in architecture

- Internet and related technology (OS)
- Systems biology (particularly, bacterial biosphere)
- System medicine and physiology
- Ecosystems (e.g. So Cal wildfire ecology)
- Aerospace systems
- Electronic Design Autom. (Platform Based Design)
- Multiscale physics (turbulence, stat mech)
- Misc: buildings/cities, Lego, clothing/fashion, barter/markets/money/finance, social/political
Simplest case studies

- Successful architectures
- Robust, evolvable
- Universal, foundational
- Accessible, familiar
- Unresolved challenges
- New theoretical frameworks
- Boringly retro?

Simplest case studies

Internet

Bacteria
- Universal, foundational
• Universal, foundational
Two lines of research:
1. Patch the existing Internet architecture so it handles its new roles

- Real time
- Control over (not just of) networks
- Action in the physical world
- Human collaborators and adversaries
- Net-centric *everything*
Ancient network architecture:
“Bell-heads versus Net-heads”
Modern theory and the Internet

### Levels of understanding

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### Topics

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## Recent progress (1995-)

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Architecture is *not* graph topology.

Architecture facilitates arbitrary graphs.
**Recent progress (1995-)**

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telephony

Diverse applications

TCP
IP

MAC Switch

MAC Pt to Pt

MAC Pt to Pt

Physical
Theoretical framework:
Constraints that deconstrain

Enormous progress
- Layering as optimization decomposition
- Optimal control
- Robust control
- Game theory
- Network coding

\[
\min_x \int \left( \|R\tilde{x} - c\|^2 + \|Rx - c\|^2 \right) dt \\
\tilde{x} = \arg\max_v L_v, p, \quad \dot{p} = Rx - c \\
\Rightarrow x_s = \arg\max_v L_s \quad v, p
\]
Theoretical framework:
Constraints that deconstrain

Enormous progress
- Layering as optimization
- Optimal control
- Robust control
- Game theory
- Network coding

- Many robustness issues left unaddressed
- Secure, verifiable, manageable, maintainable, etc
- Architecture/policy, not part of control/dynamics
- How to expand the theory?
Cyber-Physical Theories?

- Thermodynamics
- Communications
- Control
- Computation

- Same robustness issues still unaddressed
- Architecture/policy, not part of any of these
- Each assumes an architecture a priori
- How to expand the theory?
Cyber

- Thermodynamics
- Communications
- Control
- Computation

Internet

Bacteria

Case studies motivate integration
Cyber

• Thermodynamics
• Communications
• Control
• Computation

Physical

• Thermodynamics
• Communications
• Control
• Computation

Promising unifications

A start but more is needed
Two lines of research:
1. Patch the existing Internet architecture
2. Fundamentally rethink network architecture
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1. 
2. Fundamentally rethink network architecture
Biology versus the Internet

**Similarities**
- Evolvable architecture
- Robust yet fragile
- Constraints/deconstrain
- Layering, modularity
- Hourglass with bowties
- Feedback
- Dynamic, stochastic
- Distributed/decentralized
  - *Not* scale-free, edge-of-chaos, self-organized criticality, etc

**Differences**
- Metabolism
- Materials and energy
- Autocatalytic feedback
- Feedback complexity
- Development and regeneration
- >4B years of evolution
- How the parts work?
The dangers of naïve biomemetics

Feathers and flapping?

Or lift, drag, propulsion, and control?
“We know how to construct airplanes.” (lift and drag)
“Men also know how to build engines.” (propulsion)
“Inability to balance and steer still confronts students of the flying problem.” (control)
“When this one feature has been worked out, the age of flying will have arrived, for all other difficulties are of minor importance.”

Wilbur Wright on Control, 1901
Getting it right, 2010, Control++
Architecture, networks, robustness, and complexity

• Words we use all the time
• Often as their own antonym
• Thus potential sources of confusion
• Today: discuss a few basic ideas that seem necessary
• Illustrate with familiar examples
Biology versus the Internet

**Similarities**
- Evolvable architecture
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**Differences**
- Metabolism
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- Development and regeneration
- >4B years of evolution

Focus on bacterial biosphere
“Central dogma”

DNA → RNA → Protein

Network architecture?

From Pathways

Metabolic pathways

To Layers?
Recursive control structure

- Physical
  - Application
  - Error/flow control
  - Global
    - Relay/MUX
  - Local
    - Relay/MUX
    - E/F control
  - Physical

- Reactions
  - Flow
  - Protein level
  - RNA level
  - DNA level

Flow Reactions Protein level
Flow Reactions RNA level
Flow Reactions DNA level
In the real (vs virtual) world

What matters:
- Action

What doesn’t:
- Data
- Information
- Computation
- Learning
- Decision
- …
Two lines of research:
1. Patch the existing Internet architecture
2. Fundamentally rethink network architecture
Human complexity?

Robustness? Fragility?

Core theory challenges

Systems Biology & Medicine
Human complexity

Robust
😊 Metabolism
😊 Regeneration & repair
😊 Healing wound /infect

Fragile
😢 Obesity, diabetes
😢 Cancer
😢 AutoImmune/Inflame
Mechanism?

Robust
😊 Metabolism
😊 Regeneration & repair
😊 Healing wound /infect

Fragile
😊 Obesity, diabetes
😊 Cancer
😊 AutoImmune/Inflame

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

Robust

😊 Metabolism
😊 Regeneration & repair
😊 Healing wound /infect

Fragile

😊 Obesity, diabetes
😊 Cancer
😊 AutoImmune/Inflame

Fat accumulation
➢ Insulin resistance
➢ Proliferation
➢ Inflammation

Fluctuating energy

Accident or necessity?

Static energy
What’s the difference?

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Controlled Dynamic
- Low mean
- High variability

Uncontrolled Chronic
- High mean
- Low variability
Restoring robustness

Robust
- Controlled
- Dynamic
- Low mean
- High variability

Fragile
- Uncontrolled
- Chronic
- High mean
- Low variability
Human complexity

Robust

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

Yet Fragile

😊 Obesity, diabetes
😊 Cancer
😊 Parasites, infection
😊 AutoImmune/Inflame
😊 Addiction, psychosis…
확 Epidemics, war…
🔥 Catastrophes
🔥 Obfuscate, amplify,…

Accident or necessity?
• Fragility ← Hijacking, side effects, unintended…
• Of mechanisms evolved for robustness
• Complexity ← control, robust/fragile tradeoffs
• Math: New robust/fragile conservation laws

Both
Accident or necessity?
[a system] can have
[a property] **robust** for
[a set of perturbations]

Yet be **fragile** for

[a different property]

Or [a different perturbation]

Robust yet fragile = fragile robustness
A system can have a property robust for a set of perturbations. Robust yet fragile = fragile robustness. Apply recursively:

- [property] = robust for [one set of perturbations]
- [another property] or [another set of perturbations]

Robust yet fragile = fragile robustness
[a system] can have [a property] robust for [a set of perturbations]

• Some fragilities are inevitable in robust complex systems.

• But if robustness/fragility are conserved, what does it mean for a system to be robust or fragile?
• Some fragilities are inevitable in robust complex systems.

• But if robustness/fragility are *conserved*, what does it mean for a *system* to be robust or fragile?

• Robust *systems* systematically manage this tradeoff.
• Fragile *systems* waste robustness.
Definition: Resilience?

• Resilient systems effectively manage fragility tradeoffs?

• How does architecture facilitate resilience?
Robust

😊 Metabolism
😊 Regeneration & repair
😊 Healing wound /infect

- Fragility ← Hijacking, side effects, unintended...
- Of mechanisms evolved for robustness
- Complexity ← control, robust/fragile tradeoffs
- **Math: New robust/fragile conservation laws**
Mechanism?

Robust

😊 Metabolism
😊 Regeneration & repair
😊 Healing wound /infect

😢 Fat accumulation
😢 Insulin resistance
😢 Proliferation
😢 Inflammation

Controlled Dynamic

Low mean
High variability

Fluctuating energy
Organized complexity, circa 1972

Plumbing and chemistry

Mechanism?
Evolved for large energy variation and moderate trauma
Brain is crucial element.
signaling
gene expression
metabolism
lineage

source -> receiver

Biological pathways
A complex feedback system involving source, receiver, control, energy, materials, signaling, gene expression, metabolism, and lineage.
source

control

energy

materials

receiver

Autocatalytic feedback
What theory is relevant to these more complex feedback systems?
Architectures

- Case studies
  - Internet
  - Bacterial biosphere

- Principles, foundations

- Theory

Fun reading →
Architecture resources

- Networking
  - John Day, Patterns in Network Architecture
  - Content Centric (CCN, Xerox Parc, Jacobson)
  - Publish-Subscribe (PSIRP)
  - Lawyers: Zittrain, Choo

- Biology (many, but here’s a few)
  - Gerhart and Kirschner (the big picture)
  - De Duve (if you want to quickly learn biochemistry)
  - Zimmer (if you want to learn about bacteria)

- Systems
  - Donella Meadows
Applications

Client

Layered architecture

Router

Server

CPU/ Mem

Dev

Dev2

CPU/ Mem

Dev2

CPU/ Mem
Naming and addressing

• Names needed to locate objects
• 2.5 ways to resolve a name
  1. Exhaustive search, table lookup
  2. Name gives hints
• Extra $\frac{1}{2}$ is for indirection
• Address is just a name that involves locations
Operating systems

• OS allocates and shares diverse resources among diverse applications
• Clearly separate (disaster otherwise)
  – Application name space
  – Logical (virtual) name/address space
  – Physical (name/.) address space
• Name resolution within applications
• Name/address translation across layers
In operating systems:
Don’t cross layers

Direct access to physical memory?
Benefits of stricter layering

“Black box” effects of stricter layering
• Portability of applications
• Security of physical address space
• Robustness to application crashes
• Scalability of virtual/real addressing

• Optimization/control by duality?
Robust?
- Secure
- Scalable
- Verifiable
- Evolvable
- Maintainable
- Designable
- ...

Global and direct access to physical address!

IP addresses interfaces not nodes
Naming and addressing need to be
• resolved within layer
• translated between layers
• not exposed outside of layer

Related issues
• DNS
• NATS
• Firewalls
• Multihoming
• Mobility
• Routing table size
• Overlays
• …
Clean slate layering?

- Two “macrolayers” with a new, higher “waist”
  - Upper: Managing content, function, naming
  - Lower: Managing physical resources, addressing
- Lower layers: map to physical addresses (PNA)
  - Recursive “microlayers” of control and management
  - Different scopes (more global and lumped to more local and detailed)
  - No global addresses, hide details, addresses
- Cleaner role of optimization and control?
- Integration with naming and addressing
- Align robustness and security
Inside every cell

Catabolism

Precursors

AA

Nucl.

Building Blocks

ATP

Enzymes

Proteins

Ribosome

RNAP

DNAP

Crosslayer autocatalysis

ATP

AA transl.

RNA transc.

DNA Repl.

xRNA Gene
Lower layer autocatalysis
Macromolecules making ...

Three lower layers? Yes:
• Translation
• Transcription
• Replication

Enzymes

AA transl. Proteins
RNA transc. xRNA
DNA Repl. Gene
Ribosome
RNAp
DNAP
Autocatalytic within lower layers
- Collectively self-replicating
- Ribosomes make ribosomes, etc

Three lower layers? Yes:
- Translation
- Transcription
- Replication

Naturally recursive

DNA → Repl. → Gene → transc. → RNA → transl. → AA → transl. → Proteins

Enzymes

Ribosome → RNA → transc. → xRNA → RNA → transl. → AA → transl. → Proteins

RNA → transc. → xRNA → RNA → transl. → AA → transl. → Proteins

DNA → Repl. → Gene → transc. → RNA → transl. → AA → transl. → Proteins
Applications

Catabolism

Precursor

AA

Nucl.

Building Blocks

Enzymes

Proteins

Ribosome

xRNA

RNAp

Transl.

ATP

Building Blocks

Gene

Repl.

DNA

Layered architecture

Client

Server

Router

CPU/Mem

Dev

Dev

Dev

Dev
Meta-layering of cyber-phys control

Controller

Embedded virtual actuator/sensor

DIF

Network cable

Physical plant
In the brain:
Don’t cross layers

© Dale Purves and R. Beau Lotto 2002
Physiology

Meta-layers

Cortex

Prediction

Goals

Actions

errors

Physiology

Actions
From Information to “Outformation” to “Actformation”? 

Errors
Meta-layers

Cortex

Cortex

Cortex

Cells

Physiology

Organs

Cells
Maximize allowable fluctuations in 

Minimize resulting fluctuations in 

$SpO_2$

BP

(Evolution + physiology)

Maximize allowable fluctuations in 

Simple starting point.
Example design space: Speed versus efficiency
Complementary approaches

Find and fix bugs

Sharpen hard bounds
Standard theories are severely limited

- Each focuses on few dimensions
- Important tradeoffs are **across** these dimensions
- Speed vs efficiency vs robustness vs …
- Robustness is most important for complexity
- Need “clean slate” theories
- Progress is encouraging

![Diagram]

- Thermodynamics (Carnot)
- Communications (Shannon)
- Control (Bode)
- Computation (Turing)
Scientists have always relied on hypothesis and experimentation. Now, in the era of massive data, there’s a better way.

"All models are wrong, and increasingly you can succeed without them."
When will steam engines be 200% efficient?

Exponential improvement

$F = \text{Efficiency}$
When will steam engines be 200% efficient?

![Graph showing the efficiency of steam engines over time with efficiency equation F = 1 / (1 - F).]
**New words**

- **Peta-philia**: Perverse love of data and computation
- **Peta-fop**: Someone who profits from peta-philia
- **Exa-duhs**: Loss of clue from excessive peta-philia
Fortunately there seems to be a treatment not yet in widespread use.
Standard theories are severely limited

- Each focuses on few dimensions
- Important tradeoffs are across these dimensions
- Speed vs efficiency vs robustness vs …
- Robustness is most important for complexity
- Need “clean slate” theories
- Progress is encouraging

- Thermodynamics (Carnot)
- Communications (Shannon)
- Control (Bode)
- Computation (Turing)
Most dimensions are robustness

Collapse for visualization

Robust
• Secure
• Scalable
• Evolvable
• Verifiable
• Maintainable
• Designable
• …

Fragile
• Not …
• Unverifiable
• Frozen
• …

fragile
• Important tradeoffs are across these dimensions
• Speed vs efficiency vs robustness vs ...
• Robustness is most important for complexity
• Collapse efficiency dimensions
But many existing systems and architectures are clearly far from any fundamental limits.

So fixing “bugs” in existing architectures has most immediate impact.

Note: “log” suggests orders of magnitude variations.
What do we want from our systems/architectures?

• Efficient use of resources (sustainability)
  – Small consumed environmental resources and produced waste
  – Inexpensive components, small capital investment
  – Efficient processes: Design, manufacture, maintain, manage

• Robustness to perturbations
  – Reject external disturbance and suppress internal noise
  – Tolerate component failures and uncertainty
  – Secure against malicious attack and hijacking
  – Scalable to large system size
  – Evolvable on long time scales to large changes
  – Human actors have aligned incentives

• Predictable, Verifiable, Understandable
  – Limit unintended consequences
  – Experiments and data that are easily reproducible
  – Models (simple and analyzable), elegant theorems, short proofs
  – Experience that is reliable guide to the future

There are hard tradeoffs (laws) among/between these
Complexity in reality

• Illustrative examples can be bewildering
  – requires daunting domain details
  – dominated by (poorly understood) robustness tradeoffs
    *not* (more easily understood) minimal functionality

• Profound error/confusion
  – *within* mainstream science
  – even more confusion at policy level

• Lack of shared epistemologies
  – Even the most basic elements of discourse are in dispute
  – Nature of evidence, proof, statistics, valid argument,…
  – What is meant by “complexity, nonlinearity,…”
Case studies in efficiency, robustness, complexity

- Physiology/architecture/evolution
  - Bacteria
  - Human
  - Ecosystem

- Network architecture/evolution
  - Internet (comms and computing), cyberphys
  - Power, transportation, water, waste, etc...
  - Manufacturing, supply chain, ...
  - Markets, finance, economics, ...
  - Politics, sociology, religion, ...

- "Toy" examples: Lego, fashion, games, art, literature, ...
- Many popular toy models are (unfortunately) misleading
- Multiscale physics (stat mech, fluids, QM, ...
(Not) Shared Epistemologies

- Policy/politics
  - No consistent or coherent view of evidence, proof, etc
  - Ideologies/agendas (not surprising, but) frustrating
- Science (i.e. physics) of “complexity”
  - Dominates S&T input to policy and politics
  - Internally coherent, but shockingly political, ideological
  - But inconsistent with…
- Math, engineering, medicine and complexity
  - Surprisingly consistent epistemology
  - Yet fragmented and incoherent in details
  - No common language or coherent voice
  - Lose to ideologues with clear agendas
What we need to connect

• More integrated mathematics
• Real complex networks (Internet, smartgrid,...)
  – Function and structure
  – Architecture and control
• "New sciences?" (Complexity, networks, )
  – Creation science and intelligent design
  – Edge of chaos
  – Self-organized criticality
  – Scale-free
  – …
Complex systems?

Even small amounts can create bewildering complexity

Fragile

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

Even small amounts can create bewildering complexity
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Complex systems?

Robust complexity

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

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

...
Architecture

Robust complexity

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

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

...
New words

Emergulent

Emergulence at the edge of chaocritiplexity

Fragile complexity

- Scale
- Dynamics
- Nonlinearity
- Nonequilibrium
- Open
- Feedback
- Adaptation
- Intractability
- Emergence
- …
Danger: bad scholarship ahead

• Huge literatures going back a century (at least)
  – That I don’t know all that well (not my main research)
  – Bewildering amount of domain details
  – Persistent mysteries (and controversy)
  – Exist consistent, coherent components of the story
  – Even experts know only small fraction

• Large teams of collaborators (i.e. the real talent)

• Very “new” results
  – Not “written up” yet, just the slides you see (sort of)
  – Intended to be universal/accessible (but aren’t yet)
  – Illustrate principles beyond the domains
  – Pedagogy, not depth
Universals in complex, robust networks

Today’s focus on fundamentals

• Concepts: Complexity, robustness, and fragility
• Theory: Fundamental laws, constraints, tradeoffs
• Network architecture
• Illustrate with “simple” and familiar case studies

• Warm up with some (hopefully familiar) example