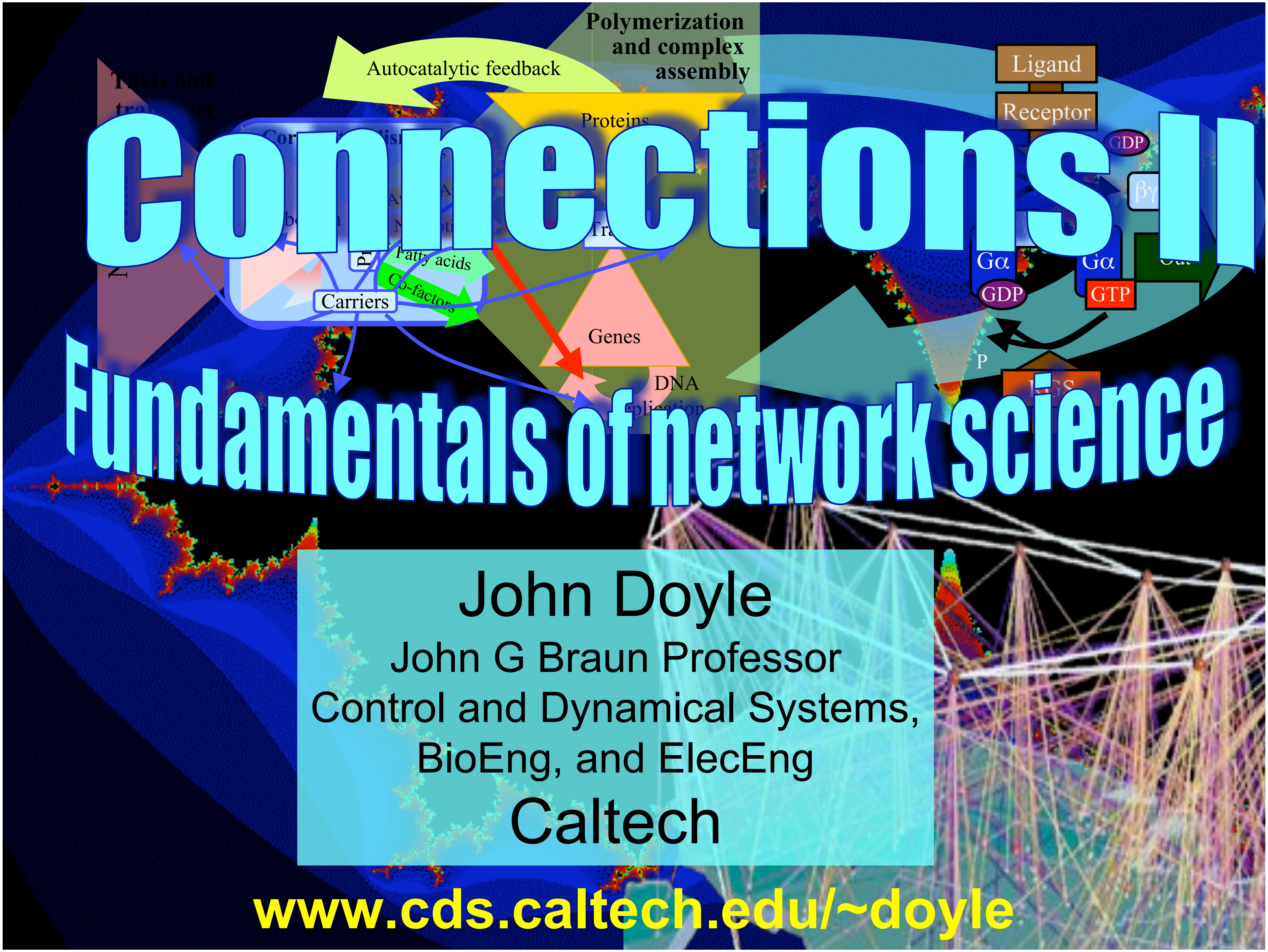
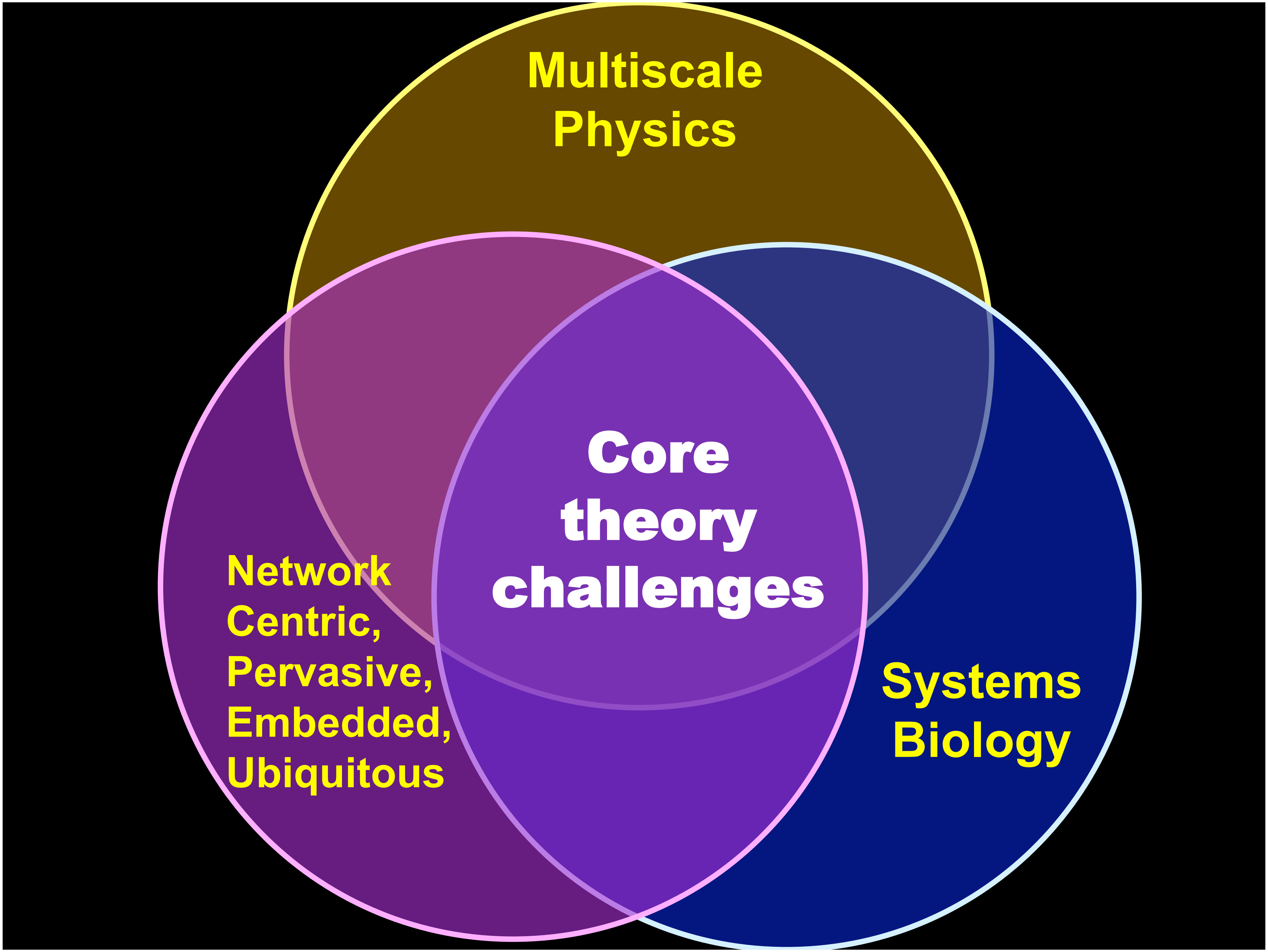


Connections II

Fundamentals of network science

John Doyle
John G Braun Professor
Control and Dynamical Systems,
BioEng, and ElecEng
Caltech

www.cds.caltech.edu/~doyle


Multiscale Physics
Network Centric, Pervasive, Embedded, Ubiquitous
Core theory challenges
Systems Biology

Core theory challenges

- Hard limits
- Short proofs
- Small models

- Architecture

Architecture?

- "*The bacterial cell and the Internet have*
  - *architectures*
  - *that are robust and evolvable*"
- What does "architecture" mean?
- What does it mean for an "architecture" to be robust and evolvable?
- Robust yet fragile?

Robust

1. Efficient, flexible metabolism
2. Complex development
3. Immune systems
4. Regeneration & renewal
5. Complex societies

Yet Fragile

1. Obesity and diabetes
2. Rich parasite ecosystem
3. Auto-immune disease
4. Cancer
5. Epidemics, war, genocide, …

Human robustness and fragility

Hard limits and tradeoffs

On systems and their components

- Thermodynamics (Carnot)
- Communications (Shannon)
- Control (Bode)
- Computation (Turing/Gödel)

Assume ***different*** architectures a priori.

- Fragmented and incompatible
- We need a more integrated view and have the beginnings

The nature of simplicity

Simple questions:
- Simple models
- Elegant theorems
- Elegant experiments

Simple answers:
- Predictable results
- Short proofs
- Simple outcomes

Reductionist science: Reduce the ***apparent complexity*** of the world to an underlying simplicity.

Physics has for centuries epitomized the success of this approach.

1930s: The end of certainty

Simple questions:

- Simple models
- Elegant theorems
- Elegant experiments

Simple answers:

- ~~Predictable results~~
- ~~Short proofs~~
- Simple outcomes

- Godel: Incompleteness
- Turing: Undecidability
- Profoundly effected mathematics and computation.
- Little impact on science.

1960s-Present: "Emergent complexity"

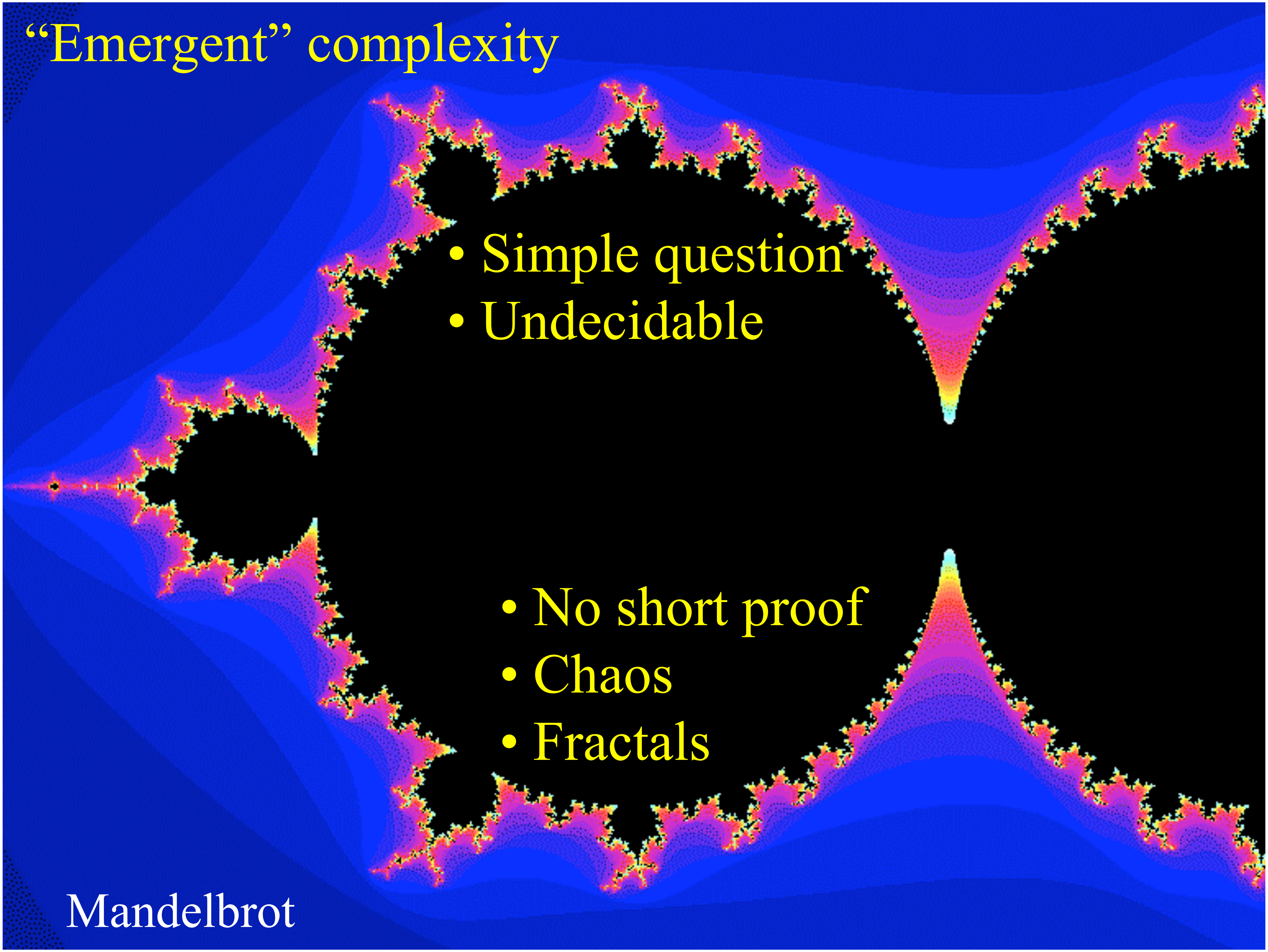
Simple questions:

- Simple models
- Elegant theorems
- Elegant experiments

Dominates scientific thinking today

Complexity:

- Unpredictabity
- Chaos, fractals
- Critical phase transitions
- Self-similarity
- Universality
- Pattern formation
- Edge-of-chaos
- Order for free
- Self-organized criticality
- Scale-free networks


“Emergent” complexity
• Simple question
• Undecidable
• No short proof
• Chaos
• Fractals
Mandelbrot

The "New Science of Complexity"

	Simple question
Predictable	Simplicity
Unpredictable	"Emergence"

Even simple systems with little uncertainty can yield completely unpredictable behavior.

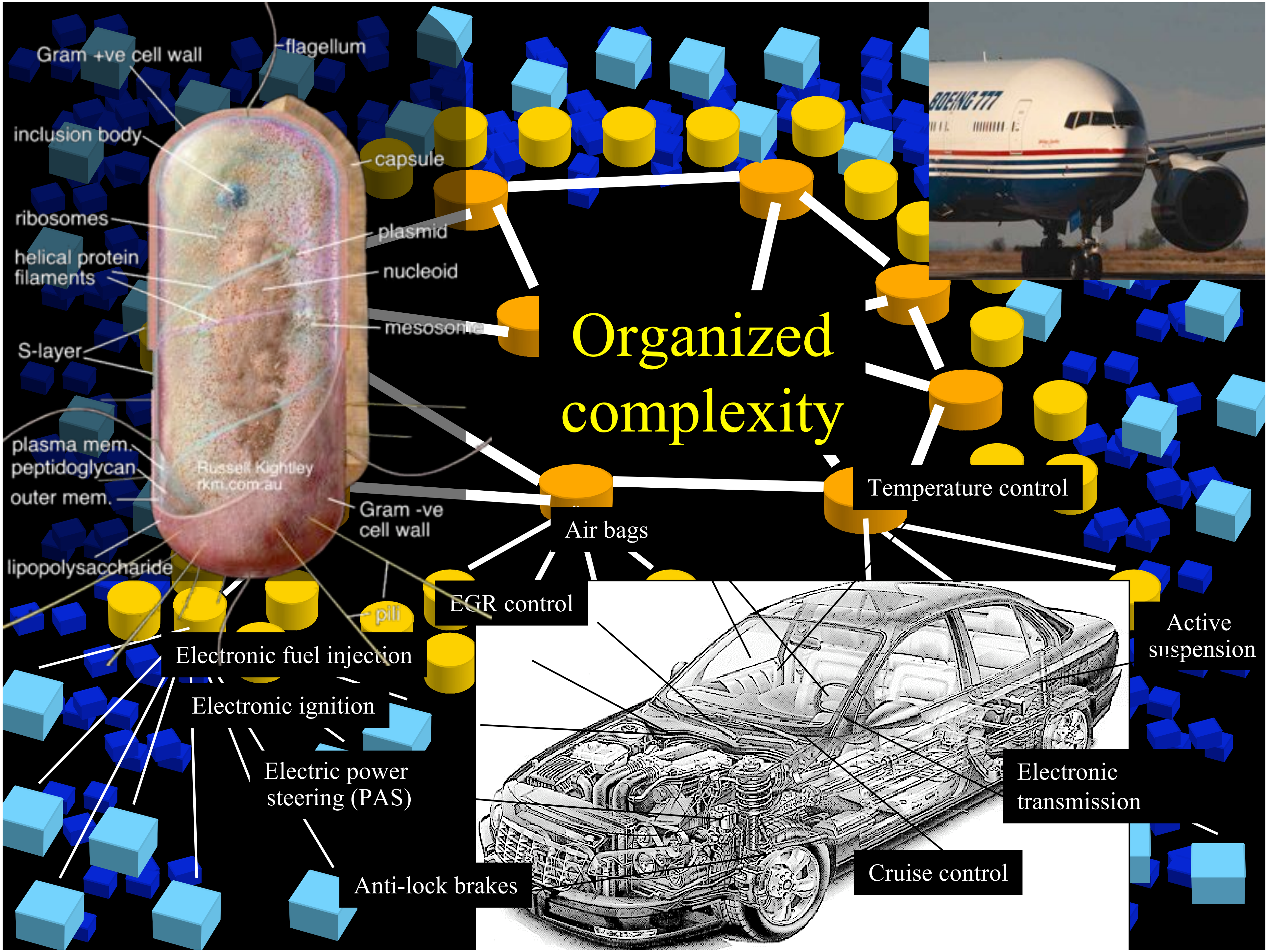
1900s: The triumph (and horror) of organization

~~Simple questions~~:
- ~~Simple models~~
- ~~Elegant theorems~~
- ~~Elegant experiments~~

Simple answers:
- Predictable results
- Short proofs
- Simple outcomes

- Complex, uncertain, hostile environments
- Unreliable, uncertain, changing components
- Limited testing and experimentation

- Yet predictable, robust, reliable, adaptable, evolvable systems


Organized complexity
Gram +ve cell wall
flagellum
inclusion body
capsule
ribosomes
plasmid
helical protein filaments
nucleoid
mesosome
S-layer
plasma mem.
peptidoglycan
outer mem.
Russell Kightley rkm.com.au
Gram -ve cell wall
lipopolysaccharide
pili
BOEING 777
Temperature control
Air bags
EGR control
Active suspension
Electronic fuel injection
Electronic ignition
Electric power steering (PAS)
Electronic transmission
Cruise control
Anti-lock brakes

Organized complexity

- Requires highly organized interactions, by design or evolution
- Completely different theory and technology from emergence

Simple answers:

- Predictable results
- Short proofs
- Simple outcomes

- Complex, uncertain, hostile environments
- Unreliable, uncertain, changing components
- Limited testing and experimentation

- Yet predictable, robust, reliable, adaptable, evolvable systems

Mathematics and technology

Question / Answer	Simple	Complex
Predictable	Simplicity	**Organization**
Unpredictable	Emergence	

Emergence and organization are opposites, but can be viewed in a unified framework.

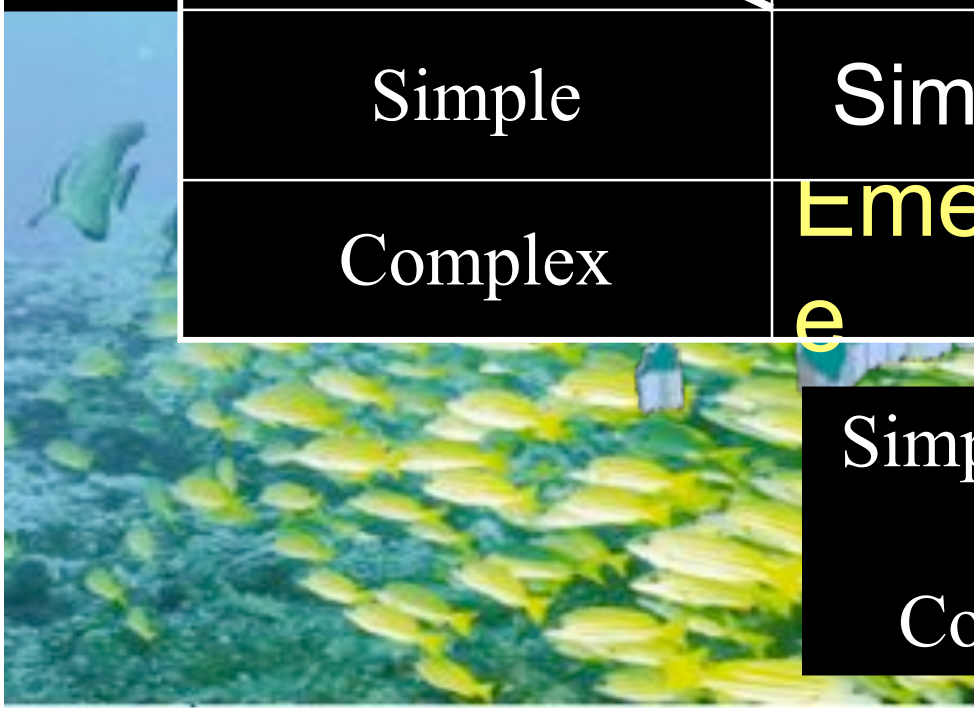
Irreducible complexity?

Question / Answer	Simple	Complex
Predictable	Simplicity	**Organization**
Unpredictable	Emergence	?

Complexity and unpredictability are the key to successful cryptography and other security technologies.

The complete picture

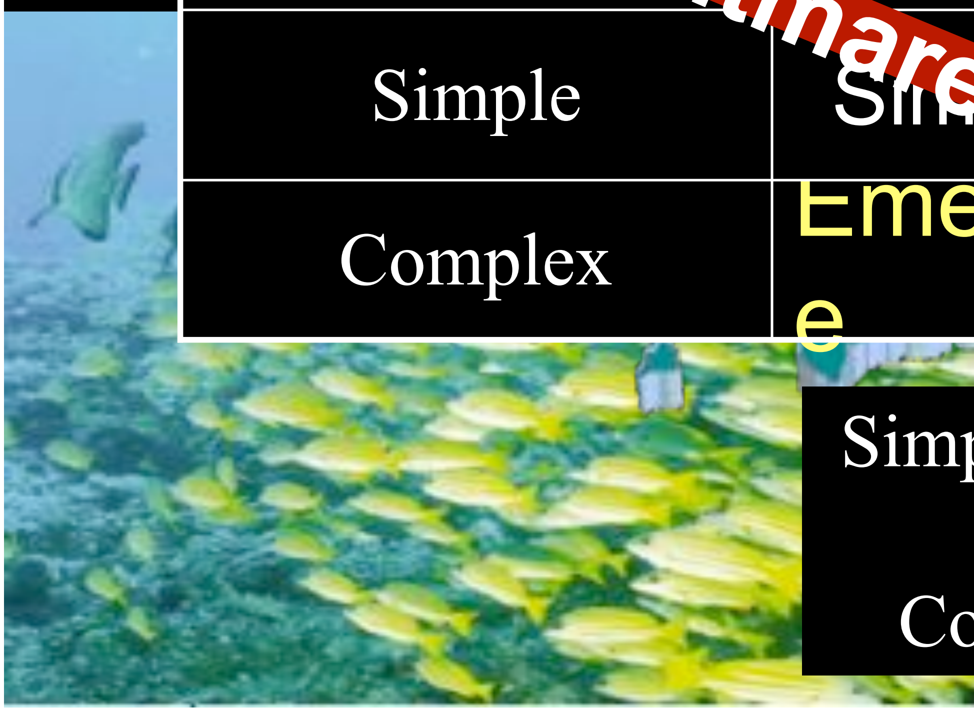
Question / Answer	Simple	Complex
Simple	Simplicity	**Organization**
Complex	Emergence	**Irreducibility**



Simple, predictable, reliable, robust
versus
Complex, unpredictable, fragile

The complete picture

Question / Answer	Simple	Complex
Simple	Simplicity	Organization
Complex	Emergence	Irreducibility



Simple, predictable, reliable, robust
versus
Complex, unpredictable, fragile

The complete picture

Answer \ Question	Simple	Complex
Simple	Simplicity	**Organization**
Complex	Emergence	**Irreducibility**

The challenge

Models / Proofs	Small	Large
Short		
Long		

How can we treat complex networks and systems with small models and short proofs?

The complete picture

Models / Proofs	Small	Large
Short	Simplicity	**Organization**
Long	Emergence	**Irreducibility**

Breaking hard problems

- SOSTOOLS proof theory and software (Parrilo, Prajna, Papachristodoulou, …)
- Nested family of (dual) proof algorithms
- Each family is polynomial time
- Recovers many "gold standard" algorithms as special cases, and immediately improves
- Nonlinear, hybrid, stochastic, …
- No a priori polynomial bound on depth (otherwise P=NP=coNP)
- Conjecture: Complexity implies fragility

Architecture?

- “*The bacterial cell and the Internet have*
  - *architectures*
  - *that are robust and evolvable* ***(yet fragile)*** ”

- What does “architecture” mean?
- What does it mean for an “architecture” to be robust and evolvable?
- Robust yet fragile?
- Rigorous and coherent theory?

A look back and forward

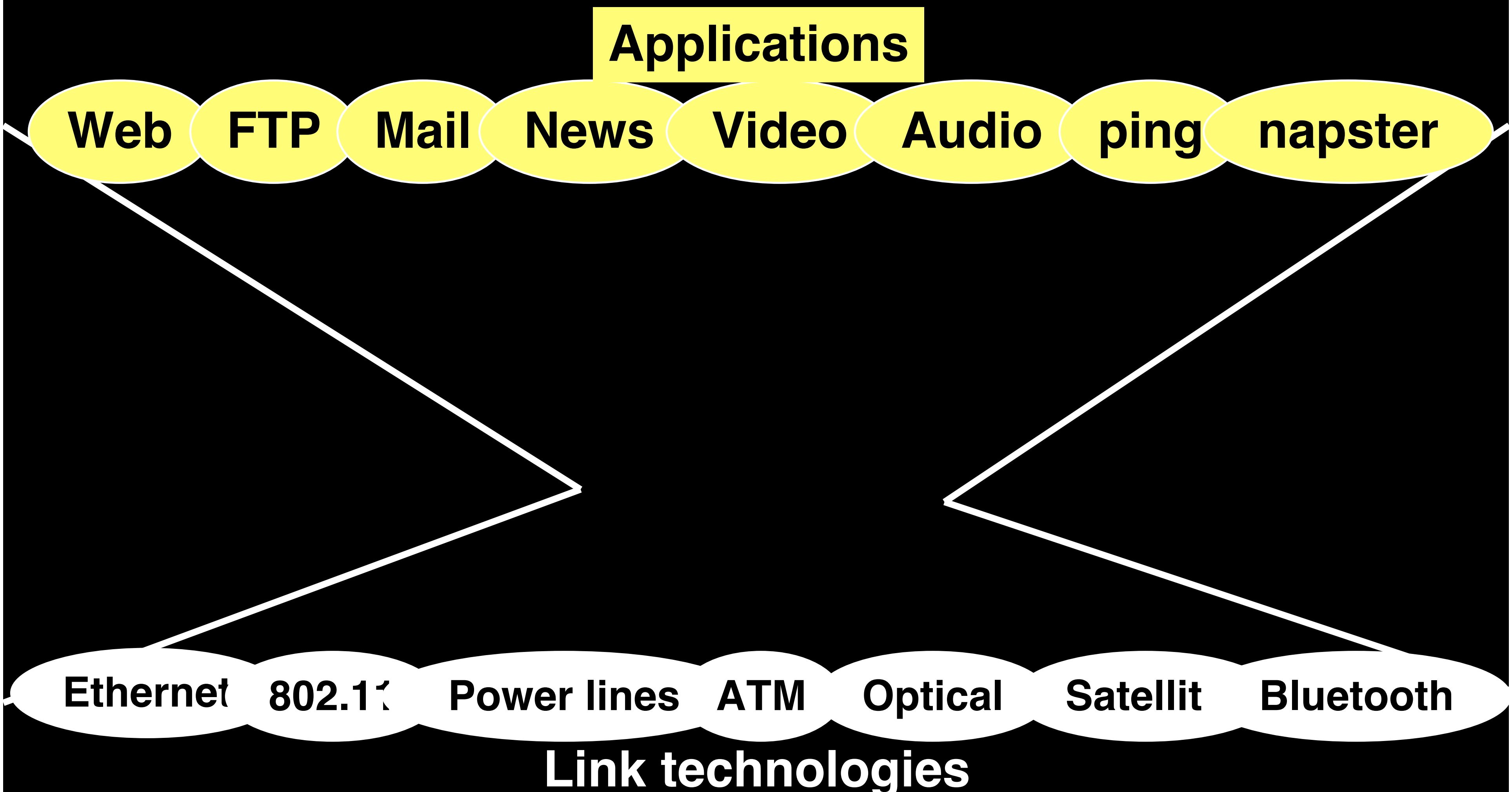
- The Internet architecture was designed without a "theory."
- Many academic theorists told the engineers it would never work.
- We now have a nascent theory that confirms that the engineers were right (Kelly, Low, Vinnicombe, Paganini, Papachristodoulou, …)

- Parallel stories exist in "theoretical biology."
- For future networks, "systems of systems," and other new technologies, as well as ***systems biology of the cell, organism and brain***, …
- …let's hope we can avoid a repeat of this history. (Looks like we have a good start…)

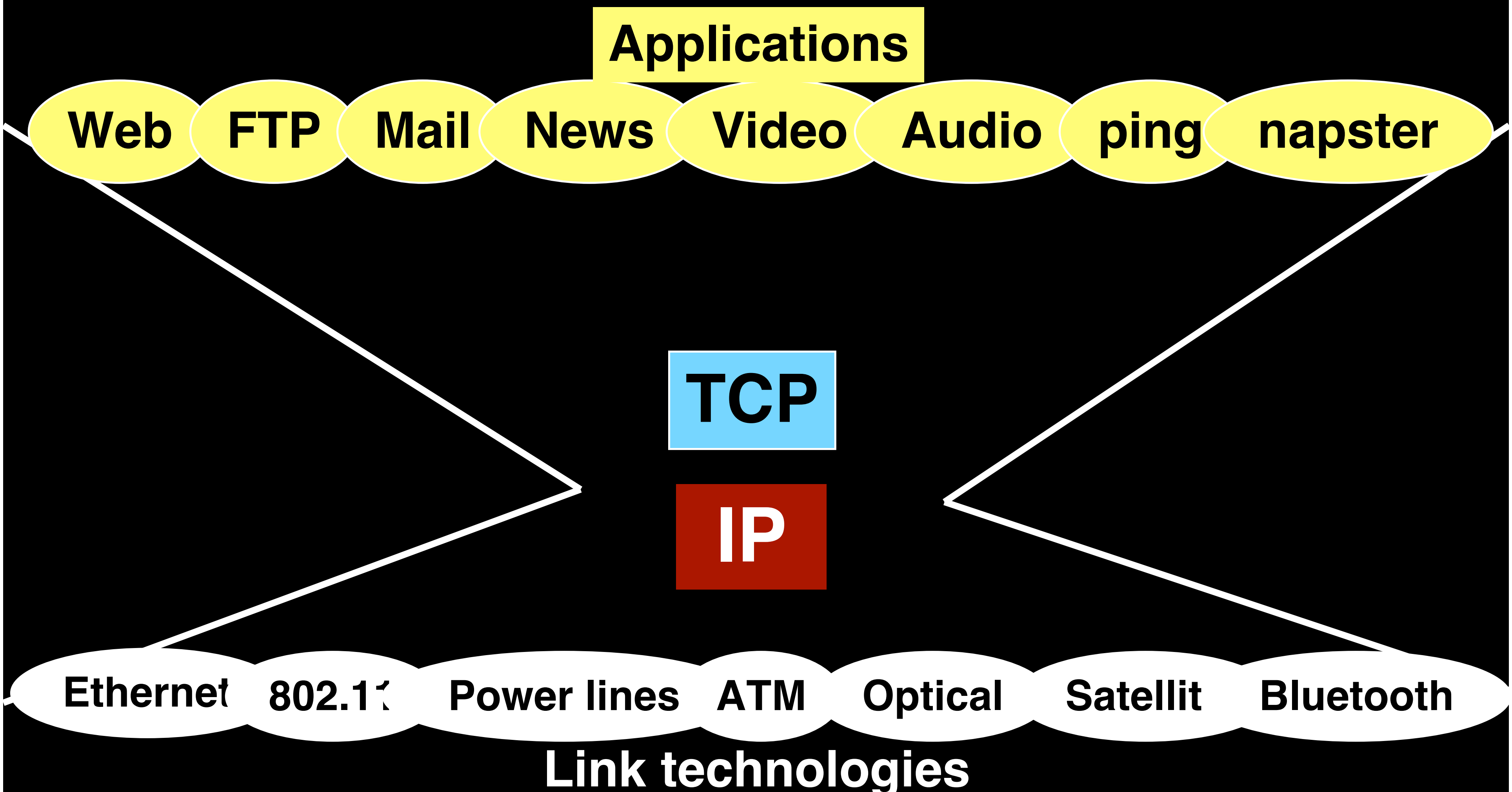
Architecture?

- "*The bacterial cell and the Internet have*
  - *architectures*
  - *that are robust and evolvable*"
- For the Internet, we know how all the parts work, and we can ask the architects

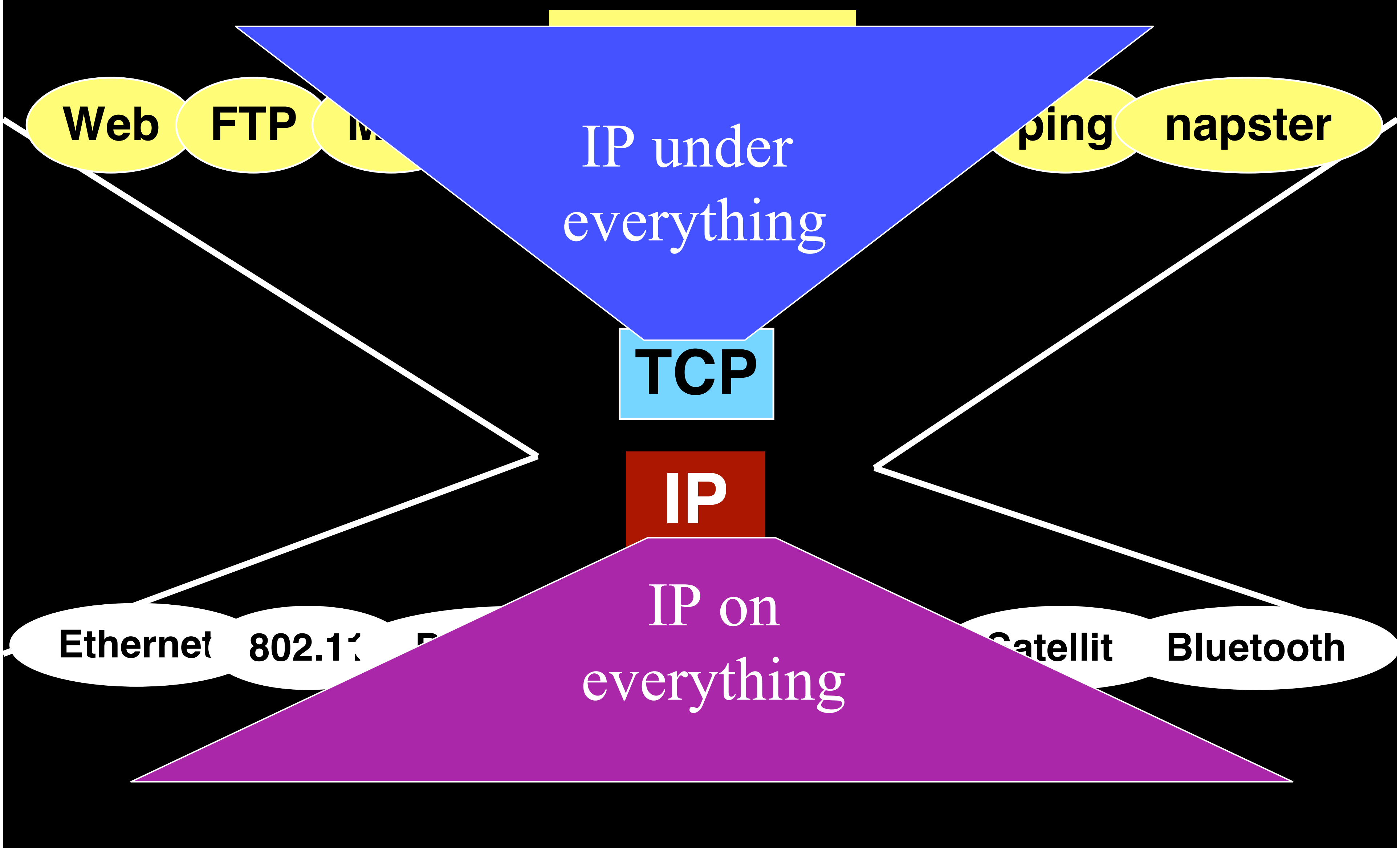
The Internet hourglass

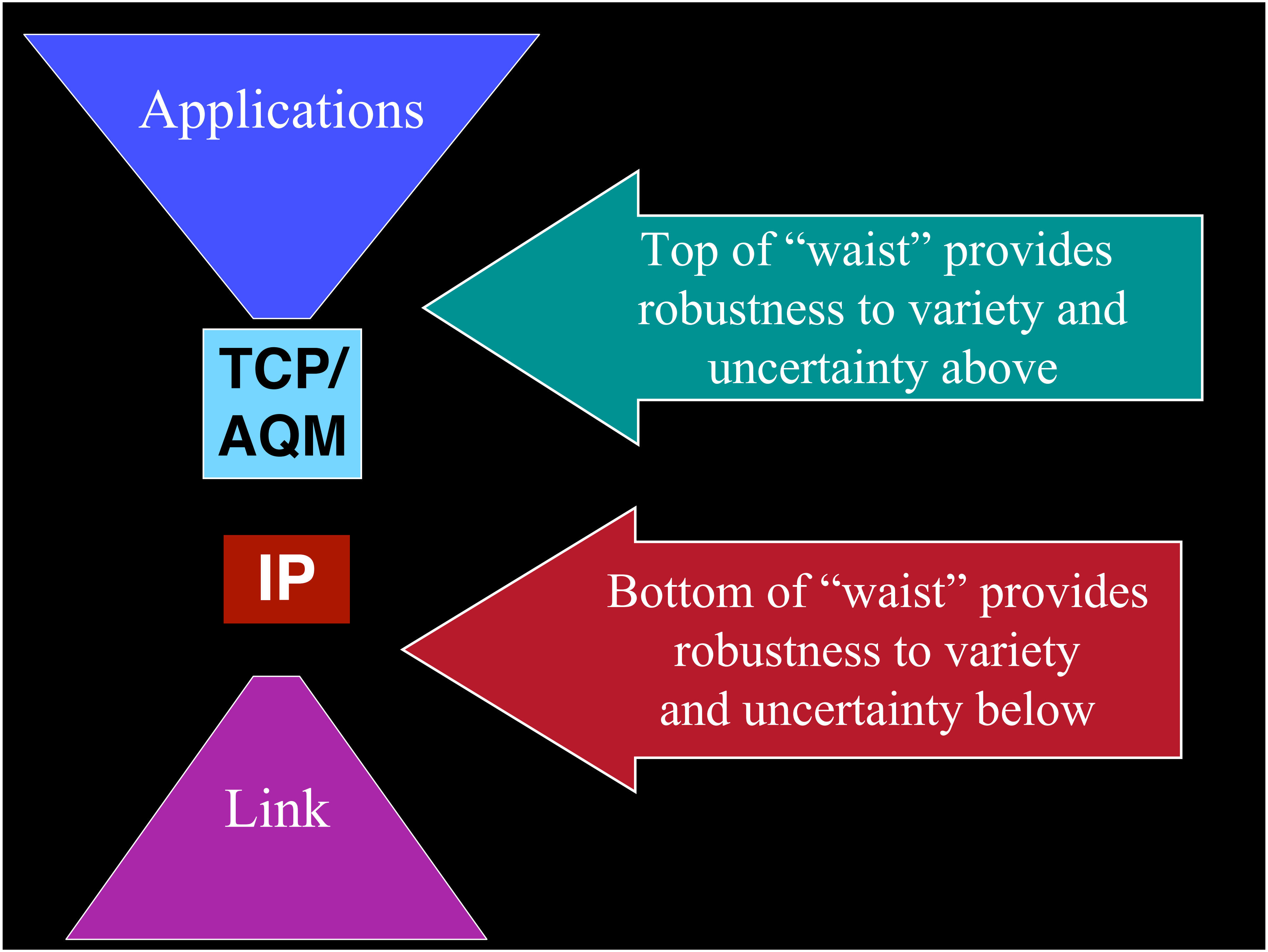


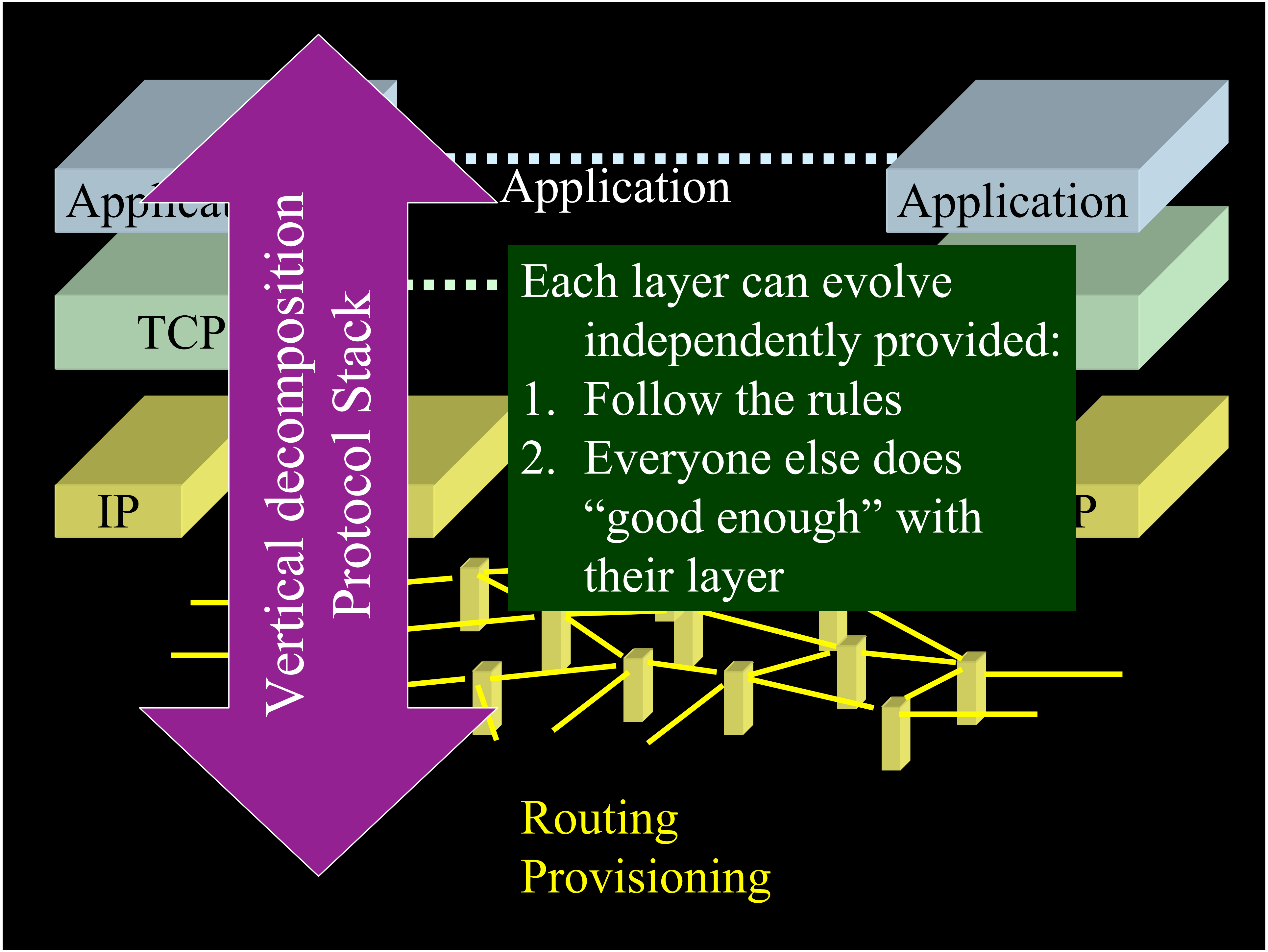
The Internet hourglass

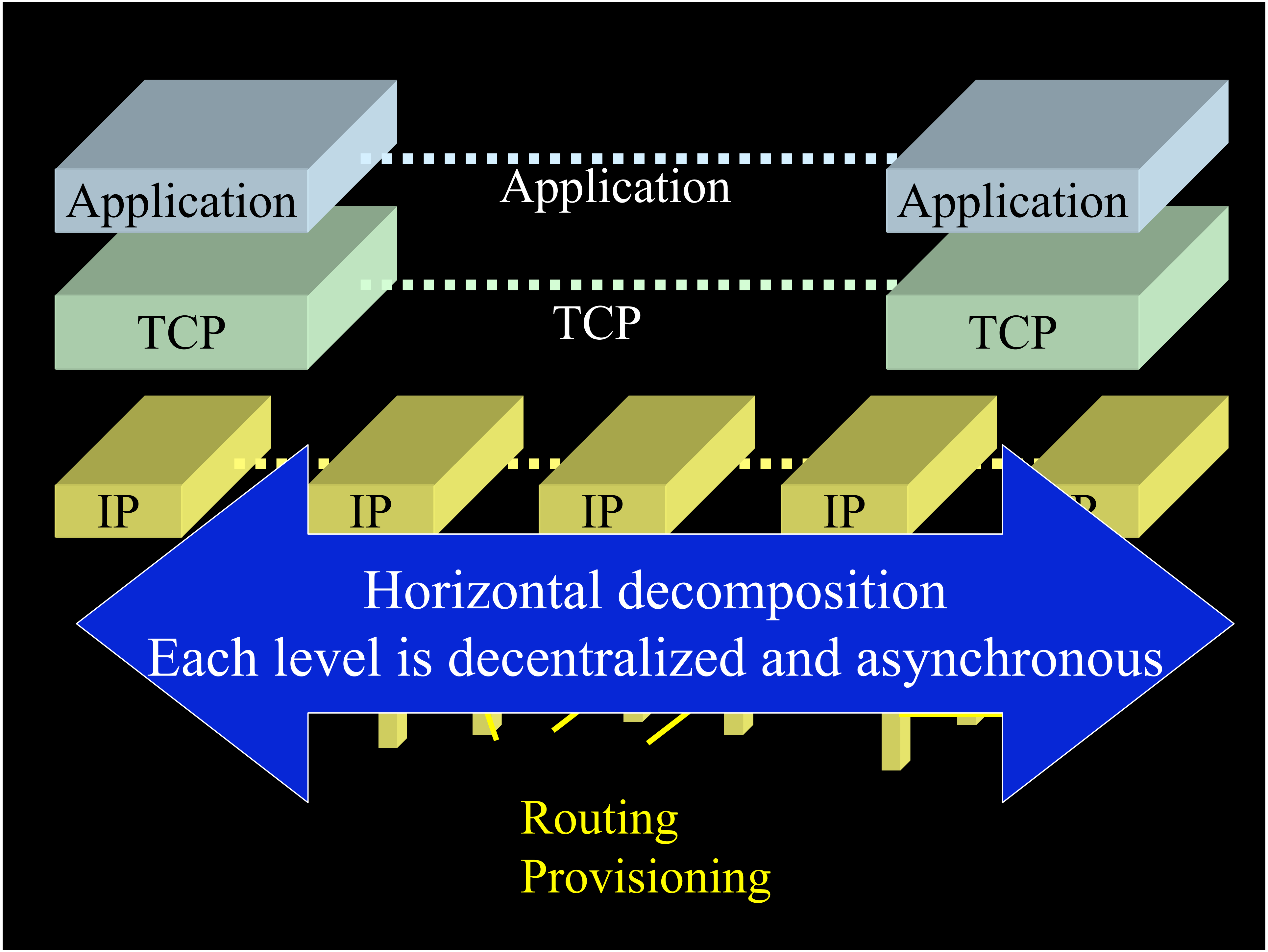


The Internet hourglass



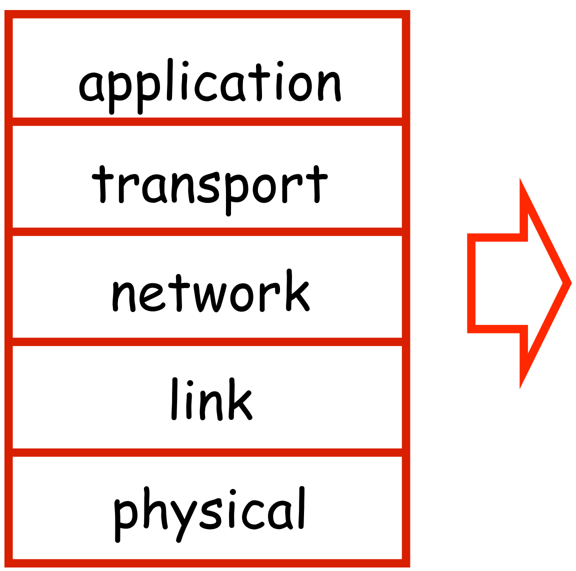

Applications
TCP/
AQM
IP
Link
Top of "waist" provides robustness to variety and uncertainty above
Bottom of "waist" provides robustness to variety and uncertainty below


Application
Application
TCP
IP
Vertical decomposition
Protocol Stack
Each layer can evolve independently provided:
1. Follow the rules
2. Everyone else does "good enough" with their layer
Routing
Provisioning


Application
Application
Application
TCP
TCP
TCP
IP
IP
IP
IP
Horizontal decomposition
Each level is decentralized and asynchronous
Routing
Provisioning

Layering as optimization decomposition

- Each layer is abstracted as an optimization problem
- Operation of a layer is a distributed solution
- Results of one problem (layer) are parameters of others
- Operate at different timescales



$$\max_{x \geq 0} \quad \sum_i U_i(x_i)$$
$$\text{subj to} \quad Rx \leq c(p)$$
$$x \in X$$

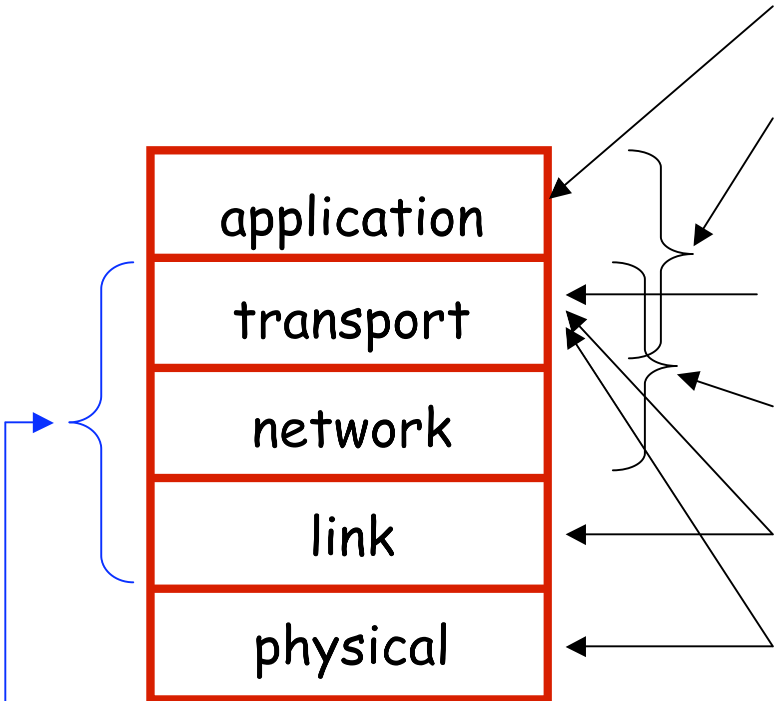
Application: utility

Phy: power

IP: routing

Link: scheduling

Examples



Optimal web layer: Zhu, Yu, Doyle '01

HTTP/TCP: Chang, Liu '04

TCP: Kelly, Maulloo, Tan '98, ...

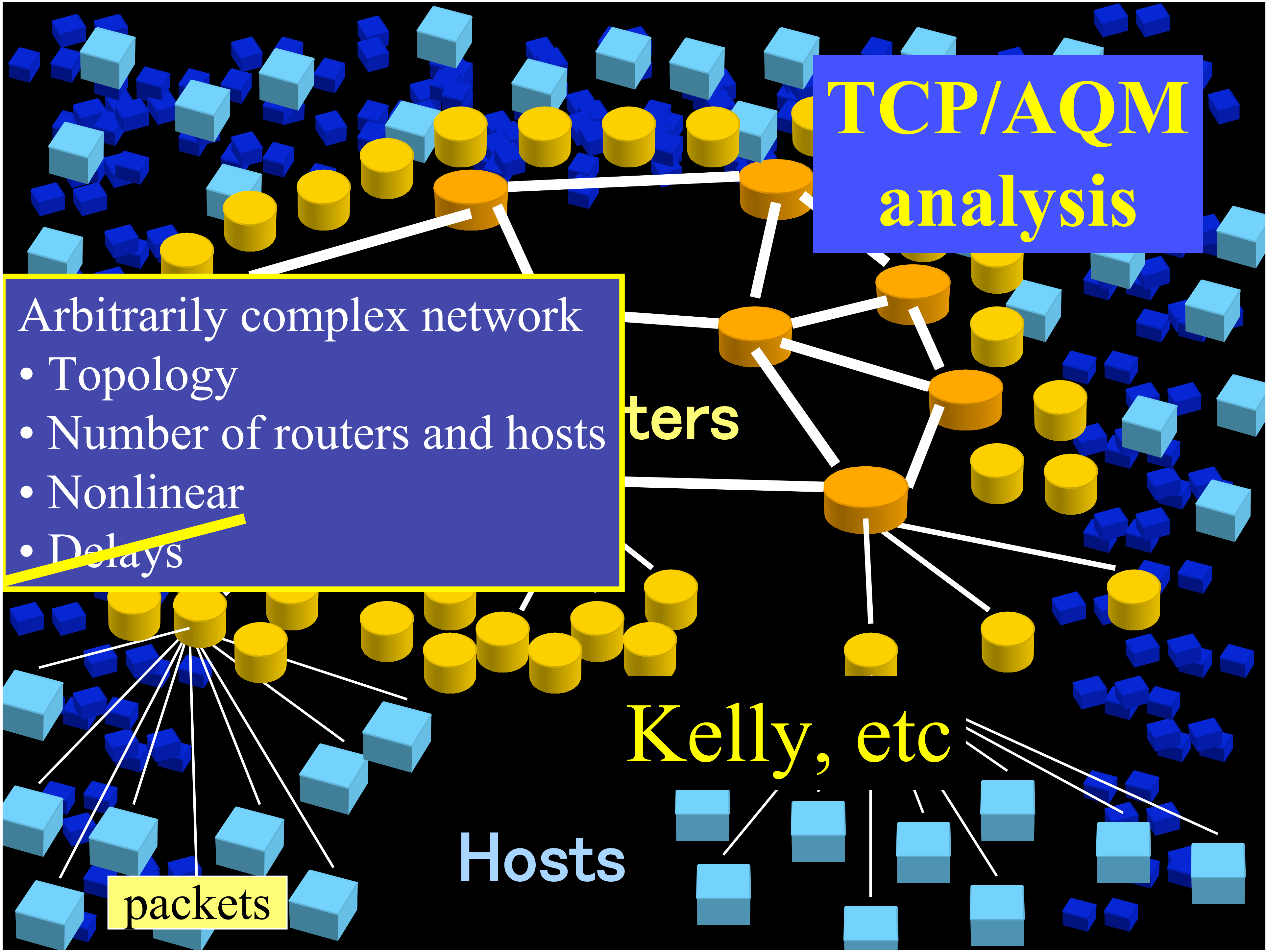
TCP/IP: Wang et al '05, ...

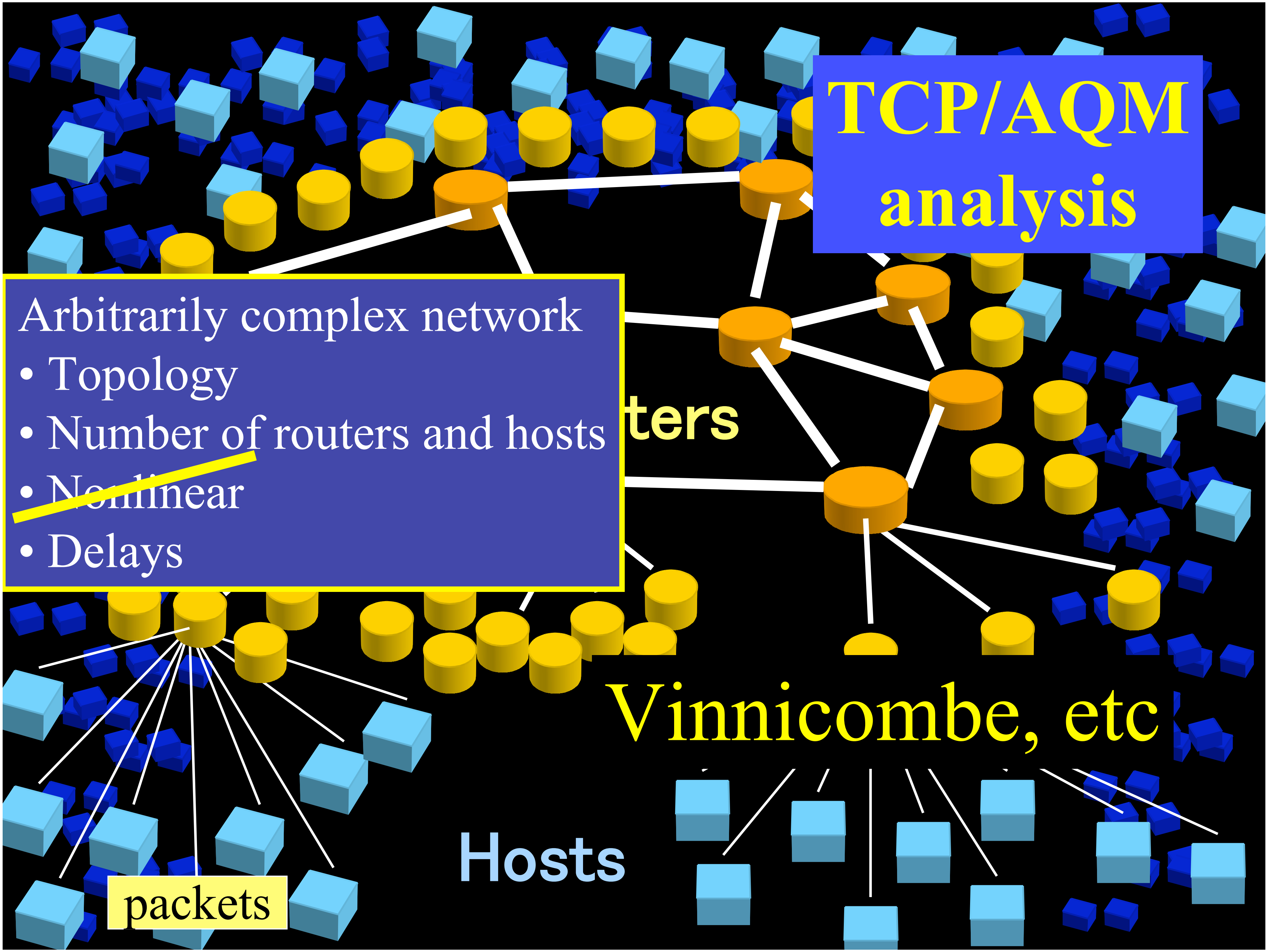
TCP/MAC: Chen et al '05, ...

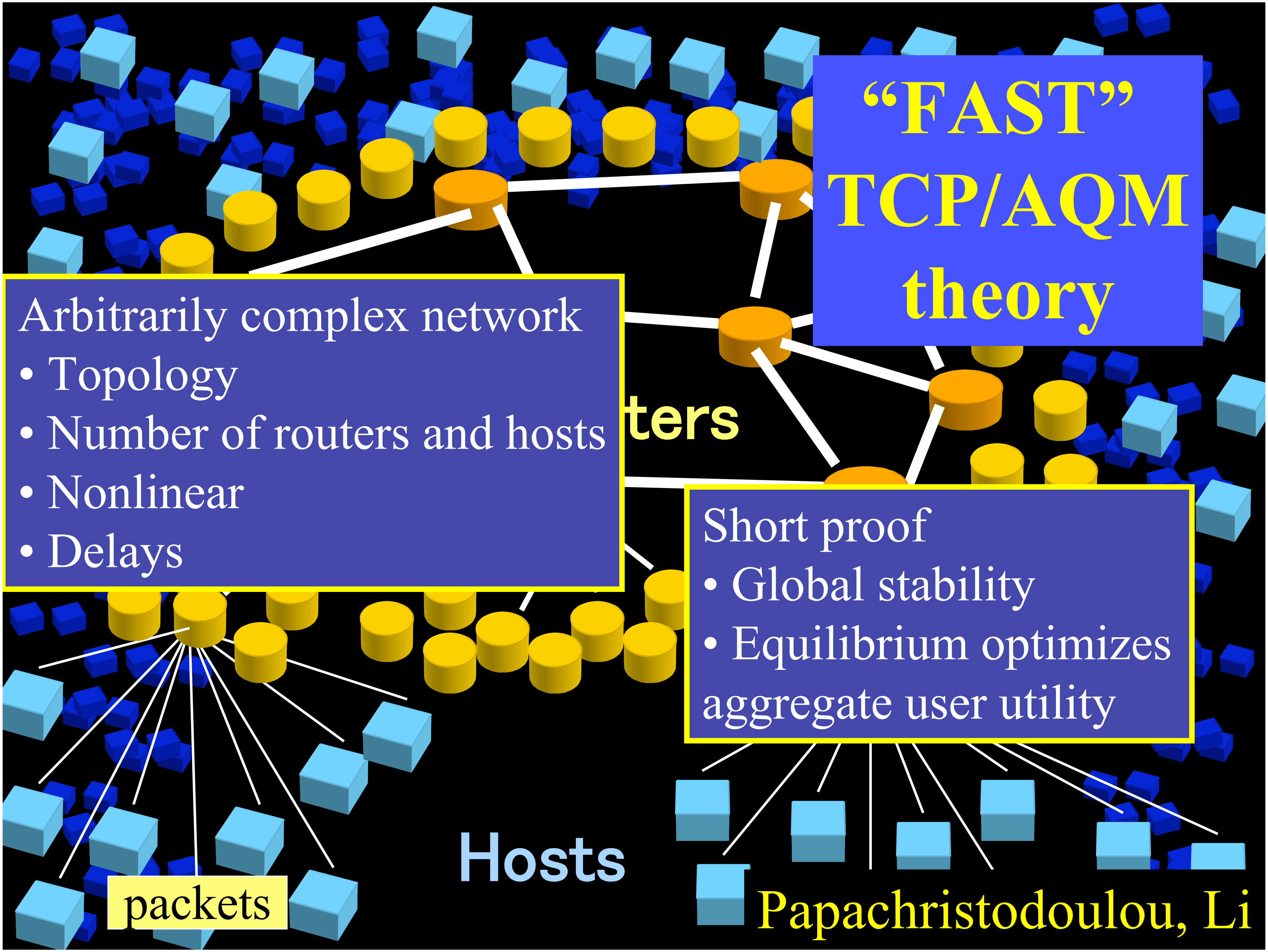
TCP/power control: Xiao et al '01, Chiang '04, ...

Rate control/routing/scheduling: Eryilmax et al '05, Lin et al '05, Neely, et al '05, Stolyar '05, this paper

detailed survey in Proc. of IEEE, 2006


TCP/AQM analysis
Arbitrarily complex network
• Topology
• Number of routers and hosts
• Nonlinear
• Delays
ters
Kelly, etc
Hosts
packets


TCP/AQM analysis
Arbitrarily complex network
• Topology
• Number of routers and hosts
• Nonlinear
• Delays
ters
Vinnicombe, etc
Hosts
packets


"FAST" TCP/AQM theory
Arbitrarily complex network
• Topology
• Number of routers and hosts
• Nonlinear
• Delays
ters
Short proof
• Global stability
• Equilibrium optimizes aggregate user utility
Hosts
packets
Papachristodoulou, Li

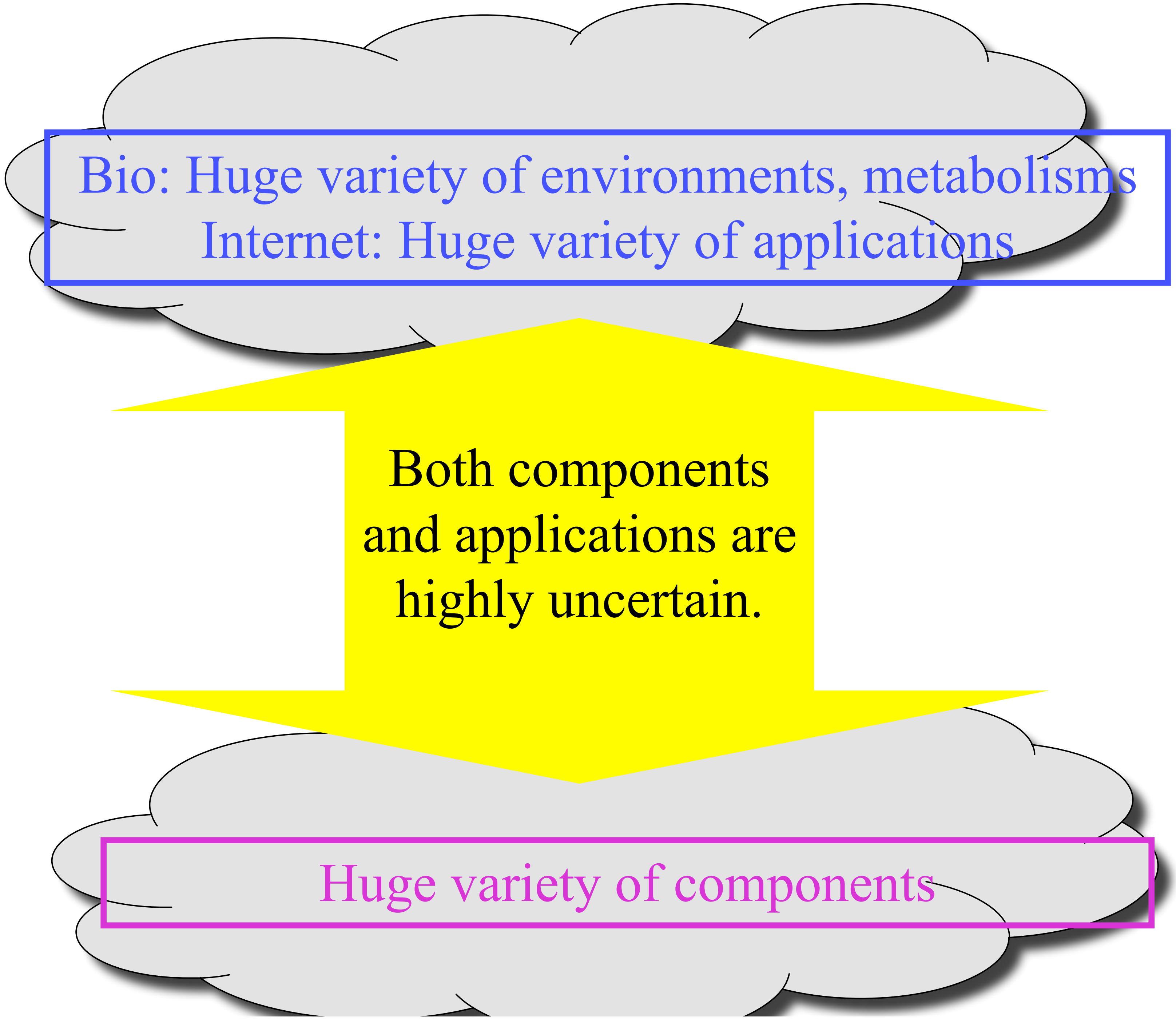
Architecture?

- "*The bacterial cell and the Internet have*
  - *architectures*
  - *that are robust and evolvable*"

- For the Internet, we know how all the parts work, and we can ask the architects
- For biology, we know how some parts work, and evolution is the "architect" (another source of confusion)

Bio: Huge variety of environments, metabolisms
Internet: Huge variety of applications

Huge variety of components


Bio: Huge variety of environments, metabolisms
Internet: Huge variety of applications
Both components and applications are highly uncertain.
Huge variety of components

Bio: Huge variety of environments, metabolisms
Internet: Huge variety of applications

Huge variety of genomes
Huge variety of physical networks

Huge variety of components

Hourglass architectures

Bio: Huge variety of environments, metabolisms
Internet: Huge variety of applications

Feedback control

Identical control architecture

Huge variety of genomes
Huge variety of physical networks

Huge variety of components

TCP/IP

Metabolism/biochem

5:Application/function: variable supply/demand

4:TCP

Feedback Control

4:Allosteric

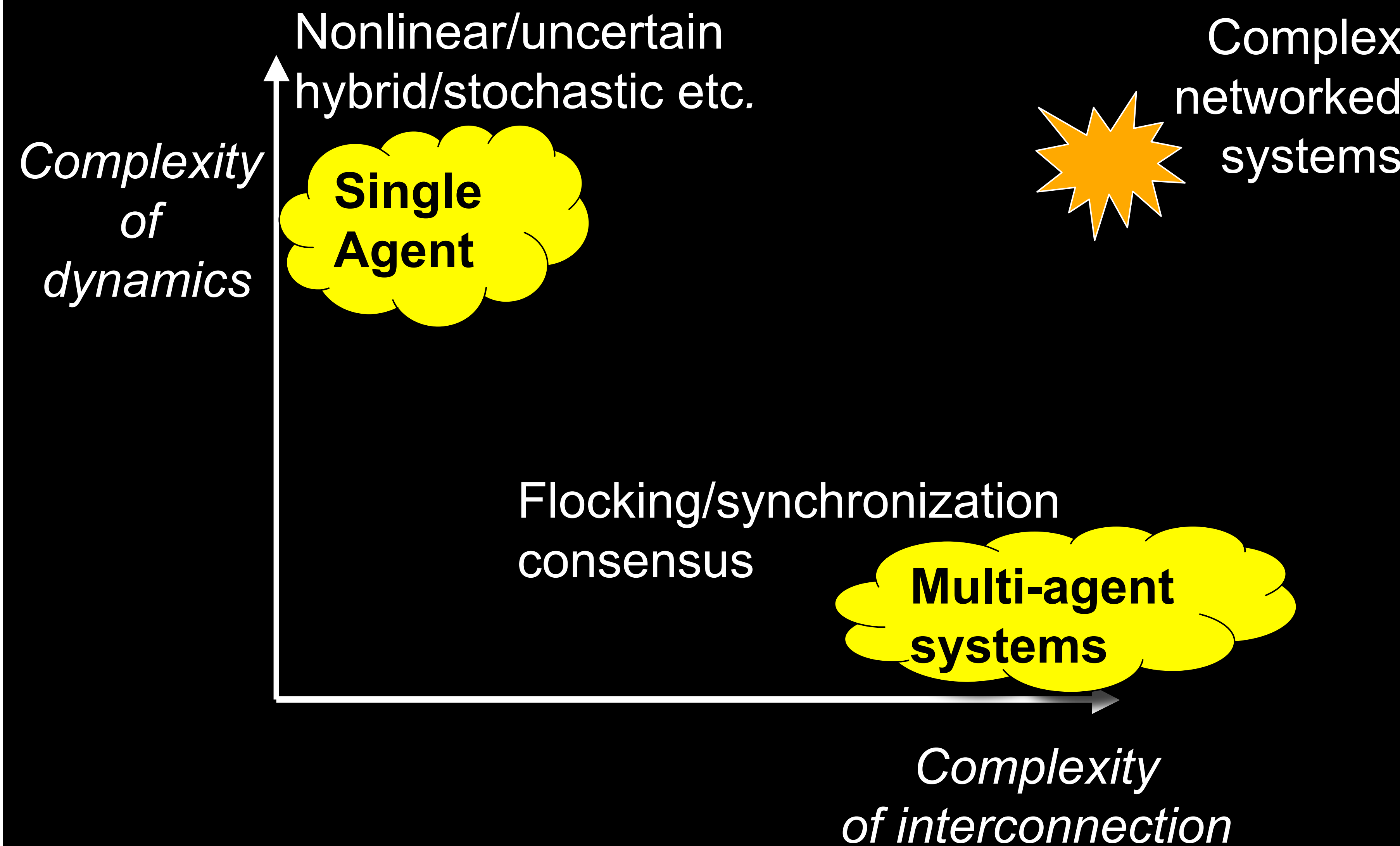
3:IP

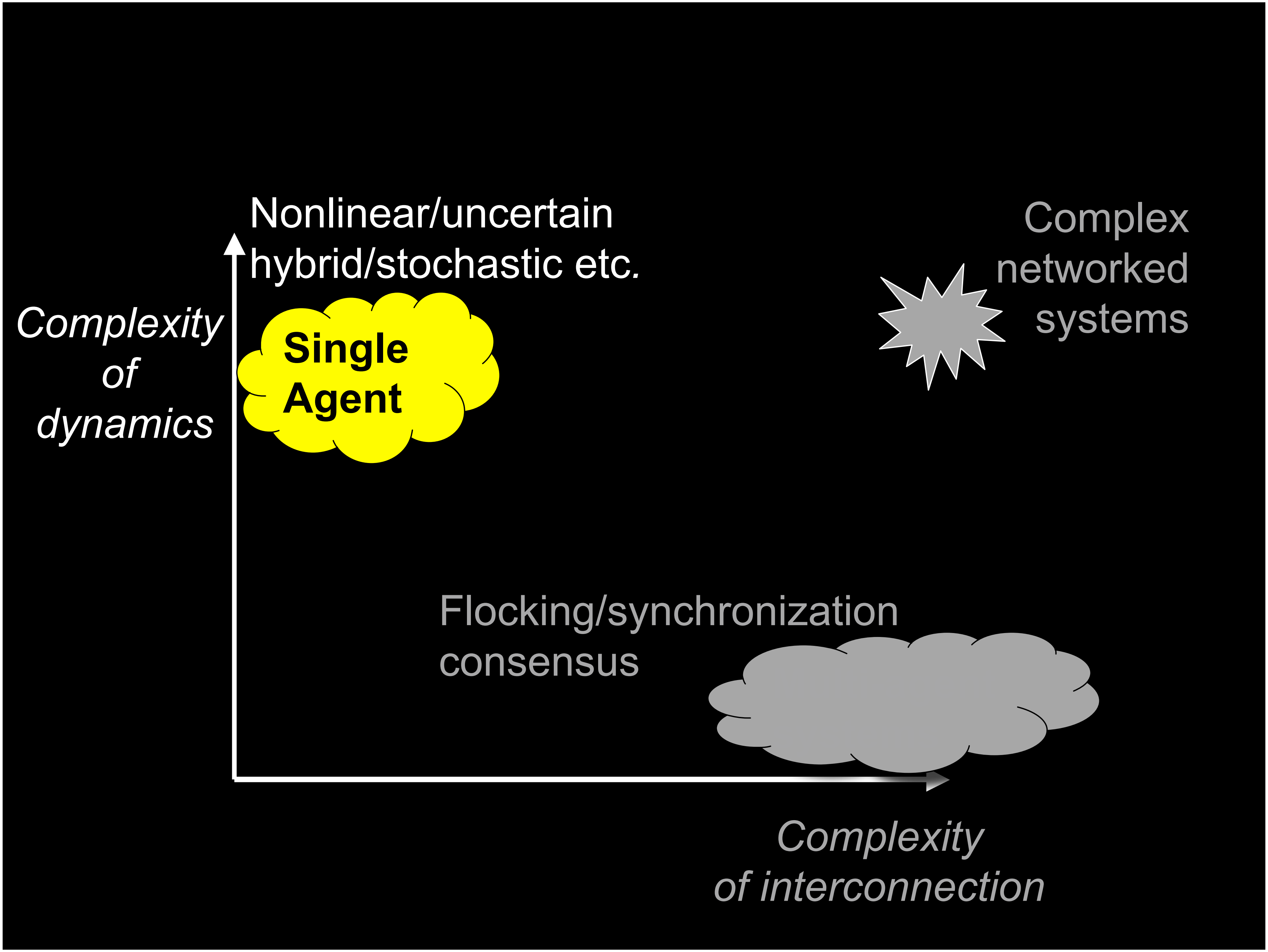
3:Transcriptional

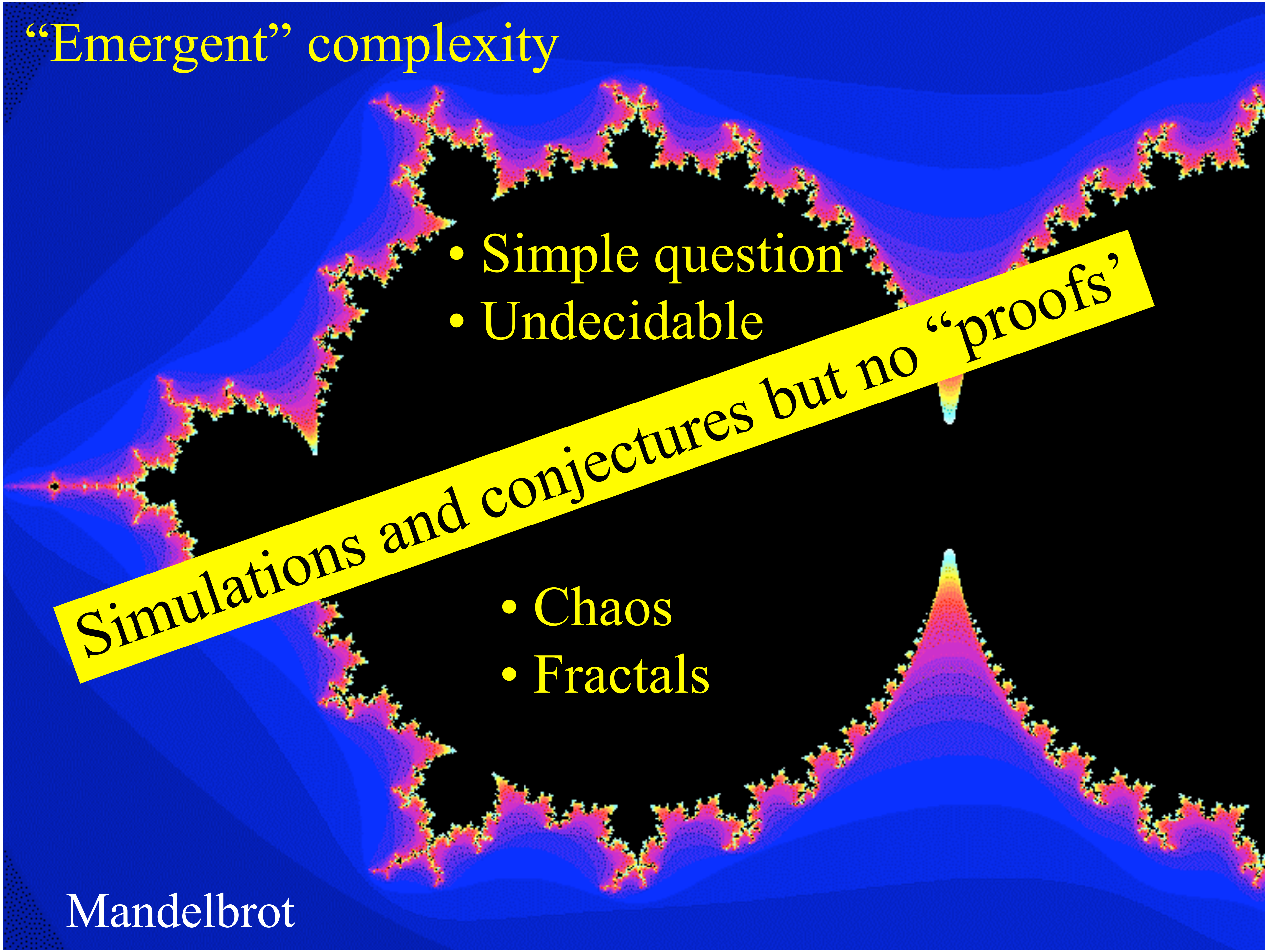
2:Potential physical network

1:Hardware components

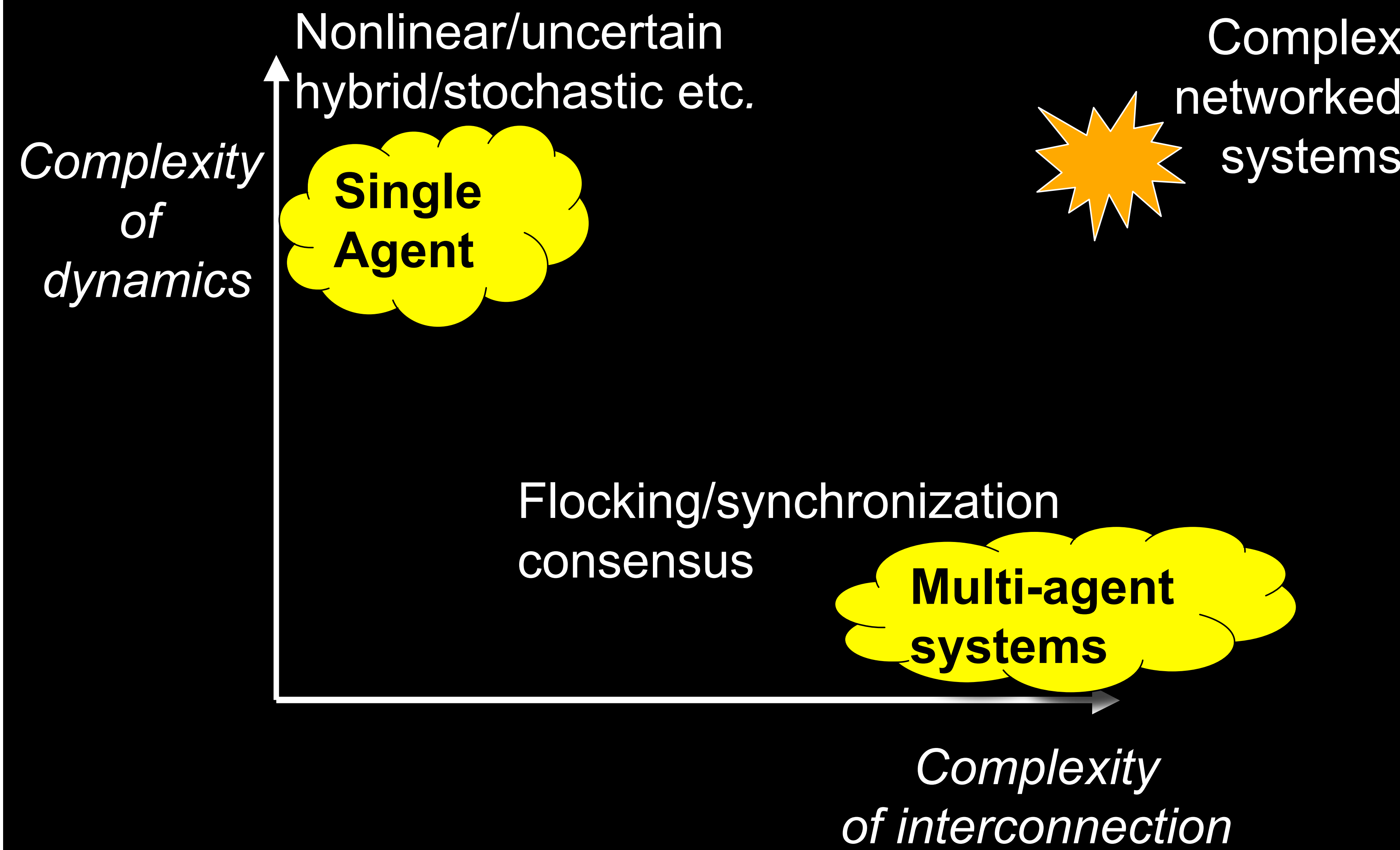
Networked dynamical systems

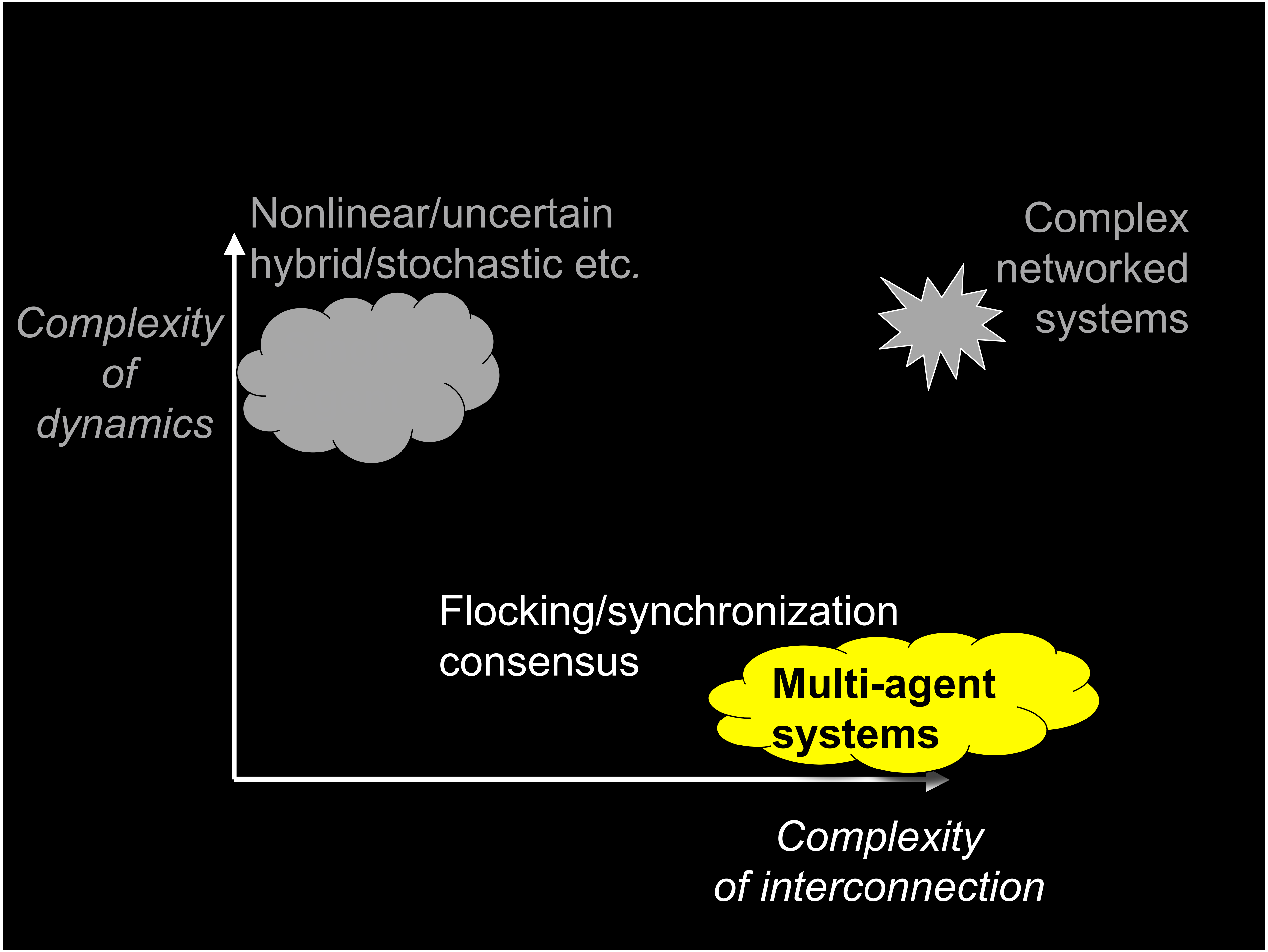



Nonlinear/uncertain
hybrid/stochastic etc.
Complexity
of
dynamics
Single
Agent
Complex
networked
systems
Flocking/synchronization
consensus
Complexity
of interconnection

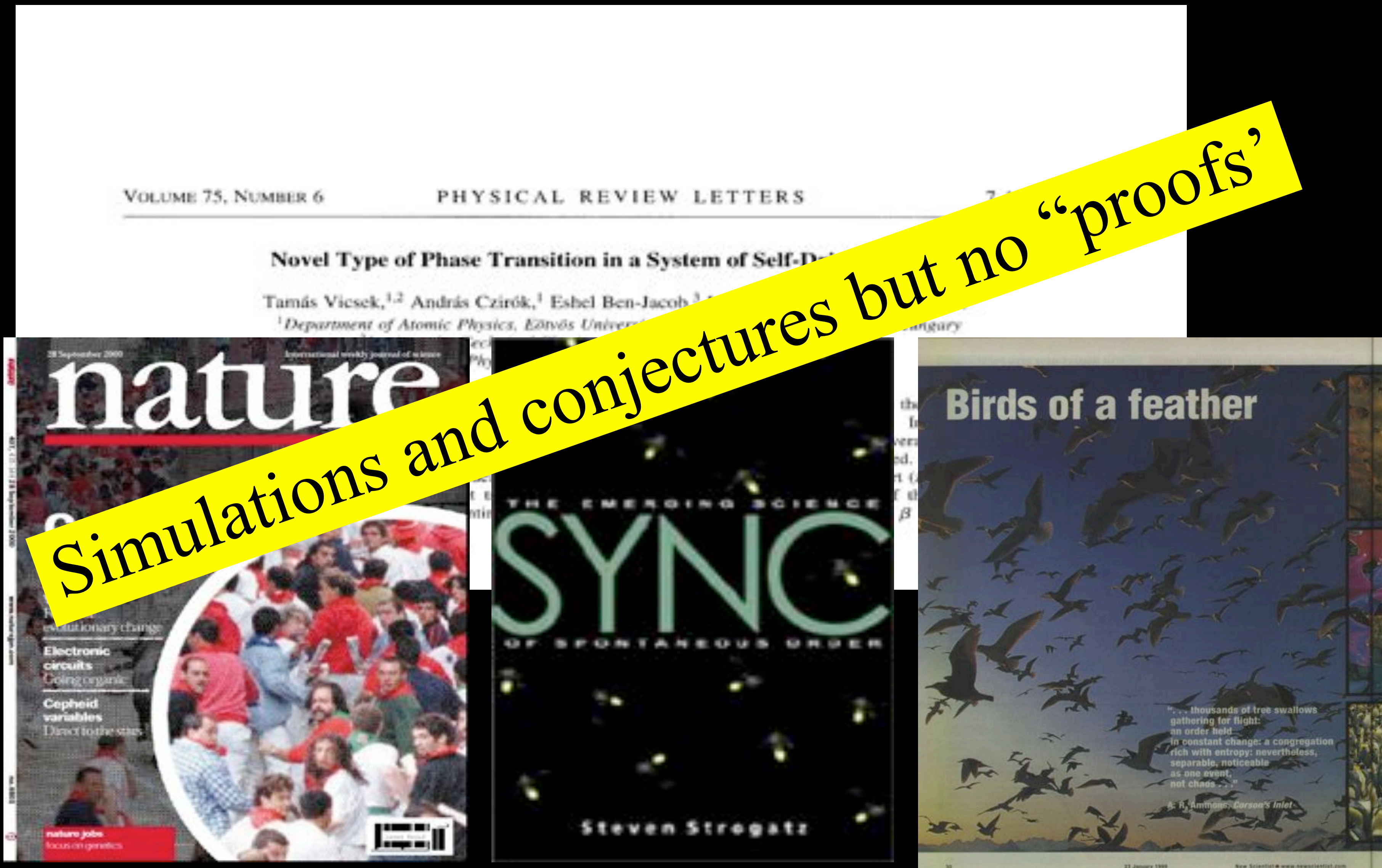

"Emergent" complexity
• Simple question
• Undecidable
Simulations and conjectures but no "proofs'
• Chaos
• Fractals
Mandelbrot

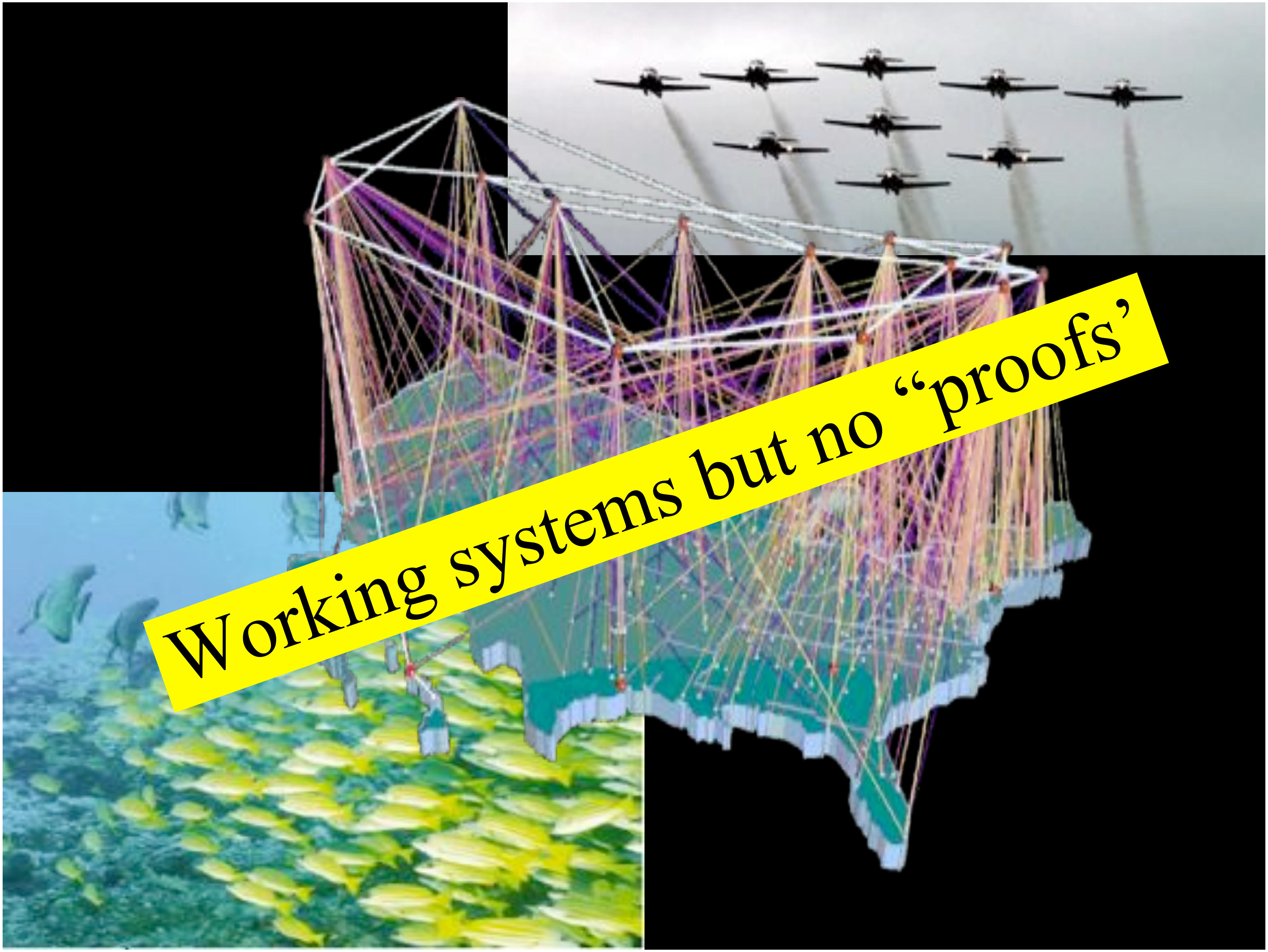
Networked dynamical systems



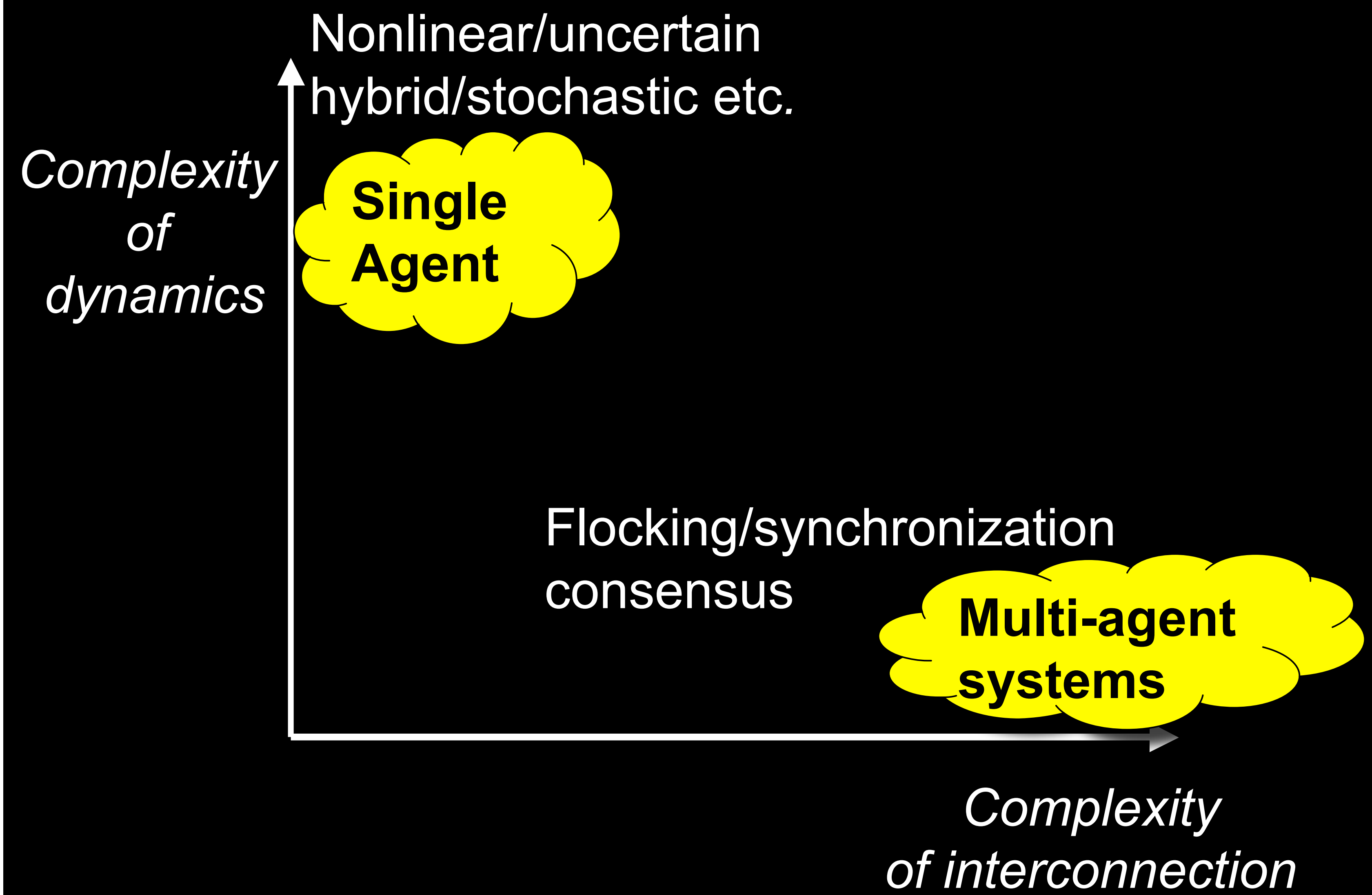

Nonlinear/uncertain
hybrid/stochastic etc.
Complex
networked
systems
Complexity
of
dynamics
Flocking/synchronization
consensus
Multi-agent
systems
Complexity
of interconnection

Statistical Physics and emergence of collective behavior

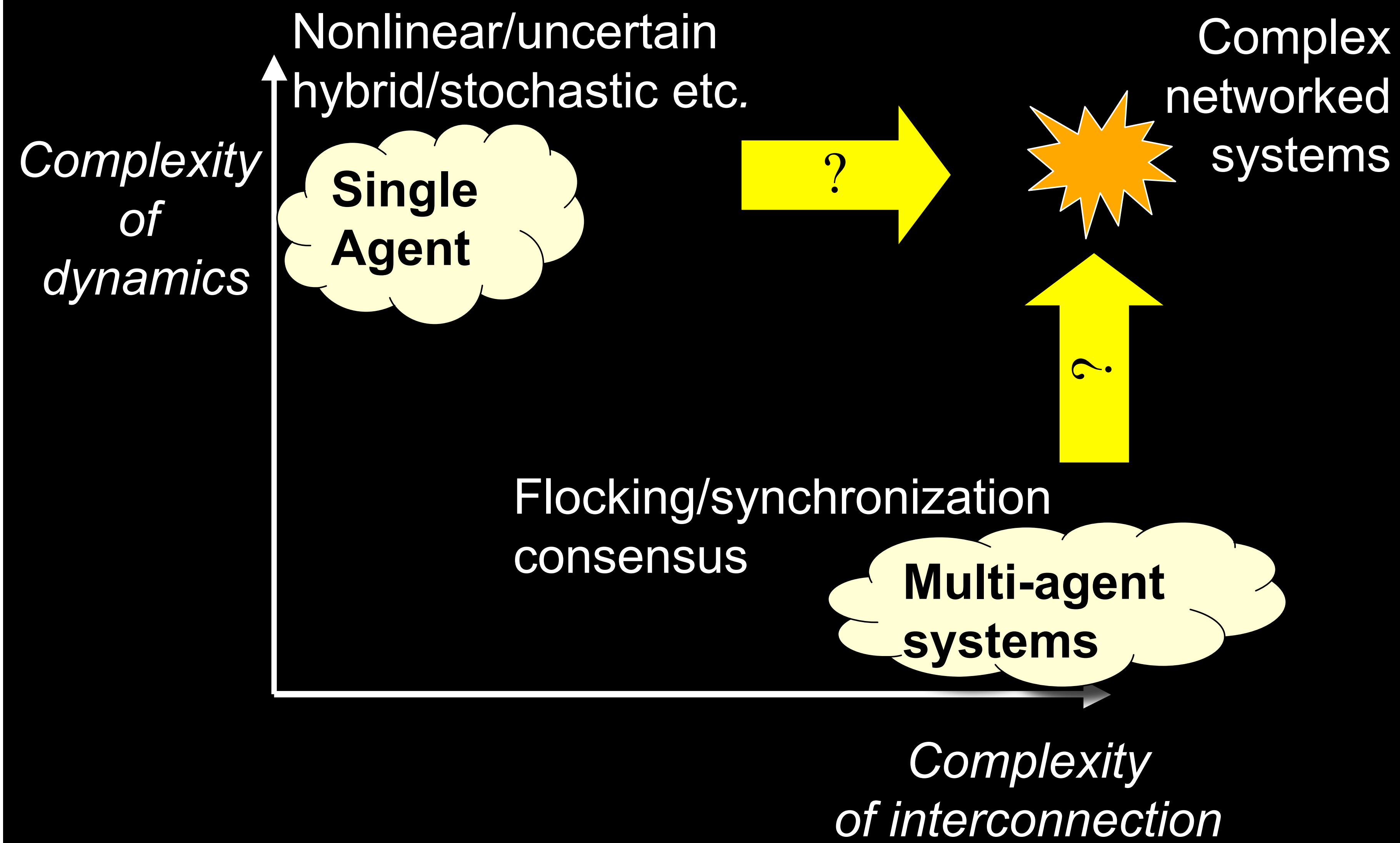



Working systems but no “proofs’

Spectacular progress



Open questions



Core theory challenges

- Hard limits
- Short proofs
- Small models

- Architecture

Today’s tutorial

- Hard limits (morning)
- Short proofs (afternoon)
- Small models

- Architecture

- Common background, standard results