Macro Trends, Architecture, and the Hidden Nature of Complexity (and what does this have to do with SDN?)

\[ \int_0^\infty \ln |S(i\omega)| \, d\omega = \int_0^\infty \ln \left| \frac{1}{1 + L(i\omega)} \right| \, d\omega = \pi \sum Re(p_k) - \frac{\pi}{2} \lim_{s \to \infty} sL(s) \]

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http://www.1-4-5.net/~dmm/talks/macro_trends_complexity_and_sdn.pdf
Agenda

• Too many words, too many slides 😊
  – This talk is about thinking about SDN (and networking) in new ways

• A Couple of Macro Trends

• SDN Context: Problem Space and Hypothesis

• Complexity, Layered Architectures, and SDN

• A Perhaps Controversial View

• Summary and Q&A if we have time
Danger Will Robinson!!!

This talk might be controversial/provocative (and perhaps a bit “sciencey”)
Premise/Goal/Context of this Talk

• Clearly systems approaches to biology, medicine, engineering, and neuroscience face converging challenges

• Why?
  – Because modern science, technology, and culture create dauntingly complex but similar and overlapping problems in these domains → Convergent Evolution (a topic in and of itself)
  – SDN has given us a new tool with which to understand/experiment with network architectures

• Goal: To convince you that we are at a point in the history of network technology at which integrated theories (and methods) applicable to all complex networked systems, including the Internet/SDN, are needed, and that the approach we should take is to concentrate on the organizational principles of complex systems.

• High Level Ideas/Hard Problems
  – Provably hard tradeoffs
    • Initially Speed vs. Generality
  – Layering
    • Layering is a candidate universal architecture that seems to give us the ability engineer the speed/flexibility tradeoff
  – Horizontal Transfer (H*T)
    • HGT, HAT
  – BTW, why are there (necessarily) hard tradeoffs?
    • Top down requirements coupled with bottom up constraints (HW) → hard tradeoffs
    • Turing, Shannon and Bode, ...

• And how is all of this connected to SDN and the Internet?
A Couple of Macro Trends
Trend: The Evolution of Intelligence
R-complex (Reptilian Brain) to Neocortex → Hardware to Software

Key Architectural Features of Scalable/Evolvable Systems
- Turing, Bode, and Shannon
- RYF-Complexity (behavior)
- Layered Architecture
- Bowties and Hourglasses
- Horizontal Transfer (H*T)
- Protocol Based Architectures

Once you have HW, it's all about code...
Trend: Open Source (hardware *and* software)

- **Community building** is a core Open Source objective
- **Code** is the coin of the realm
- **Engineering systems** are as important as artifacts

*Putting this all together*
Trend: Engineering artifacts are no longer the source of sustainable advantage and/or innovation

Perhaps surprisingly, the “hyper-scale” and open source communities have taught us that actual artifacts (in our case network applications as well as HW/SW) are ephemeral entities and that the only source of sustainable advantage/innovation consists of

- Engineering Systems¹
- Culture
- People/Process
- Multi-disciplinary Approaches

¹ Note that our Engineering Systems evolve using the same mechanisms that are used to build artifacts. This is architecturally analogous to Horizontal Gene Transfer (HGT) and the acquisition of anti-bacterial resistance in the bacteria biosphere; the same mechanisms used to create the artifact (plasmid) are used to evolve the “Engineering System” (transcriptional network). Consider: Horizontal Application Transfer?
Coming to a Network Near You...

Trend: Deep Learning

Object Recognition/Invariant Representation ("Dog")

Increasingly Complex Features

Simple Inputs

Feature Detection (feedback inference)

Prediction (feedforward input)

\[ \sum x_i w_i \]

\[ net = \sum_{i=0}^{n} w_i x_i \]

\[ o = \sigma(net) = \frac{1}{1 + e^{-net}} \]

Input nodes layer

Hidden nodes layer

Output nodes layer
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Oh Yeah, This Talk Was Supposed To Have Something To Do With SDN

- Well then, what was the SDN problem space?

- Network architects, engineers and operators are being presented with the following challenge:
  - Provide state of the art evolvable network infrastructure and services while minimizing TCO
  - → better, faster, cheaper, choose 3?
  - Evolvability and scalability? Horizontal Application Transfer?

- **SDN Hypothesis**: It is the lack of ability to innovate in the underlying network coupled with the lack of proper network abstractions results in the inability to keep pace with user requirements and to keep TCO under control.
  - Is this true? Hold that question...

- **Note future uncertain**: Can’t “skate to where the puck is going to be” because curve is unknowable (this is a consequence, as we will see, of the “software world” coupled with Moore’s law and open-loop control).
  - That is, there is quite a bit of new research that suggests that such uncertainty is inevitable

- So given this hypothesis, what was the problem?
Maybe this is the problem?
Or This?
(Note Layering)

Many protocols, many touch points, few open interfaces or abstractions,..

Network is Robust *and* Fragile ⇒ The network is RYF-complex
BTW, Complexity Isn’t Inherently “Bad”

Increasing number of policies, protocols, configurations and interactions (well, and code)

Domain of the Robust

Domain of the Fragile

Biology and technology

A system needs complexity to achieve robustness
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Connecting Complexity, Design, and Robustness

“In our view, however, complexity is most succinctly discussed in terms of functionality and its robustness. Specifically, we argue that complexity in highly organized systems arises primarily from design strategies intended to create robustness to uncertainty in their environments and component parts.”

Robustness is a Generalized System Feature

• **Scalability** is robustness to changes to the size and complexity of a system as a whole

• **Evolvability** is robustness of lineages to large changes on various (usually long) time scales

• Other system features cast as robustness
  – **Reliability** is robustness to component failures
  – **Efficiency** is robustness to resource scarcity
  – **Modularity** is robustness to component rearrangements

• Not surprisingly, these are the same features we’re seeking from the network
Just so we’re all talking about the same things – a few definitions

• **Robustness** is the preservation of a certain property in the presence of uncertainty in components or the environment
  – Systems Biology: Biological systems are robust if their important functions are insensitive to the *naturally occurring variations* in their parameters
    • Limits the number of designs that can actually work in the real environment
    • Examples: Negative autoregulation and exact adaptation in bacterial chemotaxis

• **Fragility** is the opposite of robustness
  – Both need to be specified in terms of a system, a property and a set of perturbations

• A system can have a *property* that is *robust* to one set of perturbations and yet *fragile* for a *different property* and/or perturbation → the system is **Robust Yet Fragile**
  – Or the system may collapse if it experiences perturbations above a certain threshold (K-fragile)

• For example, a possible **RYF tradeoff** is that a system with high efficiency (i.e., using minimal system resources) might be unreliable (i.e., fragile to component failure) or hard to evolve
  – Another example: HSRP (VRRP) provides robustness to failure of a router/interface, but introduces fragilities in the protocol/implementation
  – Complexity/Robustness Spirals

• **Summary**: Software, and SDN in particular, creates all kinds of RYF tradeoffs
RYF Behavior is found everywhere

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

**Yet Fragile**
- Obesity, diabetes
- Cancer
- AutoImmune/Inflame
- Parasites, infection
- Addiction, psychosis,…
- Epidemics, war,…
- Disasters, global &!%$#
- Obfuscate, amplify,…

Accident or necessity?
Robust vs. Fragile

- Metabolism
- Regeneration
- Healing wound

Fragile

- Obesity, diabetes
- Fat accumulation
- Insulin resistance
- Proliferation
- Inflammation

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

Both

Accident or necessity?

Slide courtesy John Doyle
Summary: Understanding RYF is The Challenge

• It turns out that managing/understanding RYF behavior is the most essential challenge in technology, society, politics, ecosystems, medicine, etc. This means...
  – Understanding Universal Architectural Principles
  – Managing spiraling complexity/fragility
  – Not predicting what is likely or typical
    • But rather understanding what is catastrophic (fat tailed)
  – understanding the hidden nature of complexity

• BTW, it is much easier to create the robust features than it is to prevent the fragilities
  – With, as mentioned, poorly understood “conservation laws”
BTW, can we tell this story in a “Low Dimensional” space?

fragile

robust

efficient  wasteful
Example: Airline Security Architectures

Stopping hijacking

Secure cockpits*

$millions

0 deaths

Feasible Frontier

Theorem: $C \leq \frac{1}{R}$

Where are the SDN tradeoffs?

* do cheap things engineers recommend
Alternatives

Secure cockpits

Fragile

Cheap

Robust

Costly

$millions

0 deaths

Invade

Bomb

Drone strike

X-ray

$ trillions

??? deaths

Secure cockpits

Original slide courtesy John Doyle
Universal Laws and Architectures (Turing)
Layering, Formal Systems, Hard Tradeoffs

Original slide courtesy John Doyle
So What is Universal?

- Laws, constraints, tradeoffs
  - Robust/fragile
  - Efficient/wasteful
  - Fast/slow
  - Flexible/inflexible
- Architecture
- Hijacking, parasitism, predation

What tradeoffs are we making with SDN?
Architectures

• What we have learned is that there are *universal architectural building blocks* found in systems that *scale* and are *evolvable*. These include
  
  – Layered Architectures
  
  – Bowties and Hourglasses
  
  – Horizontal Transfer (H*T)
  
  – Protocol Based Architectures
  
  – Massively distributed with *robust* control loops
Layered architectures 101

Apps
OS
Hardware
  Digital
  Lumped
  Distributed

Operating System

Apps
OS
HW

SDN Controller/Network OS?

Slide courtesy John Doyle
Layered architectures

Deconstrained (Applications)
Diverse

Horizontal App Transfer

OS

H*T

Diverse Deconstrained (Hardware)

Horizontal HW Transfer

Apps

OS

HW

Slide courtesy John Doyle
Layered architectures

Minimal diversity and change

Apps

OS

HW

Slide courtesy John Doyle
Layered architectures

Deconstrained
(Applications)

Diverse

Horizontal
App
Transfer

Maximal diversity and change

Diverse
Deconstrained
(Hardware)

Horizontal
HW Transfer

Apps

OS

HW

Slide courtesy John Doyle
Layered architectures

Deconstrained (Applications)
Diverse

Core Protocols

Constrained and *hidden*

Diverse
Deconstrained (Hardware)
Overlaying Tradeoffs

- Fast vs. Slow
- Flexible vs. Inflexible
- General vs. Special

Apps

OS

HW

Unconstrained/Diverse
Constrained
Unconstrained/Diverse

Slide courtesy John Doyle
Layered Bacteria

Slow
Cheap

Fast
Costly

HGT
DNA repair
Mutation
DNA replication

Transcription
Translation

Metabolism
Signal...

Apps

General
Flexible

Inflexible
Special

Slide courtesy John Doyle
Universal Architectural Principles

- *Hourglasses* for layering of control
- *Bowties* for flows within layers
Bowties 101

Constraints that Deconstrain

Schematic of a “Layer”

For example, the reactions and metabolites of core metabolism, e.g., ATP metabolism, Krebs/Citric Acid Cycle, … form a “metabolic knot”. That is, ATP is a Universal Carrier for cellular energy.

1. Processes L-1 information and/or raw material flows into a “standardized” format (the L+1 abstraction)
2. Provides plug-and-play modularity for the layer above
3. Provides robustness but at the same time fragile to attacks against/using the standardized interface
4. H*T

But Wait a Second
(Can we apply this to the Internet?)

The Nested Bowtie/Hourglass Architecture of the Internet

Layering of Control

HTTP Bowtie
Input: Ports, Datagrams, Connections
Output (abstraction): REST

TCP/UDP Bowtie
Input: IP Packets
Output (abstraction): Ports, Datagrams, Connections

Flowing within Layers
NDN Hourglass

See Named Data Networking, http://named-data.net/
Layered architectures make robustness and Evolvability compatible.
Of Course, in Practice Things are More Complicated
The Nested Bowtie/Hourglass Architecture of Metabolism

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OF/SDN is One Point in a Larger Design Space

• But not the only one

• The larger space includes
  – Compute, Storage, and Network Programmability
  – Security and Energy

• My model: “SDN continuum”
  – http://www.ietf.org/id/draft-haleplidis-sdnrg-layer-terminology-03.txt
A Simplified View of the SDN Continuum

Service Layers

Apps

Control and Orchestration
(overly simplified view)

Apps

May be repeated
(stacked or recursive)

Physical and Virtual Resources
(CSNSE)

FP/SDN
Properties:
-- Complete Separation of CP and FP
-- Centralized Control
-- Open Interface/programmable Forwarding Plane
-- Examples: OF, ForCES, various control platforms

CP/SDN
Properties:
-- Retains existing (distributed) Control Planes
-- Programmable control plane
-- Examples: PCE, I2RS, BGP-LS, vendor SDKs

OL/SDN
Properties:
-- Retains existing (simplified) Control Planes
-- Programmable overlay control plane
-- Examples: Various Overlay technologies

HAT
Bowties/Hourglasses?

- OF/SDN?
- CP/SDN makes existing control planes programmable
- OL/SDN is an application *from the perspective of the Internet’s waist*
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So The Future: Where’s it All Going?
But More Seriously....

*Current Events*
- ONF: Table Typing Patterns (TTPs)
- IETF: Model Driven Everything (I2RS, ...)
- Everyone else (ETSI NFV, Cablelabs, ...)
- Open Source/*Everything*
  - [http://www.opendaylight.org](http://www.opendaylight.org)
  - [http://www.openstack.org](http://www.openstack.org)
  - [http://opencompute.org/](http://opencompute.org/)

*High Order Bit:*
- System(s) we’re building are inherently uncertain → cloudy crystal balls
- Architect for change and rapid evolution – see XP/Agile methodologies for a clue
- *Increasing roles for s/w and programmability + Moore’s law → volatility/uncertainty*
- Lucky thing for many of us: we work primarily around the narrow waist, most stable place to be
- “Above the waist” characterized by uncertainty, e.g., [http://spotcloud.com/](http://spotcloud.com/)

*Conventional Technology Curves – S & F*
- Moore’s Law and the reptilian brain
  - Someone eventually has to forward packets on the wire
- 400G and 1.2 T in the “near” term
- Silicon photonics, denser core count, ....

*The future is all about Software Ecosystems*
- Open Interfaces: Protocols, APIs, Code, Tool Chains
- Open Control Platforms at every level
- “Best of Breed” markets

*Theoretical Frameworks*
- Systems thinking
Where To From Here?

• Robust systems “might be” intrinsically hard to understand
  – RYF complexity is an inherent property of advanced technology
  – Software (e.g., SDN, NFV, Cloud, ...) exacerbates the situation
  – And the Internet has reached an unprecedented level of complexity...

• Nonetheless, many of our goals for the Internet architecture revolve around how to achieve robustness...
  – which requires a deep understanding of the necessary interplay between complexity and robustness, modularity, feedback, and fragility¹
    • which is neither accidental nor superficial
  – Rather, architecture arises from “designs” to cope with uncertainty in environment and components
  – The same “designs” make some protocols hard to evolve
  – Does SDN help or hurt, and can we build formal models that help us reason about “universal laws”?

• Understanding these universal architectural features will help us achieve the scalability and evolvability (operability, deployability, understandability) we’re seeking from the Internet architecture today and going forward
  – Multi-disciplinary approaches provide a template of how we might go about this (e.g., Systems Biology)

• BTW – SDN ~ DDN (DevOPs Defined Networking)
  –  http://www.slideshare.net/mestery/next-gennetworkengineerskills

¹ See Marie E. Csete and John C. Doyle, “Reverse Engineering of Biological Complexity”, http://www.cds.caltech.edu/~doyle/wiki/images/0/05/ScienceOnlinePDF.pdf
Q&A

Thanks!