On the Complexity of Designed Systems
(and its effect on technology deployment)

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http://www.iab.org/activities/workshops/itat
dmm@{brocade.com,uoregon.edu,1-4-5.net,...}
http://www.1-4-5.net/~dmm/talks/itat2013.pdf (talk)
http://www.1-4-5.net/~dmm/papers/itat.pdf (position paper)

Agenda

- Premise of this Talk
- Connecting Complexity, Design, and Robustness
- Universal Principles
- A Few Conclusions and Q&A if we have time
- Appendix -- One Approach to understanding Complex Systems

Premise of this Talk

Much of the difficulty that we have had in modifying certain protocols, in particular those that reside in a waist or knot structure in an architecture, is actually "by design". That is, the difficultly we have had in deploying a protocol that significantly modifies a “waist protocol”, IP for example, is an important consequence of robust network design.

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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****.***"

See Alderson, D. and J. Doyle, "Contrasting Views of Complexity and Their Implications For Network-Centric Infrastructures", IEEE TRANSACTIONS ON SYSTEMS, MAN, AND CYBERNETICS—PART A: SYSTEMS AND HUMANS, VOL. 40, NO. 4, JULY 2010

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
- Of course, these are the same features we're seeking from the network

BTW, on "Evolvability"

- **Robustness** of lineages to large changes on long timescales
- Essentially an ***architectural*** question
  - What makes an architecture evolvable?
  - What does "architecture" mean here?
- What are the limits on evolvability?
- How does architecture, evolvability, robustness, and complexity relate?

- Key: tradeoffs, robustness, layering

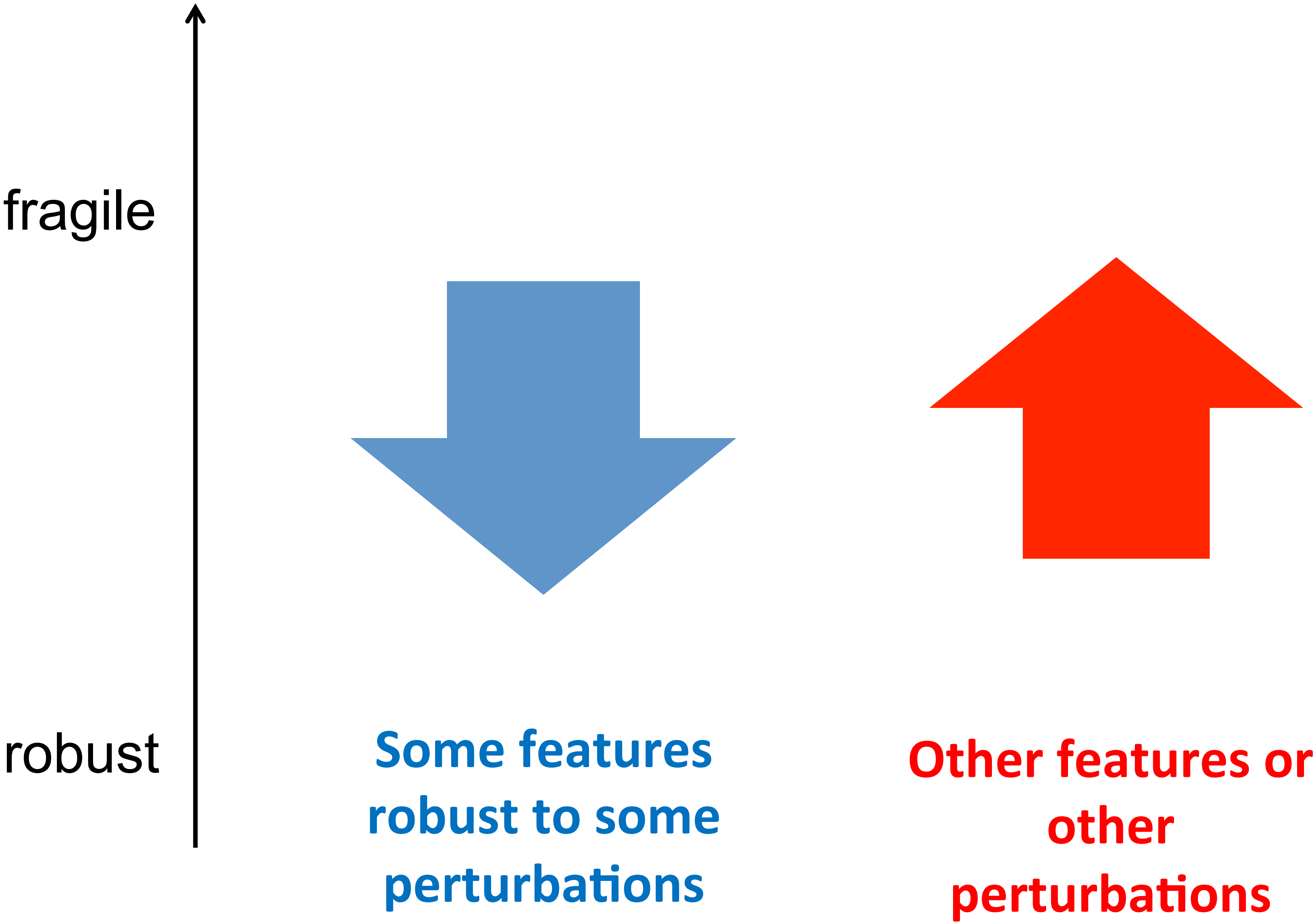
Just so we're all talking about the same things – a few definitions

- **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

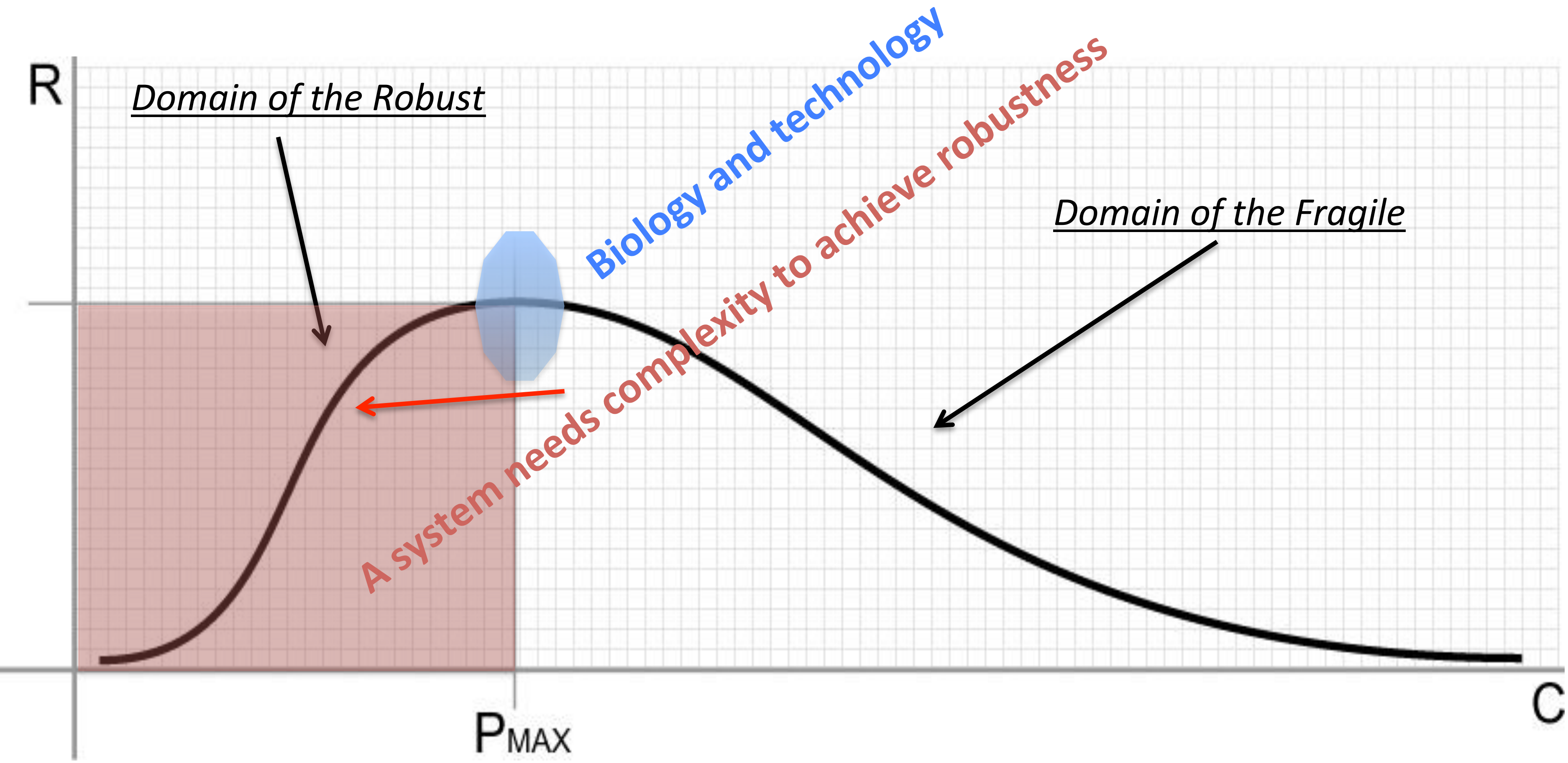
- A system can have a *property* that is *robust* to one set of perturbations and yet *fragile* for a *different property* and/or perturbation → the system is ***Robust Yet Fragile***
  - Or the system may collapse if it experiences perturbations above a certain threshold (K-fragile)

- 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: VRRP provides robustness to failure of a router/interface, but introduces fragilities in the protocol/implementation
    - Complexity/Robustness Spirals



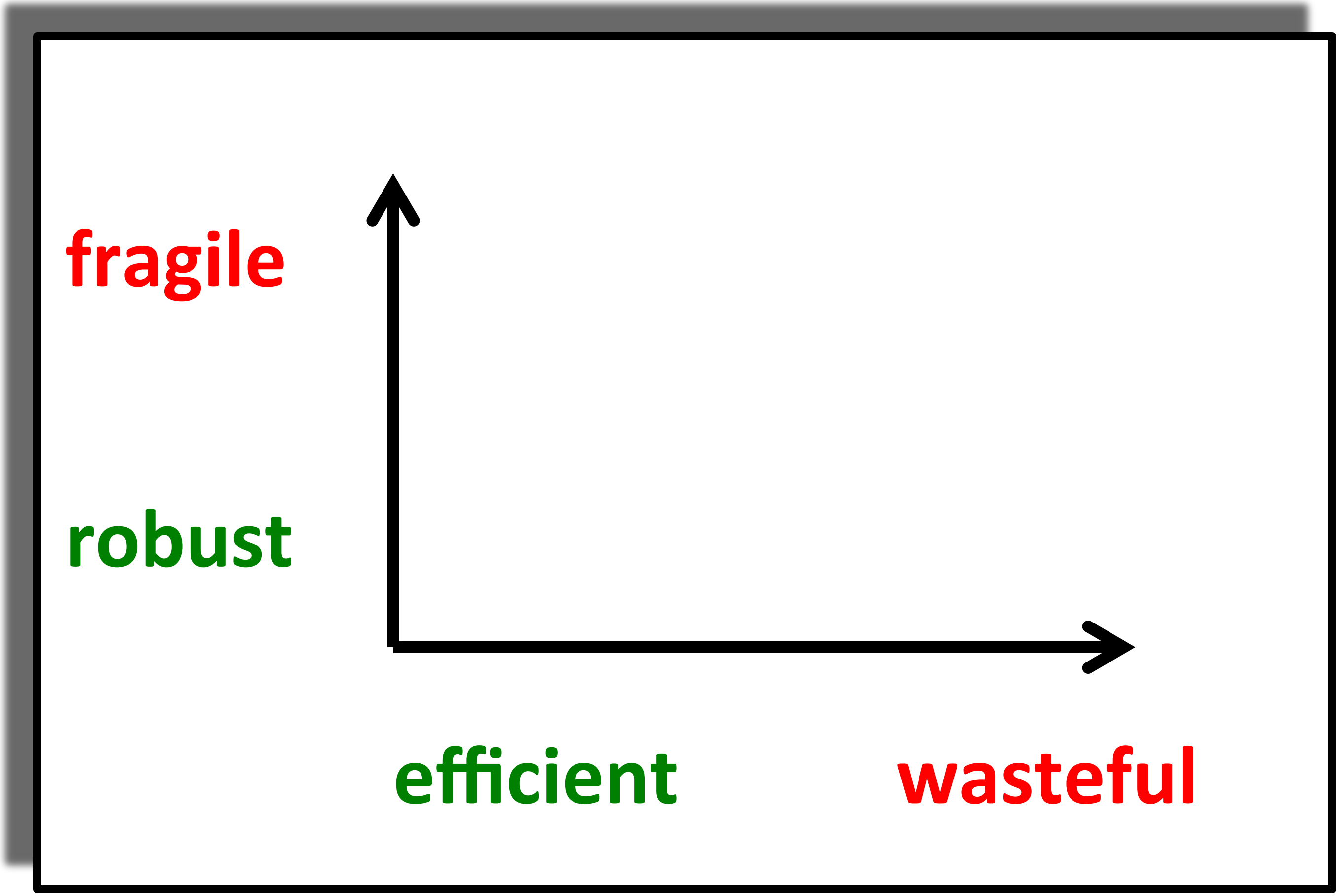
Slide courtesy John Doyle

BTW, Complexity Isn't Inherently "Bad"



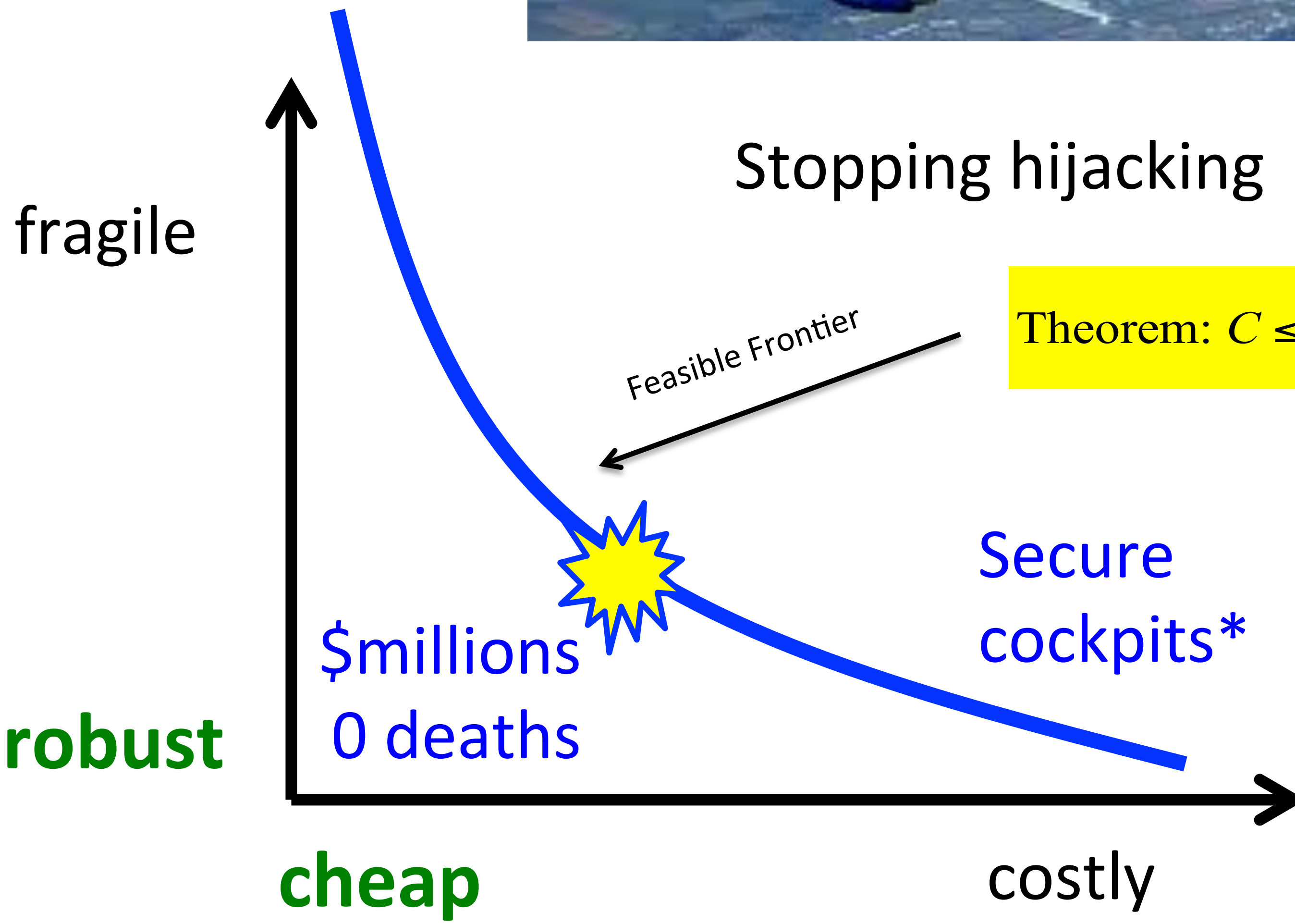
Increasing number of policies, protocols, configurations and interactions (well, and code)

Can we model the RYF tradeoff space as simple dichotomous pairs?



Slide courtesy John Doyle

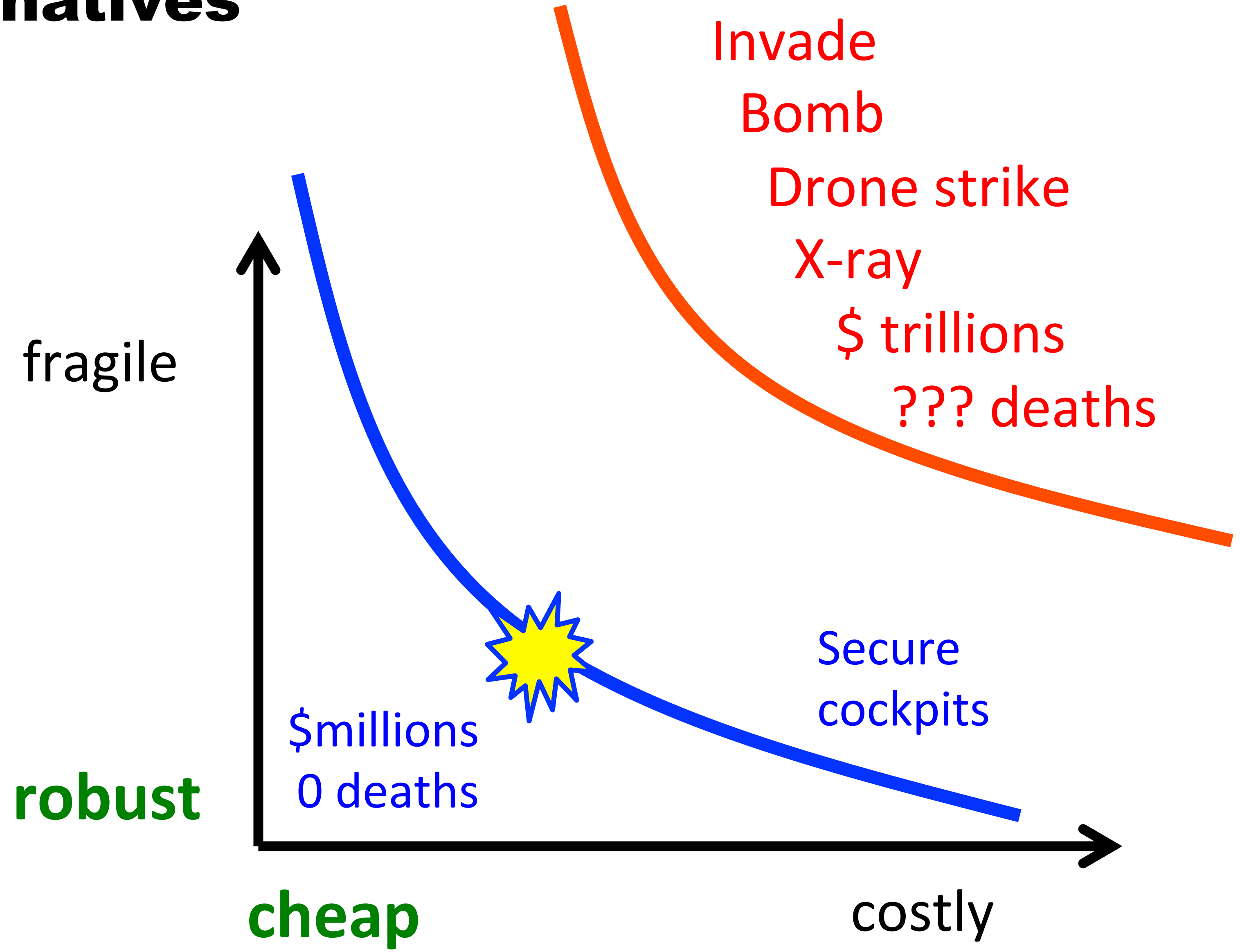
Example: Airline Security Architectures



* do cheap things engineers recommend

Original slide courtesy John Doyle

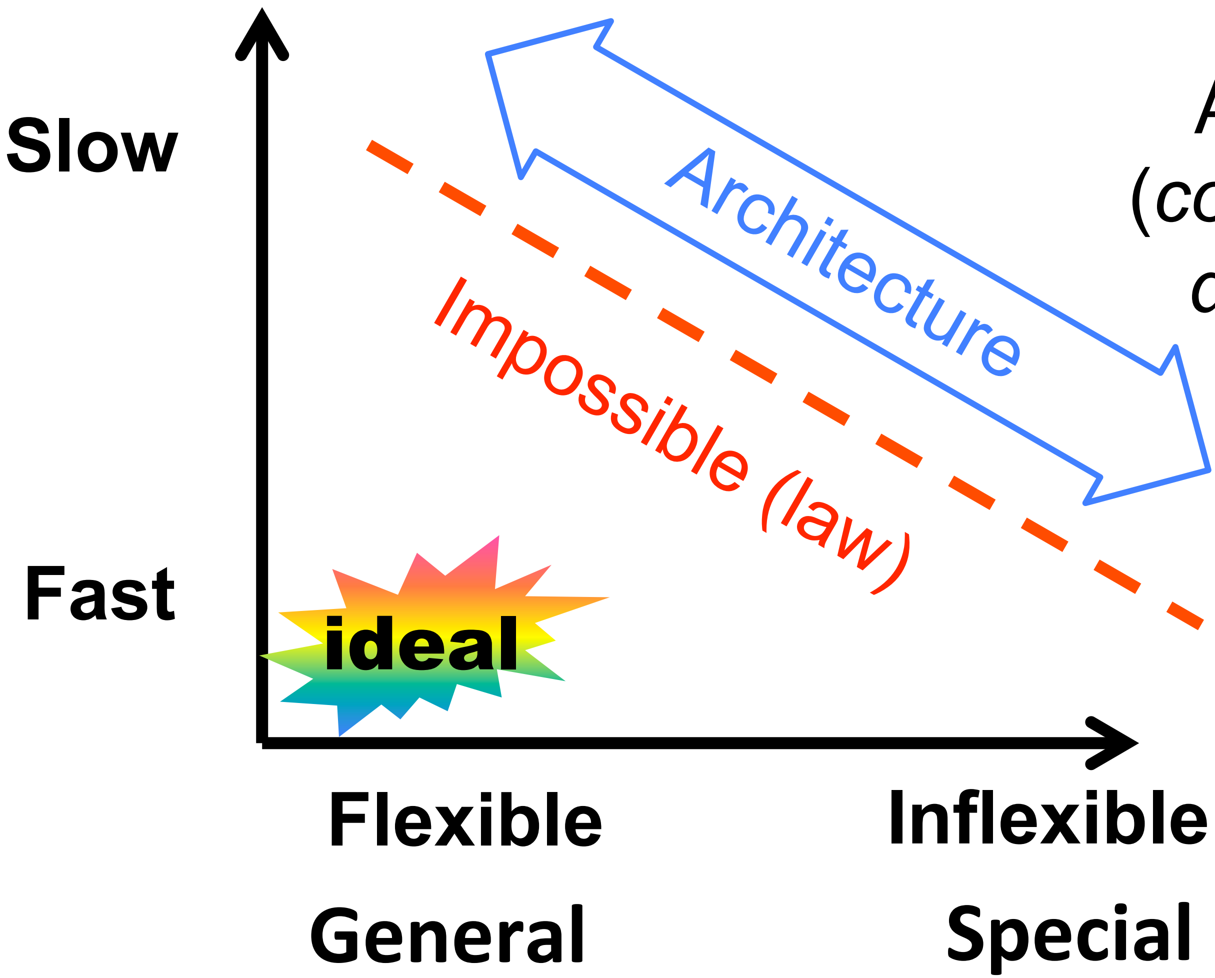
Alternatives



Original slide courtesy John Doyle

Computability Perspective

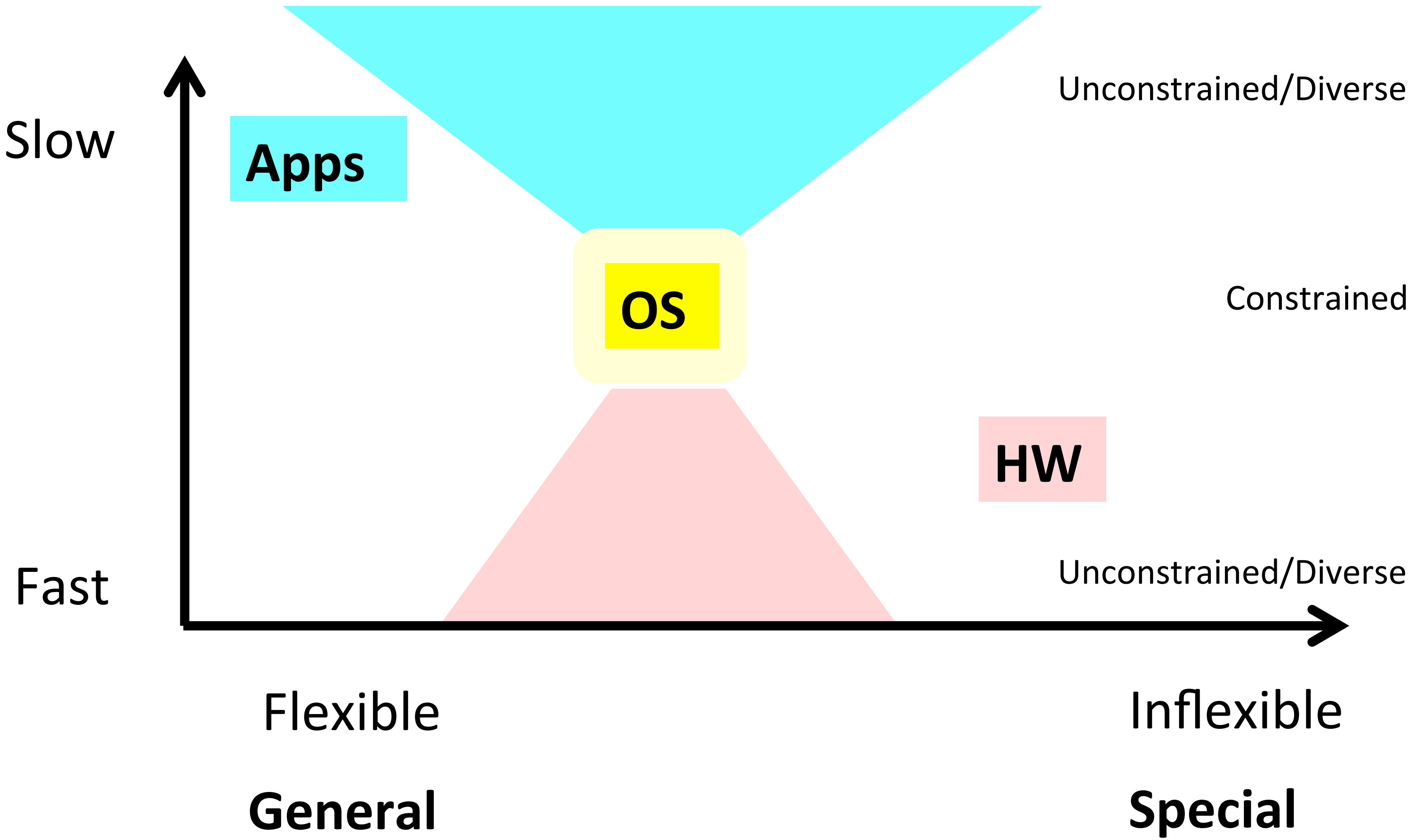
Universal Laws and Architectures (Turing)



Architecture (*constraints that deconstrain*)

Slide courtesy John Doyle

Case Study: Operating Systems Stack



Slide courtesy John Doyle

RYF Behavior is found everywhere

Robust	*Yet Fragile*
☺ Metabolism	☹ Obesity, diabetes
☺ Regeneration & repair	☹ Cancer
☺ Immune/inflammation	☹ AutoImmune/Inflame
☺ Microbe symbionts	☹ Parasites, infection
☺ Neuro-endocrine	☹ Addiction, psychosis,…
🗐 Complex societies	☠ Epidemics, war,…
🗐 Advanced technologies	💣 Disasters, global &!%$#
🗐 Risk “management”	💣 Obfuscate, amplify,…

Accident or necessity?

Robust	Fragile
☺ Metabolism	☹ Obesity, diabetes
☺ Regenerati
☺ Healing wo	une/Inflame

☹ Fat accumulation
☹ Insulin resistance
☹ Proliferation
☹ Inflammation

Same Mechanisms

- 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?

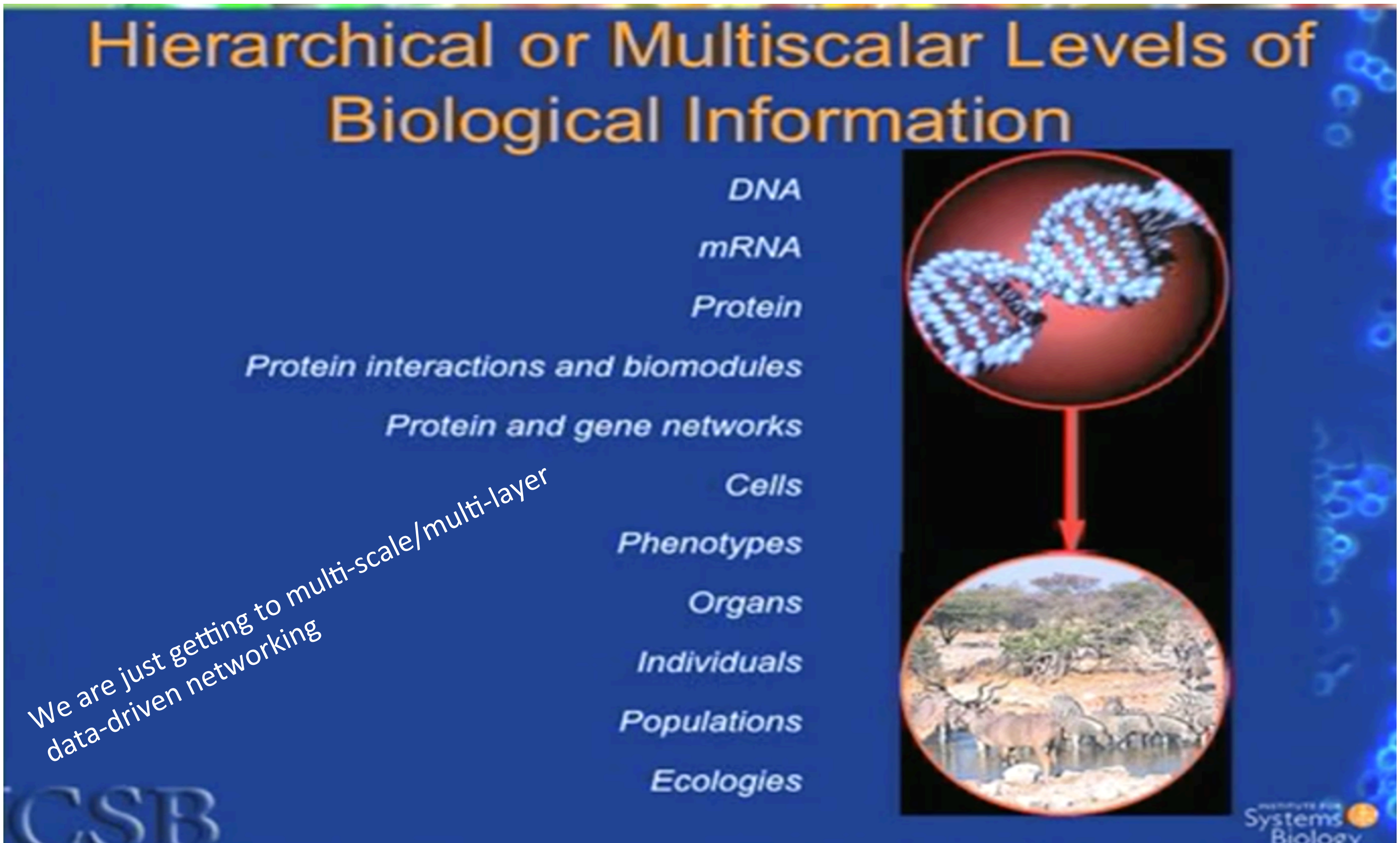
Slide courtesy John Doyle

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"

How Might We Attack The Problem?



We are just getting to multi-scale/multi-layer data-driven networking

Slide courtesy Leroy Hood

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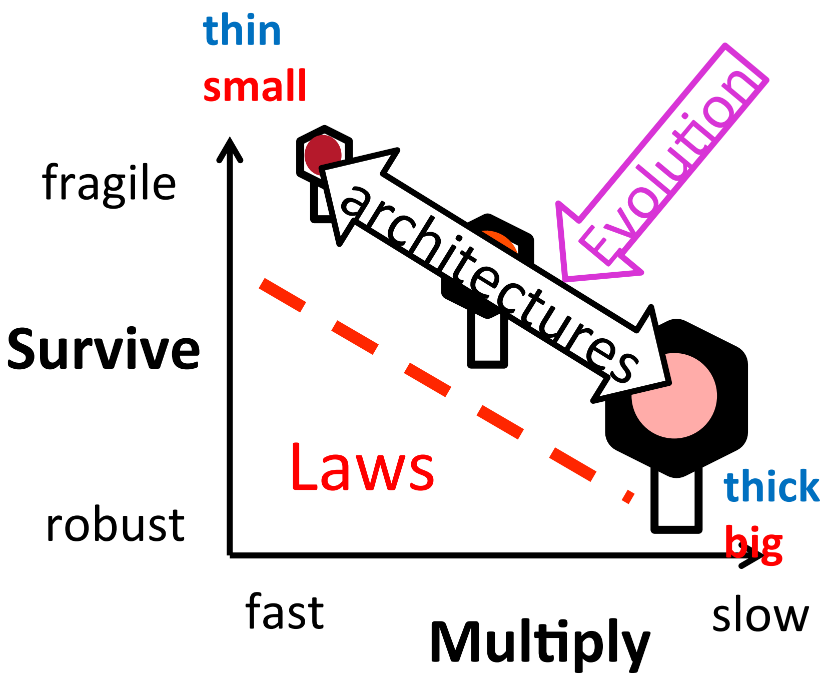
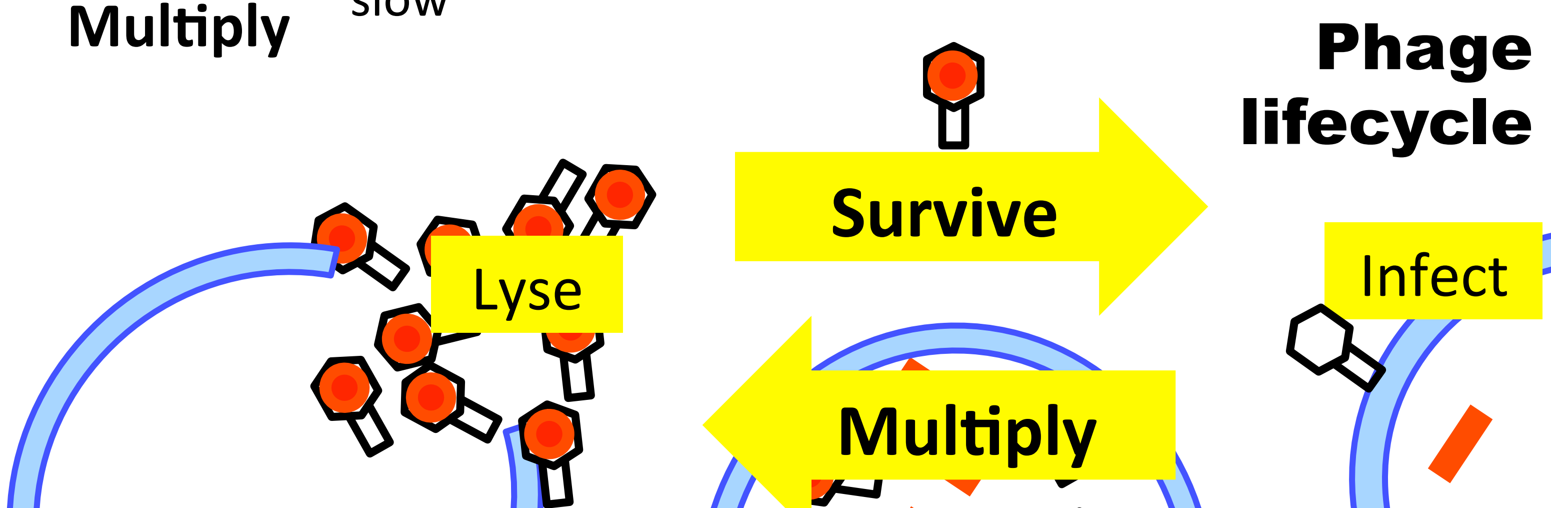
So What is Universal?

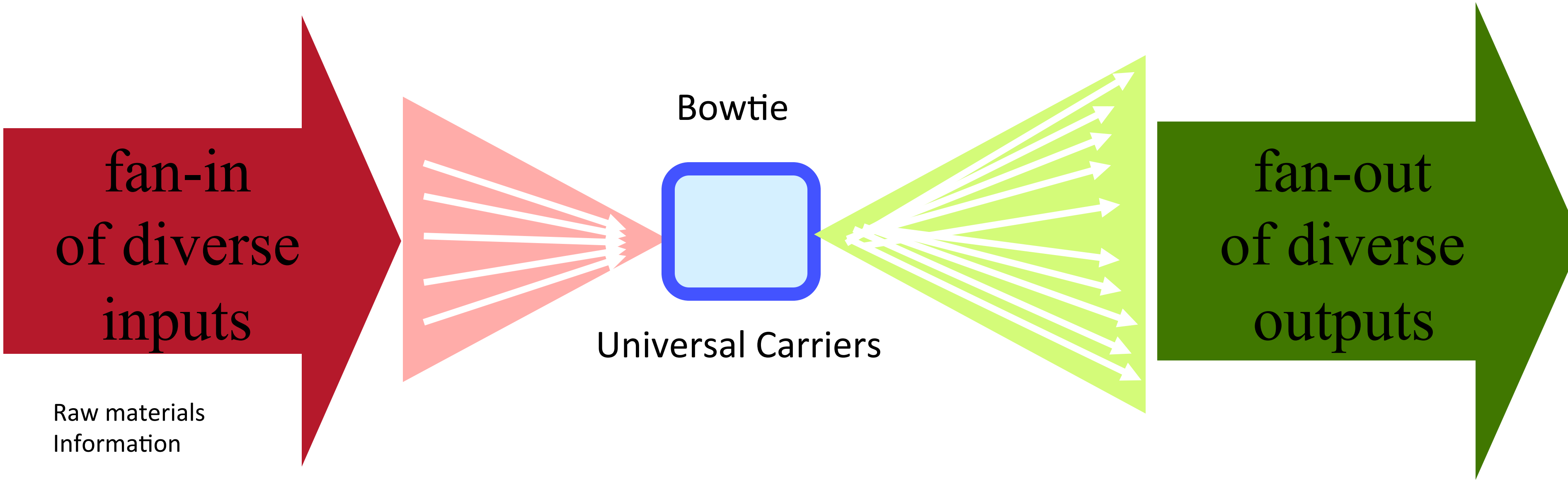


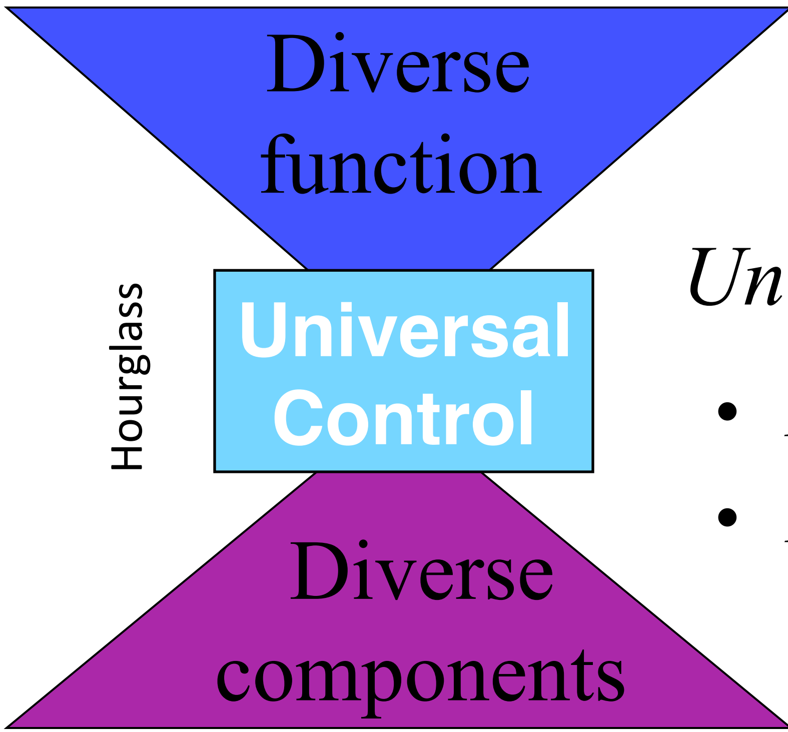
- *Laws, constraints, tradeoffs*
  - Robust/fragile
  - Efficient/wasteful
  - Fast/slow
  - Flexible/inflexible
- *Architecture*
- *Hijacking, parasitism, predation*



Architectures

- What we have learned is that there are ***universal architectural building blocks*** found in systems that scale and are evolvable. These include
  - **RYF complexity (really a behavior)**
  - **Bowtie/Hourglass architectures**
  - **Layered Architectures**
  - Protocol Based Architectures
  - Massively distributed with *robust* control loops





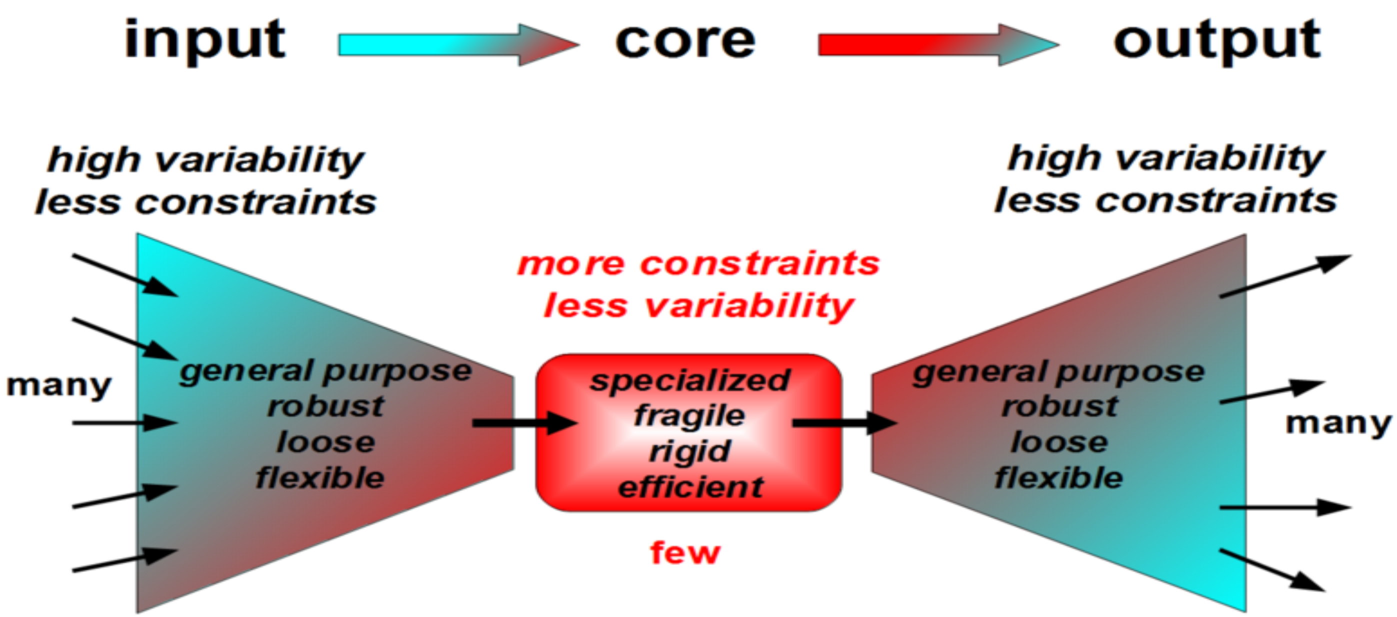
Universal Architectural Principles

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

Slide courtesy John Doyle

Bowties 101

Constraints that Deconstrain
Schematic of a "Layer"



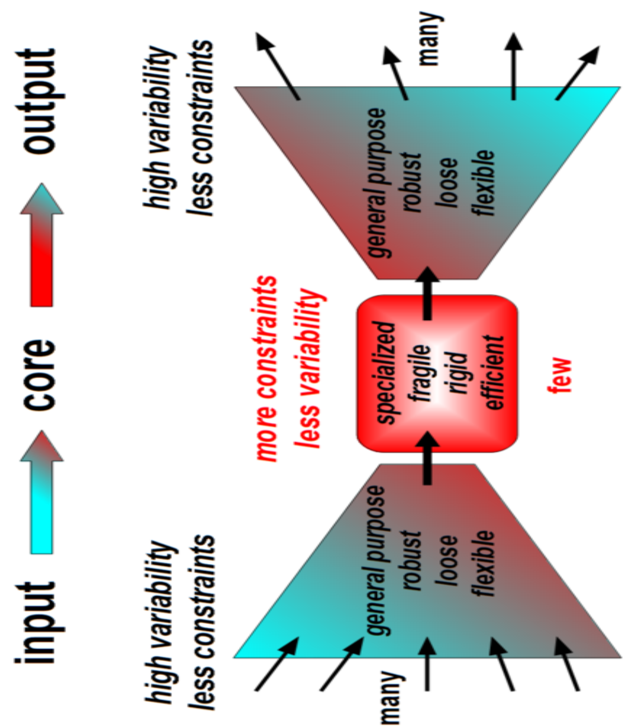
For example, the reactions and metabolites of core metabolism, e.g., *ATP metabolism*, Krebs/Citric Acid Cycle, … form a "metabolic knot". That is, ATP is a ***Universal Carrier*** for cellular energy.

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

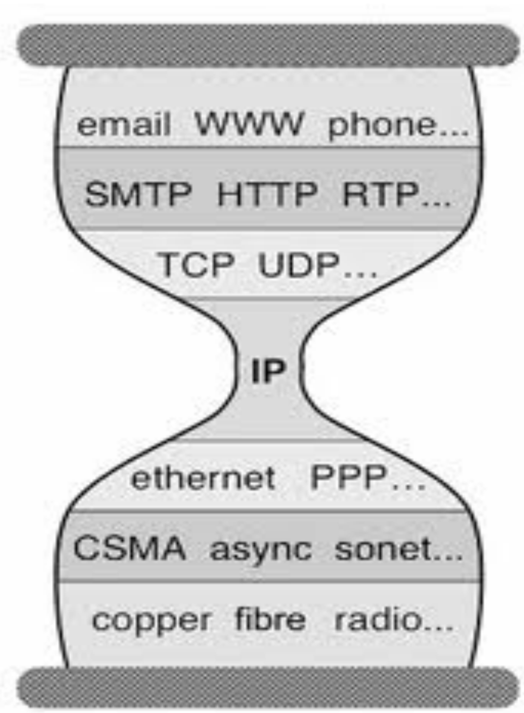
See Kirschner M., and Gerhart J., "Evolvability", Proc Natl Acad Sci USA , 95:8420–8427, 1998.

But Wait a Second

Anything Look Familiar?
(horizontal vs. vertical layering)



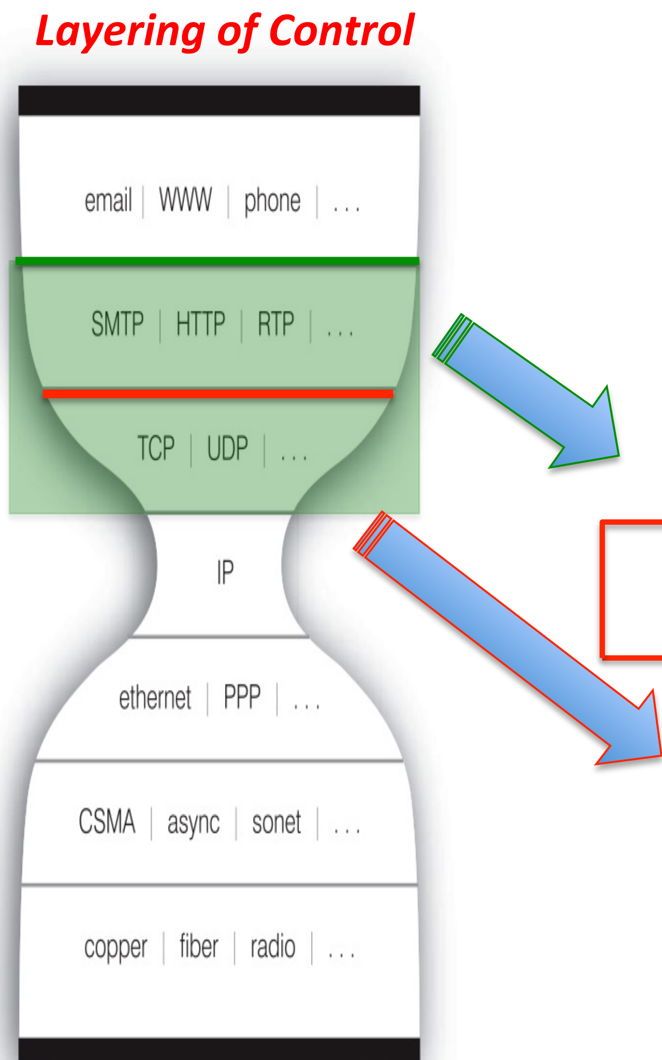
Bowtie Architecture



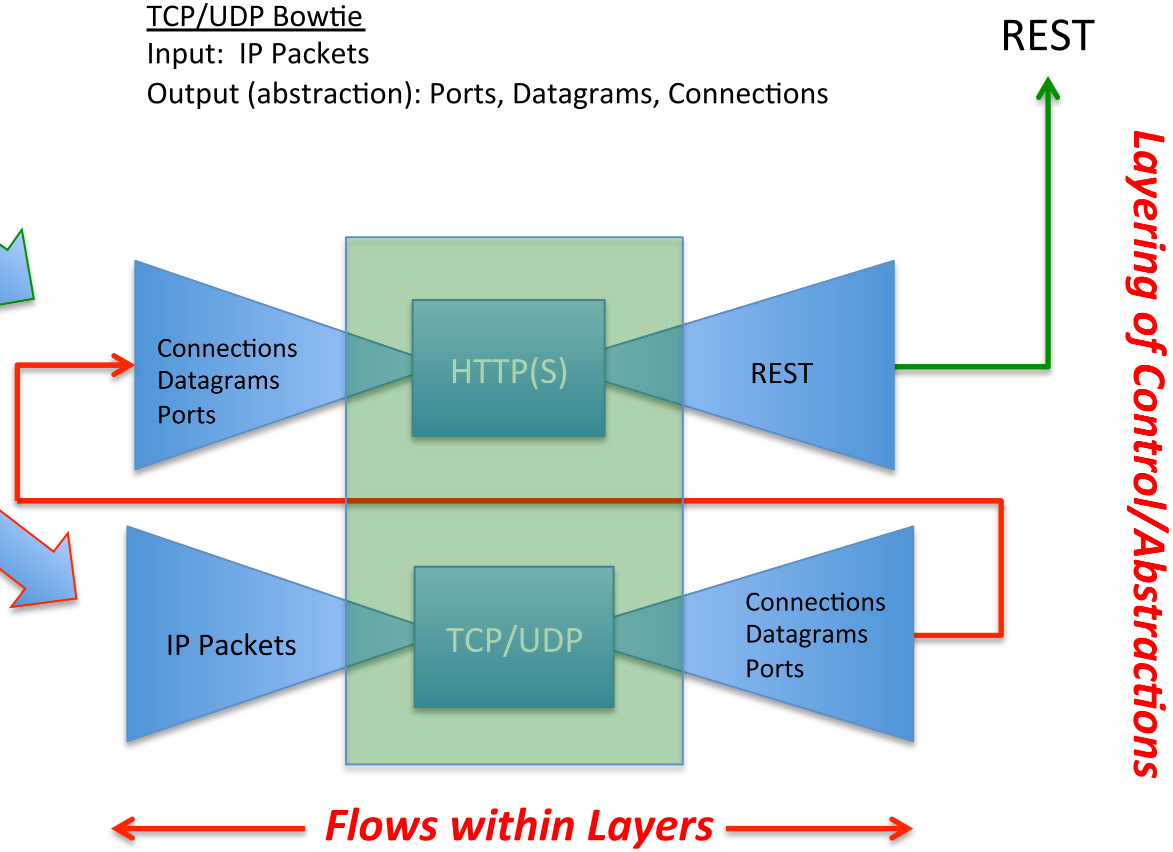
Hourglass Architecture

The *Protocol Hourglass* idea appears to have originated with Steve Deering. See Deering, S., "Watching the Waist of the Protocol Hourglass", IETF 51, 2001, http://www.iab.org/wp-content/IAB-uploads/2011/03/hourglass-london-ietf.pdf. See also Akhshabi, S. and C. Dovrolis, "The Evolution of Layered Protocol Stacks Leads to an Hourglass-Shaped Architecture", http://conferences.sigcomm.org/sigcomm/2011/papers/sigcomm/p206.pdf.

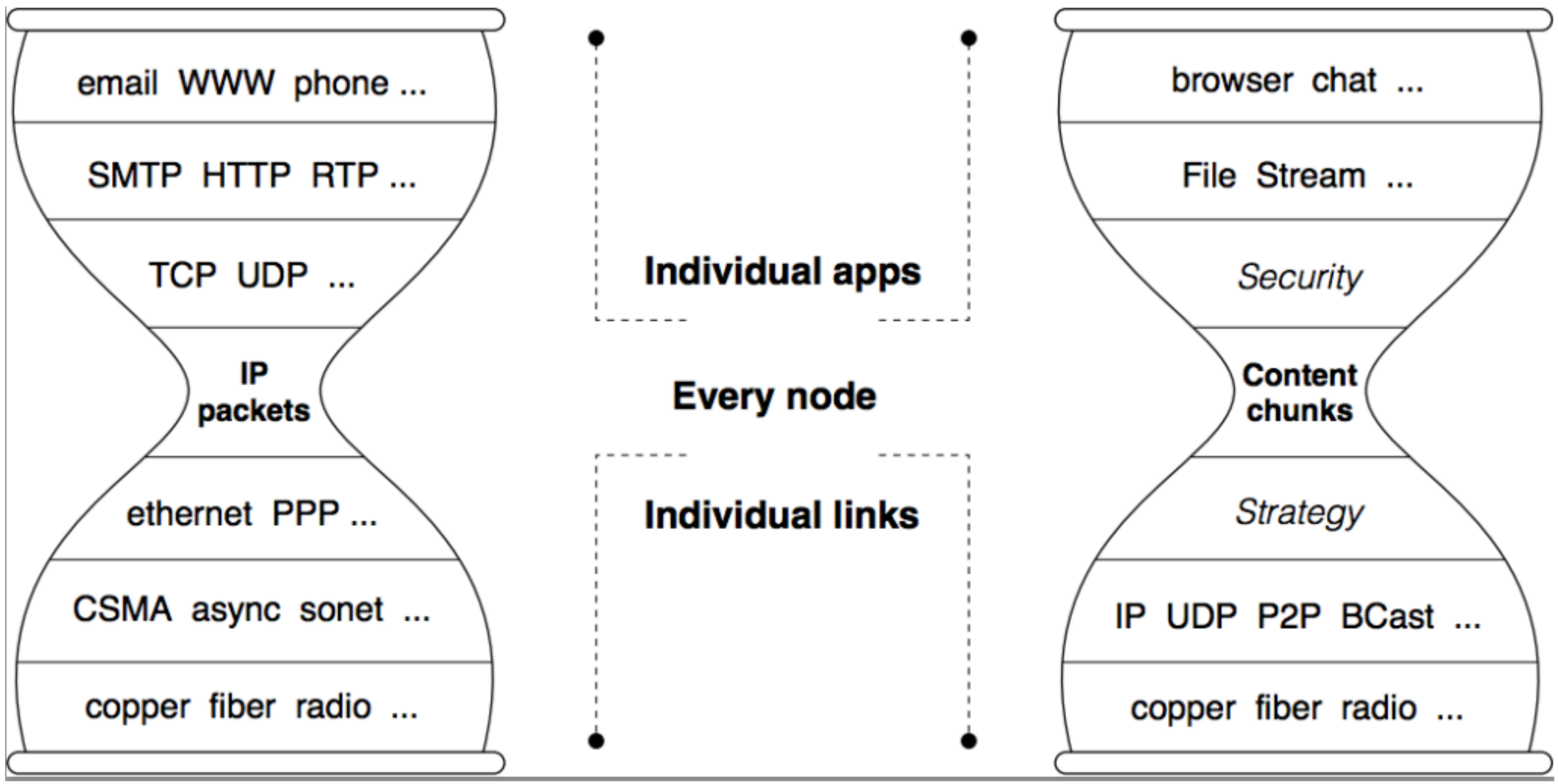
The Nested Bowtie/Hourglass Architecture of the Internet



<u>HTTP Bowtie</u>
Input: Ports, Datagrams, Connections
Output (abstraction): REST
<u>TCP/UDP Bowtie</u>
Input: IP Packets
Output (abstraction): Ports, Datagrams, Connections

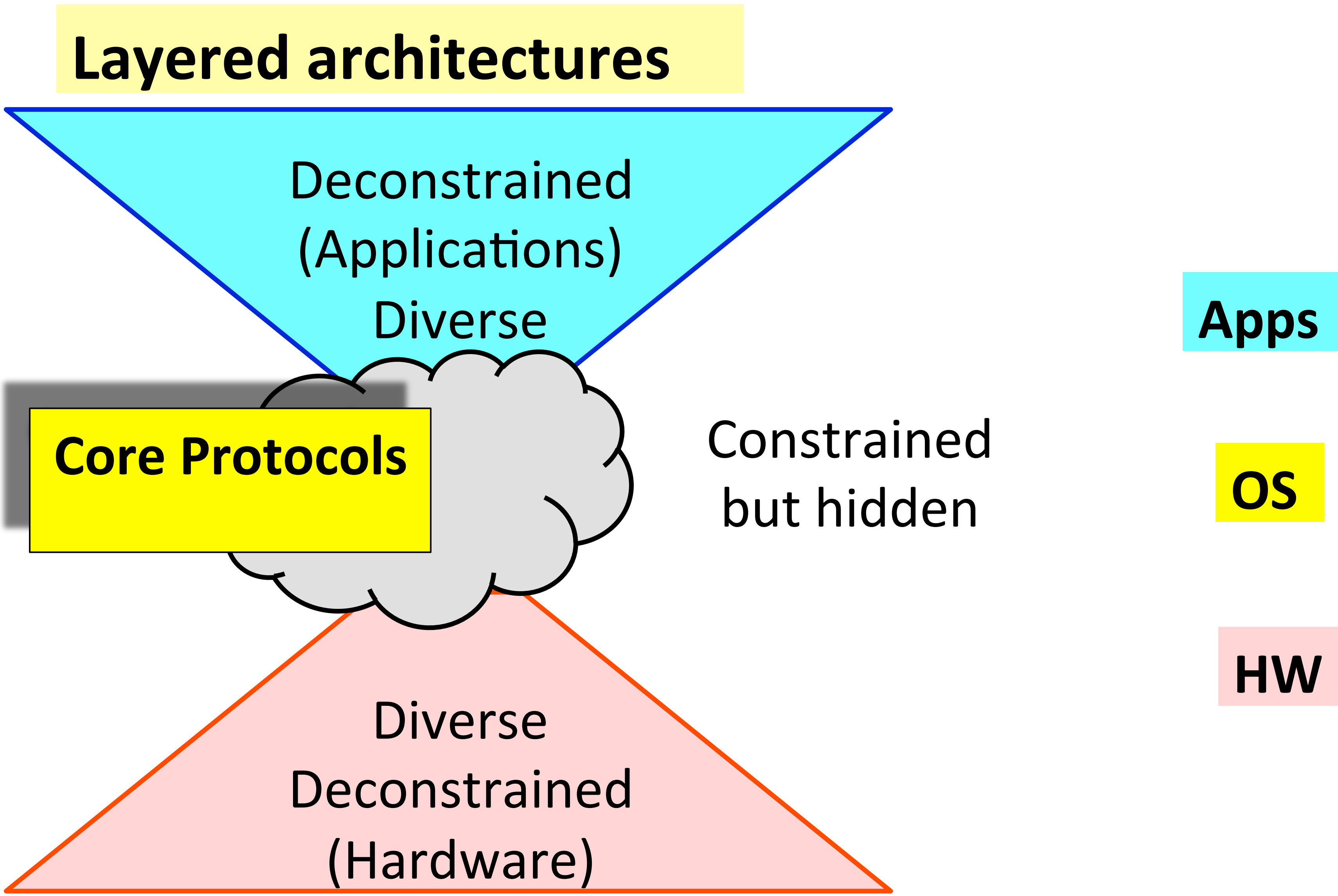


NDN Hourglass



See Named Data Networking, http://named-data.net/

Summary: Layered Architectures make *Robustness* and *Evolvability* Compatible



Mapping to Biology

Layered Bacteria

Apps

Slow
Cheap

HGT

DNA repair

Mutation

OS

DNA replication

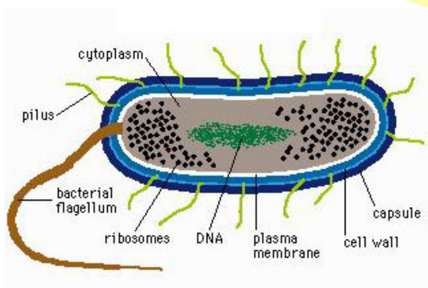
HW

Transcription

Translation

Metabolism

Signal…



Fast
Costly

Flexible

Inflexible

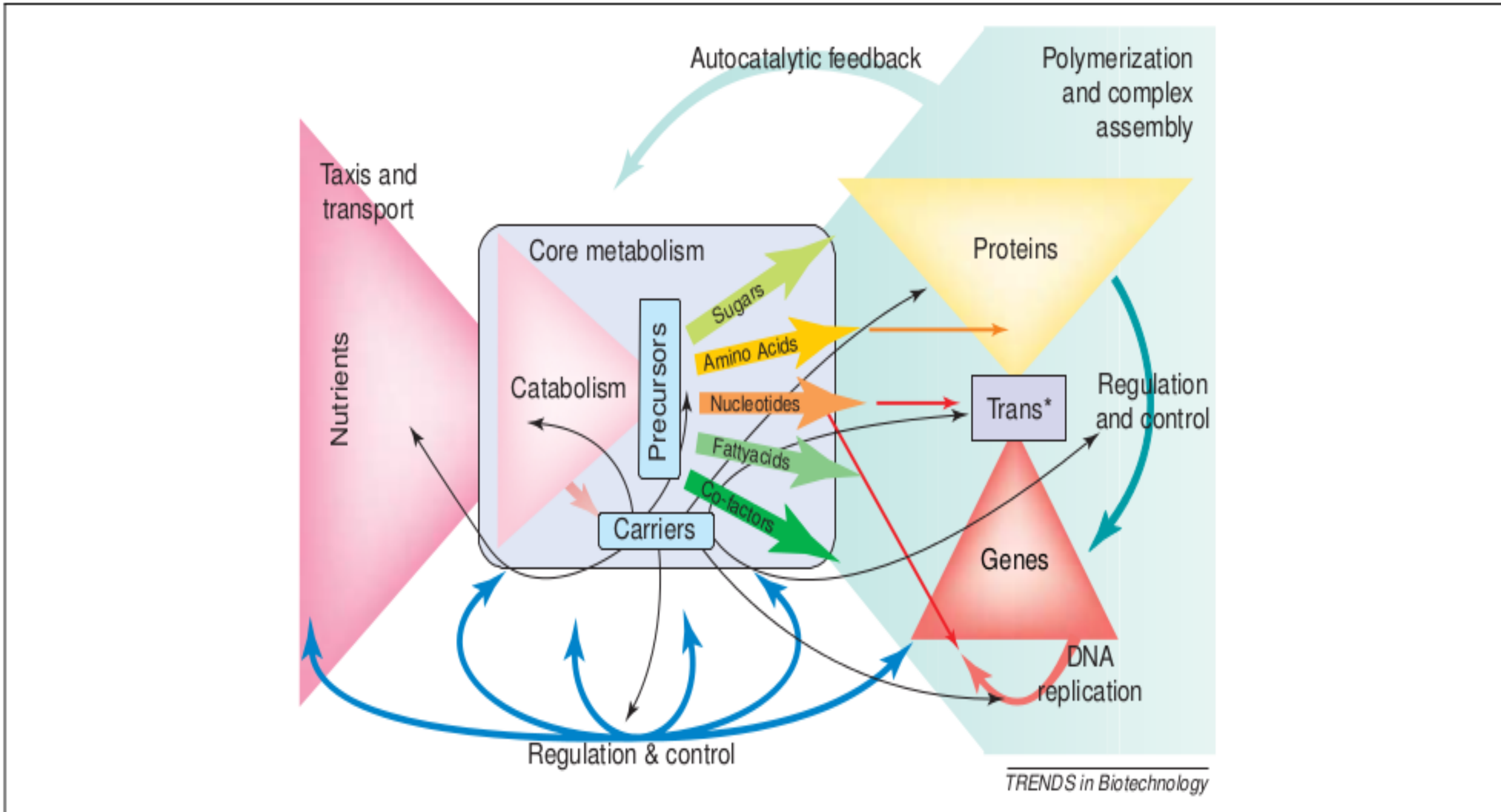
General

Special

Slide courtesy John Doyle

BTW, In Practice Things are More Complicated

The Nested Bowtie/Hourglass Architecture of Metabolism



See Csete, M. and J. Doyle, "Bowties, metabolism and disease", TRENDS in Biotechnology, Vol. 22 No. 9, Sept 2004

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Summarizing…

The *same* (universal) architectural features that make the Internet scalable and evolvable also make some protocols hard to evolve and/or deploy.

In particular, the difficulty we find in evolving protocols that form the knot or waist of a bowtie or hourglass is "by design".

Looked at this way, the difficultly deploying IPv6 (DNSSec,…) can be seen as a direct and inescapable consequence of robust network design.

So What Are Our Options?

- 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 fragility*[1]
    - 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

- 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)

[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

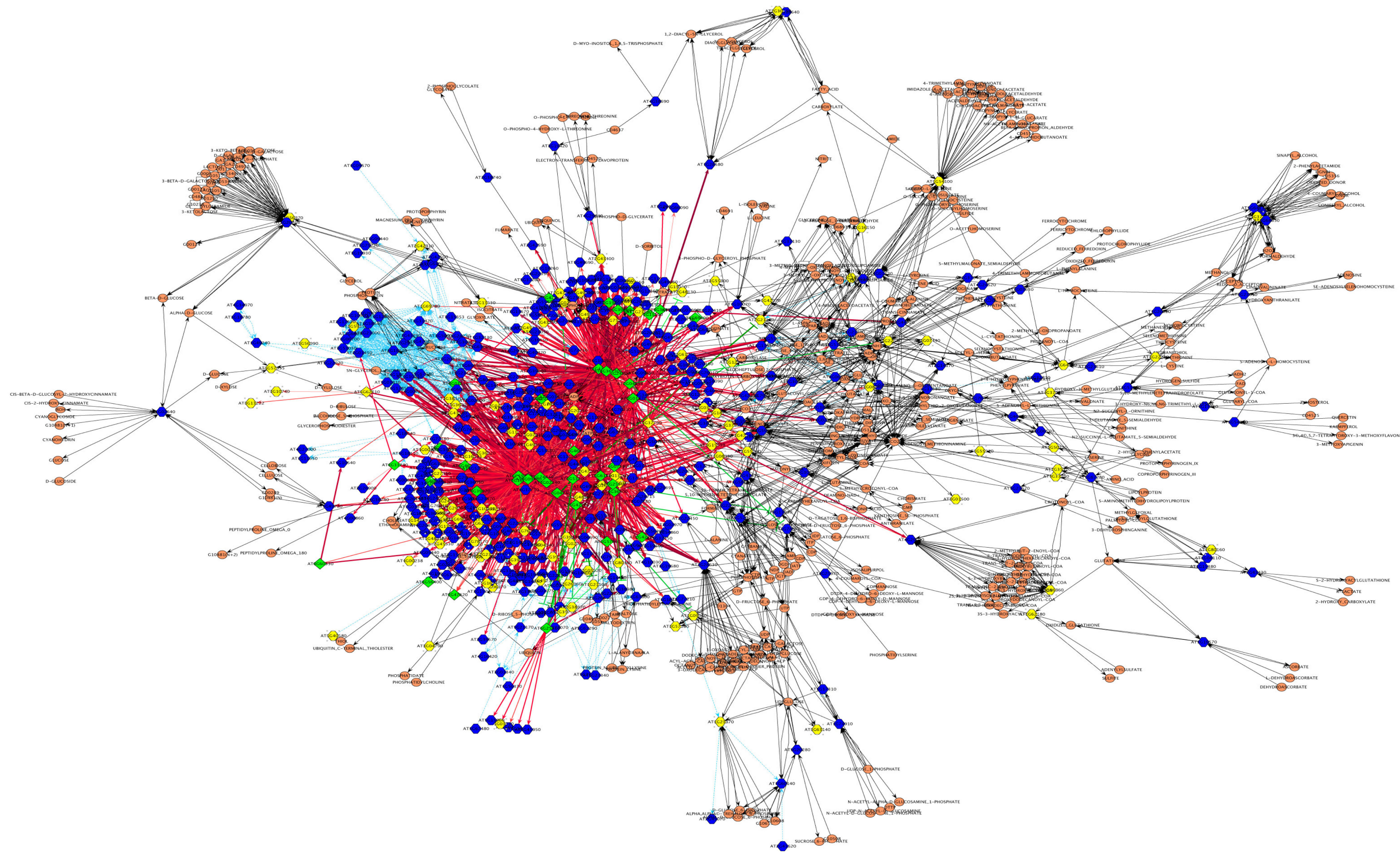
Q&A

Thanks!

Appendix

Systems Biology

One Approach To Understanding Complex Systems



So First and Remarkably, the Universal Architectural Principles we Discussed Span Advanced Technology and Biology

- Clearly Biology and Advanced Technology differ widely at the molecular and device levels

- However, they show remarkable convergence at higher layers of organization…why?
  - *Convergent Evolution*
    - Fruit fly, bird, bat, 747 → Wings + control might be a good idea if you want to fly
    - "Network Motifs" in Escherichia coli and Saccharomyces cerevisiae
    - …

- These same universal architectural building blocks occur over and over again in systems that scale and are evolvable.

- Example: Biological Transcription Networks and Engineered Circuits

Biological Transcription Networks

(a 30 second tour through Biology's "Central Dogma")

Signals

Transcription factors

DNA

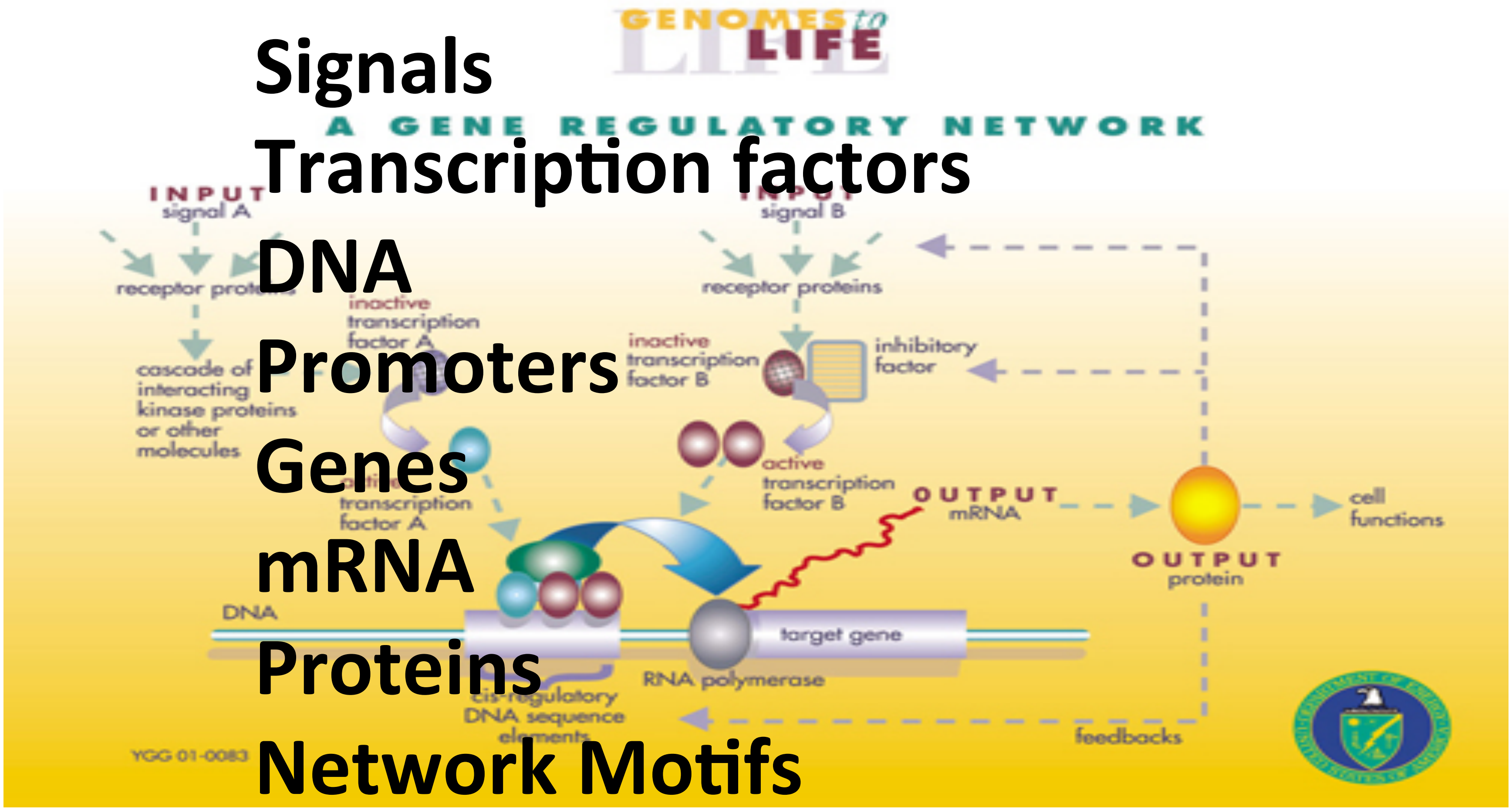
Promoters

Genes

mRNA

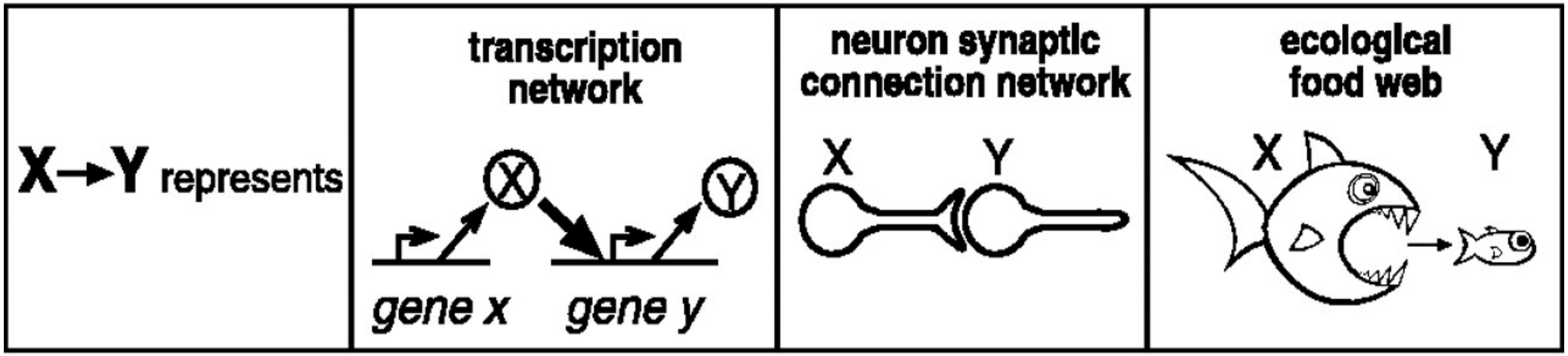
Proteins

Network Motifs

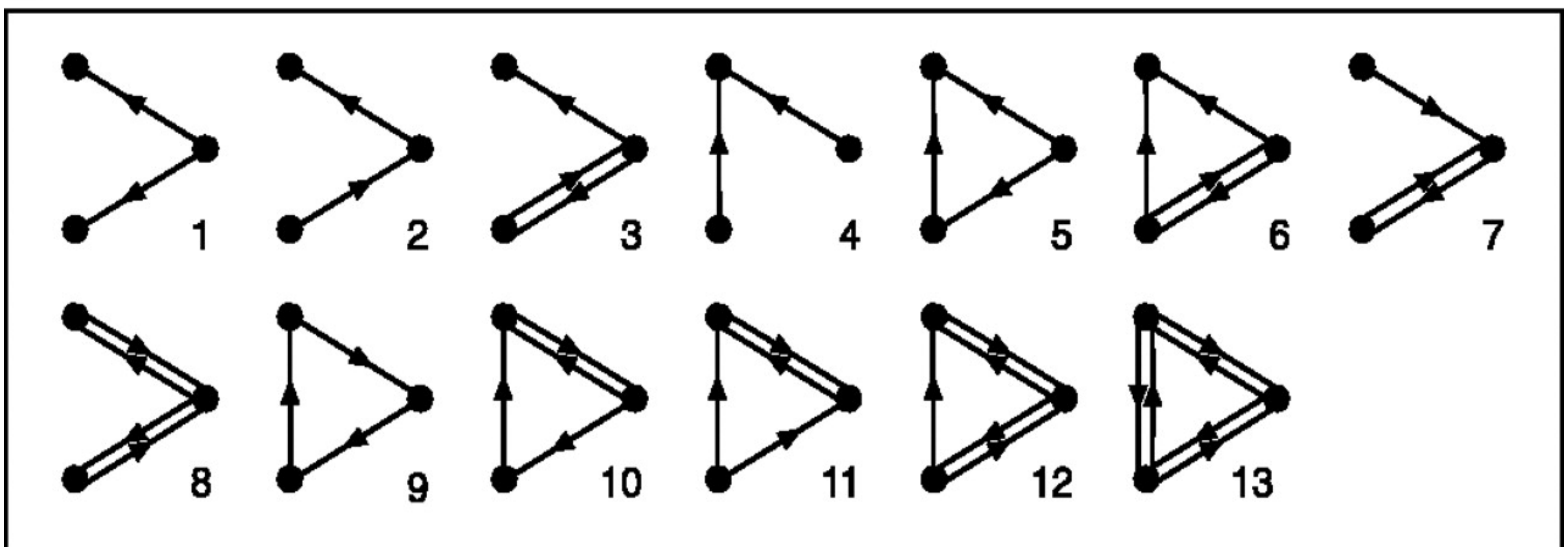


Network Motifs
There are 13 three node motifs

A



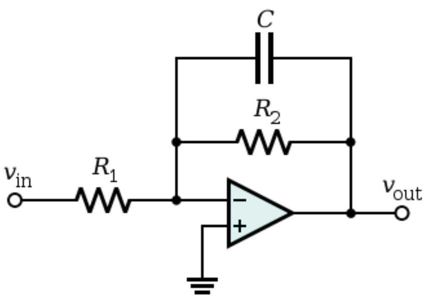
B



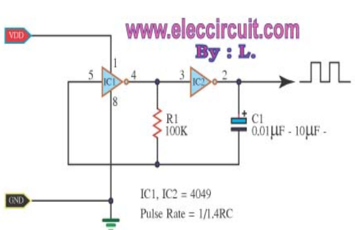
Feed Forward Loops

Technology

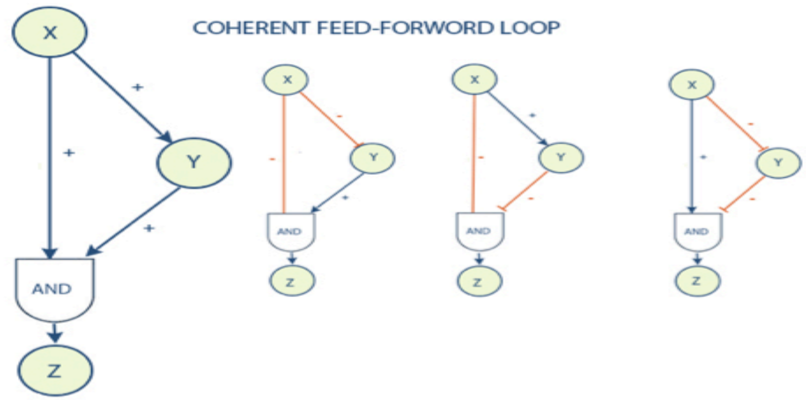
Sign Sensitive Low Pass Filter

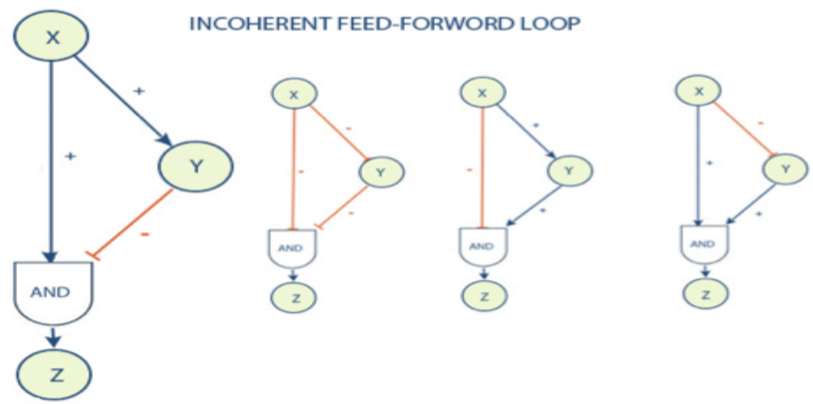


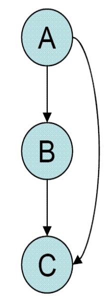
Pulse Generator



Biology





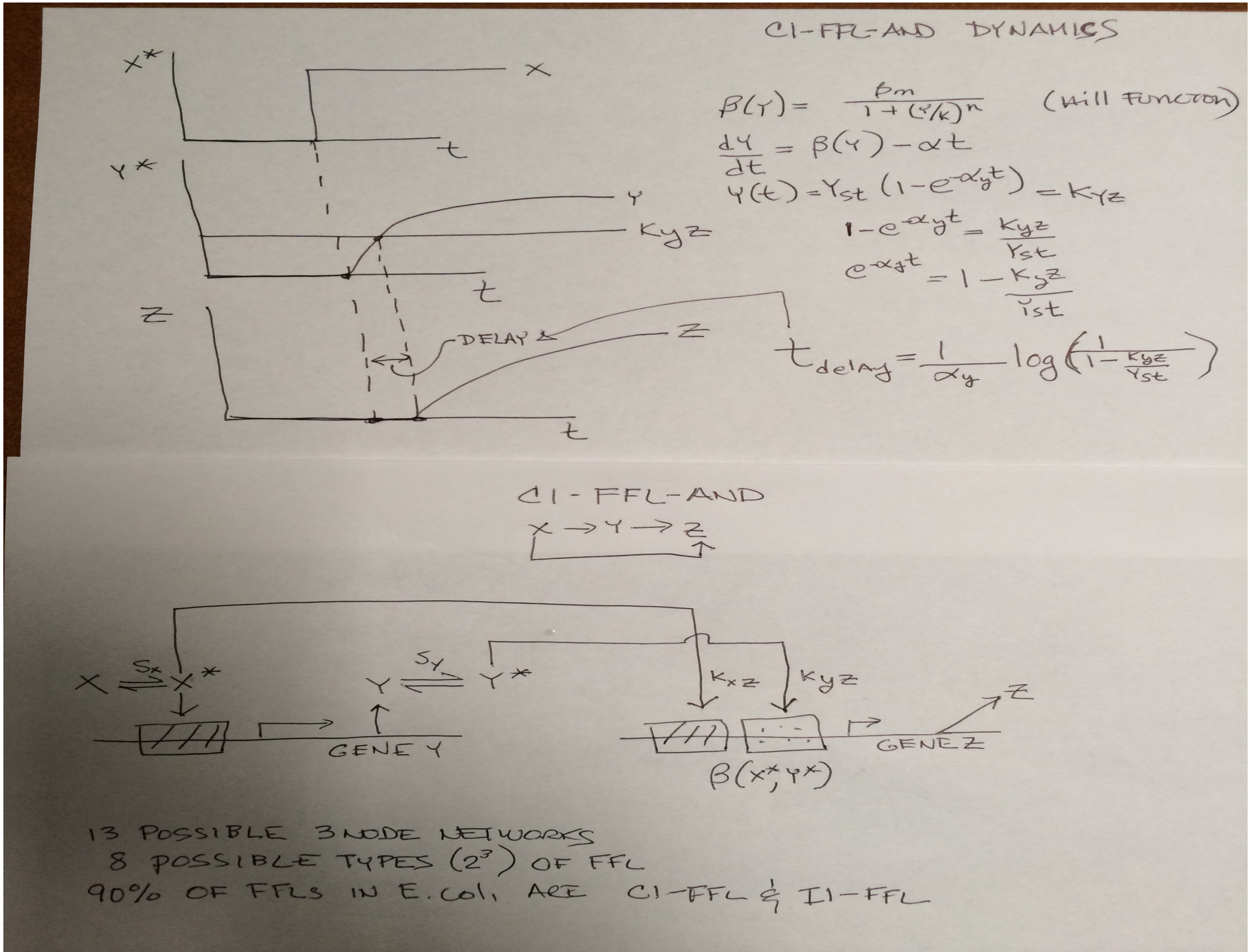


See Alon, U., et.al. "Coherent FeedForward Loops Serves as a Sign-Sensitive Delay Element in Transcription Networks", http://ender.bu.edu/~tgardner/be567_readings/Cell signalling/Feedforward/Mangan.S_JMB_03.pdf

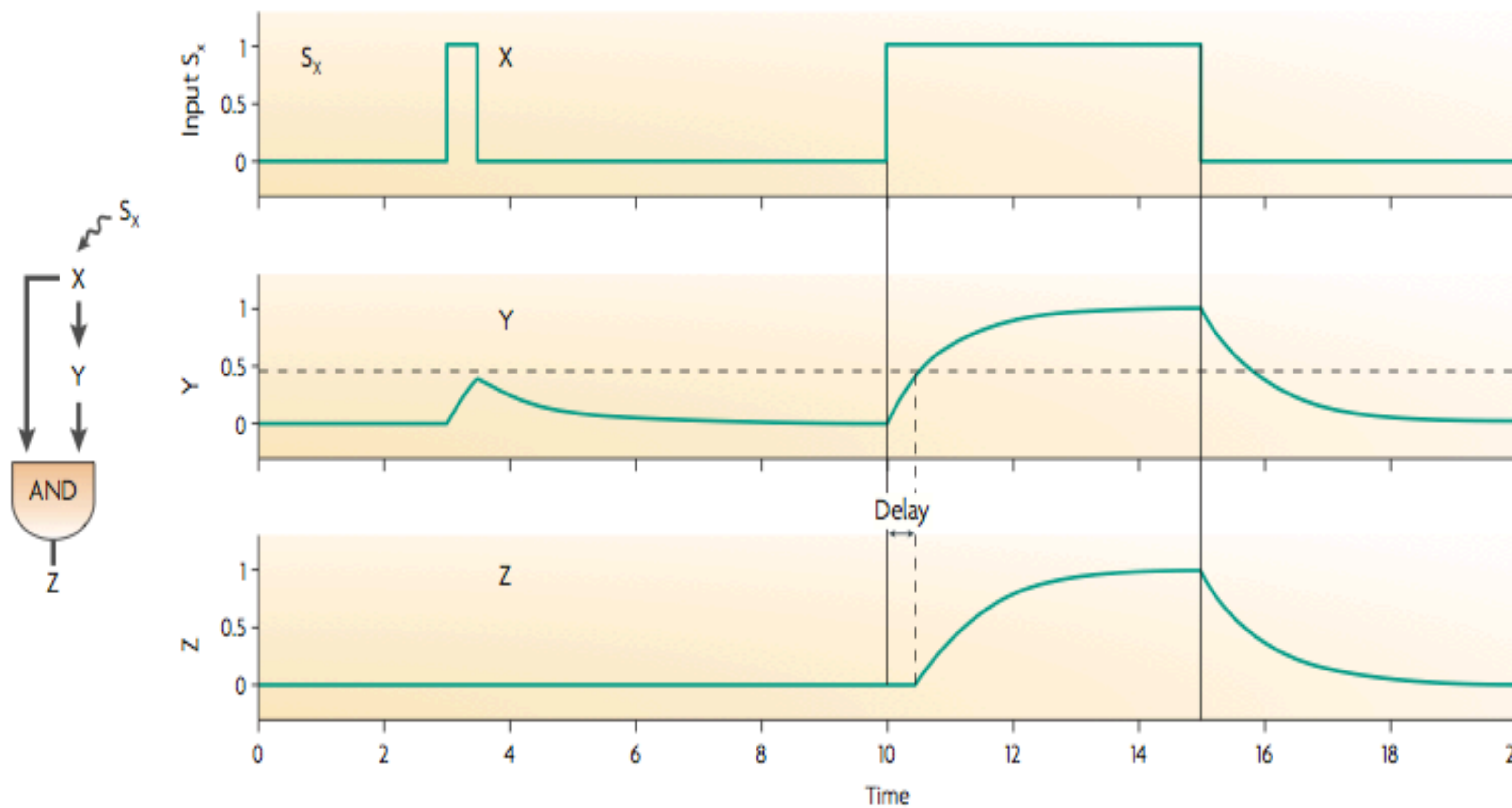
How Does This Actually Work?
(ON step for C1FFL-AND)

Dynamics

Biology



C1FFL-AND Dynamics



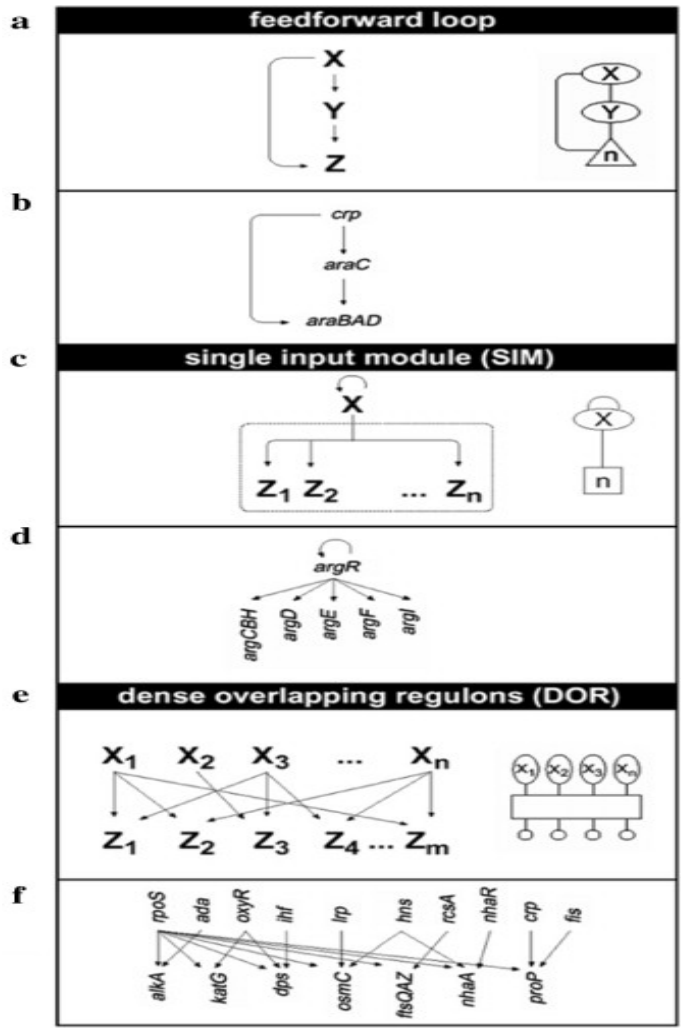
Graphic courtesy Alon, Uri, "Network motifs: theory and experimental approaches",
Nature Reviews Genetics 8, 450-461 (June 2007) | doi:10.1038/nrg2102

Surprisingly, E.coli and S. cerevisiae transcriptional networks use the same 3 network motifs[1]

Sign-sensitive filter

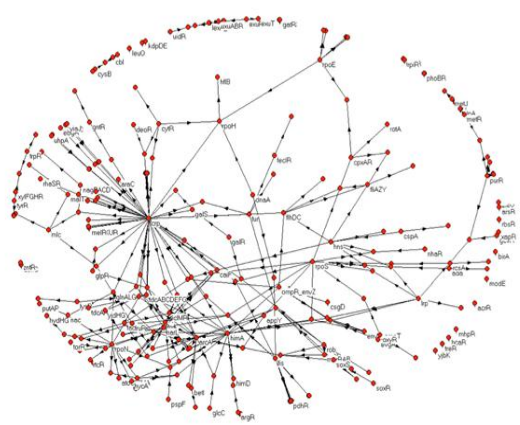
Temporal Sequencing

Gate Array

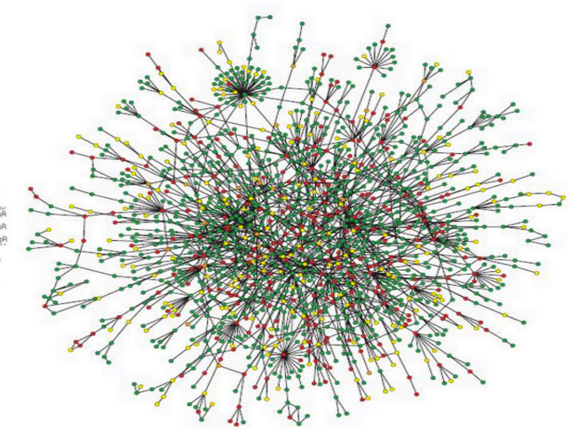


Number of Nodes	Number of Possible Motifs
3	13
4	199
5	9364
6	1,530,843

<u>E.coli</u>



<u>S. cerevisiae</u>



[1] Another example of *convergent evolution*

New Regulatory Networks

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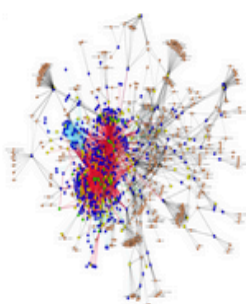
Vast New Regulatory Network Discovered in Mammalian Cells

Fri, 10/14/2011 - 13:51 — bioquicknews



Researchers at Columbia University Medical Center (CUMC) and other institutions have uncovered a vast new gene regulatory network in mammalian cells that could explain genetic variability in cancer and other diseases. Four studies bearing on this new regulatory network appear in the October 14, 2011 issue of Cell. "The discovery of this regulatory network fills in a missing piece in the puzzle of cell regulation and allows us to identify genes never before associated with a particular type of tumor or disease," said Dr. Andrea Califano, professor of systems biology, director of the Columbia Initiative in Systems Biology, and senior author of the CUMC research team's article. For decades, scientists have thought that the primary role of messenger RNA (mRNA) is to shuttle information from the DNA to the ribosomes, the sites of protein synthesis. However, these new studies suggest that the mRNA of one gene can control, and be controlled by, the mRNA of other genes via a large pool of microRNA molecules, with

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Anything Look Familiar?