Universals and fundamentals

- Network architecture? Complexity? Robustness?
- Lots of appealing ideas, few fundamentals
- Can we change this?
- Theory: Fundamental laws, constraints, tradeoffs
- Illustrate with “simple” and familiar case studies whenever possible
- Start with Internet but expand our thinking outside networking

John Doyle

John G Braun Professor

Control and Dynamical System, Electrical Engineering, BioEngineering

Caltech

Laws, more laws, and architecture

- Conservation laws, constraints, hard limits
  - Important tradeoffs are *between*
  - Control, computation, communication, energy, materials, measurement
  - Existing theory is fragmented and incompatible
  - Continuing progress on unifications
- Power laws, data, models, high variability
- Architecture= “constraints that deconstrain”
  - Expand “layering as optimization”
  - Achieving hard limits

IEEE TRANS ON SYSTEMS, MAN, AND CYBERNETICS, JULY 2010

Alderson and Doyle

Contrasting Views of Complexity and Their Implications For Network-Centric Infrastructures

David L. Alderson, *Member, IEEE*, and John C. Doyle

***Abstract*—There exists a widely recognized need to better understand and manage complex "systems of systems," ranging from biology, ecology, and medicine to network-centric technologies. This is motivating the search for universal laws of highly evolved systems and driving demand for new mathematics and methods that are consistent, integrative, and predictive. However, the theoretical frameworks available today are not merely fragmented but sometimes contradictory and incompatible. We argue that complexity arises in highly evolved biological and technological systems primarily to provide mechanisms to create robustness. However, this complexity itself can be a source of new fragility, leading to "robust yet fragile" tradeoffs in system design. We focus on the role of robustness and architecture in networked infrastructures, and we highlight recent advances in the theory of distributed control driven by network technologies. This view of complexity in highly organized technological and biological systems is fundamentally different from the dominant perspective in the mainstream sciences, which downplays function, constraints, and tradeoffs, and tends to minimize the role of organization and design.**

***Index Terms*—Architecture, complexity theory, networks, optimal control, optimization methods, protocols.**

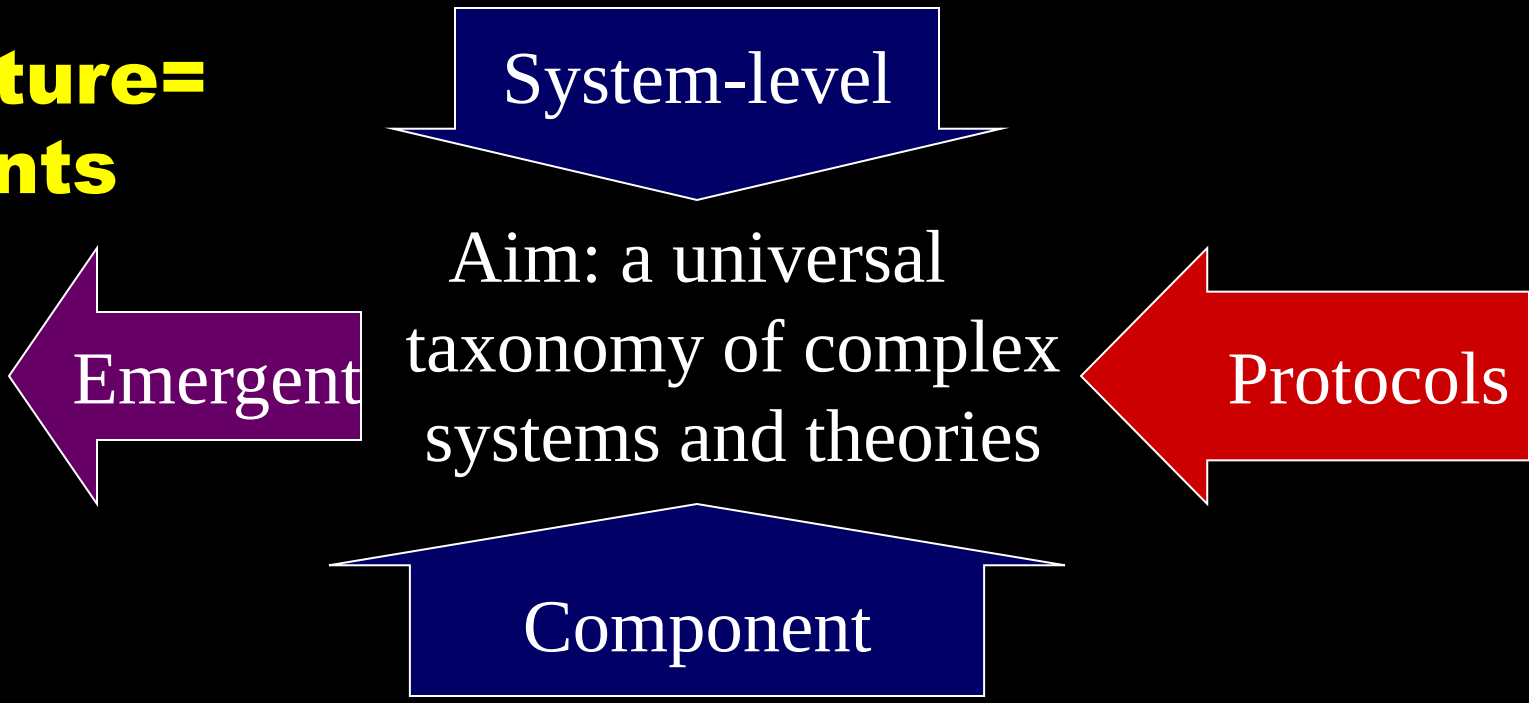
other complex engineering systems, but much of advanced technology has, if anything, made things worse. Computer-based simulation and rapid prototyping tools are now broadly available and powerful enough that it is relatively easy to demonstrate almost anything, provided that conditions are made sufficiently idealized. We are much better at designing, mass-producing, and deploying network-enabled devices than we are at being able to predict or control their collective behavior once deployed in the real world. The result is that, when things fail, they often do so cryptically and catastrophically.

The growing need to understand and manage complex systems of systems, ranging from biology to technology, is creating demand for new mathematics and methods that are consistent and integrative. Yet, there exist fundamental incompatibilities in available theories for addressing this challenge. Various "new sciences" of "complexity" and "networks" dominate the mainstream sciences [3] but are at best disconnected from medicine, mathematics, and engineering. Computing, communication, and control theories and technologies flourish but

“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

Architecture= Constraints

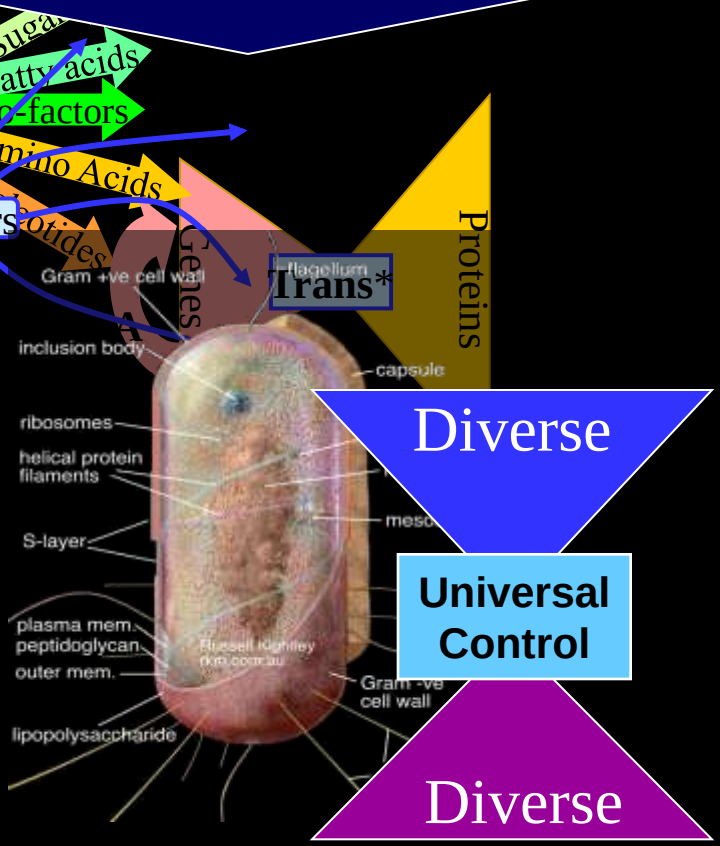


- Describe systems/components in terms of constraints on what is possible
- Decompose constraints into component, system-level, protocols, and emergent
- Not necessarily unique, but hopefully illuminating nonetheless

Systems requirements:
functional, efficient,
robust, evolvable

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

Constraints



Diverse

Universal Control

Diverse

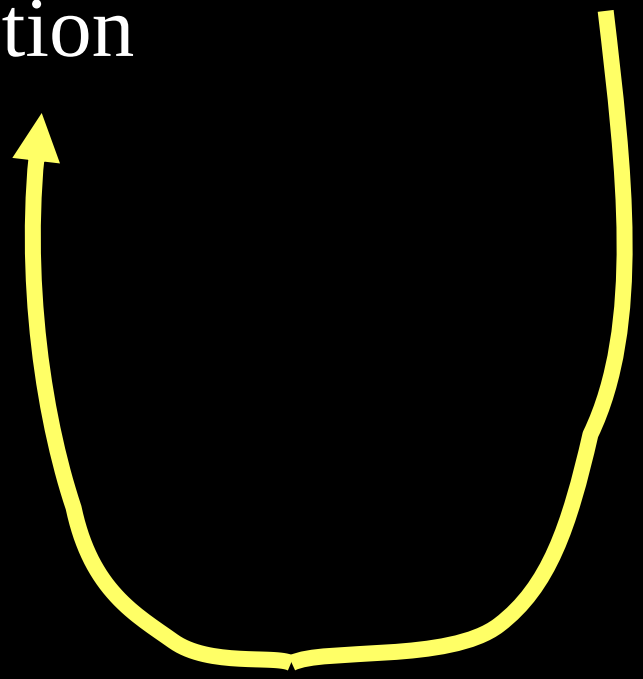
Protocols

Components and materials:
Energy, moieties

In the real (vs virtual) world

What matters:

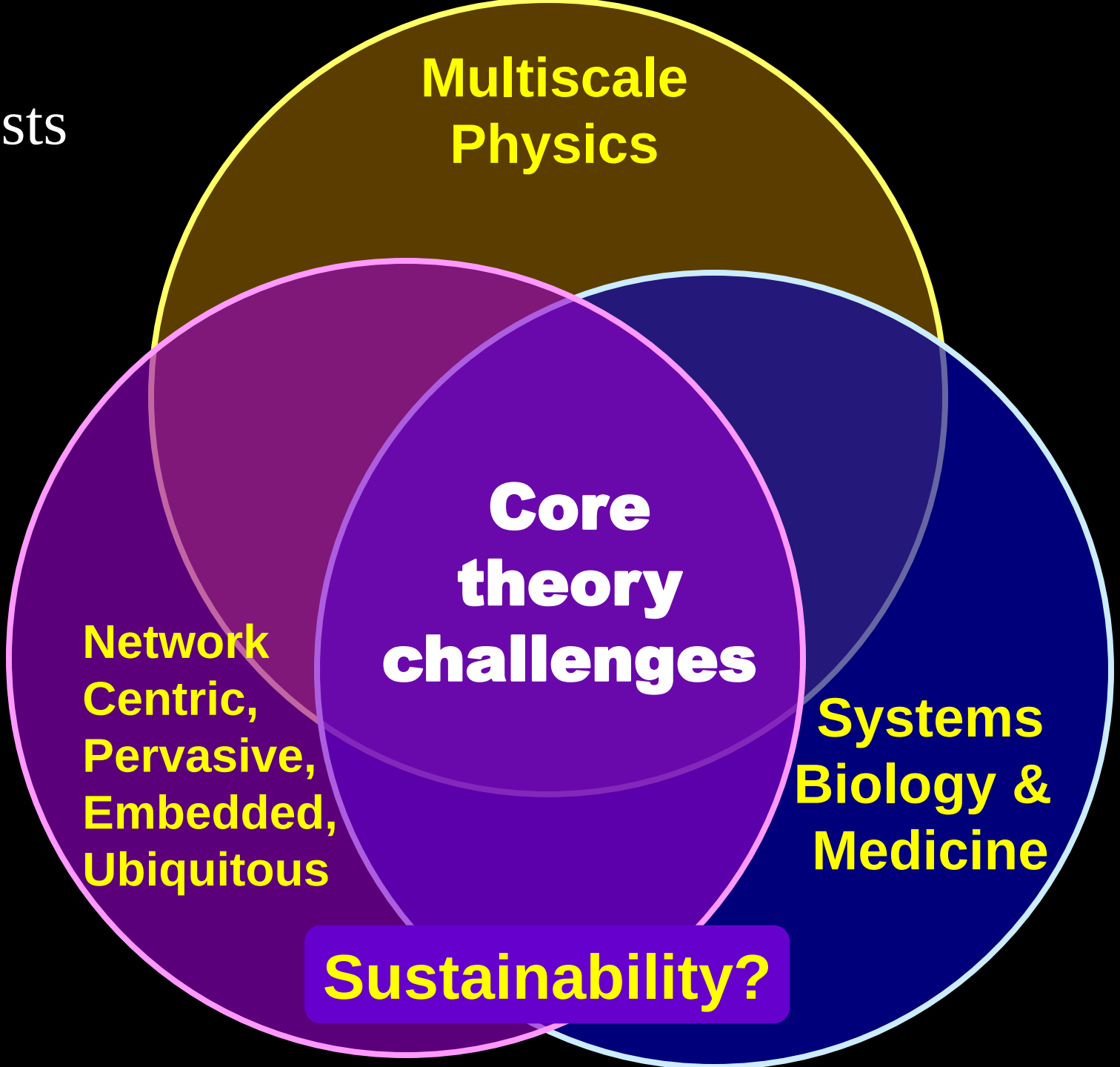
- Action



What doesn’t:

- Data
- Information
- Computation
- Learning
- Decision
- …

My interests



Human complexity?

Robustness?

Fragility?

Human complexity

Robust	Fragile
☺ Metabolism	☹ Obesity, diabetes
☺ Regeneration & repair	☹ Cancer
☺ Healing wound /infect	☹ AutoImmune/Inflame

Mechanism?

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

What's the difference?

Robust

- ☺ Metabolism
- ☺ Regeneration & repair
- ☺ Healing wound /infect

Fragile

- ☹ Obesity, diabetes
- ☹ Cancer
- ☹ AutoImmune/Inflame

- ☹ Fat accumulation
- ☹ Insulin resistance
- ☹ Proliferation
- ☹ Inflammation

Static energy

Accident or necessity?

What's the difference?

Robust

- ☺ Metabolism
- ☺ Regeneration & repair
- ☺ Healing wound /infect

Fragile

- ☹ Obesity, diabetes
- ☹ Cancer
- ☹ AutoImmune/Inflame

- ☹ Fat accumulation
- ☹ Insulin resistance
- ☹ Proliferation
- ☹ Inflammation

Controlled
Dynamic

Low mean
High variability

Uncontrolled
Chronic

High mean
Low variability

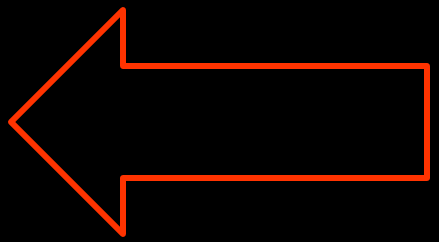
Restoring robustness

Robust

Fragile

Controlled
Dynamic

Low mean
High variability



Uncontrolled
Chronic

High mean
Low variability

Mechanism?

Robust

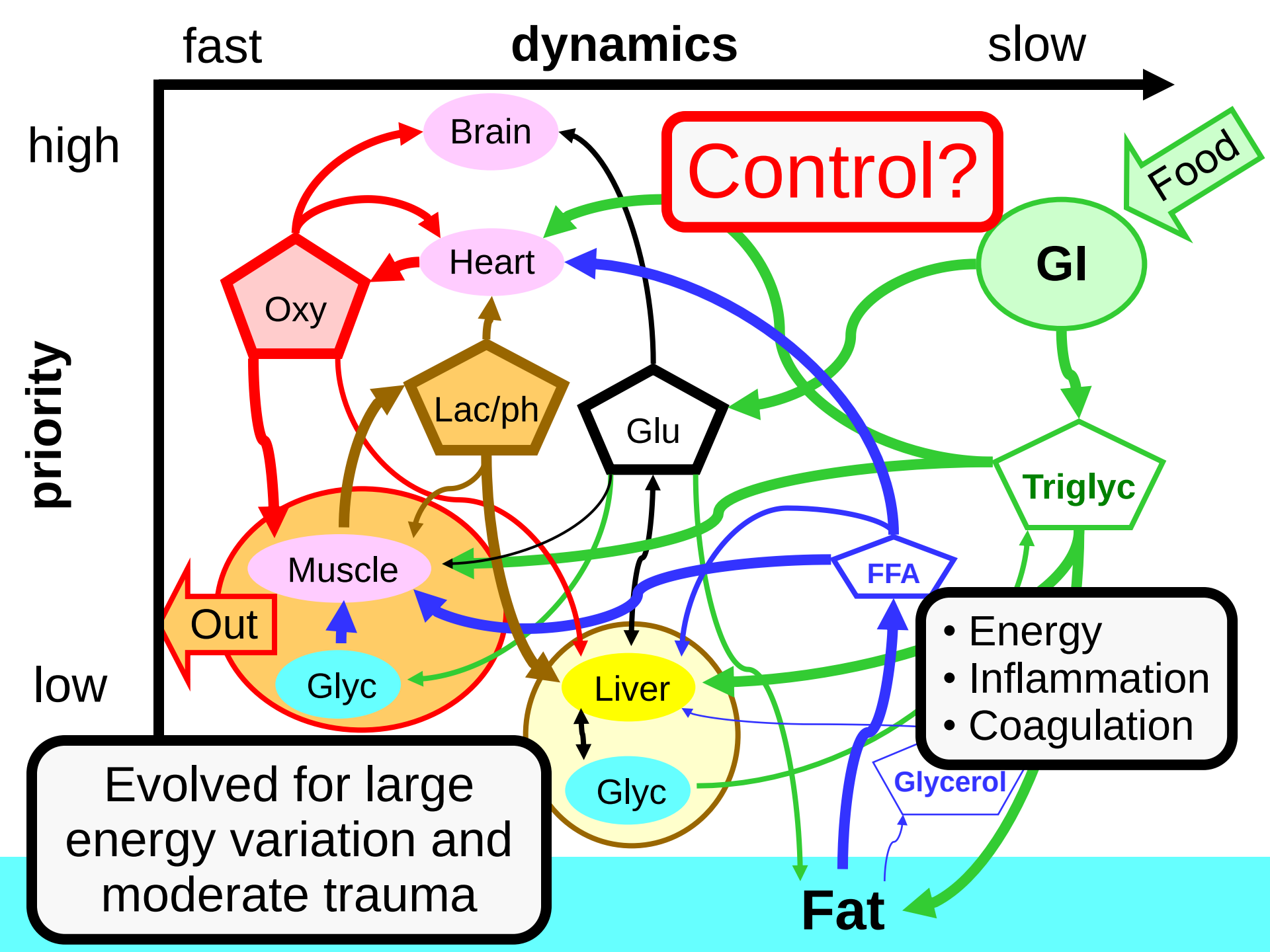
☺ Metabolism
☺ Regeneration & repair
☺ Healing wound /infect

☹ Fat accumulation
☹ Insulin resistance
☹ Proliferation
☹ Inflammation

Controlled
Dynamic

Low mean
High variability

Fluctuating energy


fast
dynamics
slow
high
priority
low
Brain
Control?
Food
Heart
Oxy
GI
Lac/ph
Glu
Triglyc
Muscle
FFA
Out
Glyc
Liver
• Energy
• Inflammation
• Coagulation
Glyc
Glycerol
Fat
Evolved for large energy variation and moderate trauma

Human complexity

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

Accident or necessity?

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

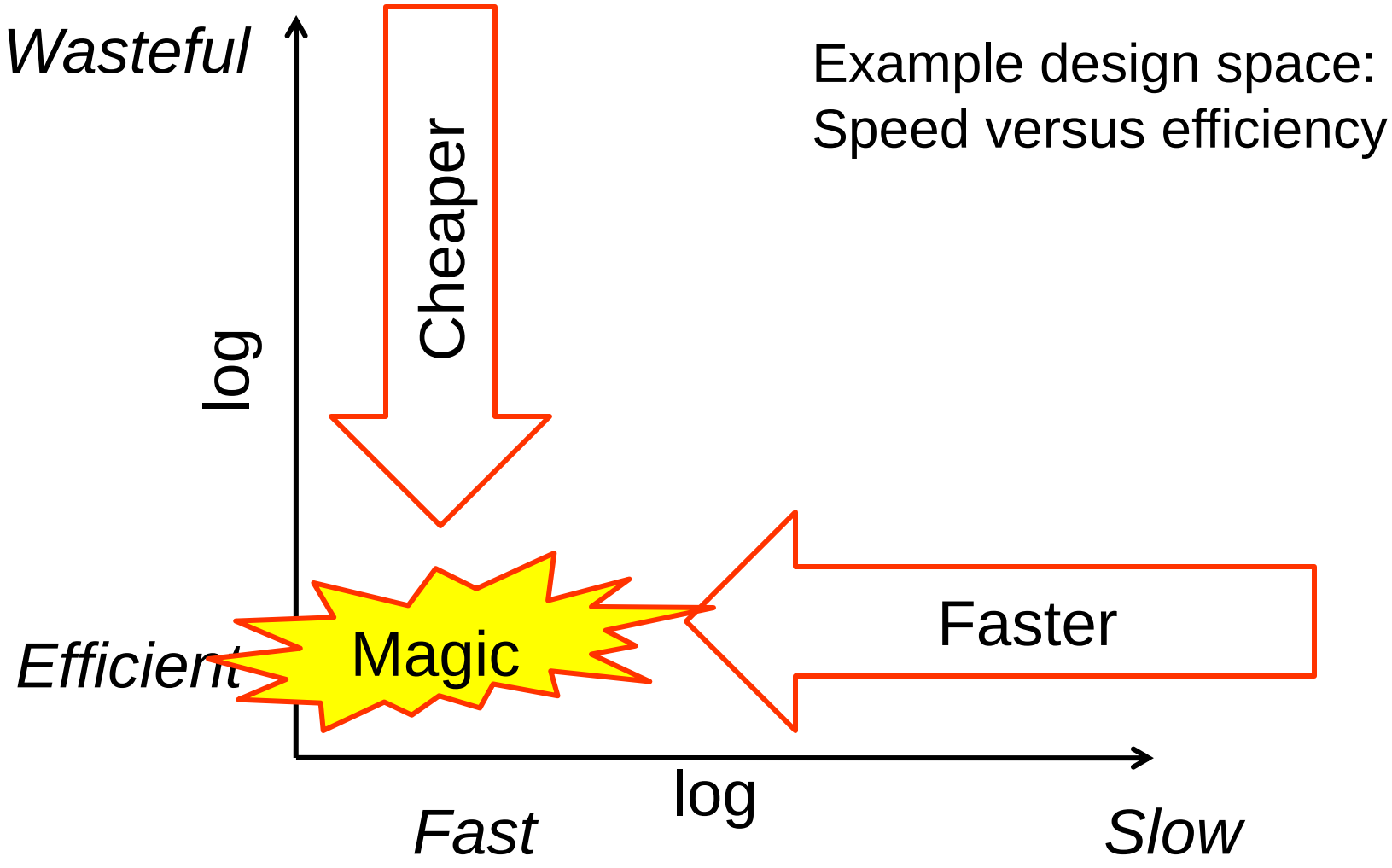
☹ Fat accumulation
☹ Insulin resistance
☹ Proliferation
☹ Inflammation

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

Both

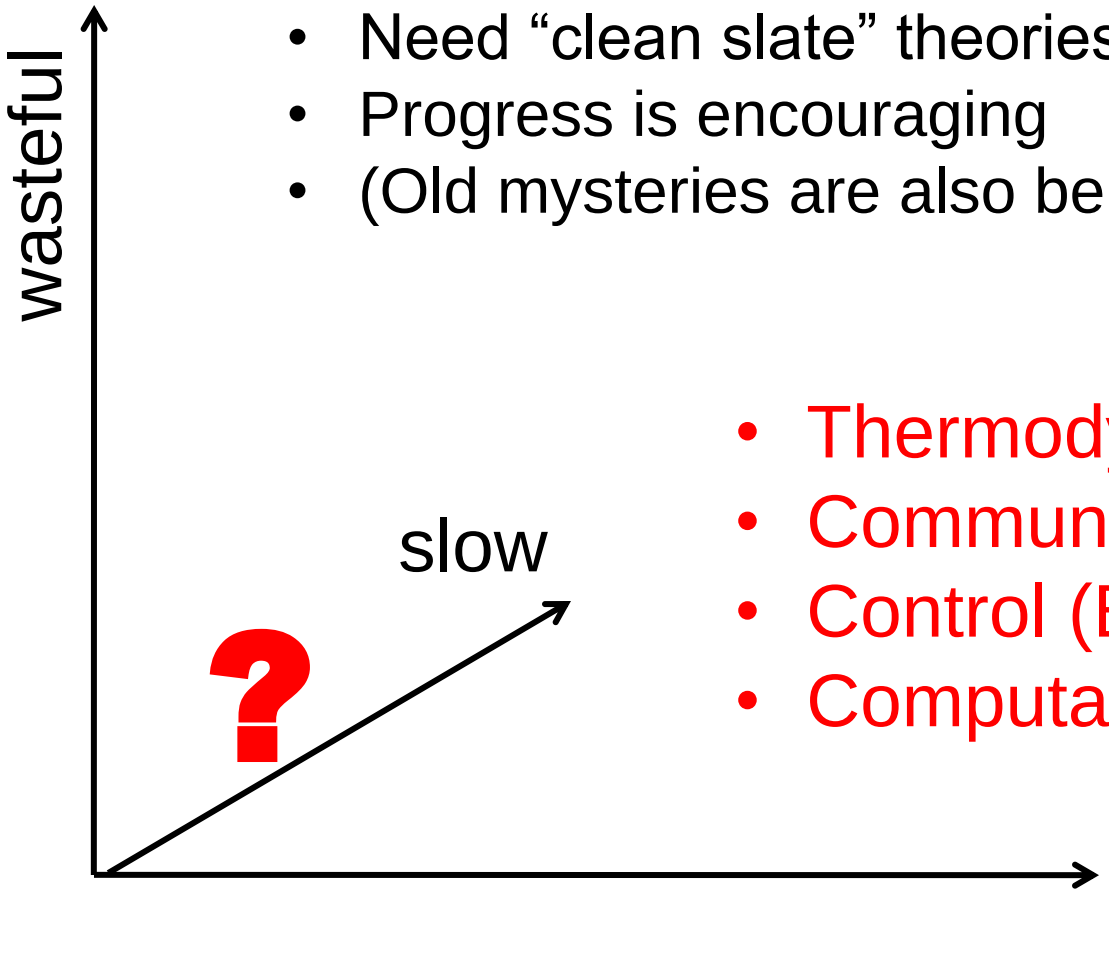
Accident or necessity?

Design tradeoffs



Standard system theories are severely limited

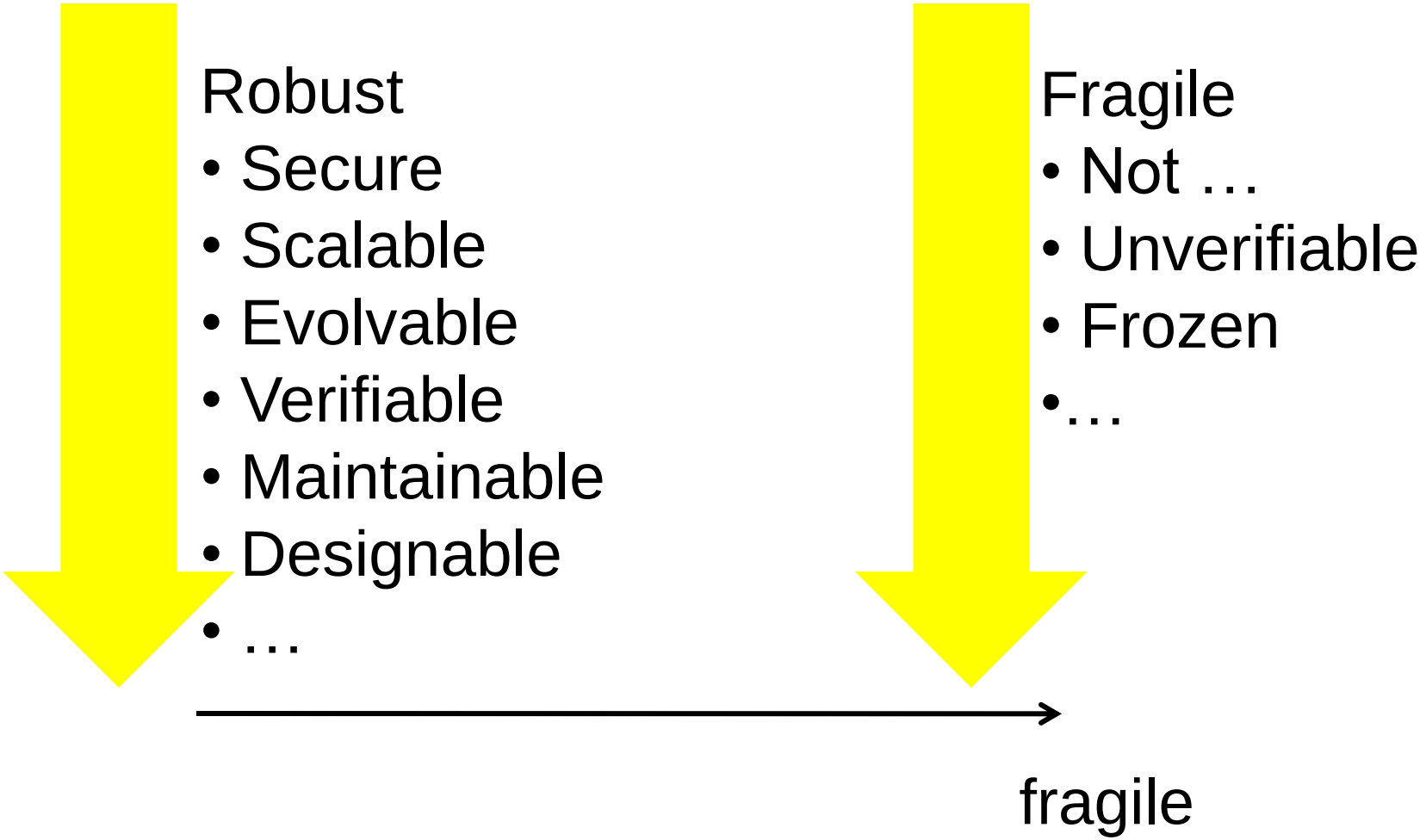
- Each focuses on one dimension
- Important tradeoffs are ***across*** these dimensions
- Need “clean slate” theories
- Progress is encouraging
- (Old mysteries are also being resolved)



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

Most dimensions are robustness

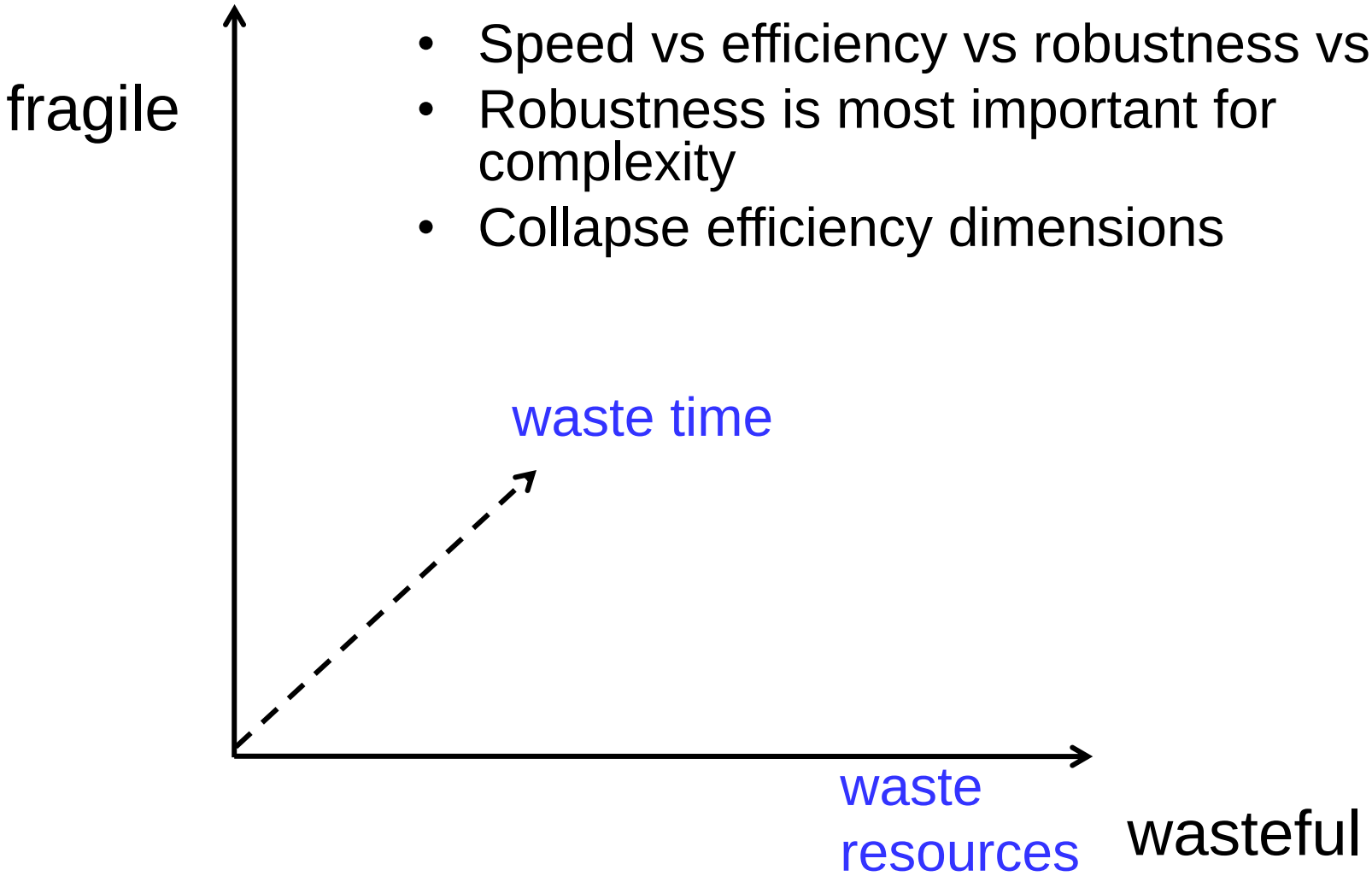
Collapse for visualization



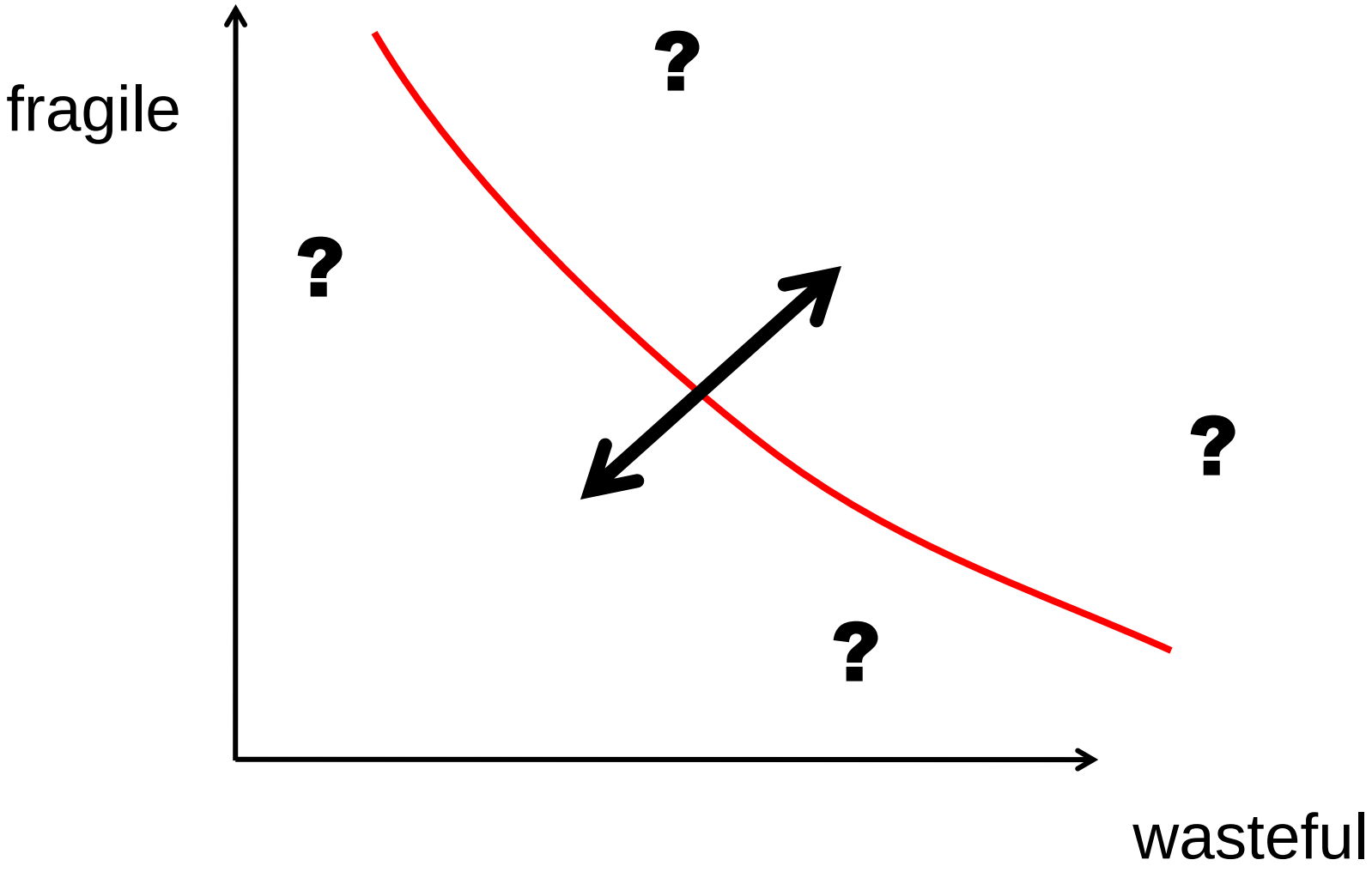
fragile

Conservation laws

- Important tradeoffs are ***across*** these dimensions
- Speed vs efficiency vs robustness vs …
- Robustness is most important for complexity
- Collapse efficiency dimensions



Conservation laws



Bad architectures?

fragile

?

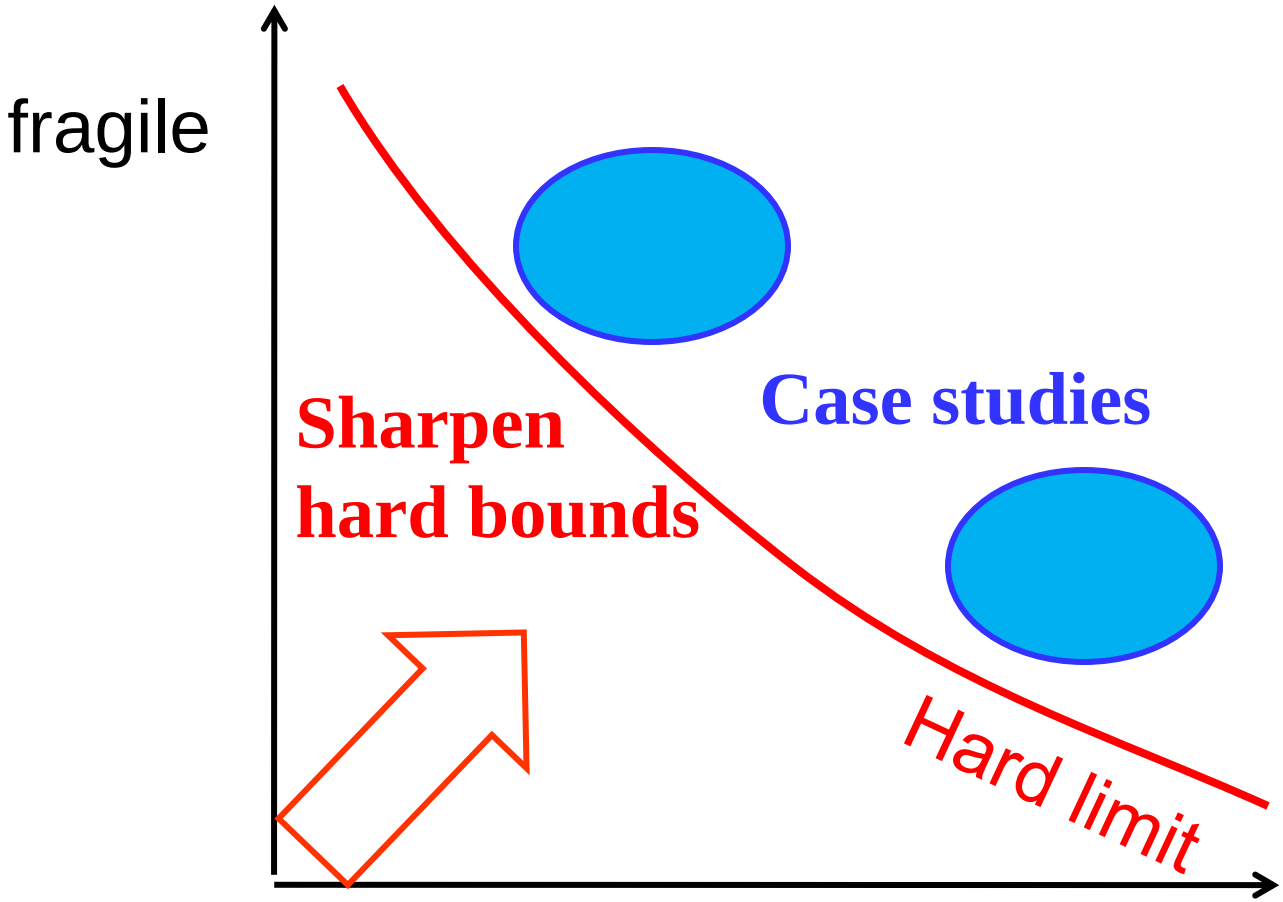
gap?

Bad theory?

?

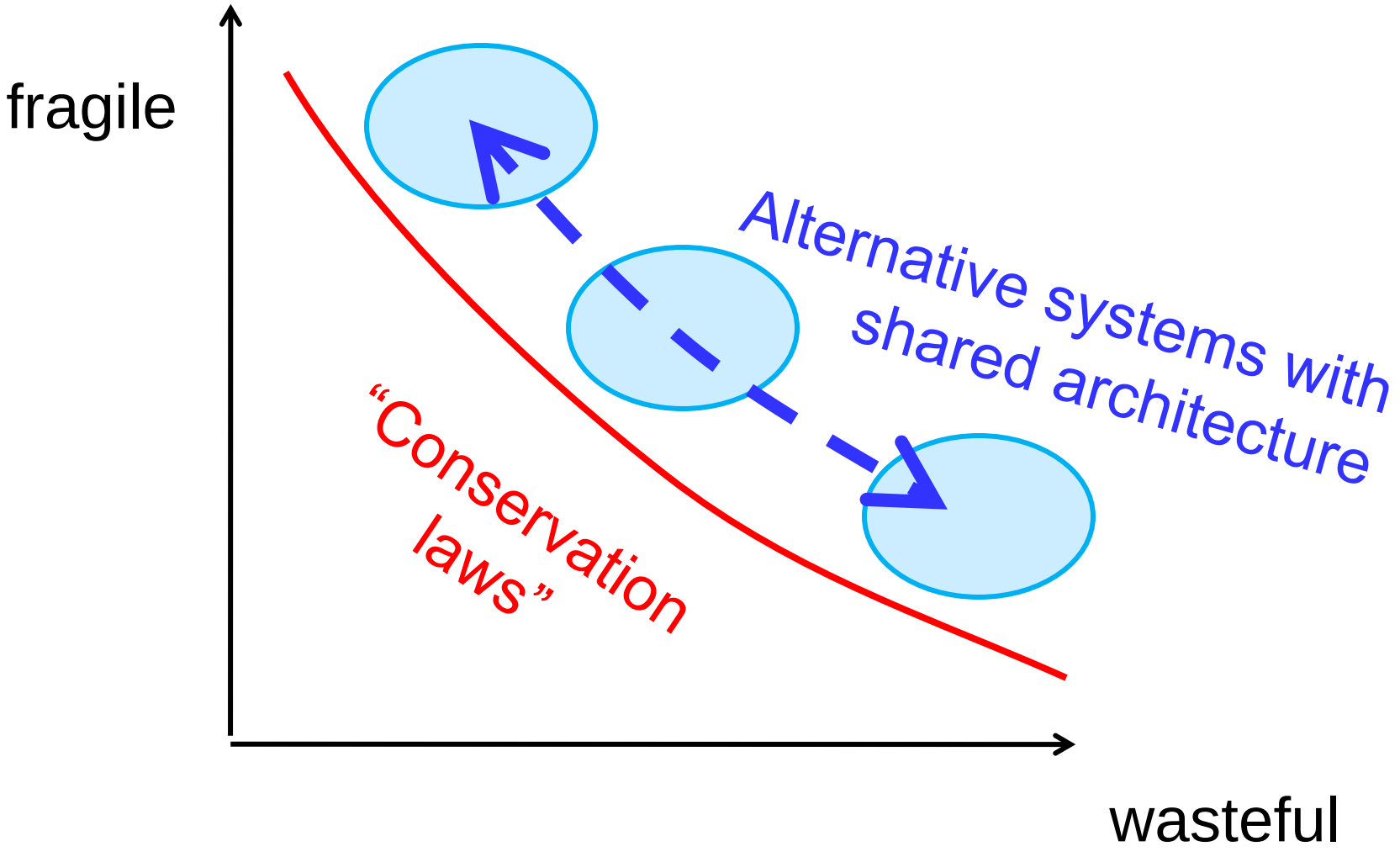
wasteful

Conservation laws

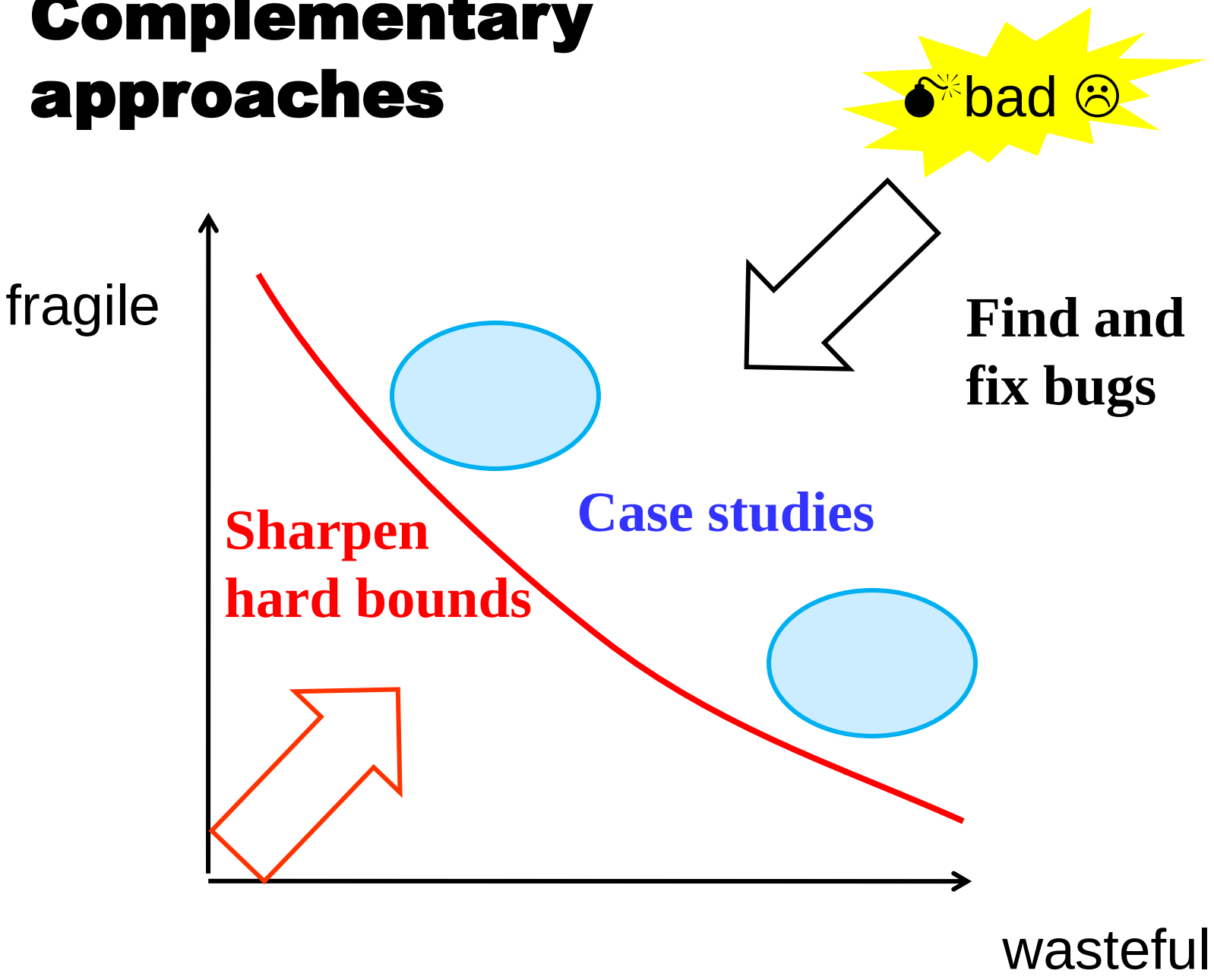


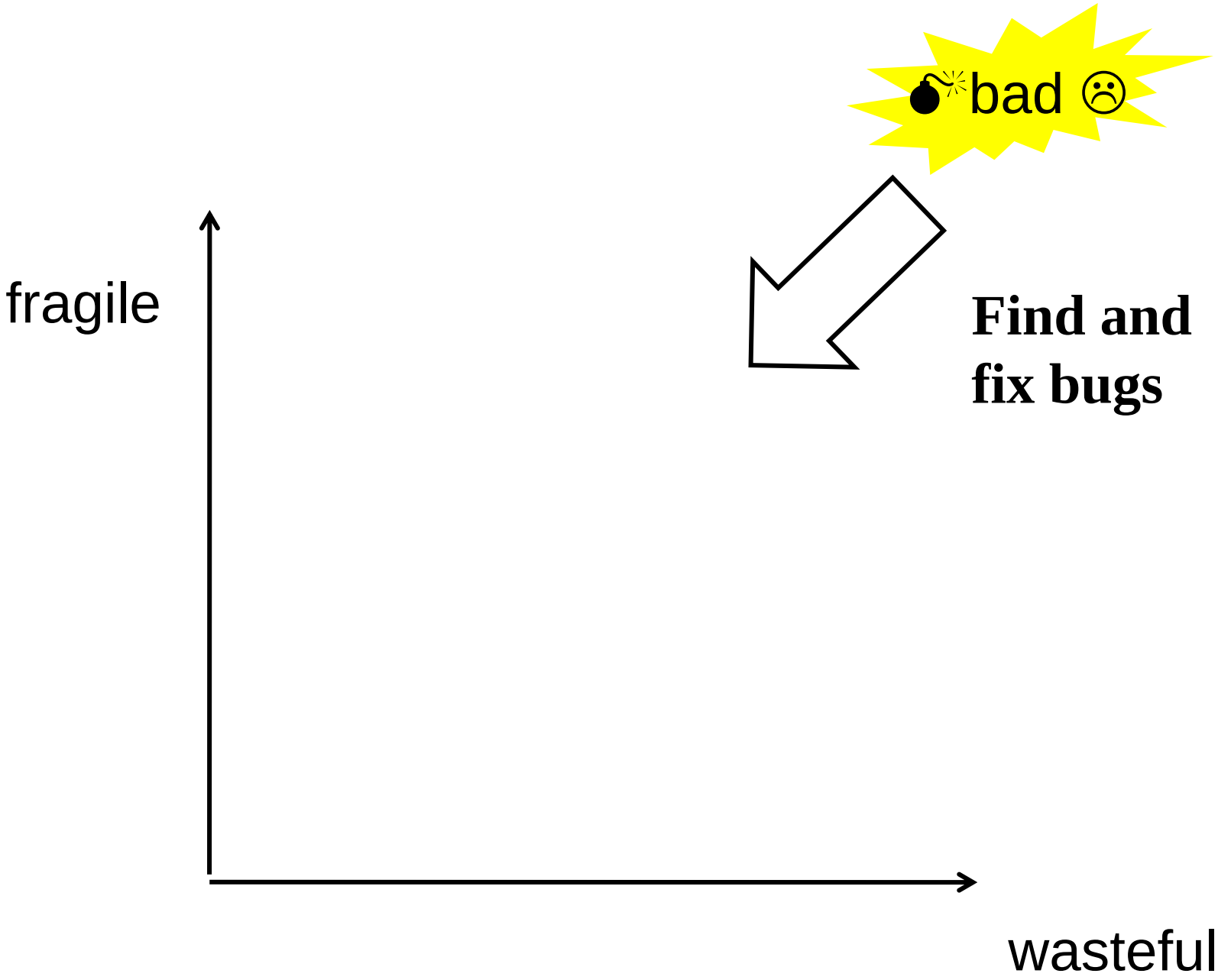
Architecture

Good architectures allow for effective tradeoffs



Complementary approaches



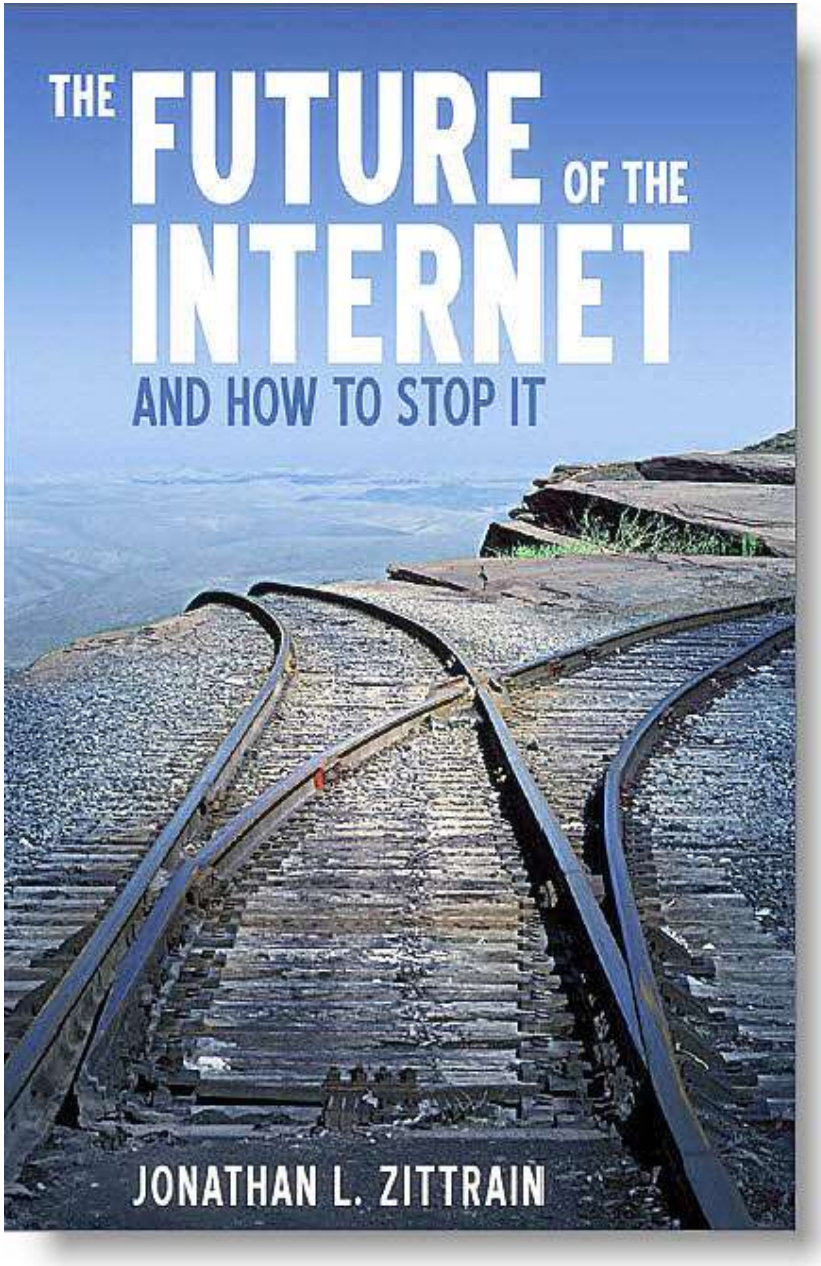

bad ☹
fragile
Find and
fix bugs
wasteful

Architectures

- Case studies
  - Internet
  - Bacterial biosphere
- Principles, foundations
- Theory

Fun reading,

great picture →



Theoretical framework:
Constraints that deconstrain

Applications Deconstrained

$$\min_{\mathbf{x}} \left\{ \int \left(\left\| R\tilde{\mathbf{x}} - \mathbf{c} \right\|^2 + \left\| R\mathbf{x} - \mathbf{c} \right\|^2 \right) dt \right\}$$

$$\left| \begin{array}{l} \tilde{\mathbf{x}} = \arg\max_{\mathbf{v}} L(\mathbf{v}, \mathbf{p}), \quad \dot{\mathbf{p}} = R\mathbf{x} - \mathbf{c} \\ \Rightarrow x_s = \arg\max_{v} L_s(v, \mathbf{p}) \end{array} \right.$$

Resources Deconstrained

Enormous progress

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

Theoretical framework:
Constraints that deconstrain

Enormous progress

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

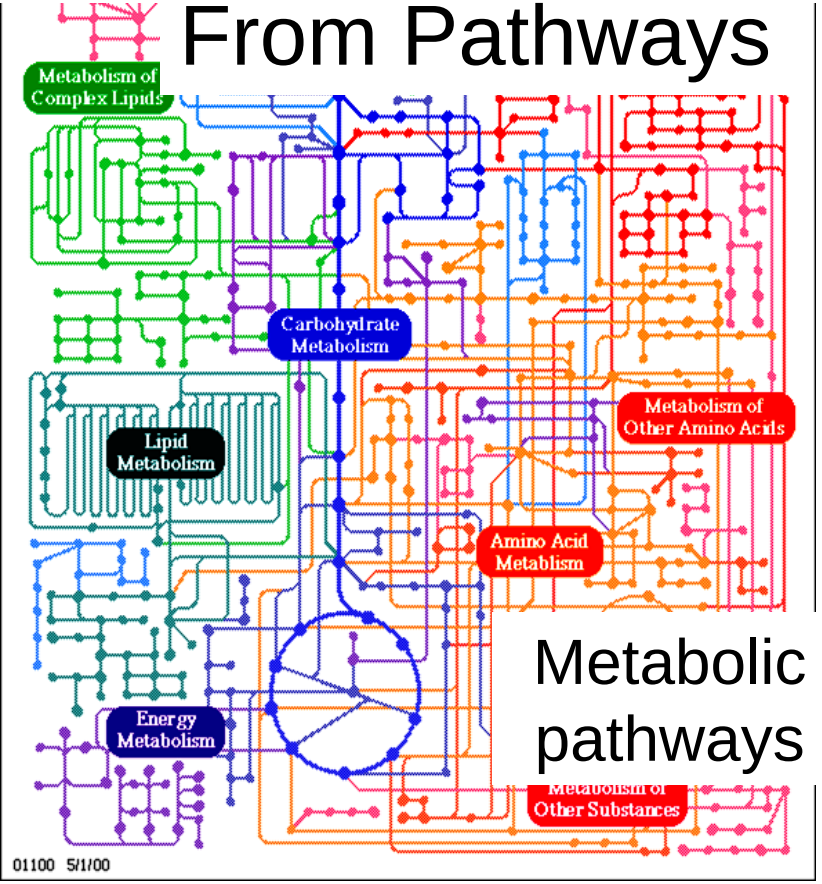
- Many robustness issues left unaddressed
- Secure, verifiable, manageable, maintainable, etc
- Architecture/policy, not part of control/dynamics
- How to expand the theory?

"Central dogma"

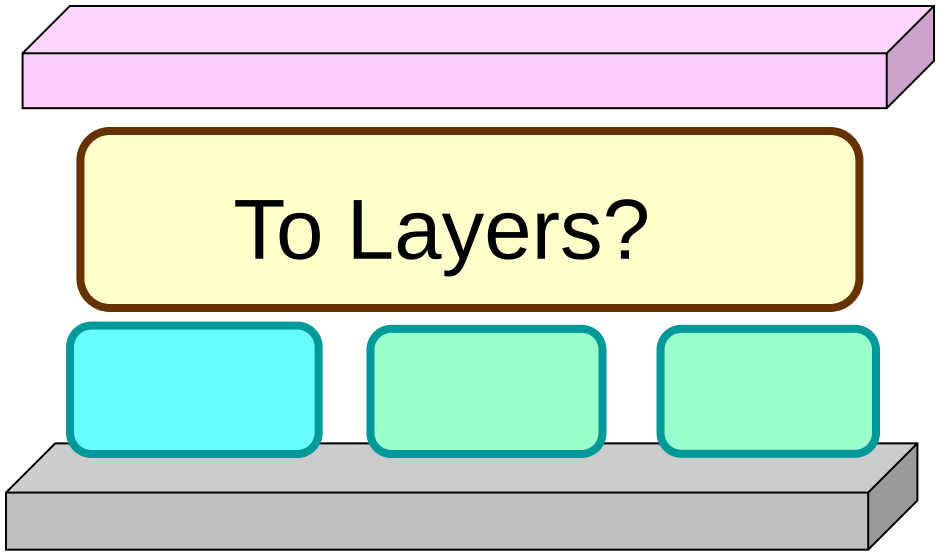
DNA → RNA → Protein

Network architecture?

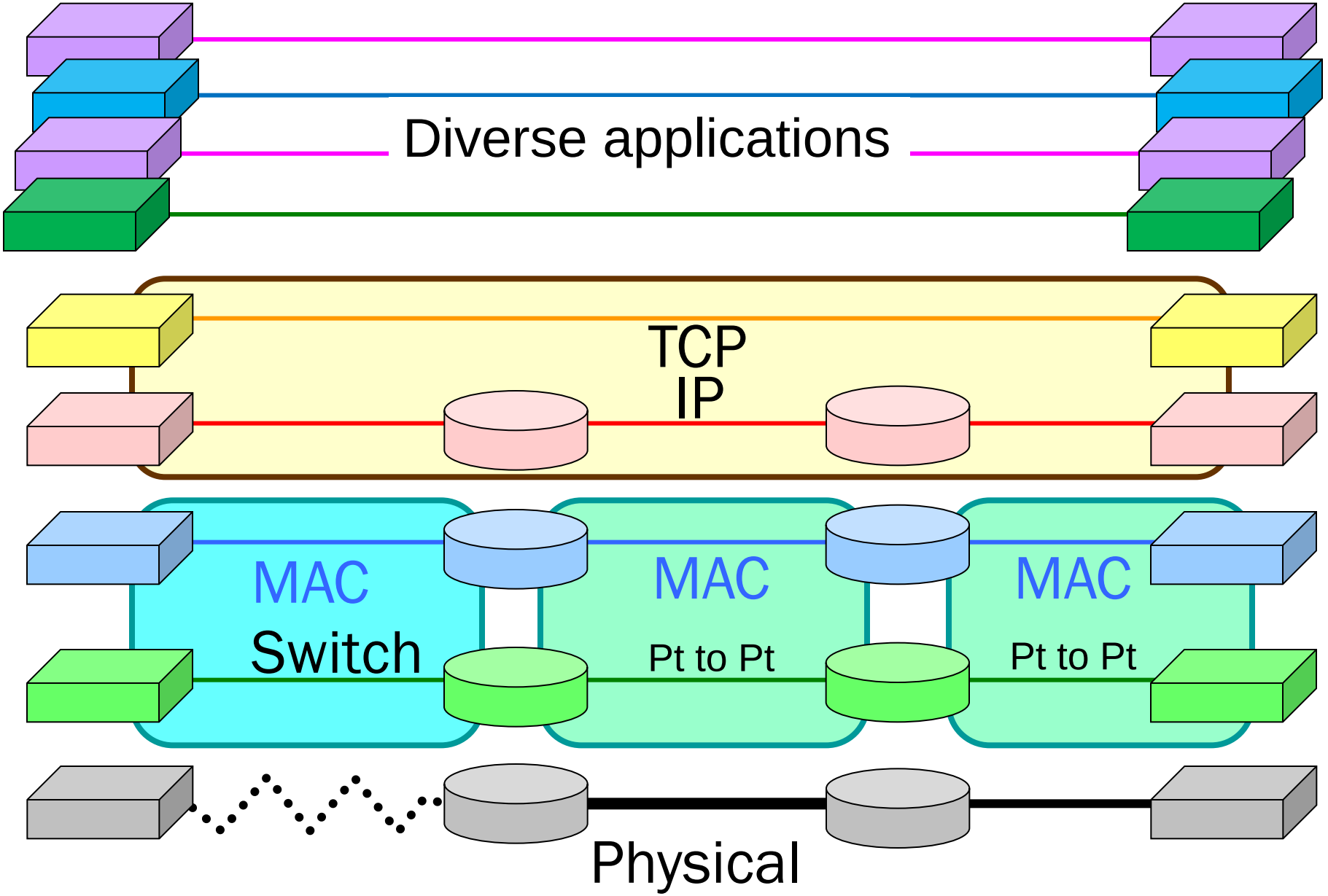
From Pathways



Metabolic pathways



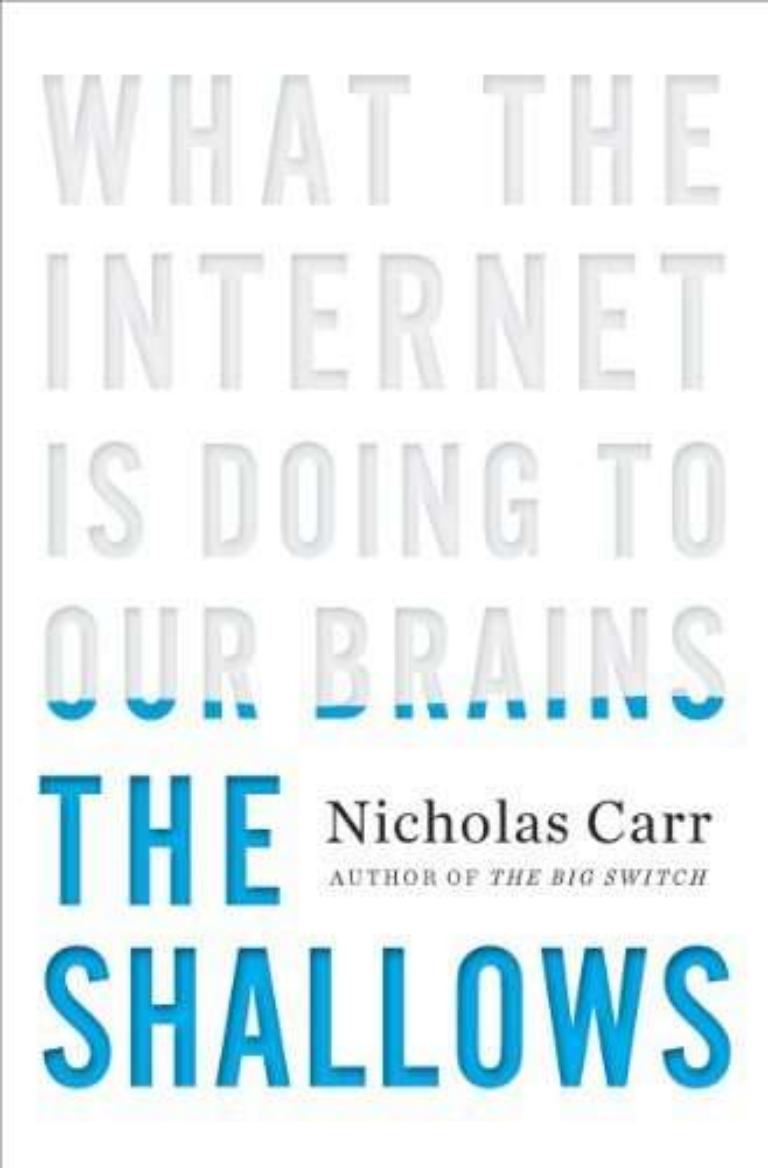
Layered architectures



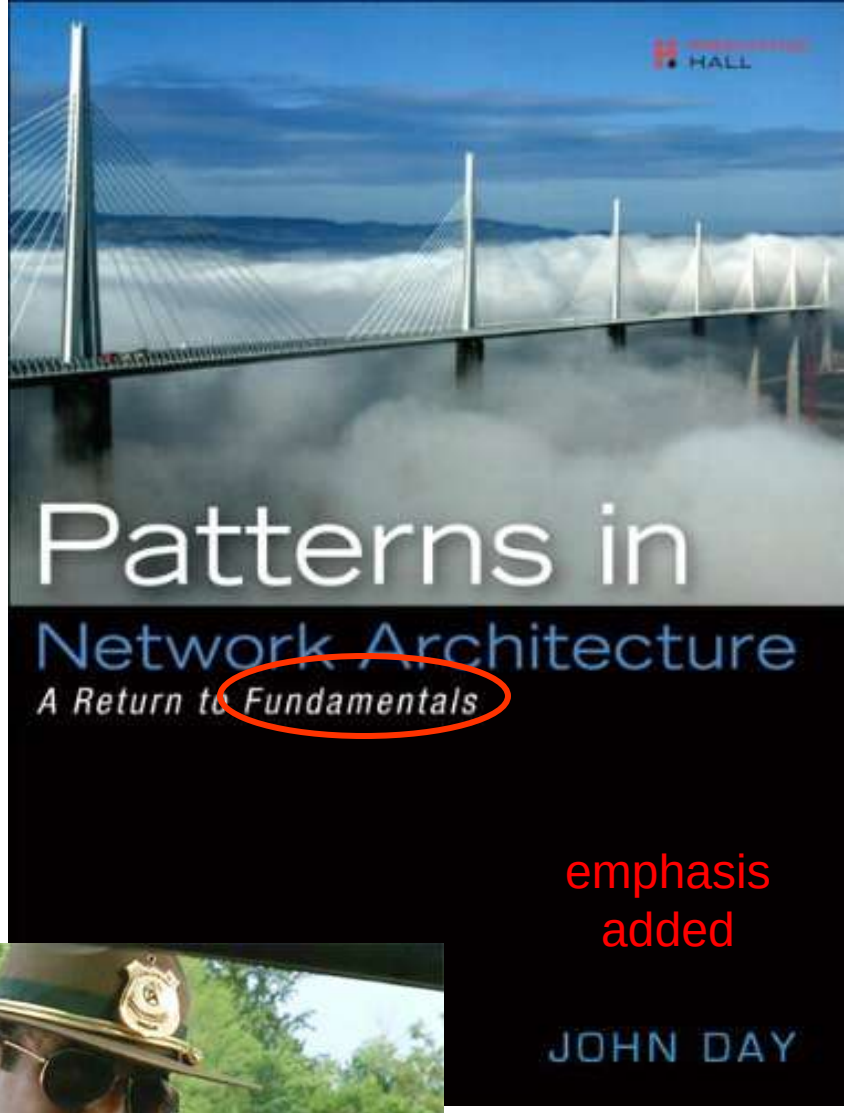
Architecture resources

- 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

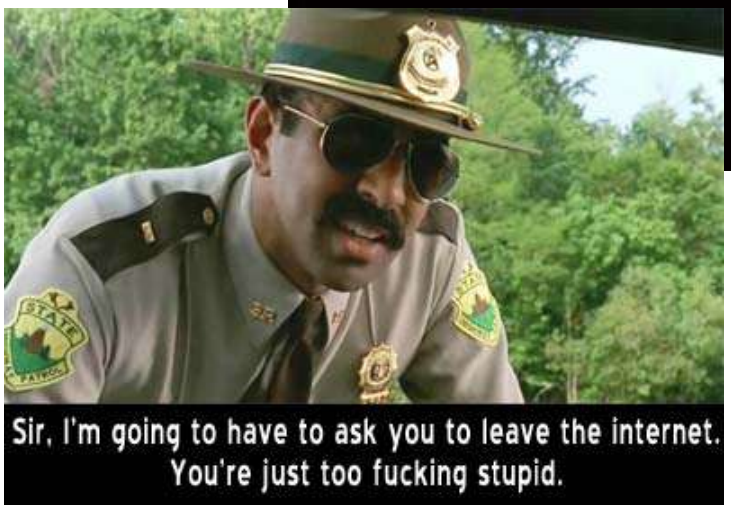
What follows is an attempt to paraphrase this work.

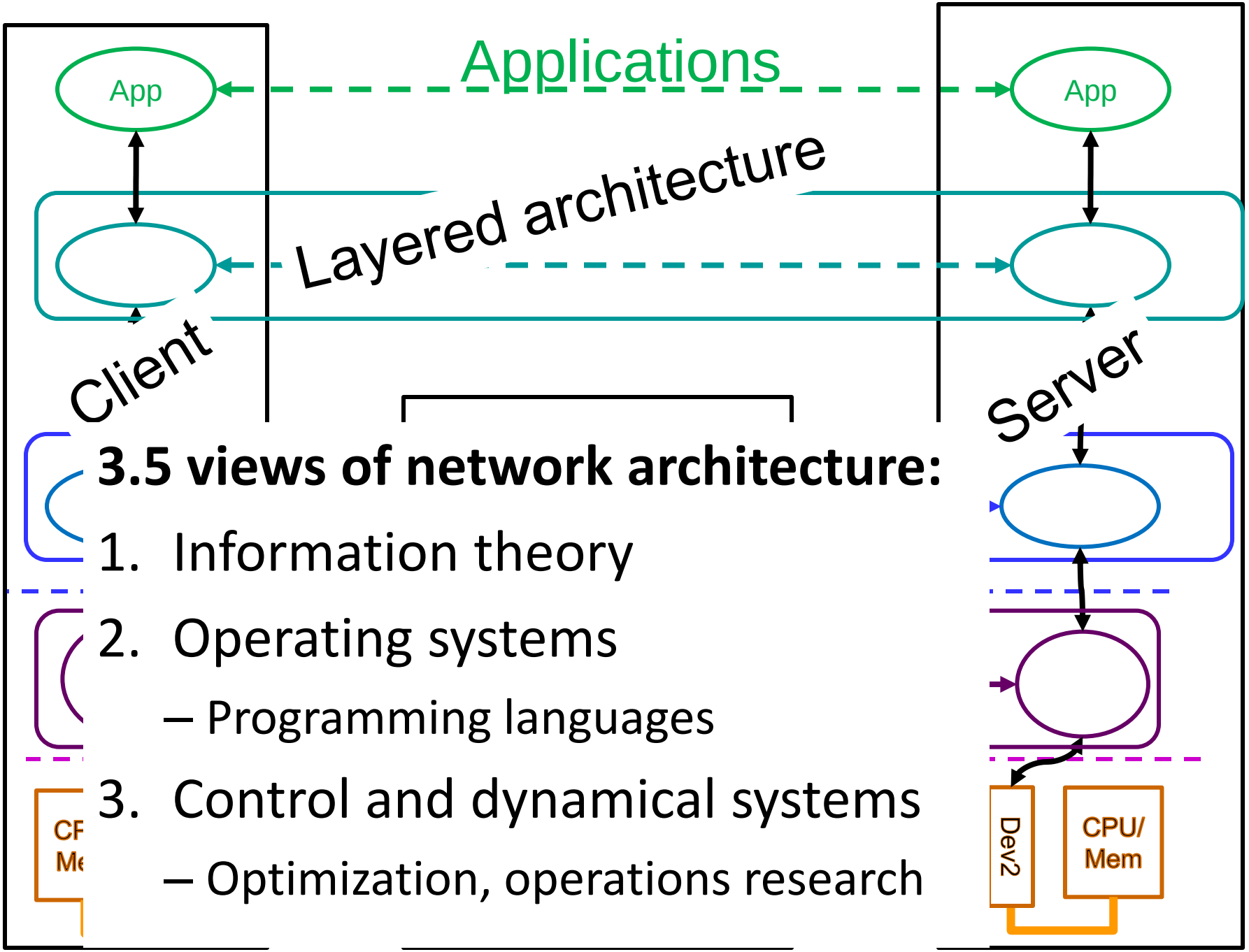


↑
great title



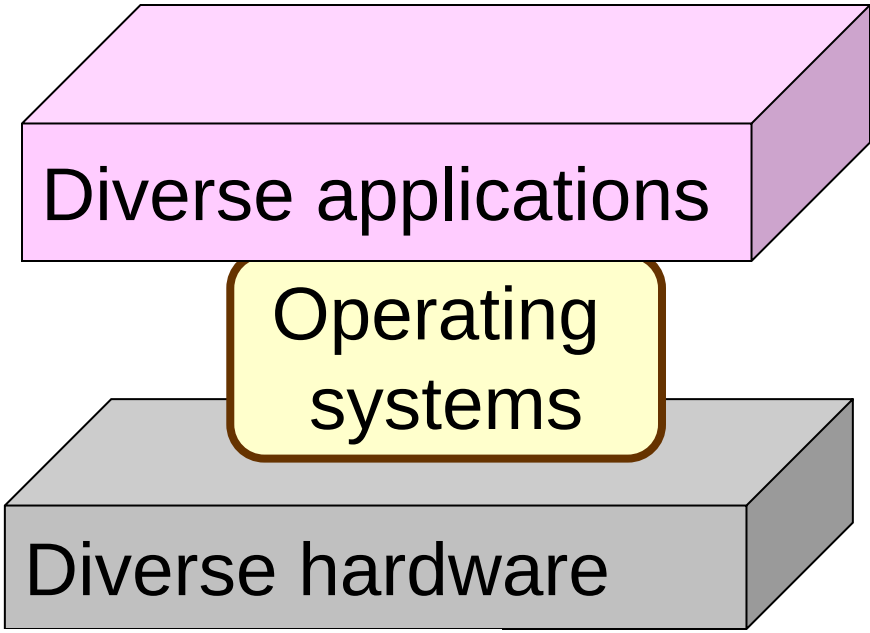
emphasis added





3.5 views of network architecture:

1. Information theory
2. Operating systems
   - Programming languages
3. Control and dynamical systems
   - Optimization, operations research

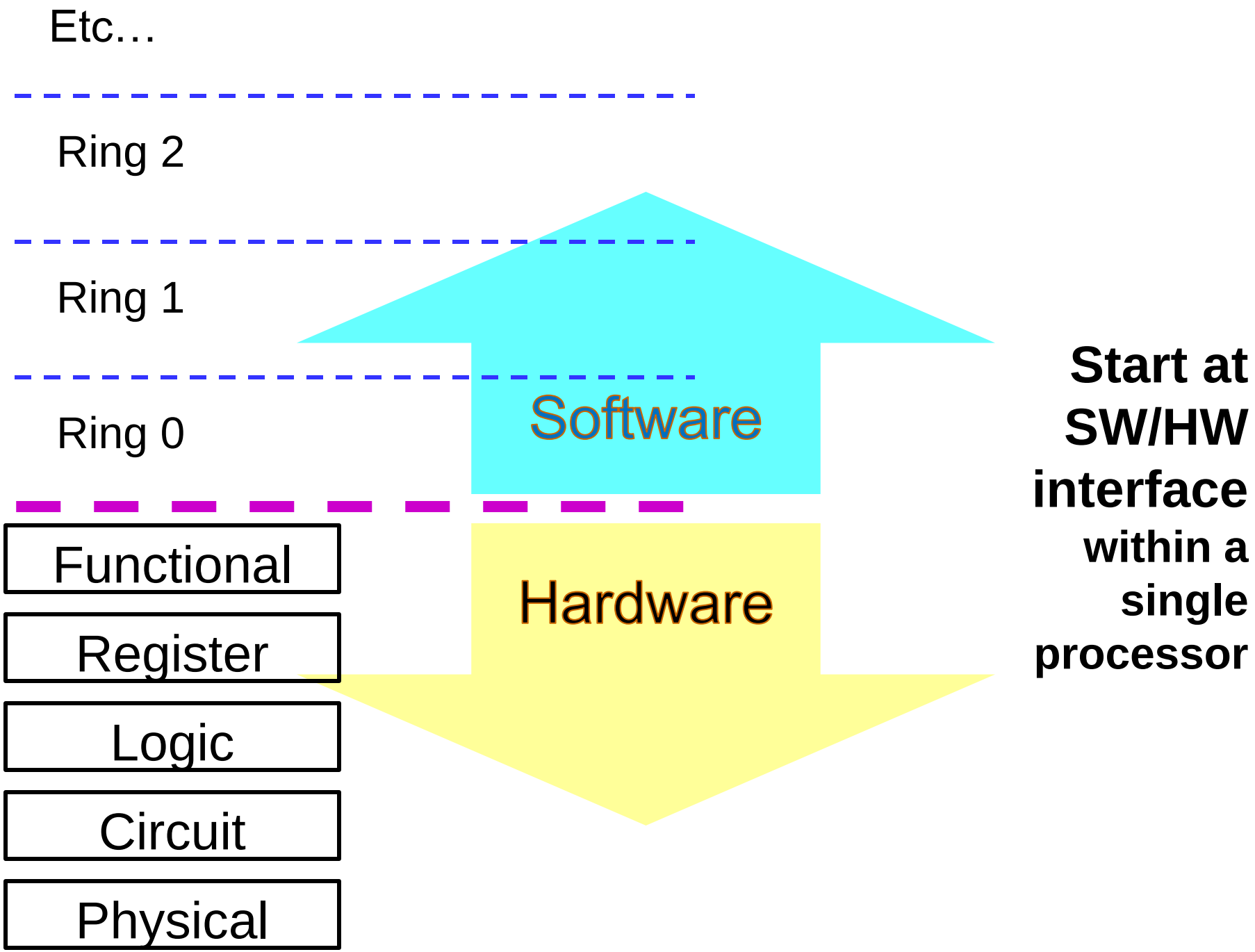


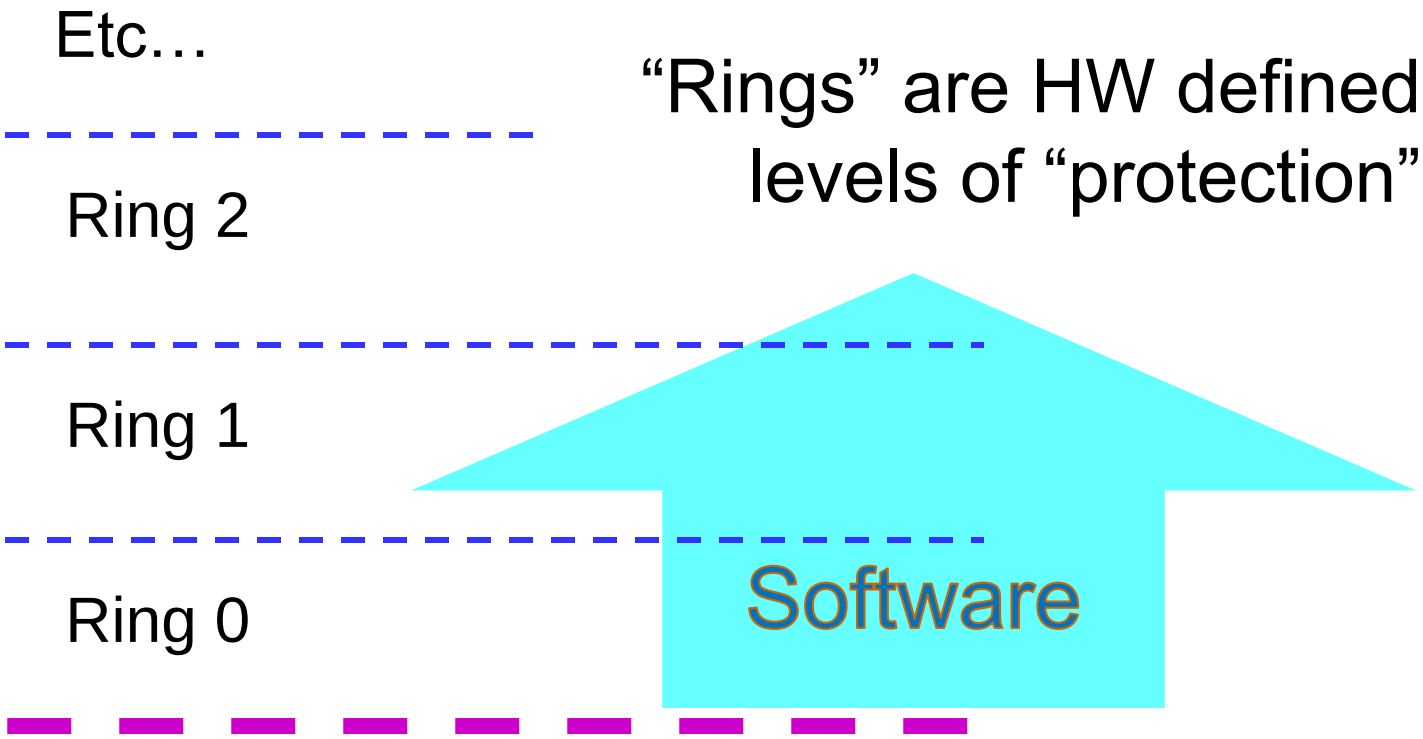
3.5 views of network architecture:

1. Information theory
2. **Operating systems**
   - Programming languages
3. Control and dynamical systems
   - Optimization, operations research

Operating systems

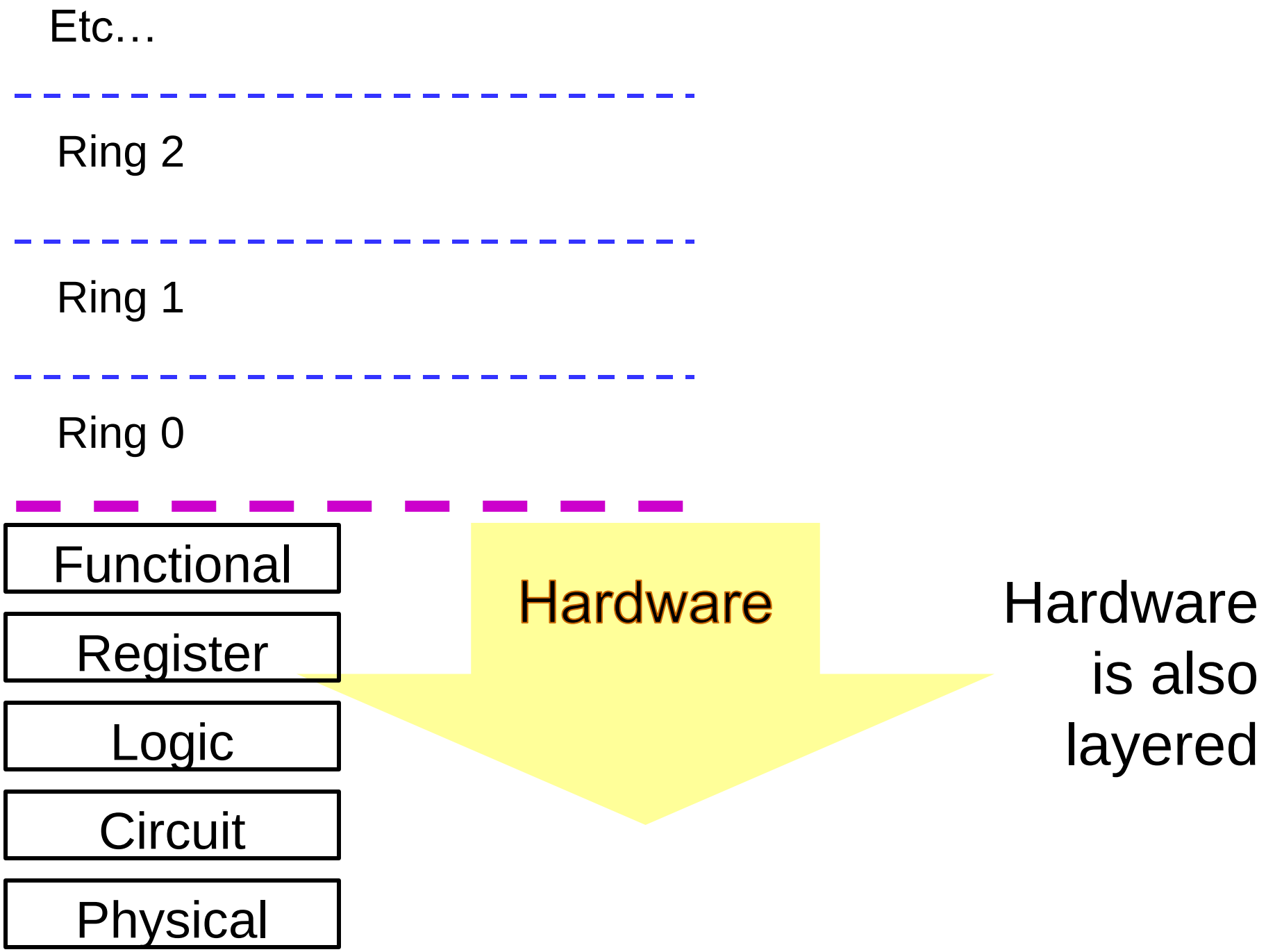
- OS allocates and shares diverse resources among diverse applications
- “Strict layering” is crucial
- e.g. clearly separate
  - Application name space
  - Logical (virtual) name/address space
  - Physical (name/) address space
- Name resolution within applications
- Name/address translation across layers

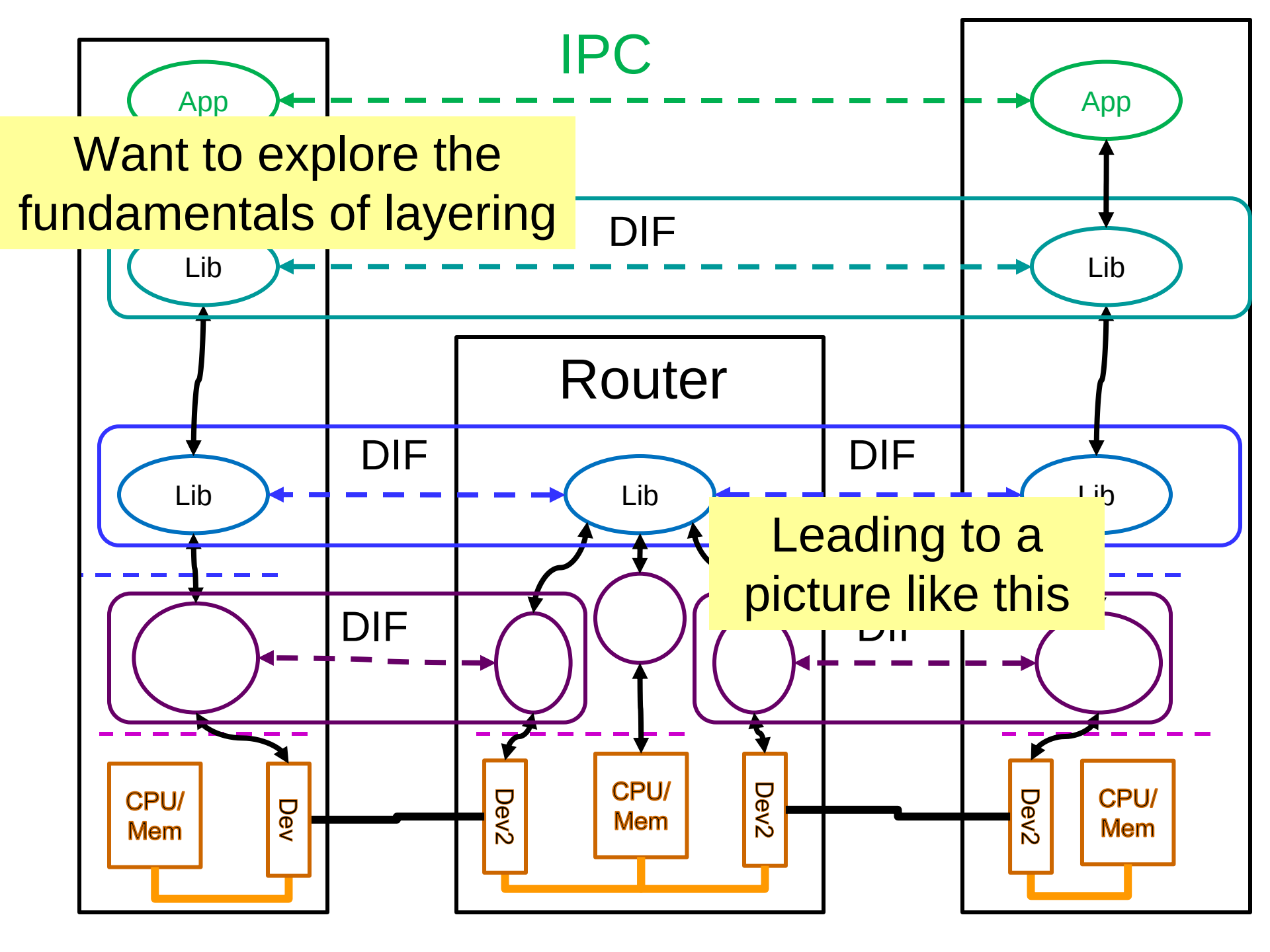

Etc…
Ring 2
Ring 1
Ring 0
Software
Hardware
Functional
Register
Logic
Circuit
Physical
Start at SW/HW interface within a single processor



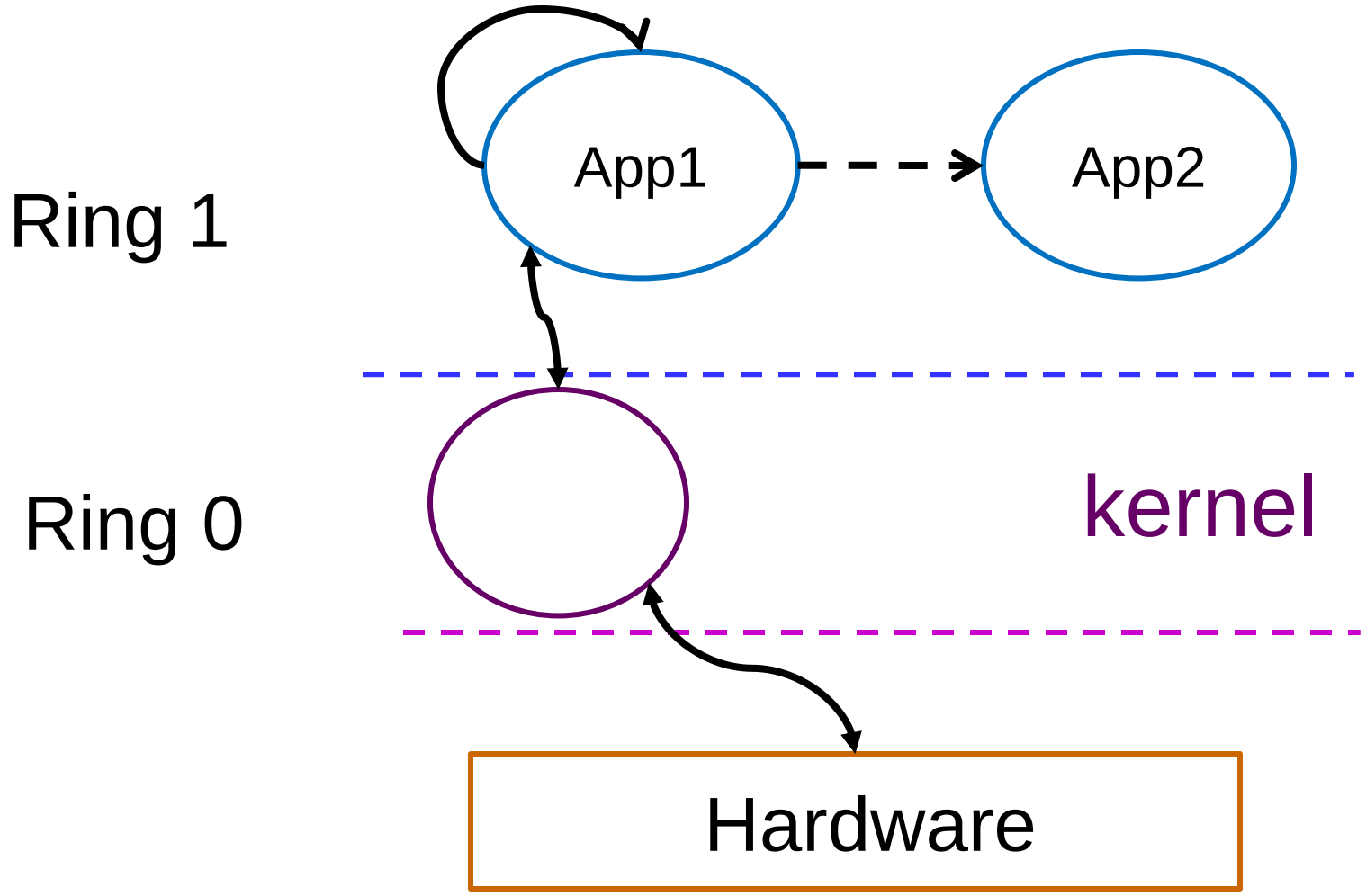
"Rings" are HW defined levels of "protection"

Start at SW/HW interface within a single processor


Etc…
Ring 2
Ring 1
Ring 0
Functional
Register
Logic
Circuit
Physical
Hardware
Hardware is also layered


IPC
App
App
Want to explore the fundamentals of layering
DIF
Lib
Lib
Router
DIF
DIF
Lib
Lib
Lib
Leading to a picture like this
DIF
CPU/ Mem
Dev
Dev2
CPU/ Mem
Dev2
Dev2
CPU/ Mem

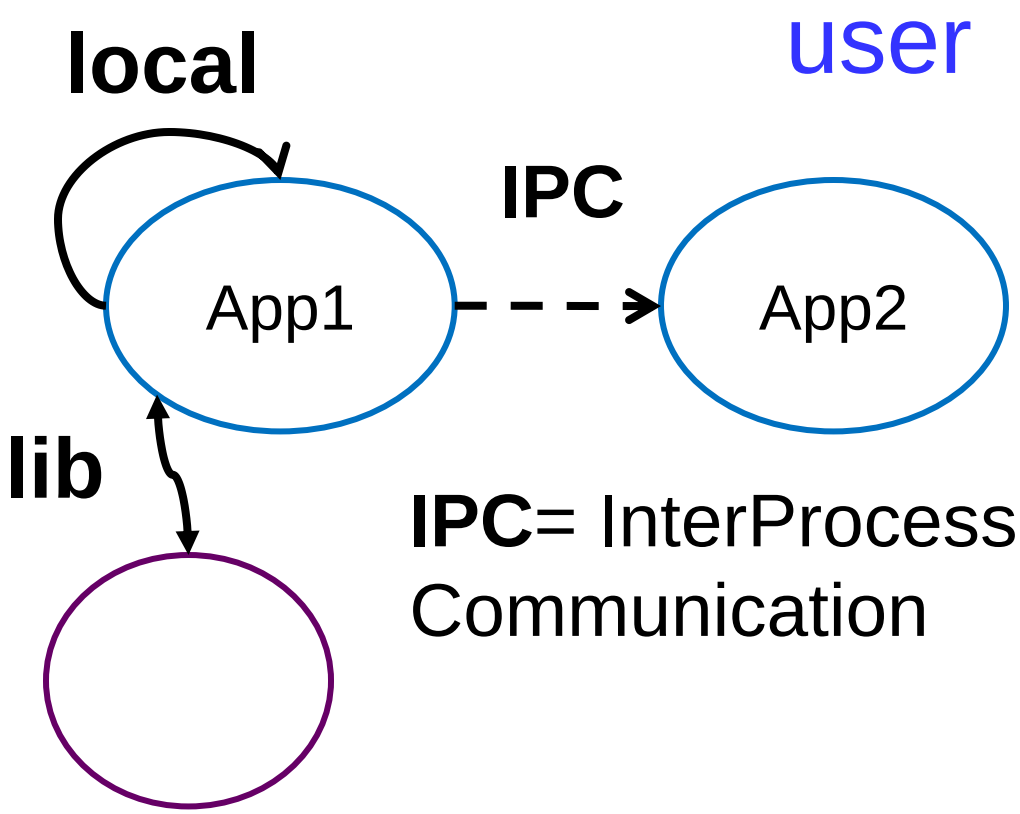
Minimal toy model



Within a single processor

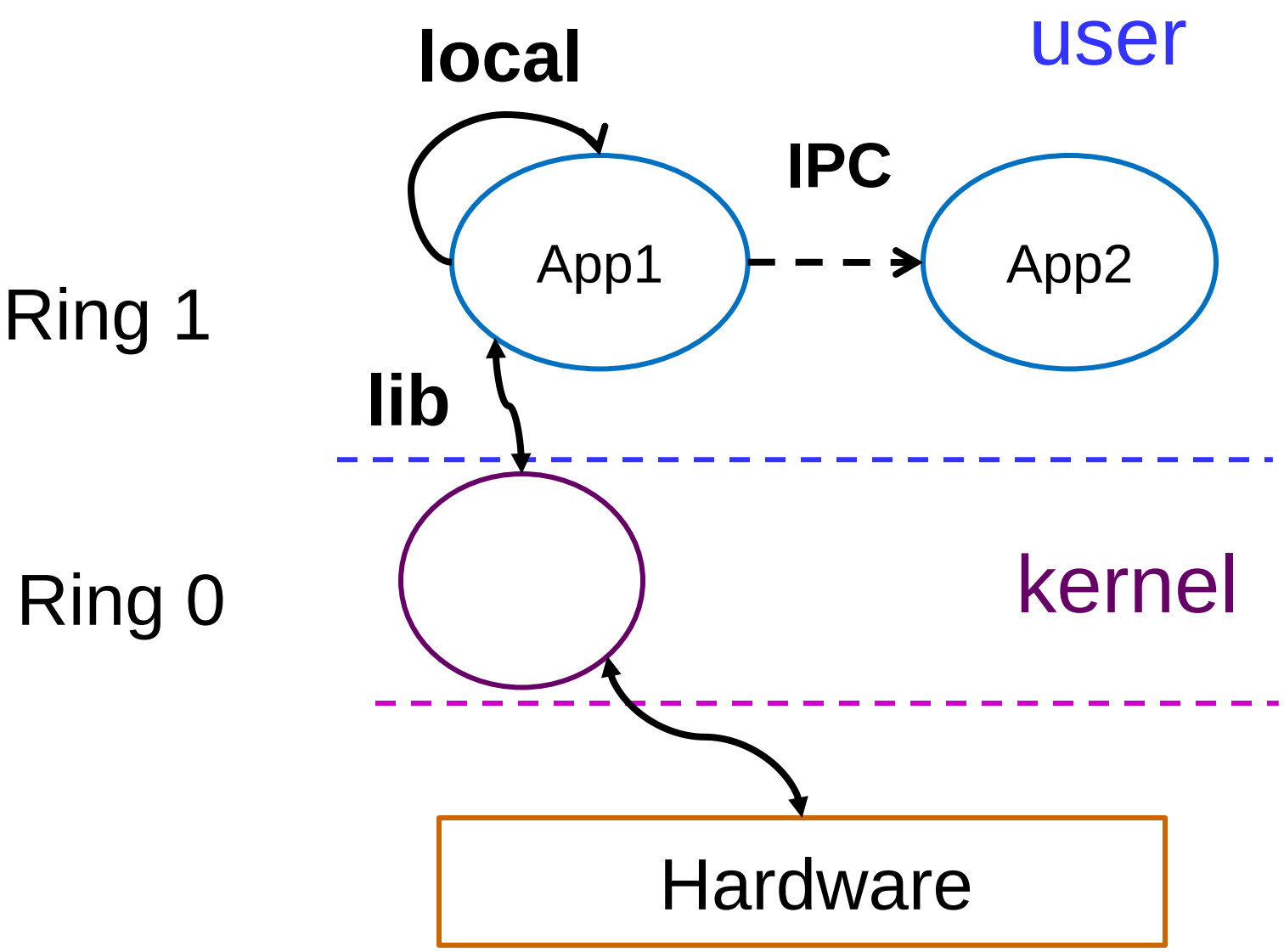
A function call can be

- Local
- Library (system)
- IPC



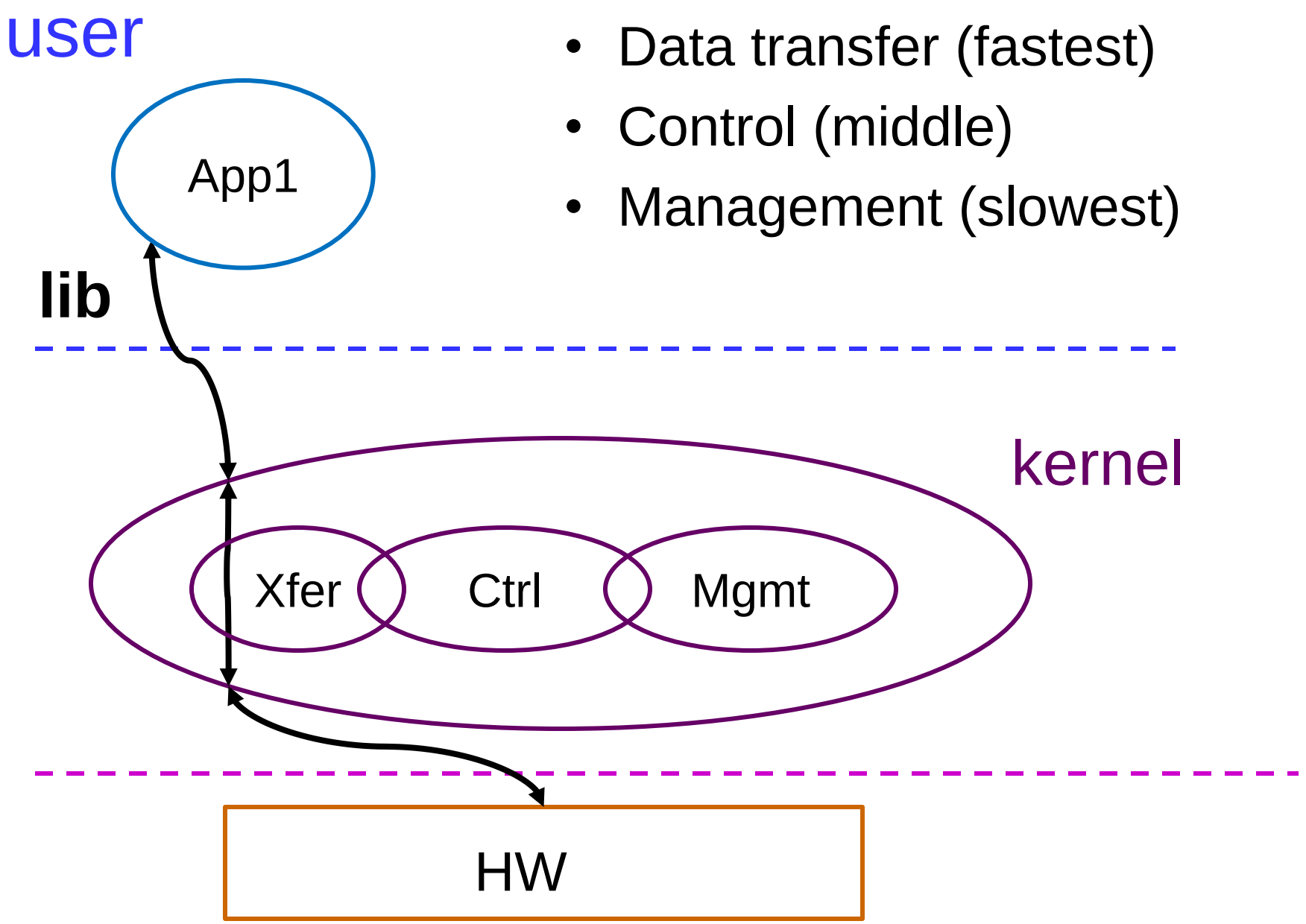
IPC= InterProcess Communication

Within a single processor



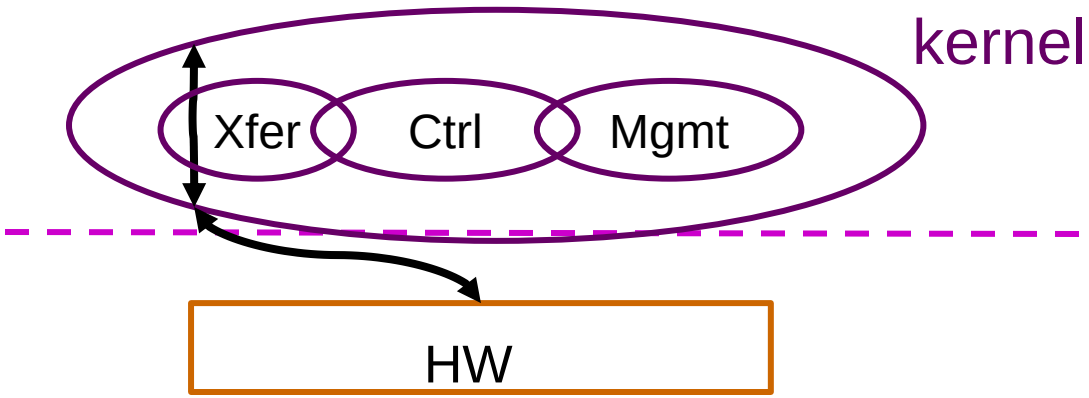
Within-layer functions are

- Data transfer (fastest)
- Control (middle)
- Management (slowest)

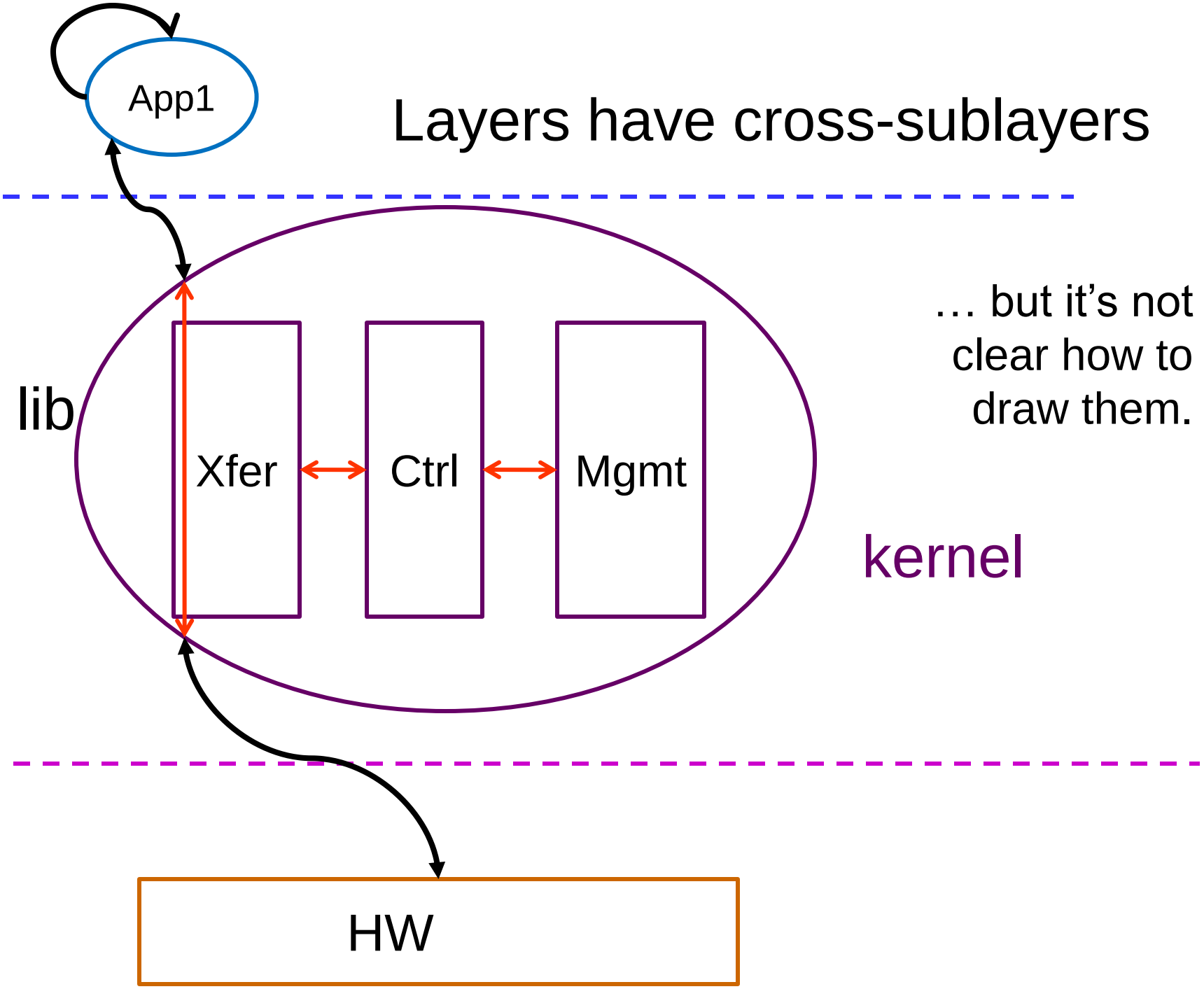


The kernel layer functions are

- Data transfer (fastest time scale)
  - Within memory (and memory hierarchies)
  - Between devices and memory
  - Between memory and computing elements
- Control (middle time scales)
  - Scheduling/Multiplexing resources
  - In time and space
- Management (slowest time scale)
  - ***What*** resources are available?
  - ***Where*** are they?

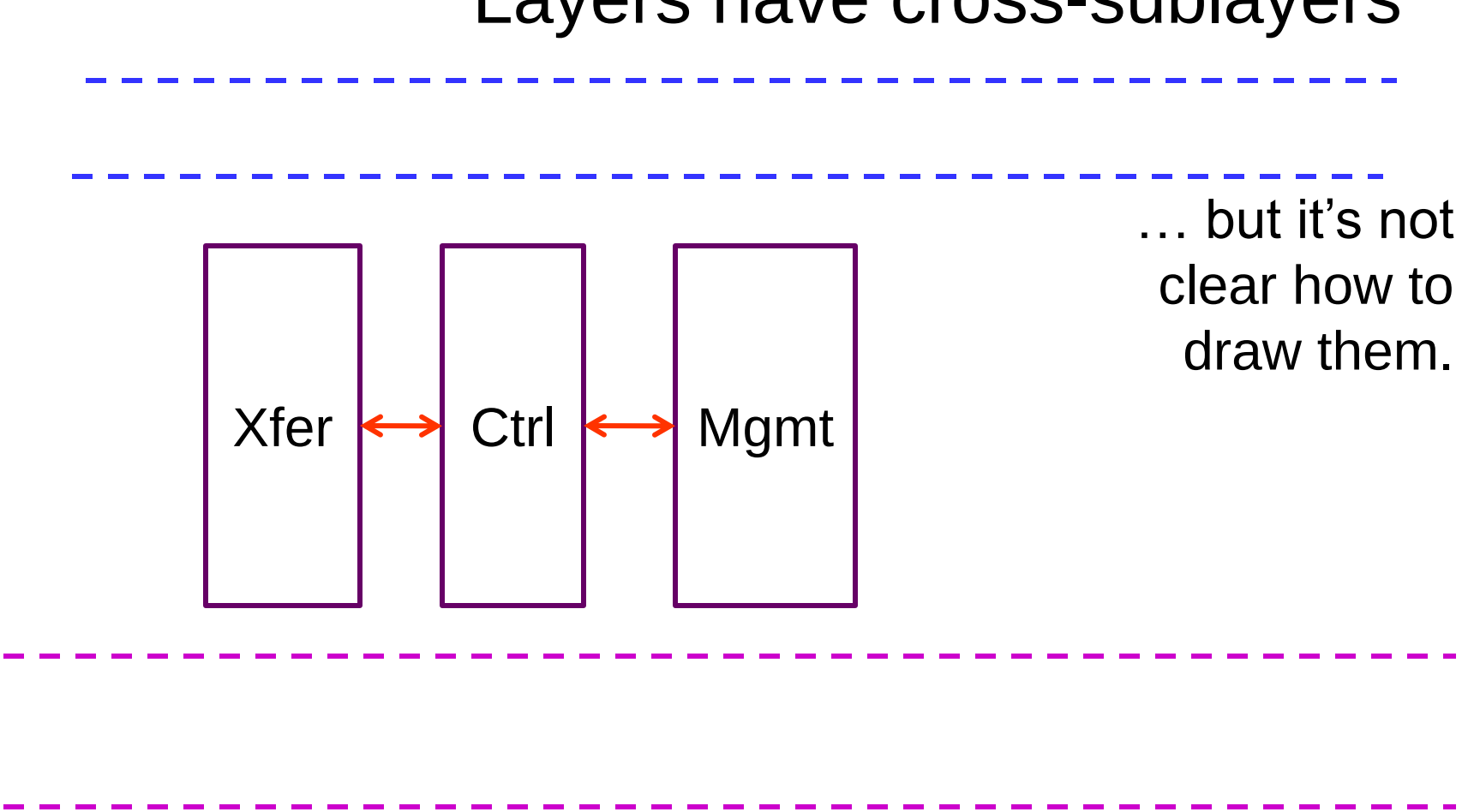


Layers have cross-sublayers



… but it's not clear how to draw them.

Layers have cross-sublayers



… but it's not clear how to draw them.

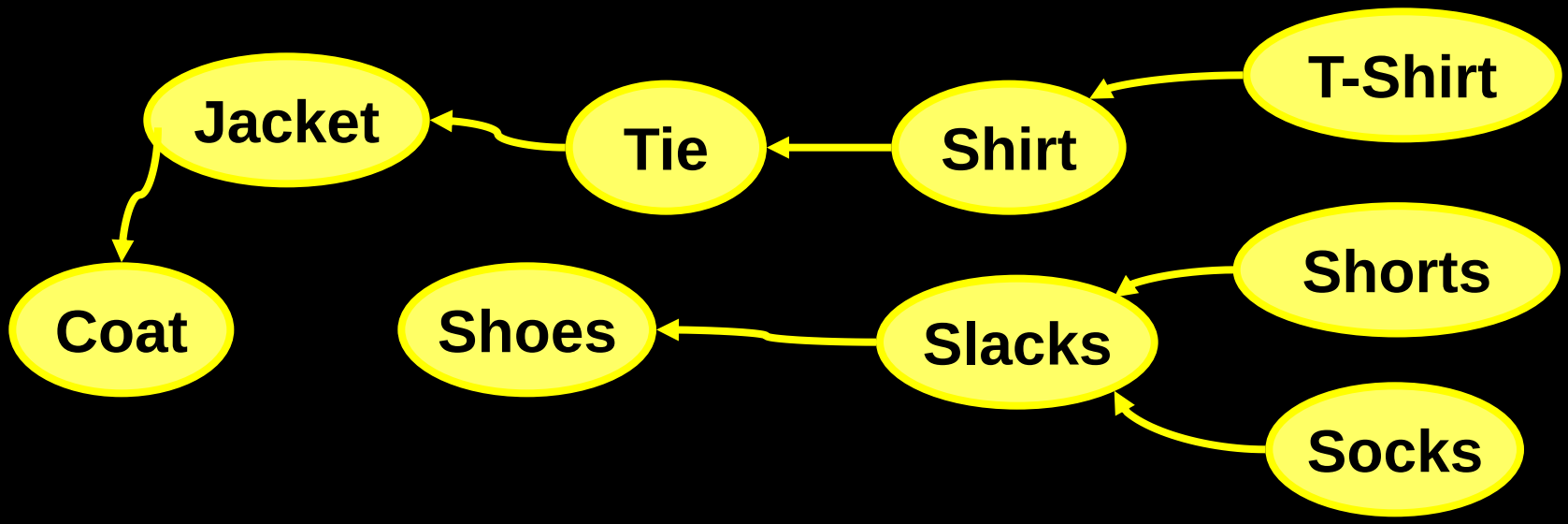
Other examples

Clothing

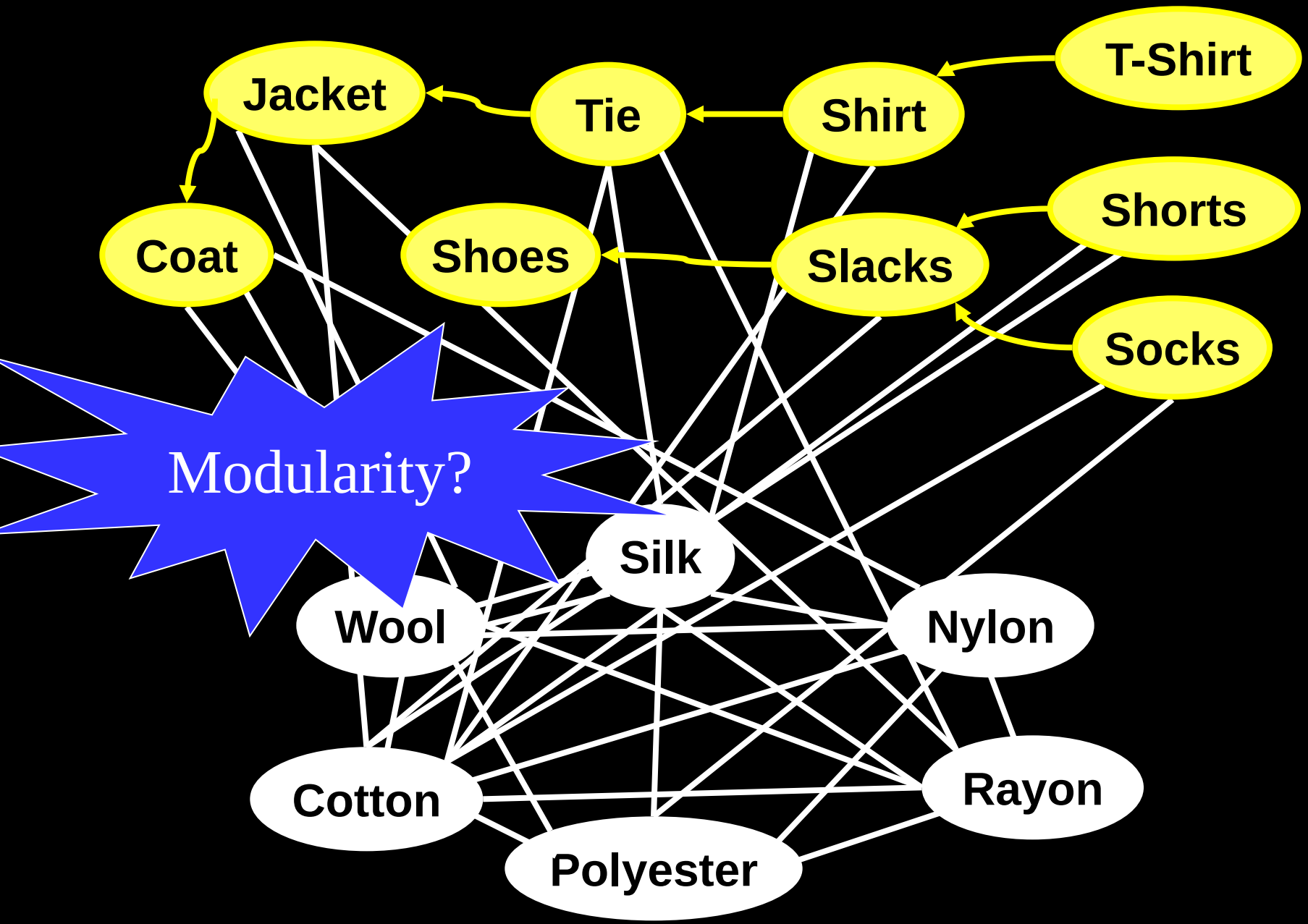
Lego

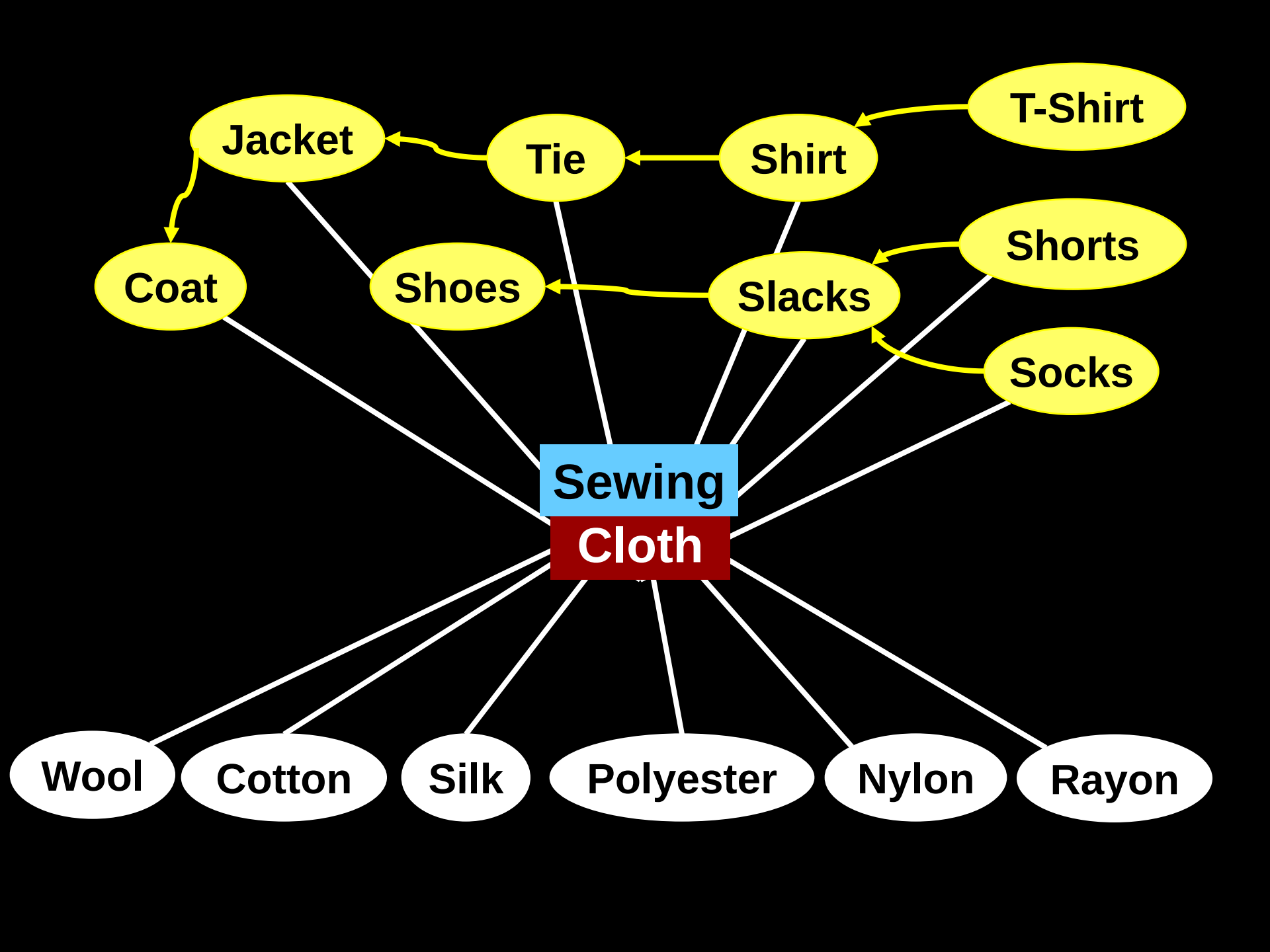
Money

Cell biology

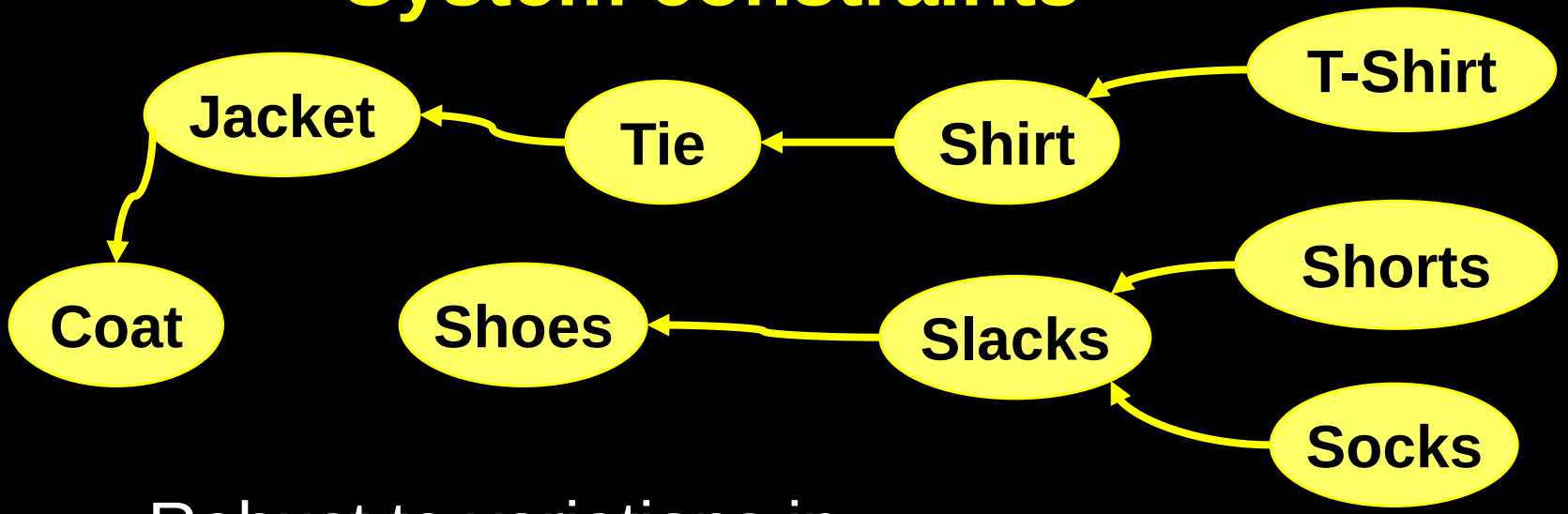


Soft layering


T-Shirt
Jacket
Tie
Shirt
Shorts
Coat
Shoes
Slacks
Socks
Modularity?
Silk
Wool
Nylon
Cotton
Rayon
Polyester


T-Shirt
Jacket
Tie
Shirt
Shorts
Coat
Shoes
Slacks
Socks
Sewing
Cloth
Wool
Cotton
Silk
Polyester
Nylon
Rayon

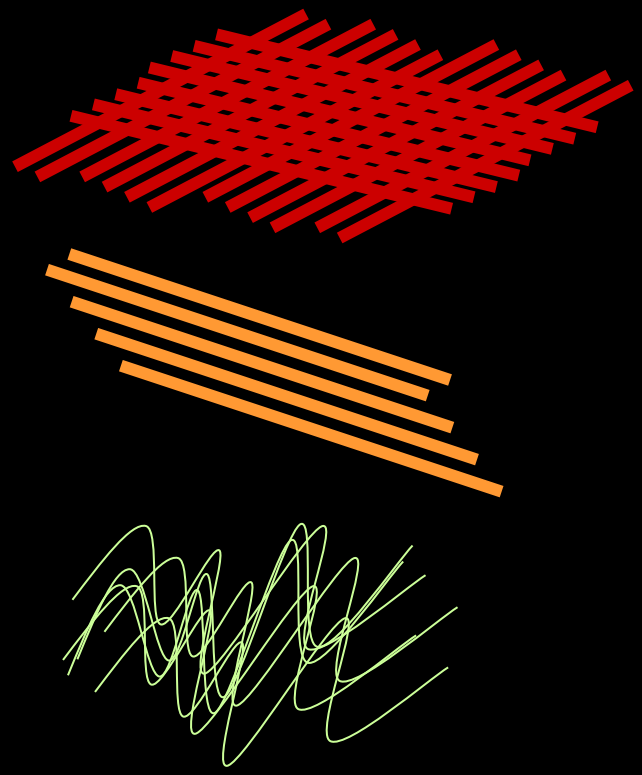
System constraints

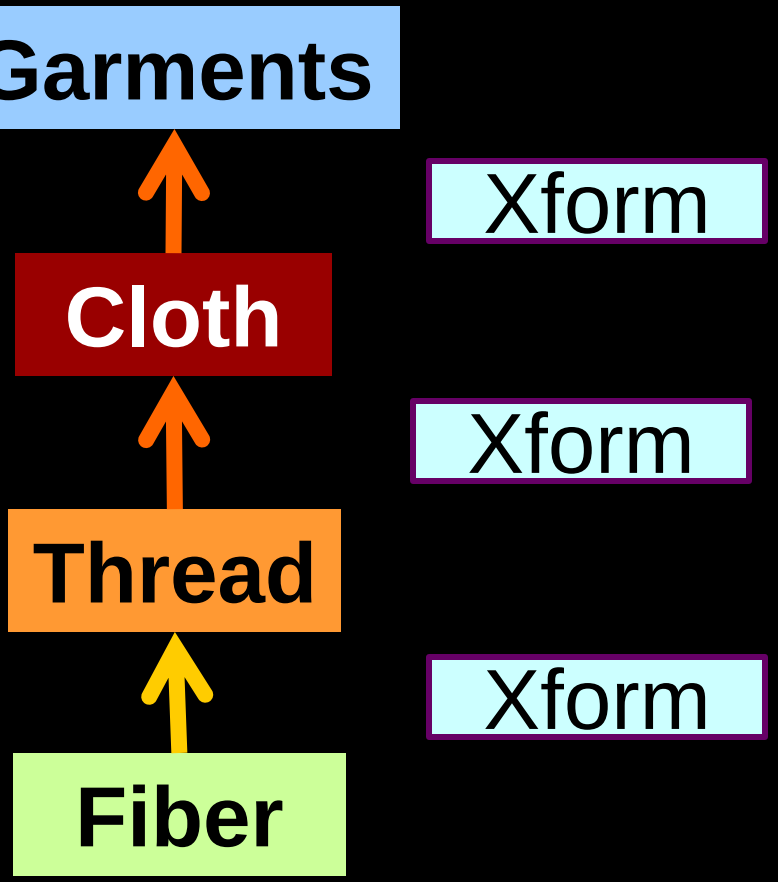


Robust to variations in

- weather
- activity
- appearance requirements
- wear and tear
- cleaning

Universal strategies?



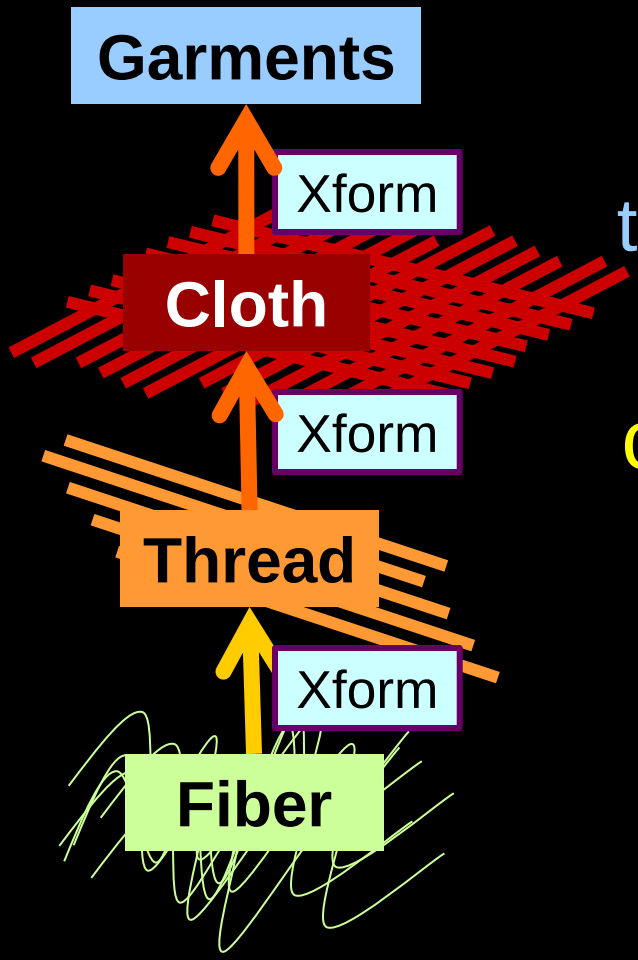


Prevents unraveling of lower layers

Universal strategies?

Even though garments seem analog/continuous

quantization for robustness



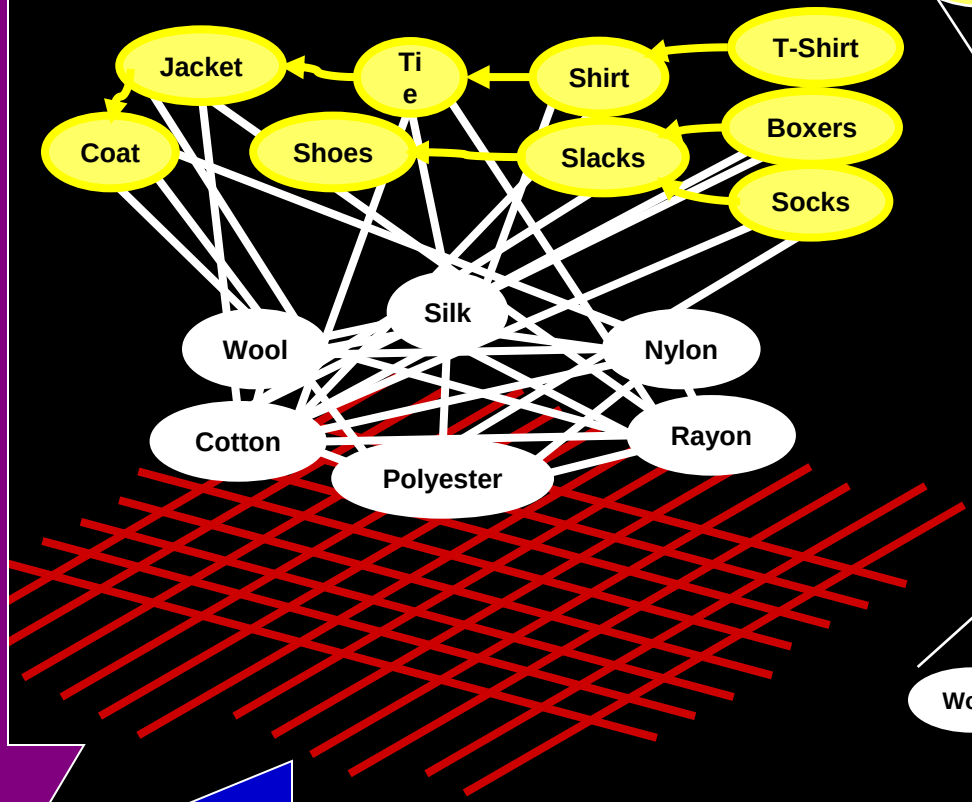
Garments have limited access to threads and fibers

constraints on cross-layer interactions

Prevents unraveling of lower layers

Horizontal networks of garments

Vertical decomposition



Garments

Dress Shirt Slacks Lingerie Coat Scarf Tie

Sewing

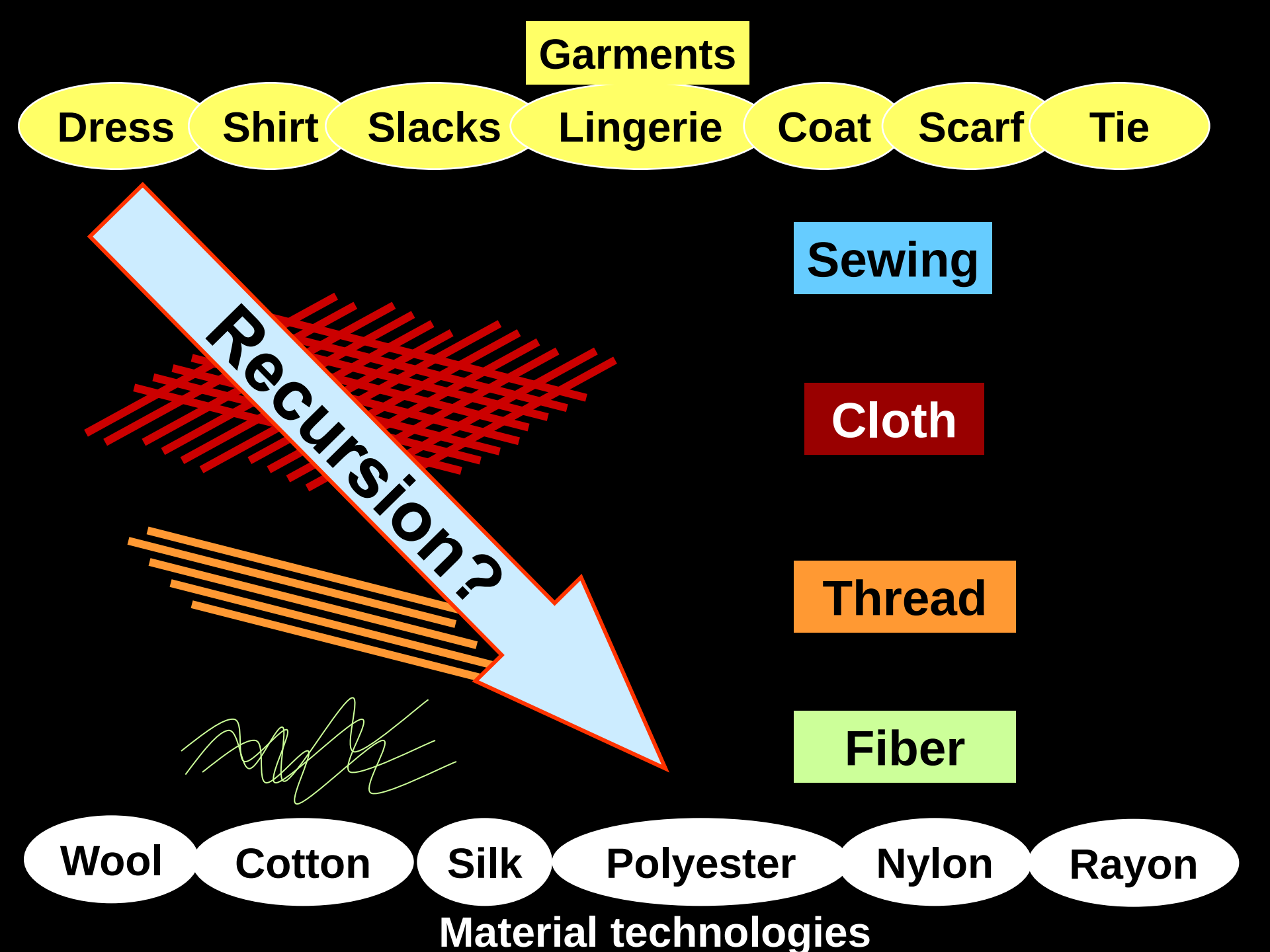
The hourglass?

Cloth

Wool Cotton Silk Polyester Nylon Rayon

Material technology

Horizontal networks of fibers


Garments
Dress
Shirt
Slacks
Lingerie
Coat
Scarf
Tie
Recursion?
Sewing
Cloth
Thread
Fiber
Wool
Cotton
Silk
Polyester
Nylon
Rayon
Material technologies

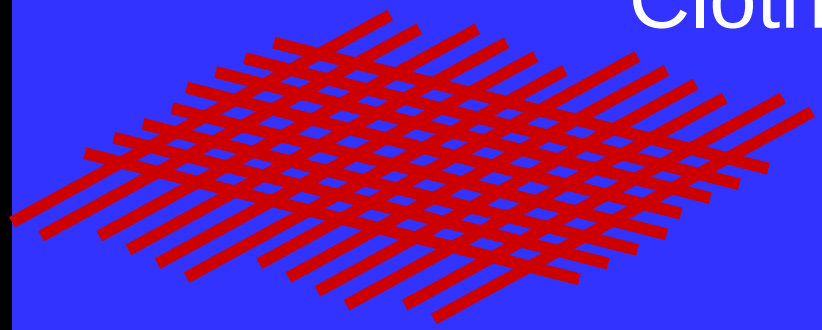
Garments

Sewing

Xform ↔ Ctrl ↔ Mgmt

Universal functions?

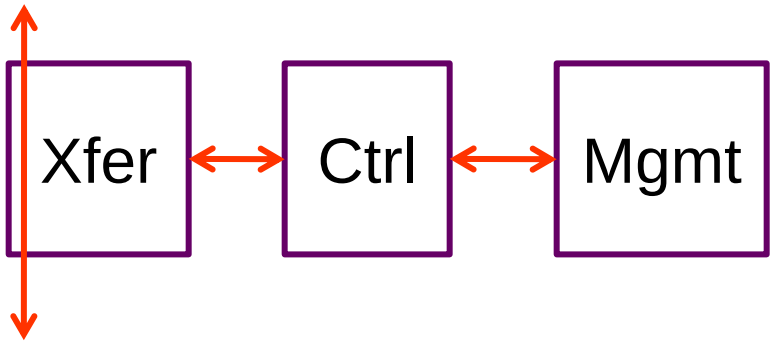
Cloth available



Cloth

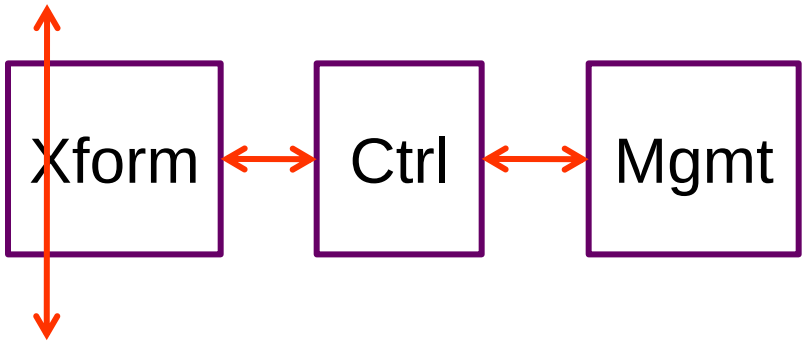
Thread

Fiber



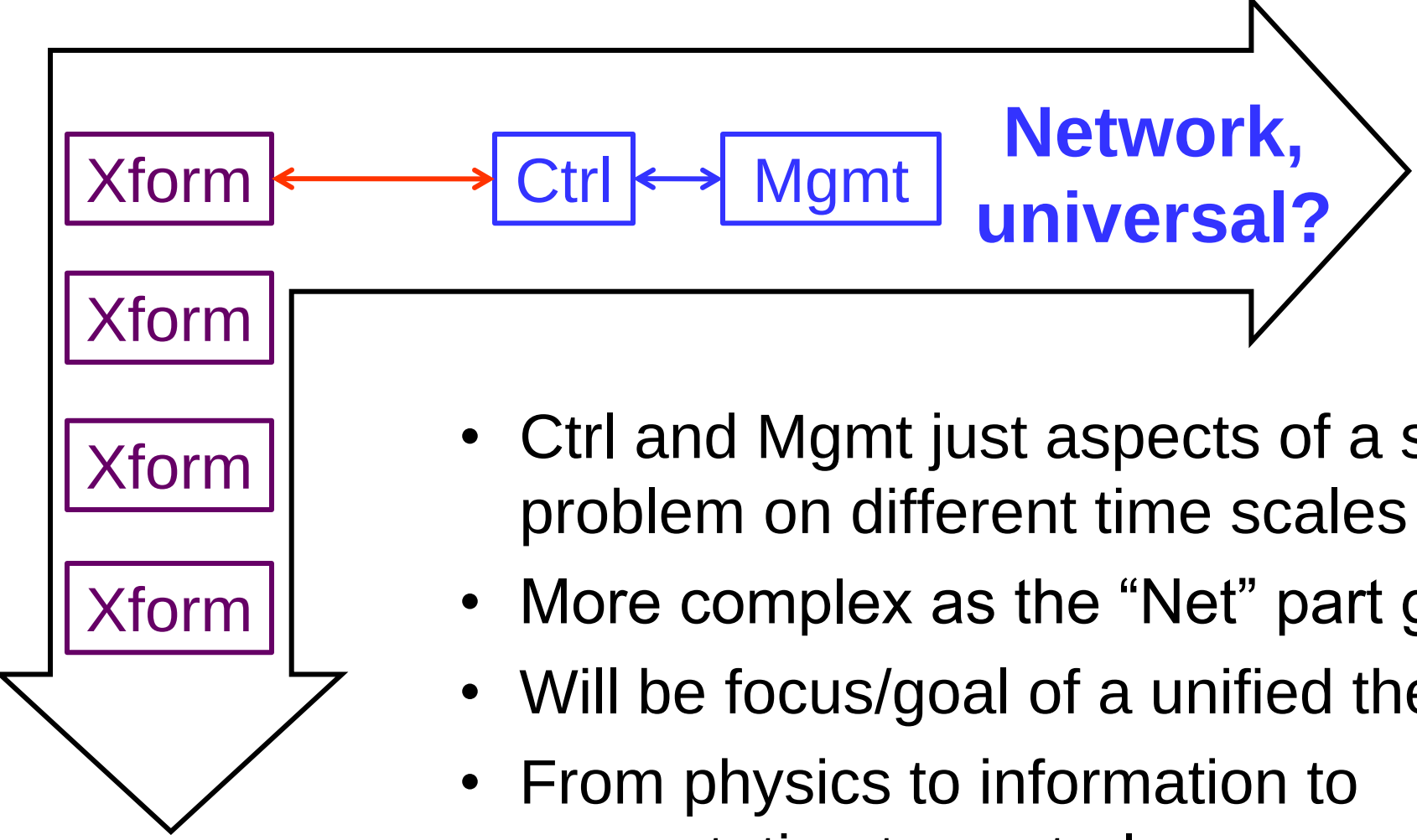
Universal functions?

- Transfer or transform (fastest)
  - **Domain specific (data, power, goods, etc)**
  - Depends on demand and supply
- Control (middle)
  - Schedule/MUX resources in time and space
  - Flow and error control
- Management (slowest)
  - ***What*** resources are available?
  - ***Where*** are they?
  - Cost? Risk? etc



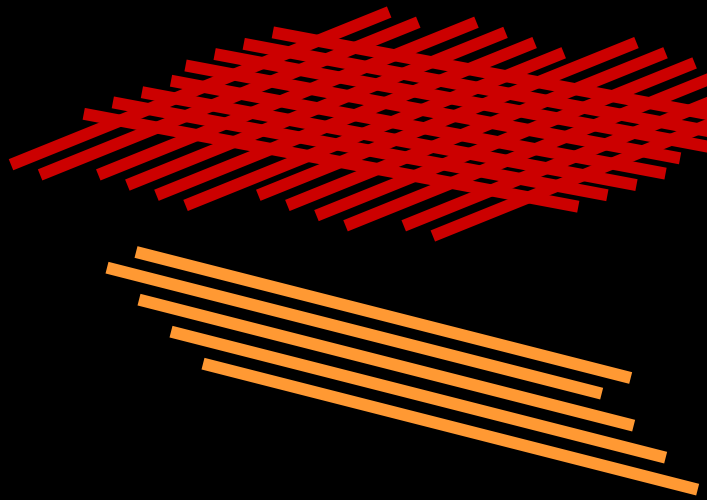
Sewing function?

- Transfer or transform (fastest)
  - **Transform cloth to garments**
  - Depends on demand and supply
- Control (middle)
  - Schedule/MUX resources in time and space
  - Flow and error control
- Management (slowest)
  - ***What*** resources are available?
  - ***Where*** are they?
  - Cost? Risk? etc



- Ctrl and Mgmt just aspects of a single problem on different time scales :
- More complex as the “Net” part grows
- Will be focus/goal of a unified theory
- From physics to information to computation to control

Universal functions?



Garments

Xform ↔ Ctrl ↔ Mgmt

Cloth

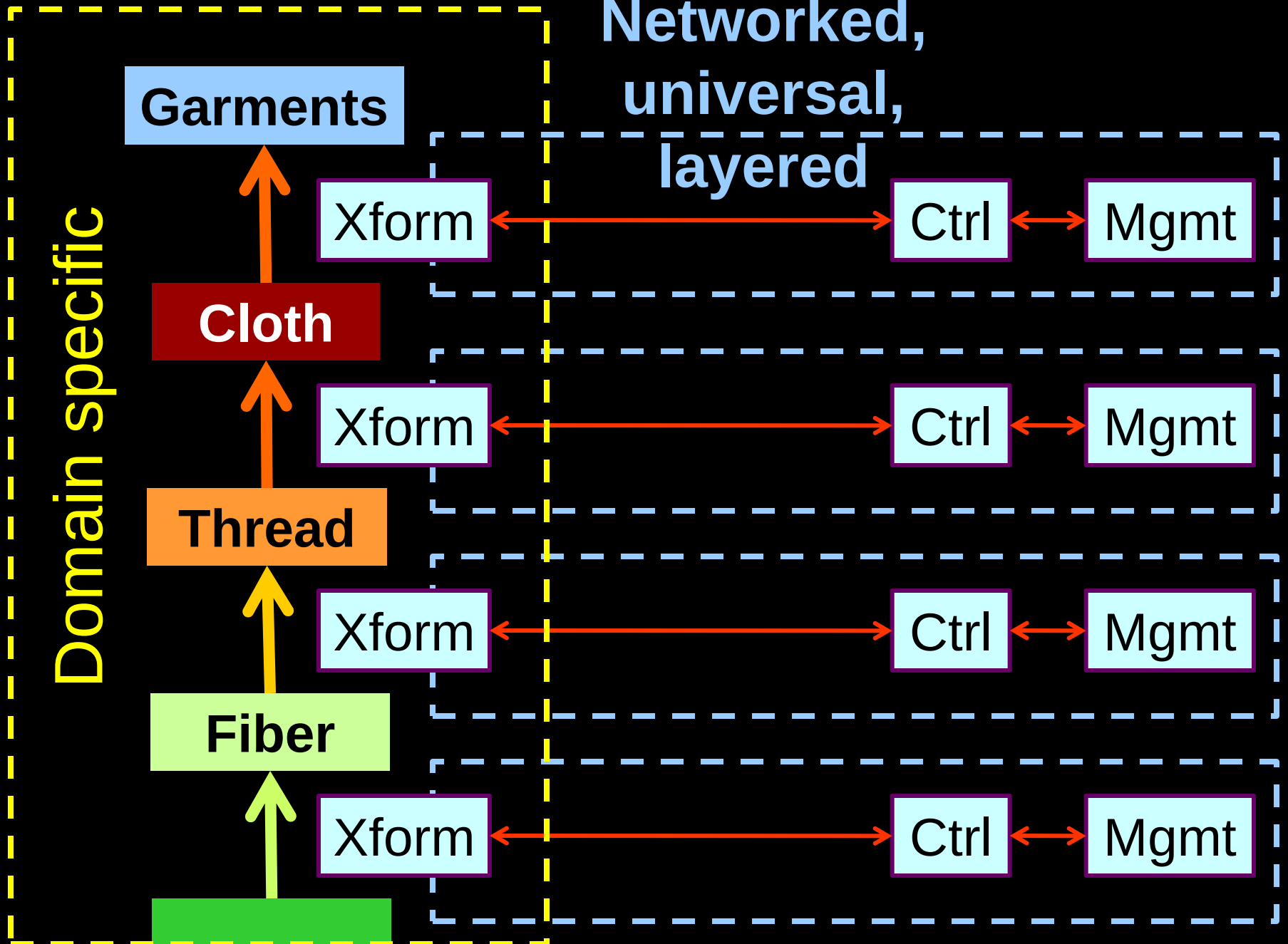
Xform ↔ Ctrl ↔ Mgmt

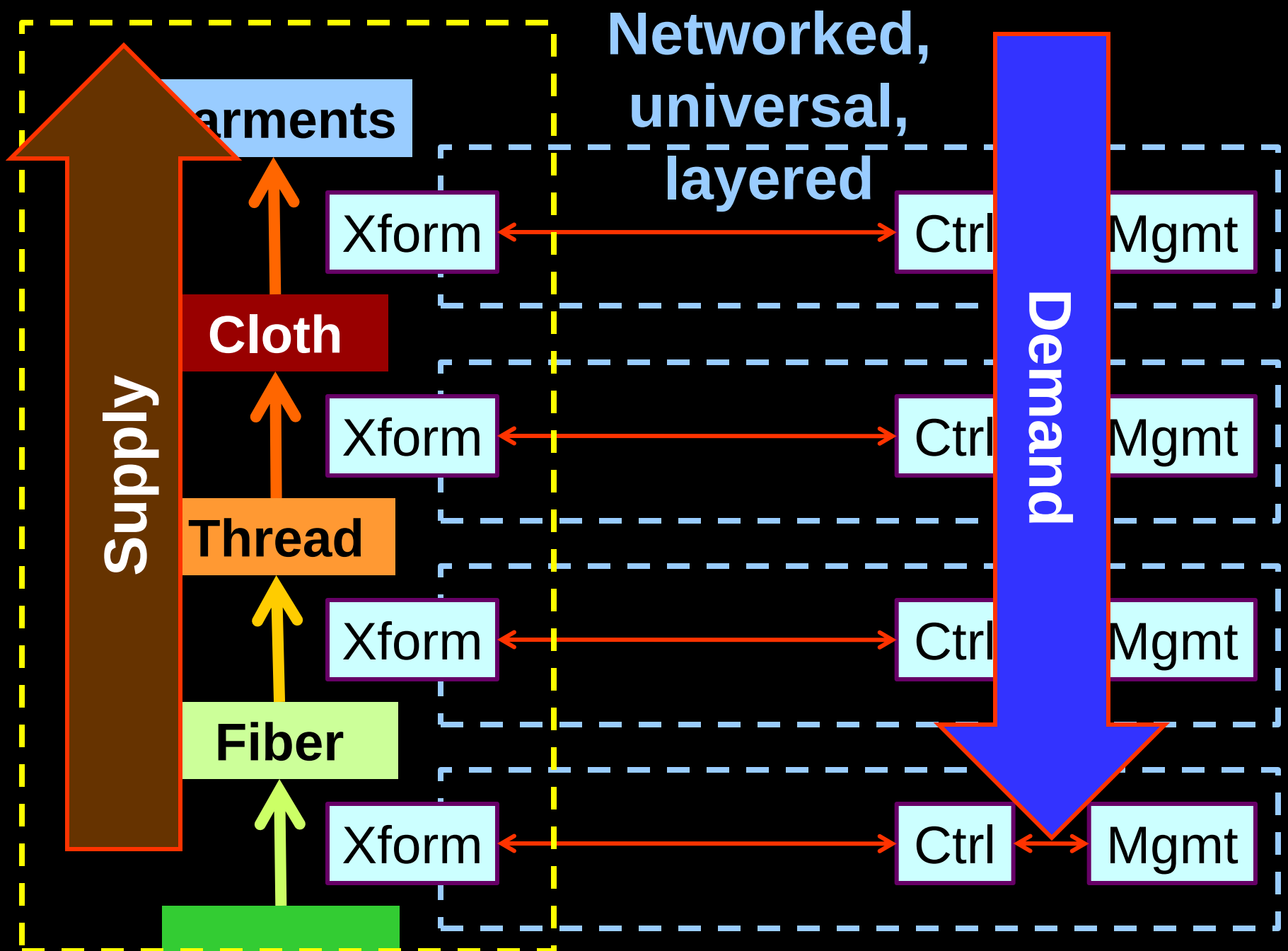
Thread

Xform ↔ Ctrl ↔ Mgmt

Fiber

Xform ↔ Ctrl ↔ Mgmt

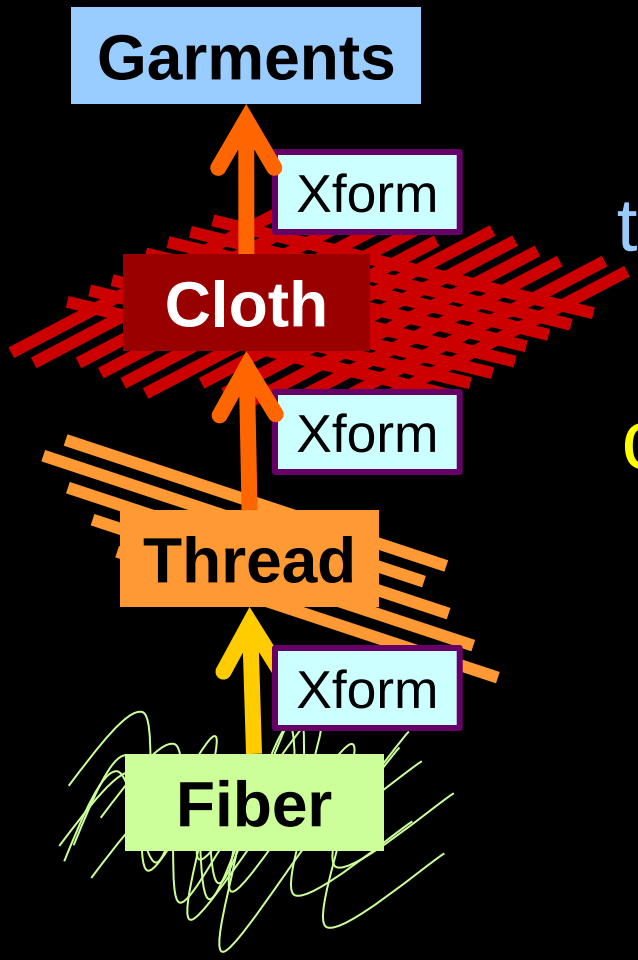

Networked, universal, layered
Domain specific
Garments
Cloth
Thread
Fiber
Xform
Ctrl
Mgmt
Xform
Ctrl
Mgmt
Xform
Ctrl
Mgmt
Xform
Ctrl
Mgmt


Networked,
universal,
layered
arments
Cloth
Thread
Fiber
Supply
Demand
Xform
Ctrl
Mgmt
Xform
Ctrl
Mgmt
Xform
Ctrl
Mgmt
Xform
Ctrl
Mgmt

Universal strategies?

Even though garments seem analog/continuous

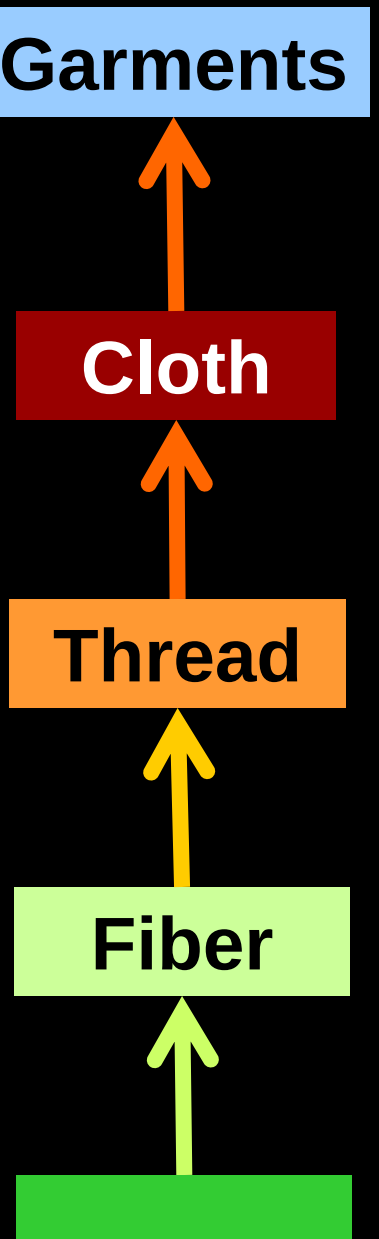
quantization for robustness



Garments have limited access to threads and fibers

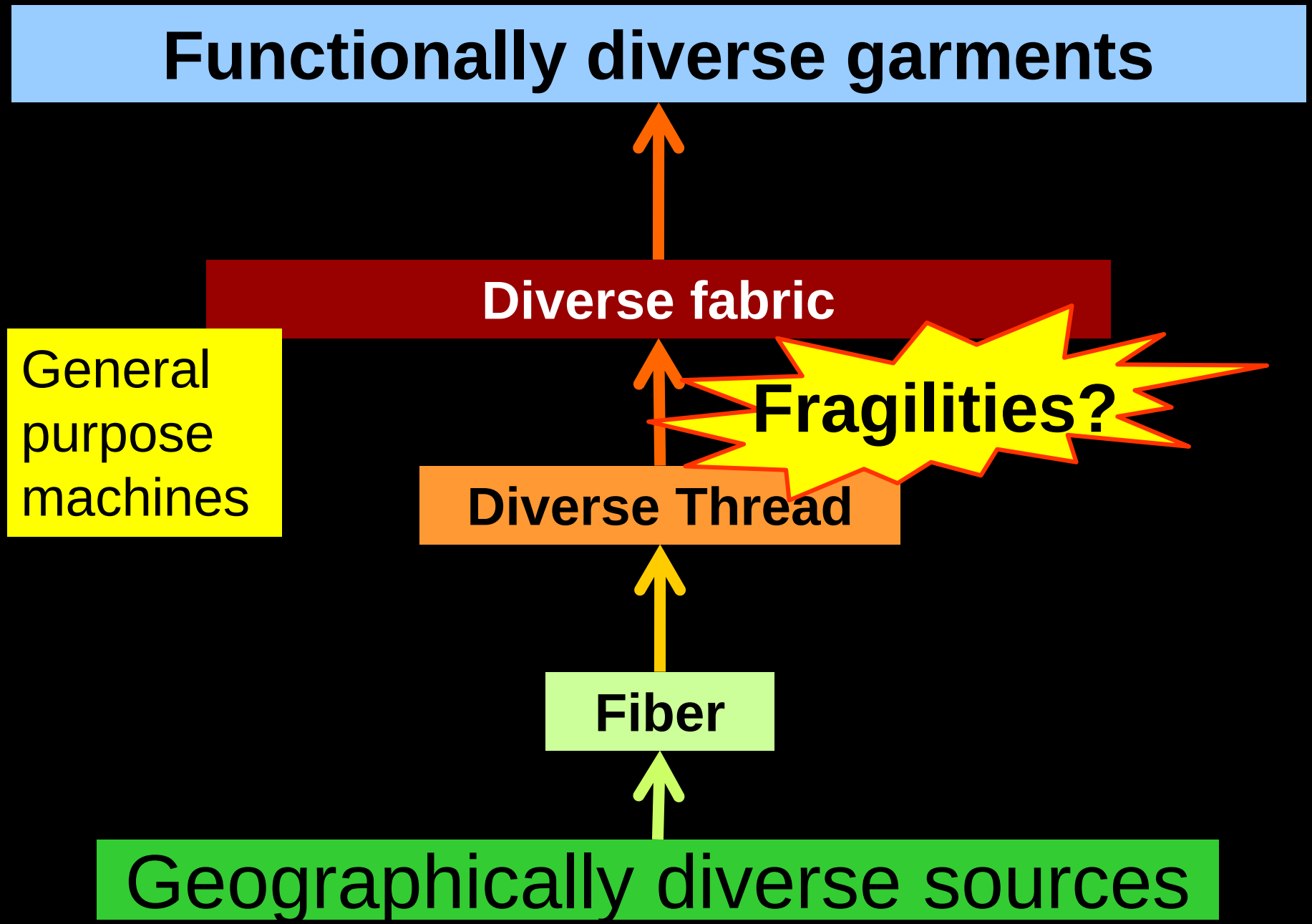
constraints on cross-layer interactions

Prevents unraveling of lower layers

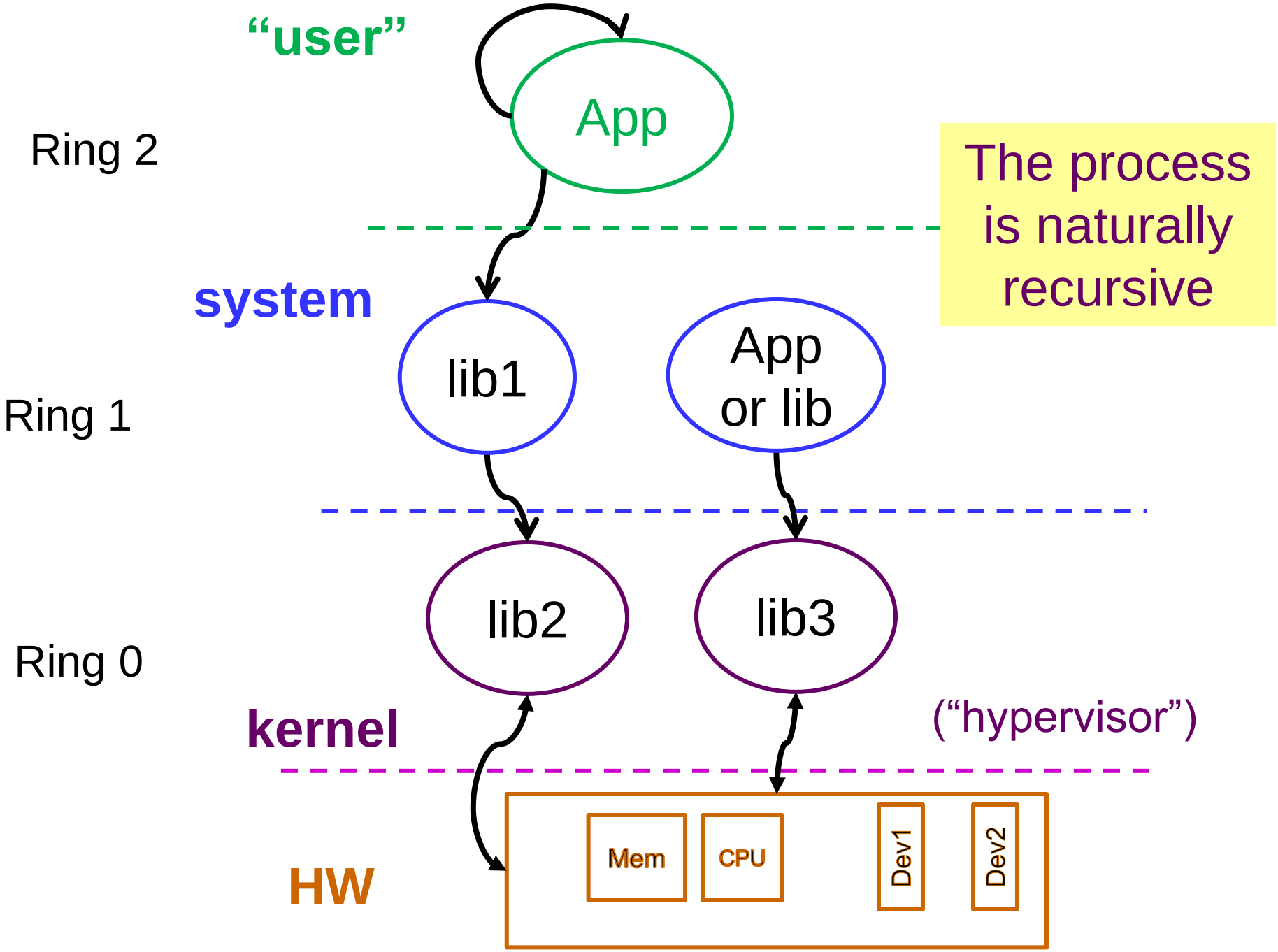


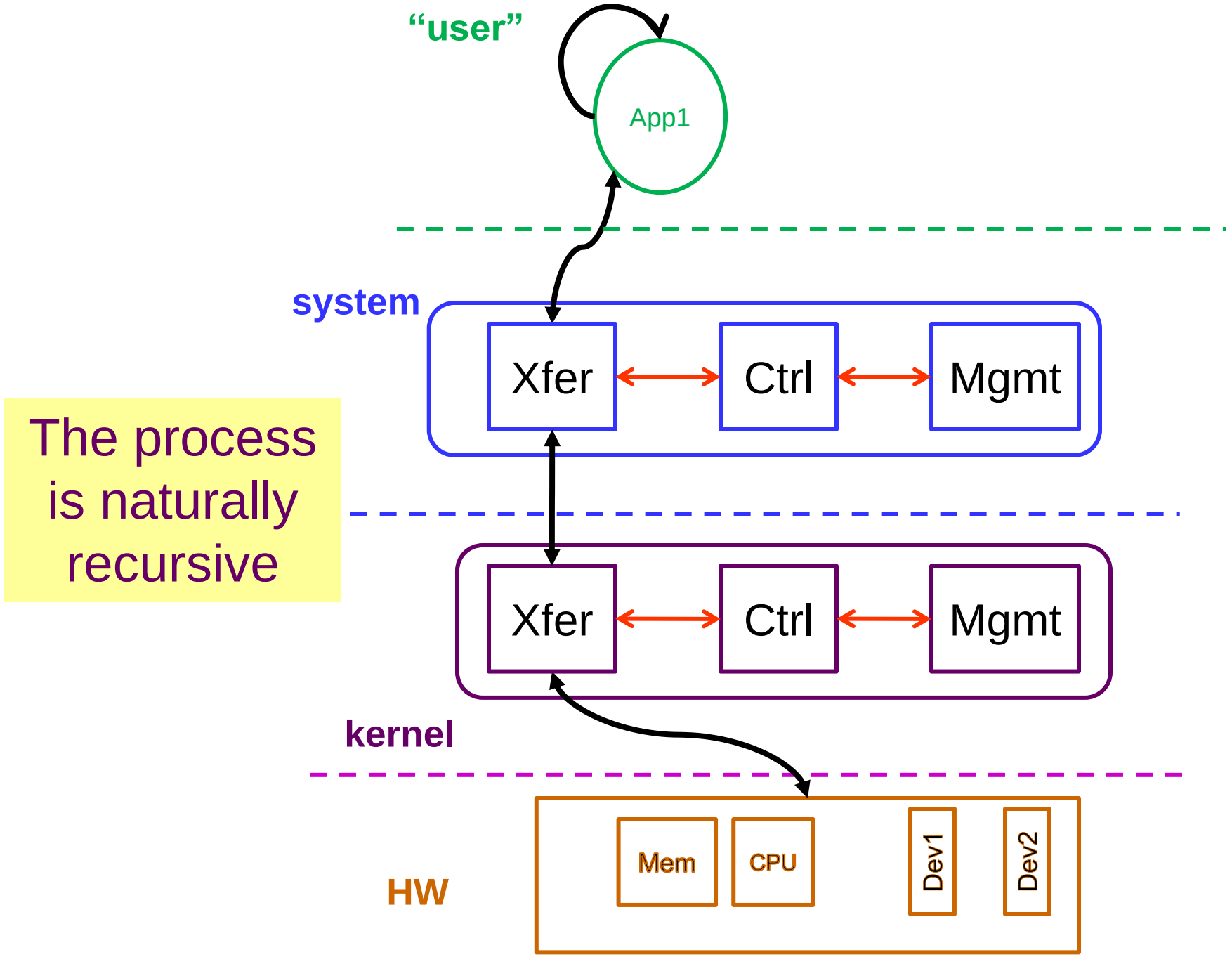
Scalable

Sustainable?


Functionally diverse garments
Diverse fabric
General purpose machines
Fragilities?
Diverse Thread
Fiber
Geographically diverse sources

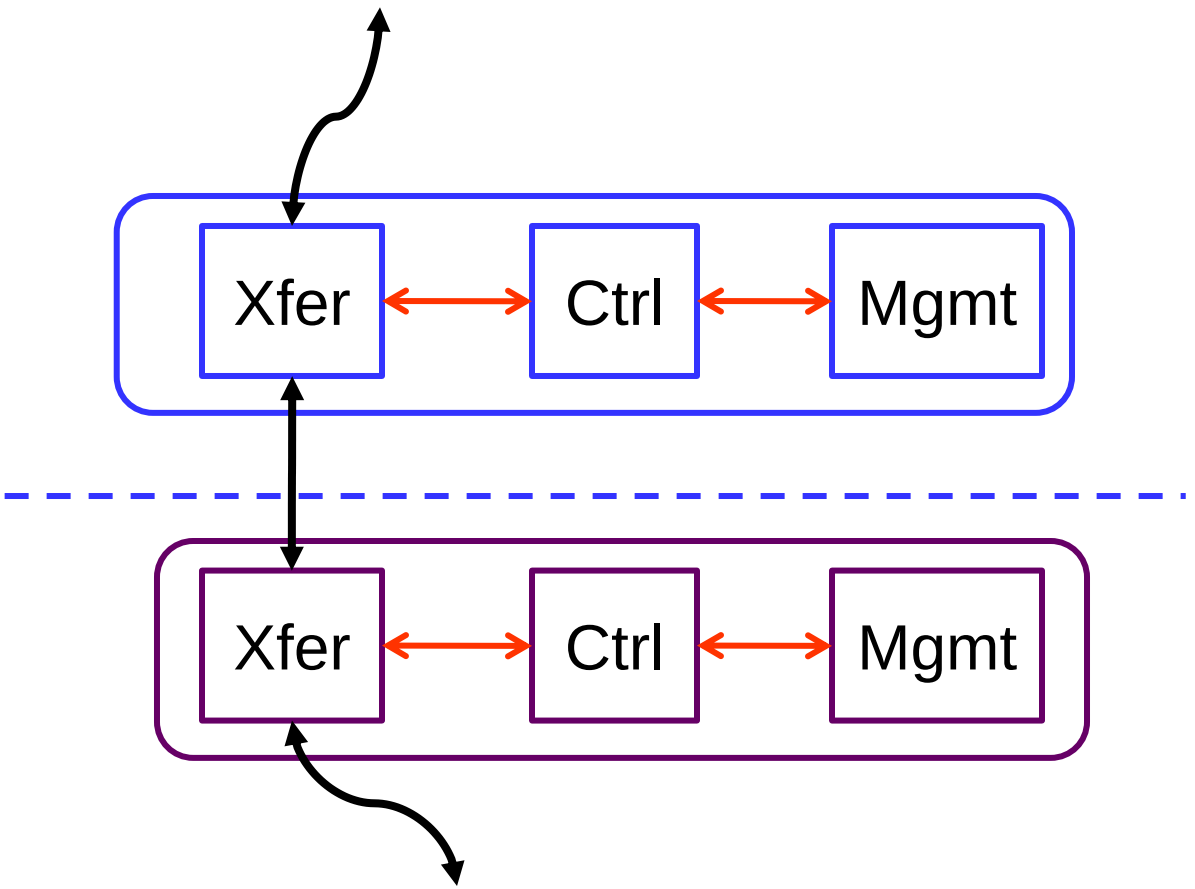

FASHION WARS
NEW YORK SPRING 2009
Garments
Fragilities?
Thread
Fiber


“user”
App
Ring 2
The process is naturally recursive
system
lib1
App or lib
Ring 1
lib2
lib3
Ring 0
kernel
(“hypervisor”)
HW
Mem
CPU
Dev1
Dev2

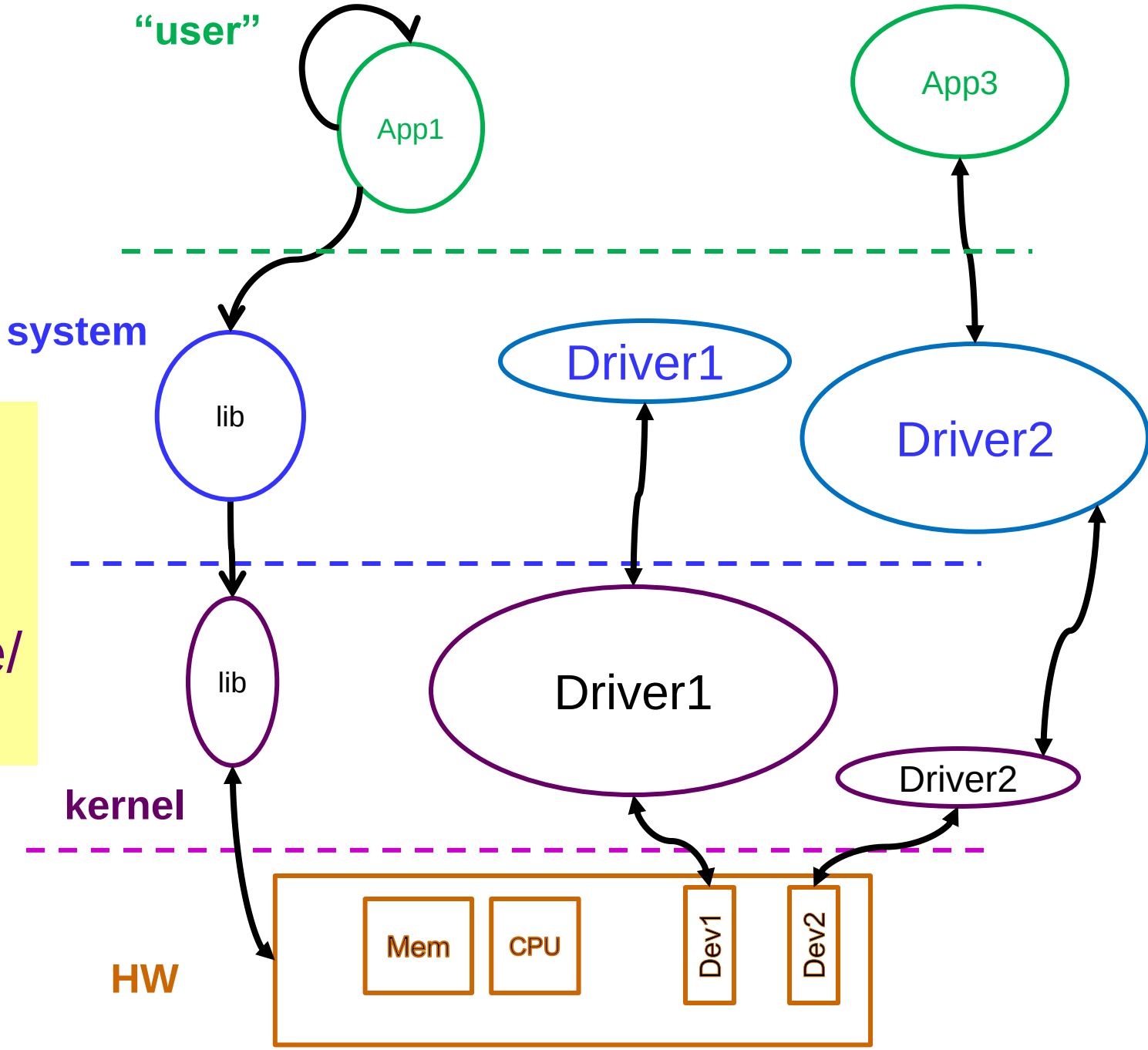

"user"
App1
system
Xfer
Ctrl
Mgmt
The process is naturally recursive
Xfer
Ctrl
Mgmt
kernel
HW
Mem
CPU
Dev1
Dev2

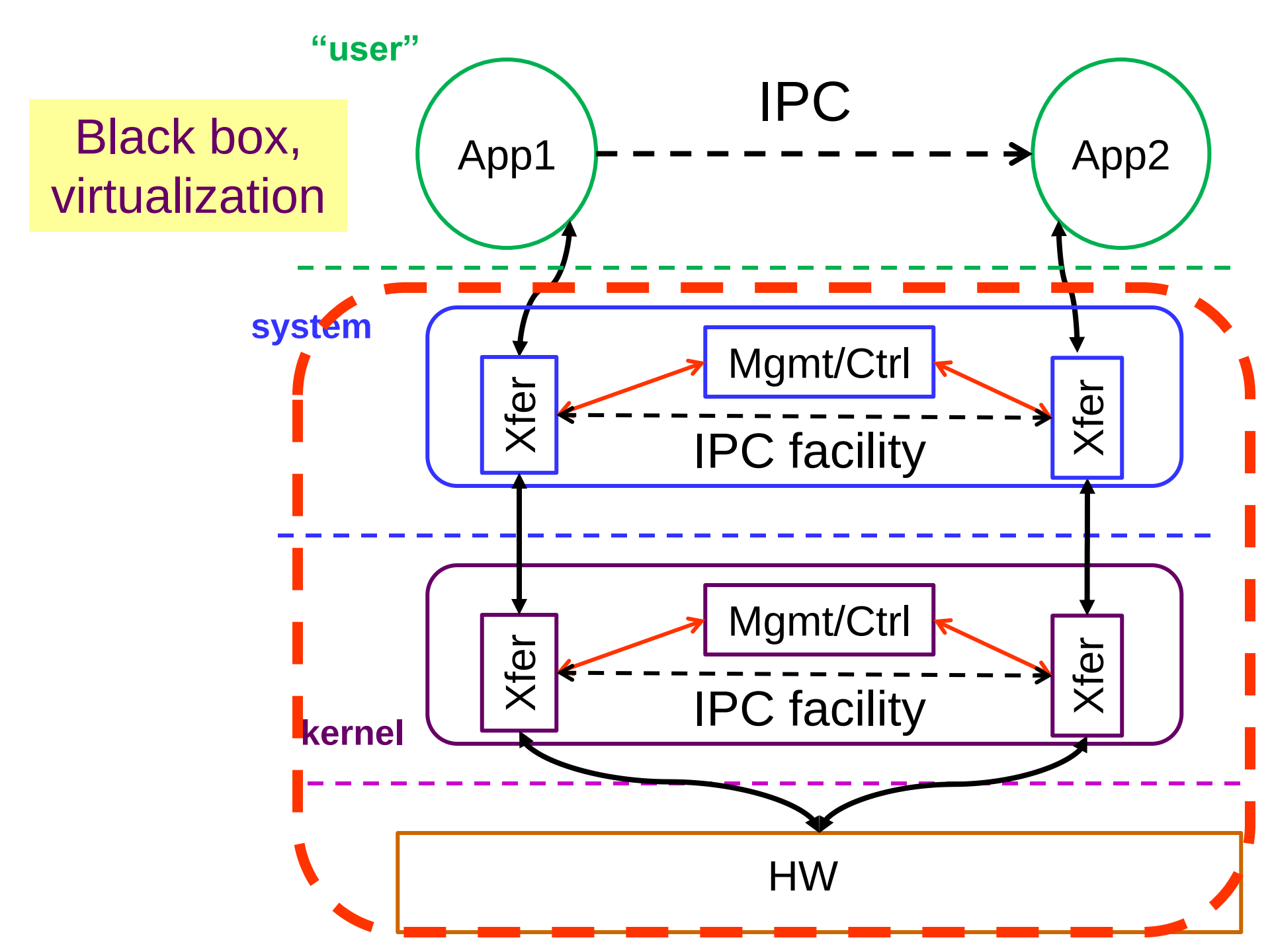
Layers have sublayers

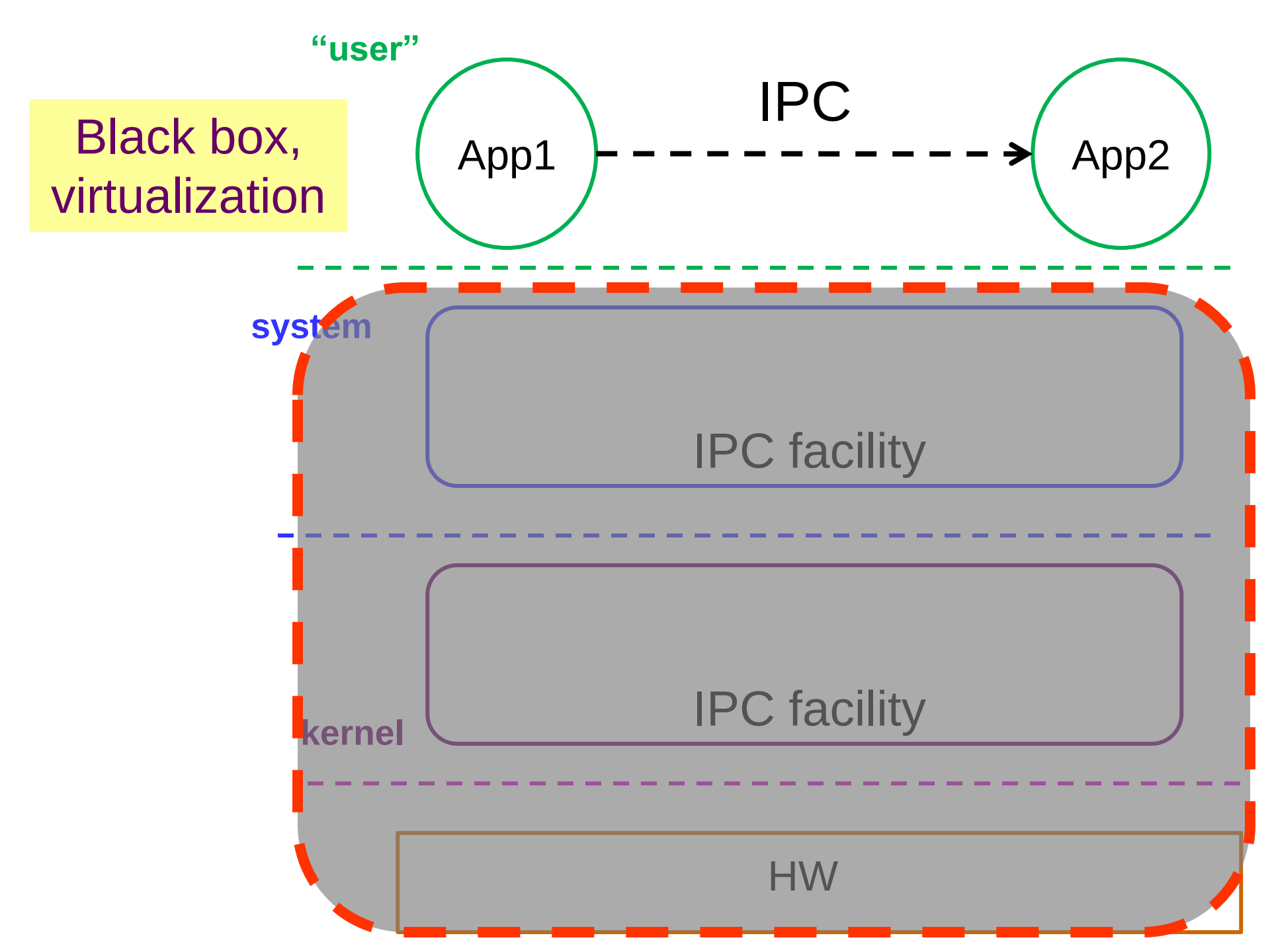
Layers are naturally recursive



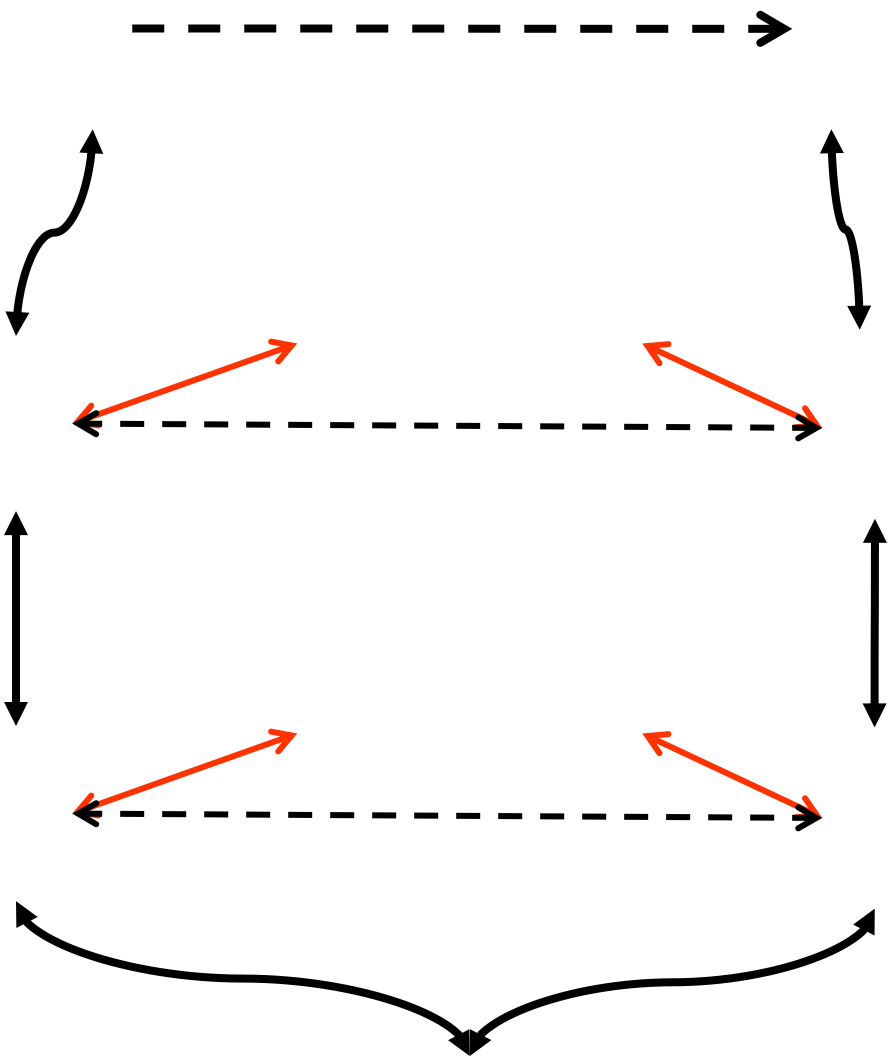
Design choices effect performance/ robustness



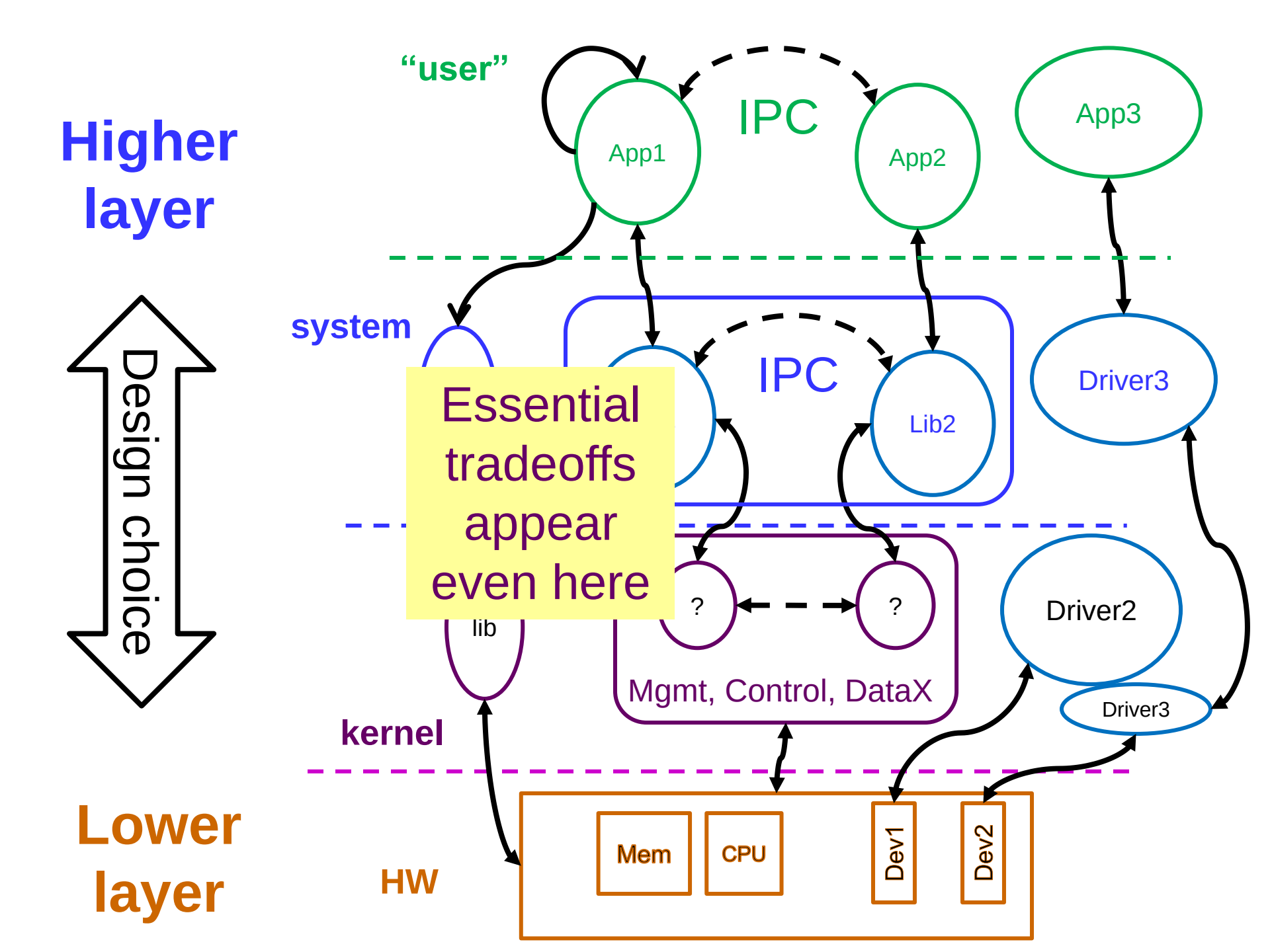

Black box, virtualization
"user"
IPC
App1
App2
system
Xfer
Mgmt/Ctrl
Xfer
IPC facility
Xfer
Mgmt/Ctrl
Xfer
IPC facility
kernel
HW


“user”
Black box, virtualization
App1
IPC
App2
system
IPC facility
IPC facility
kernel
HW

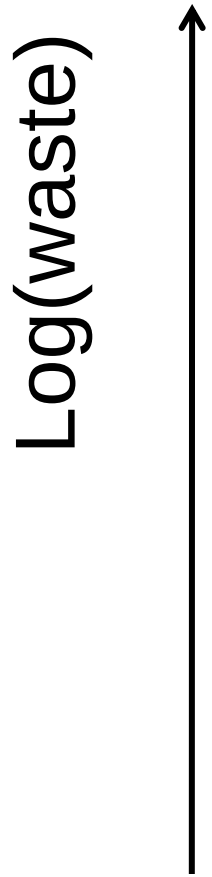
All these signals are “virtual”



The only “real” signals are not shown


Higher layer
Design choice
Lower layer
"user"
App1
IPC
App2
App3
system
IPC
Lib2
Driver3
Essential tradeoffs appear even here
lib
?
?
Mgmt, Control, DataX
Driver2
Driver3
kernel
HW
Mem
CPU
Dev1
Dev2

Slow, Wasteful

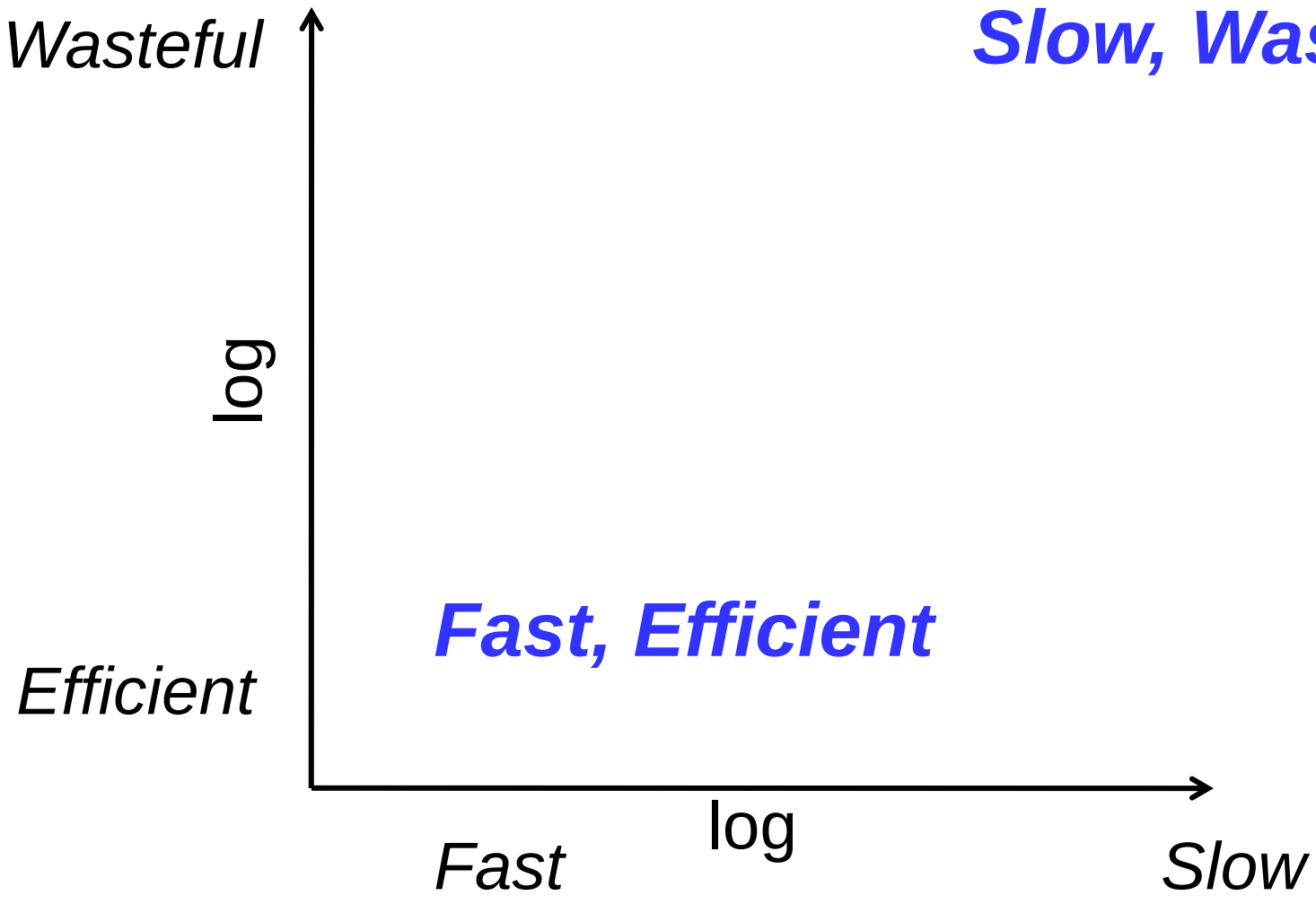


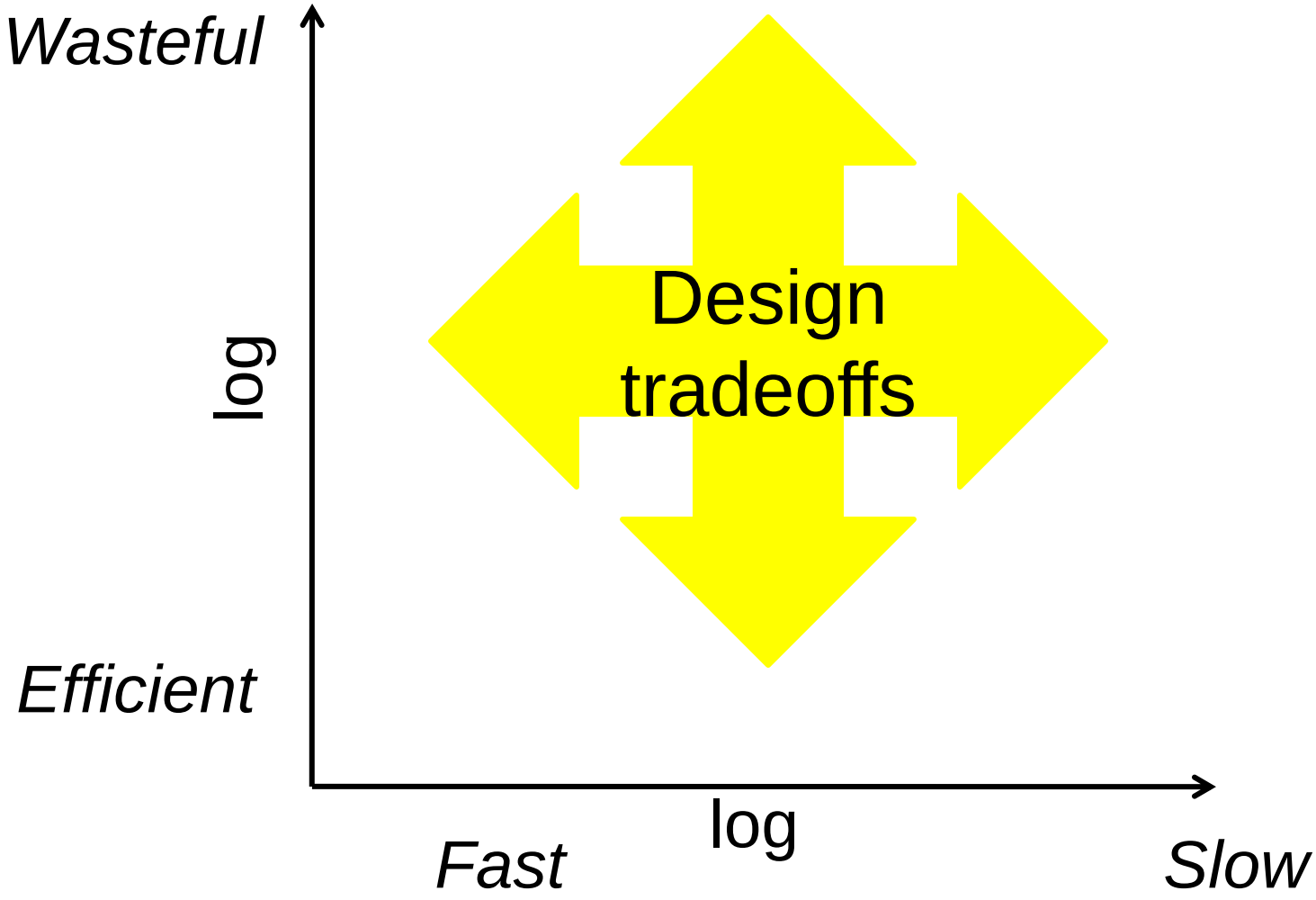
Fast, Efficient

Higher layer

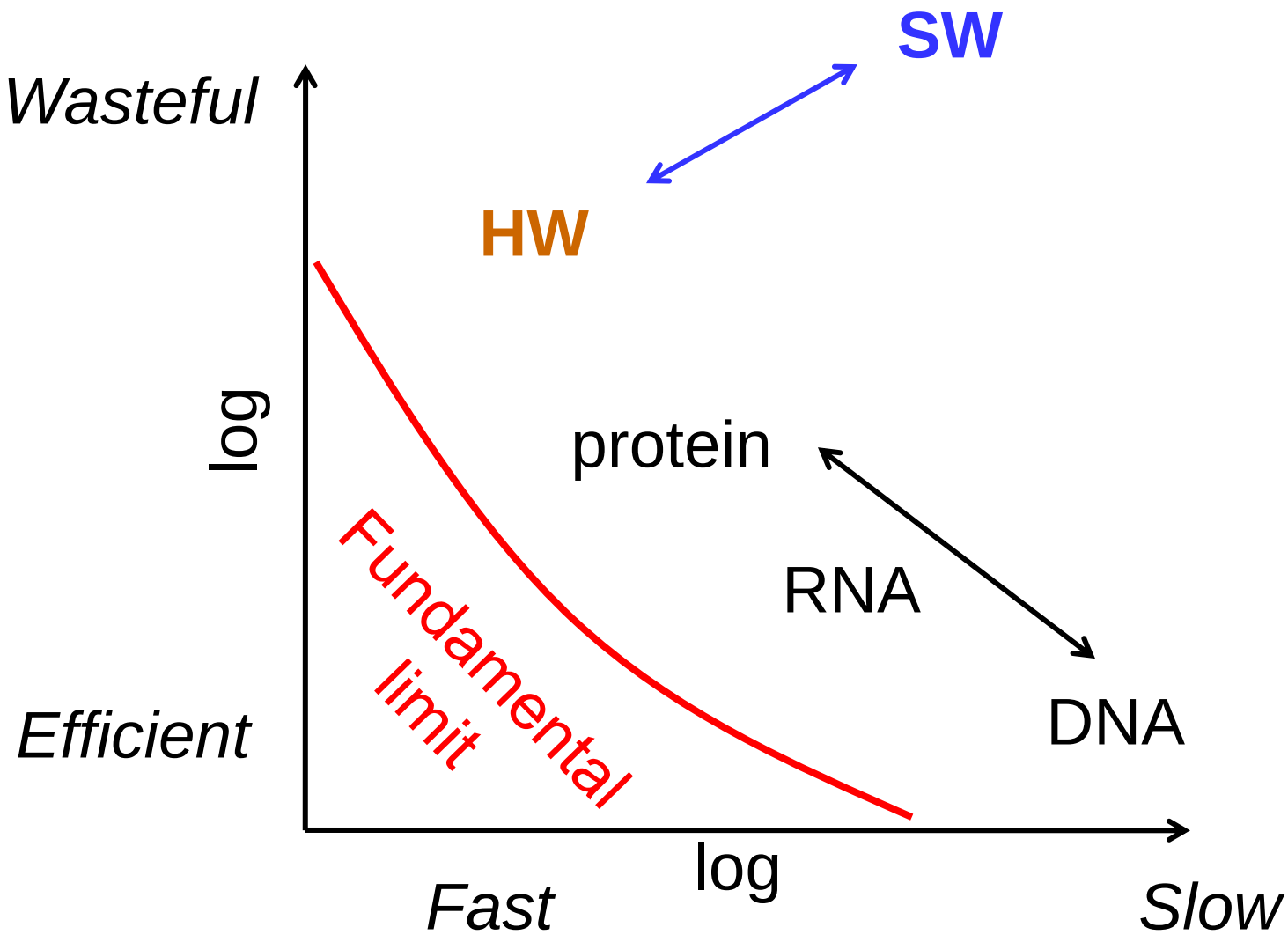
Lower layer

Expand dimensions

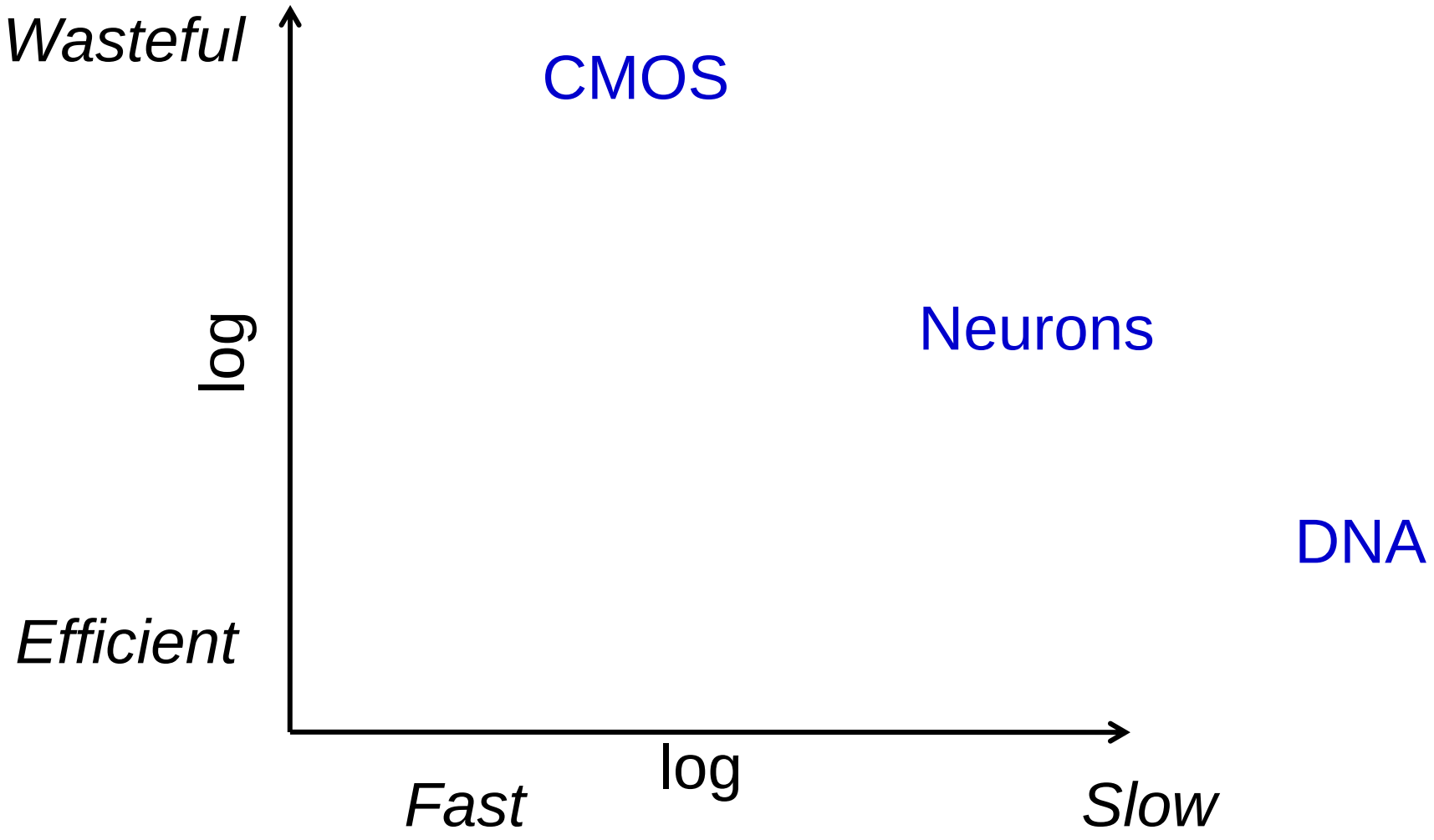



Wasteful
log
Efficient
Design
tradeoffs
Fast
log
Slow

Tradeoffs are universal,
but the details are not.

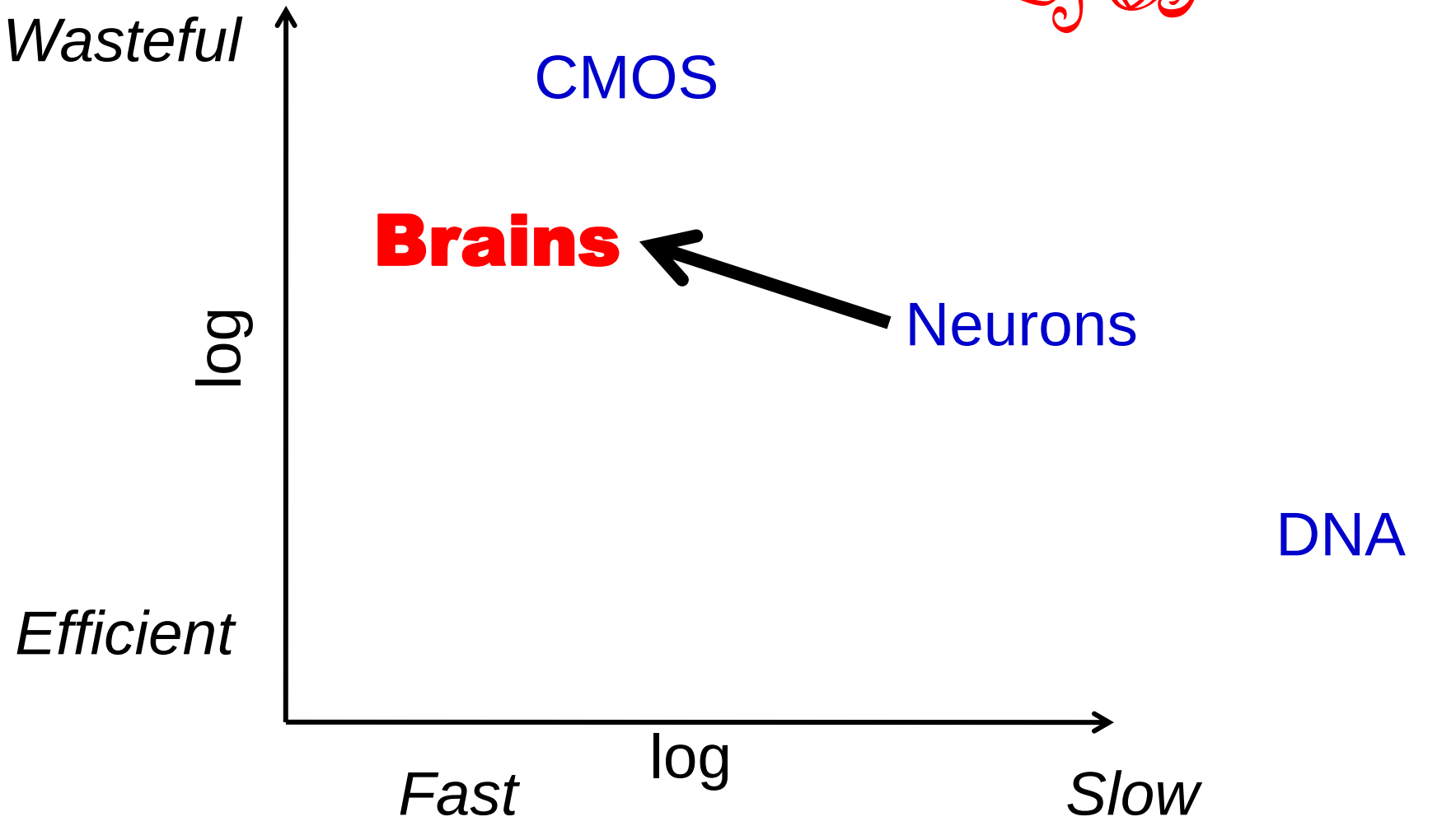


Computational hardware substrates

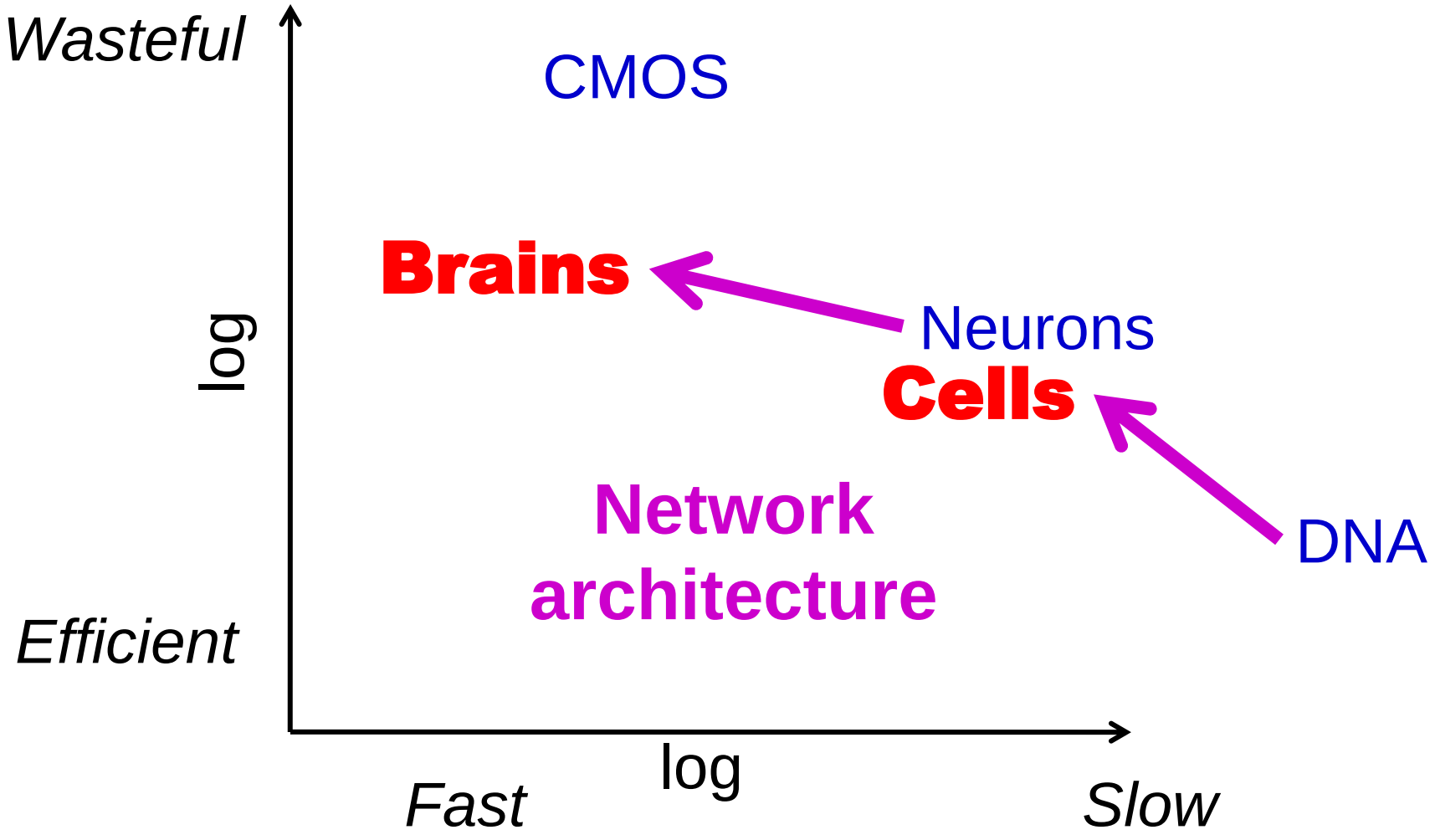


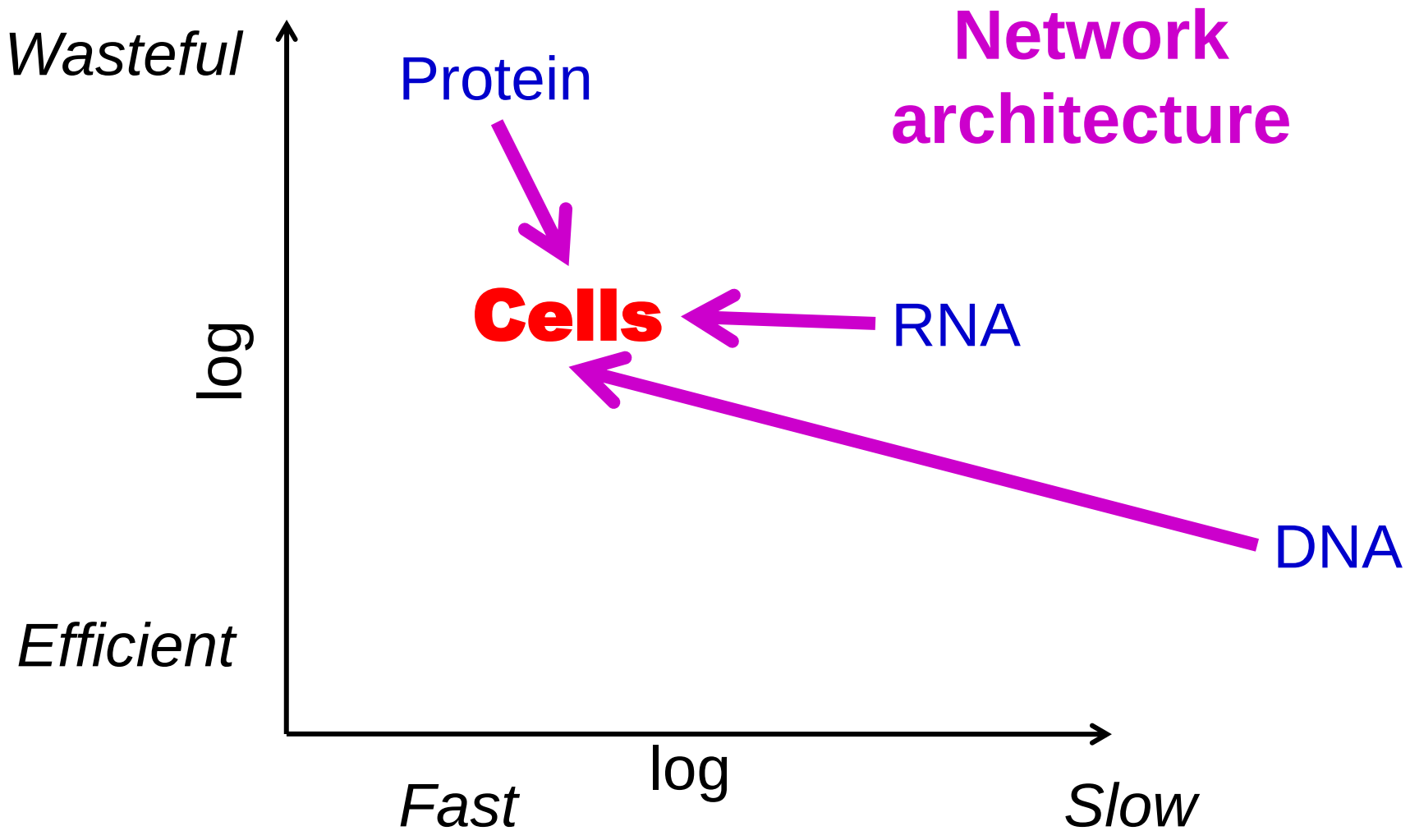
Some tasks: HARD for computers

EASY for us

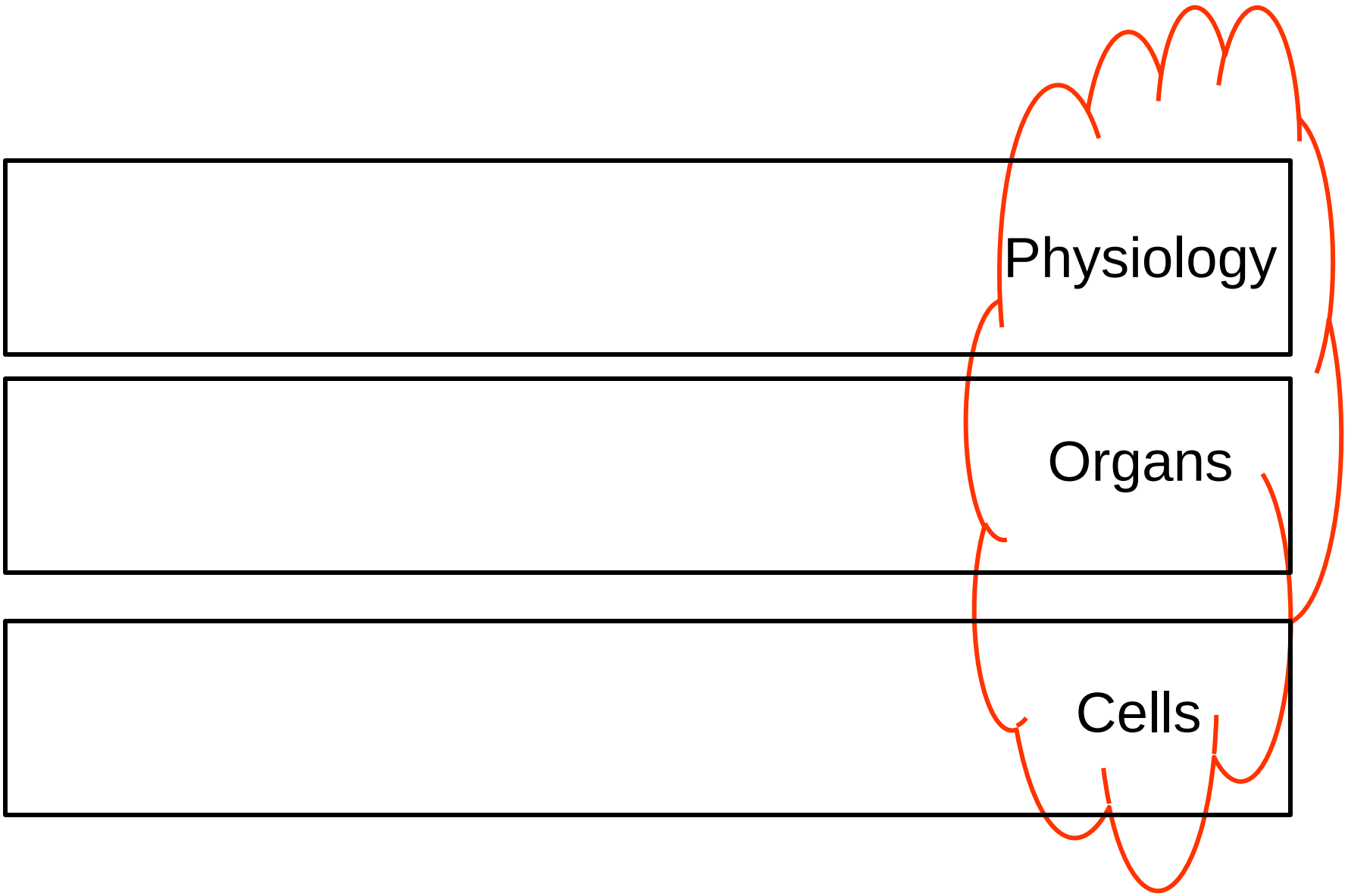


What makes this possible?

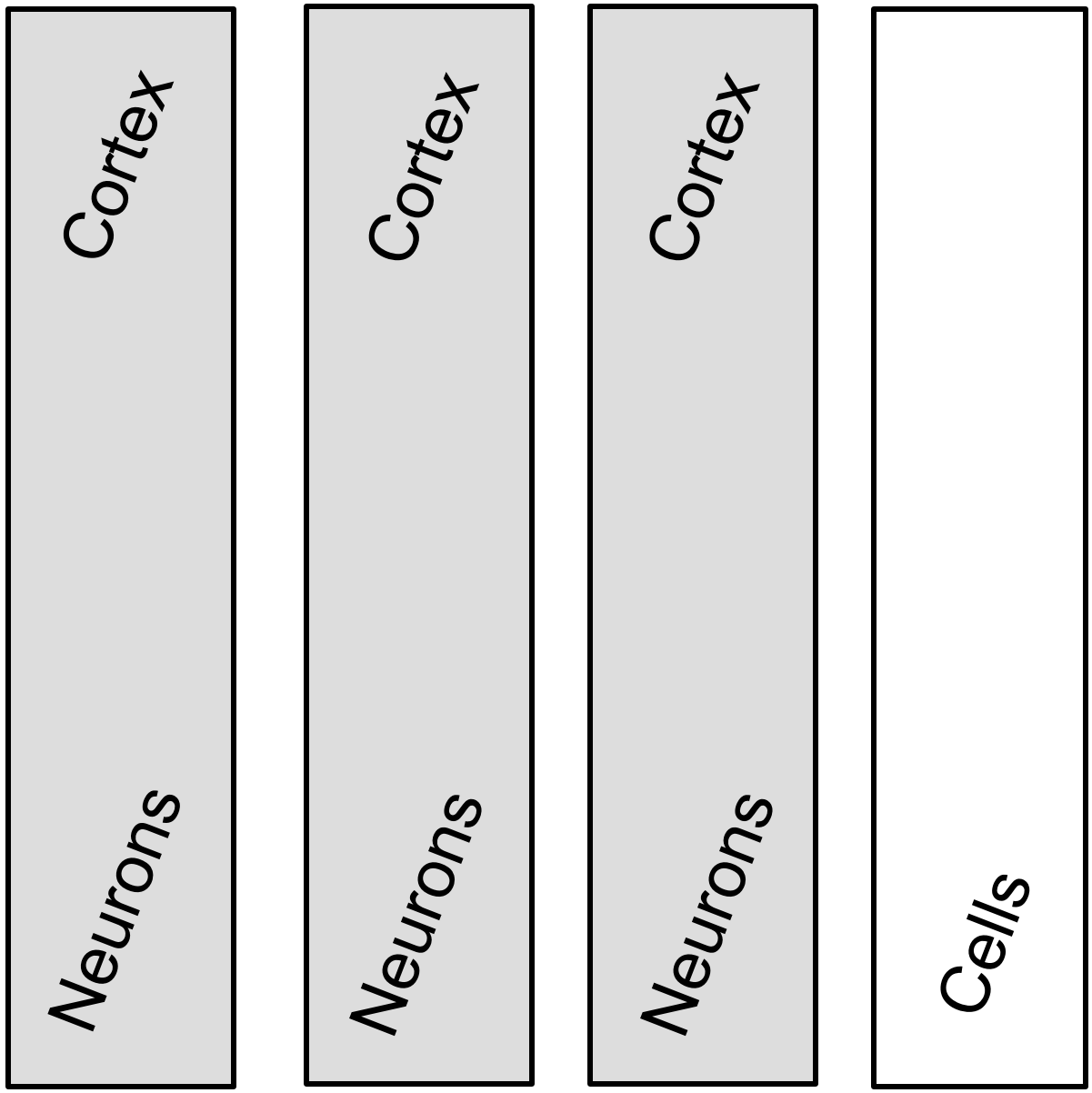


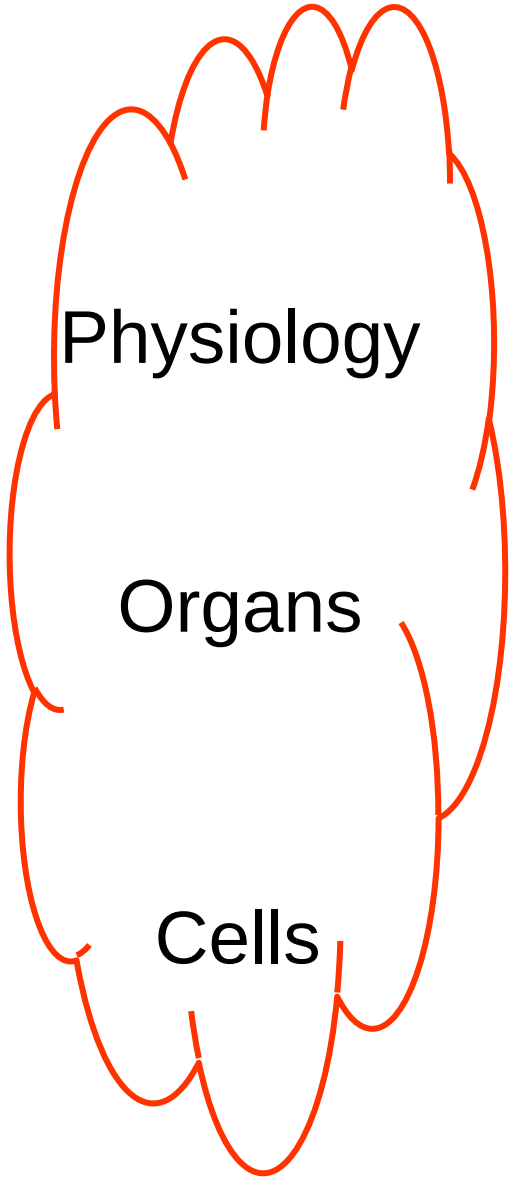

Wasteful
log
Efficient
Protein
Network
architecture
Cells
RNA
DNA
Fast
log
Slow

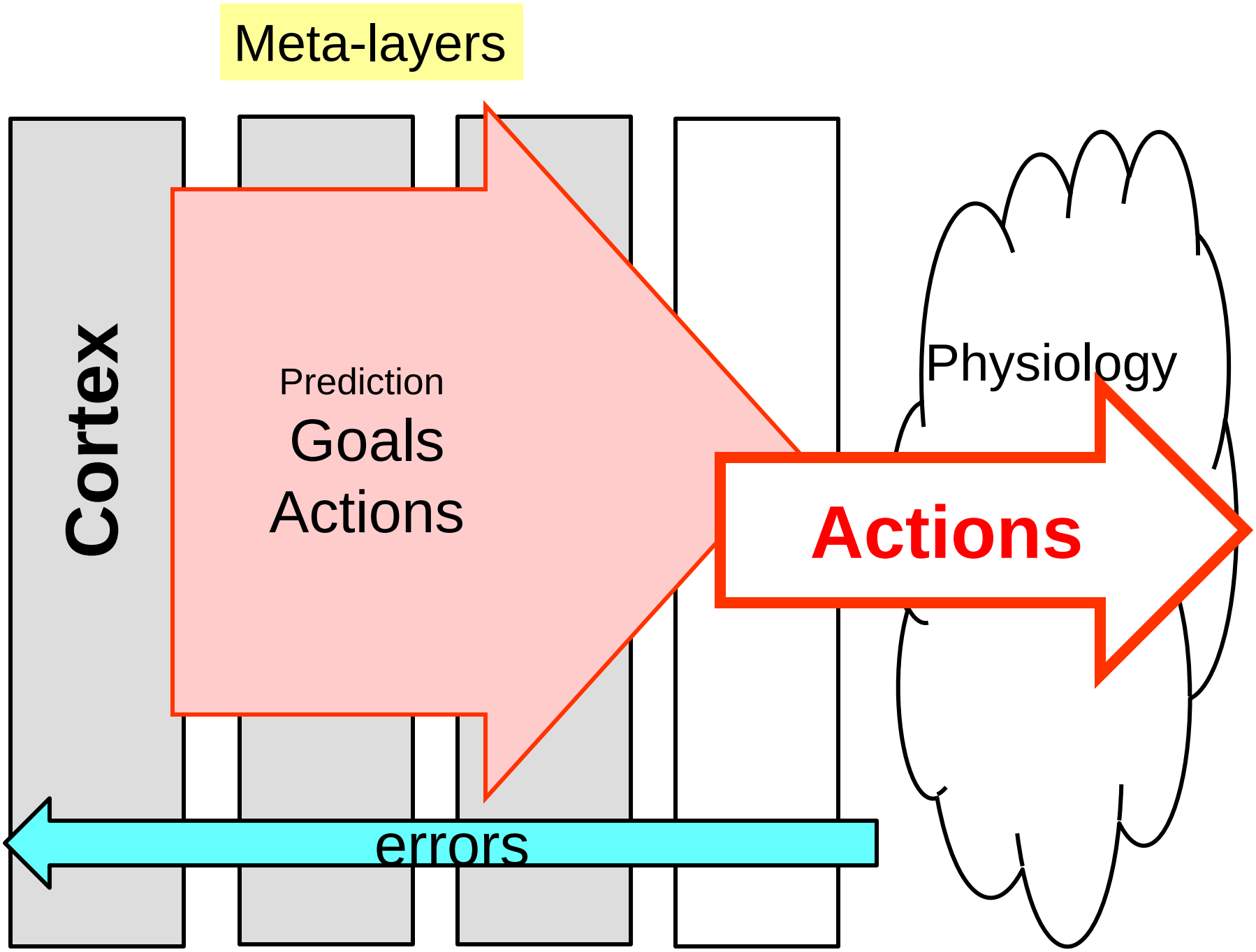
Layered architectures



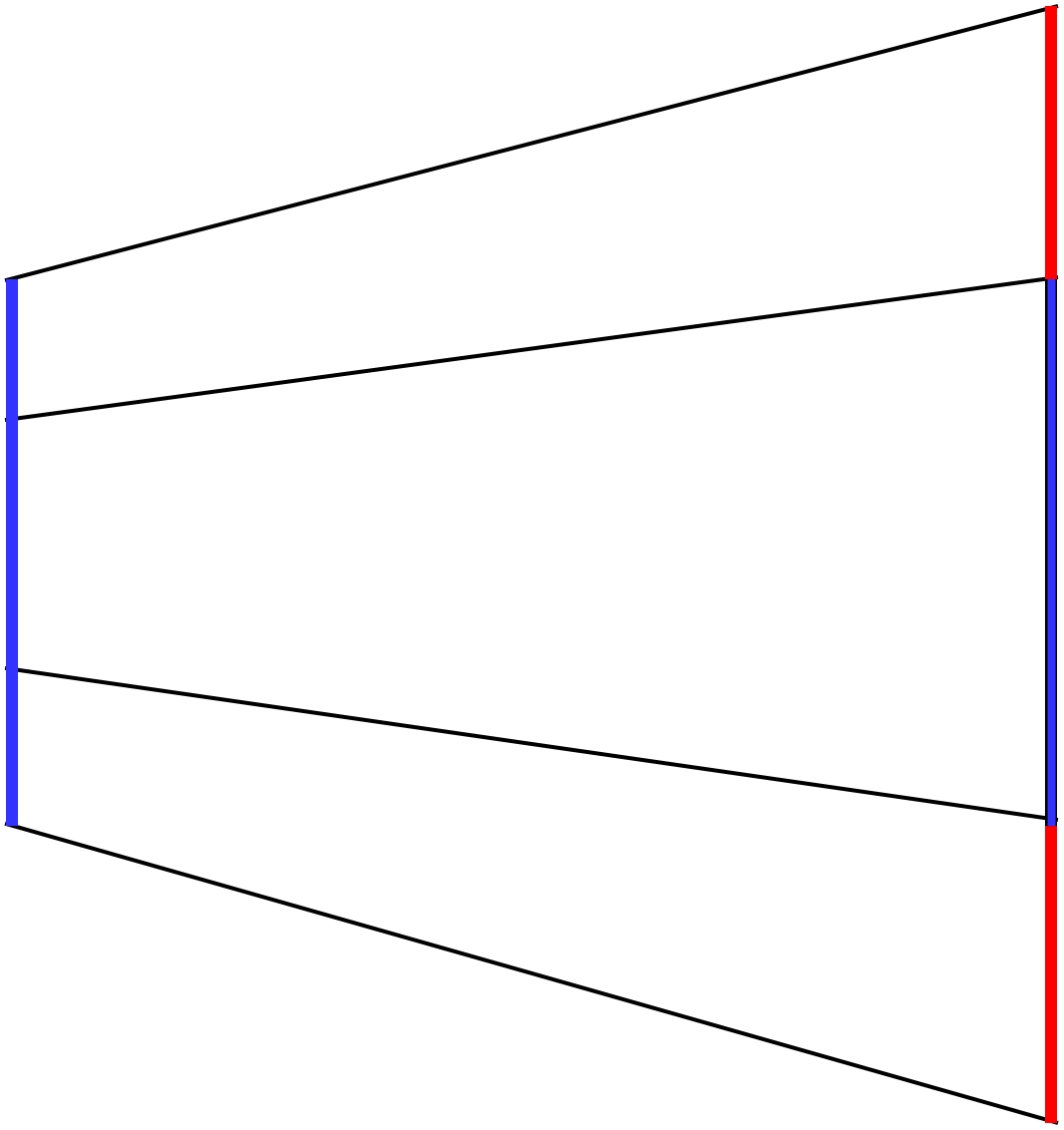
Layered architectures



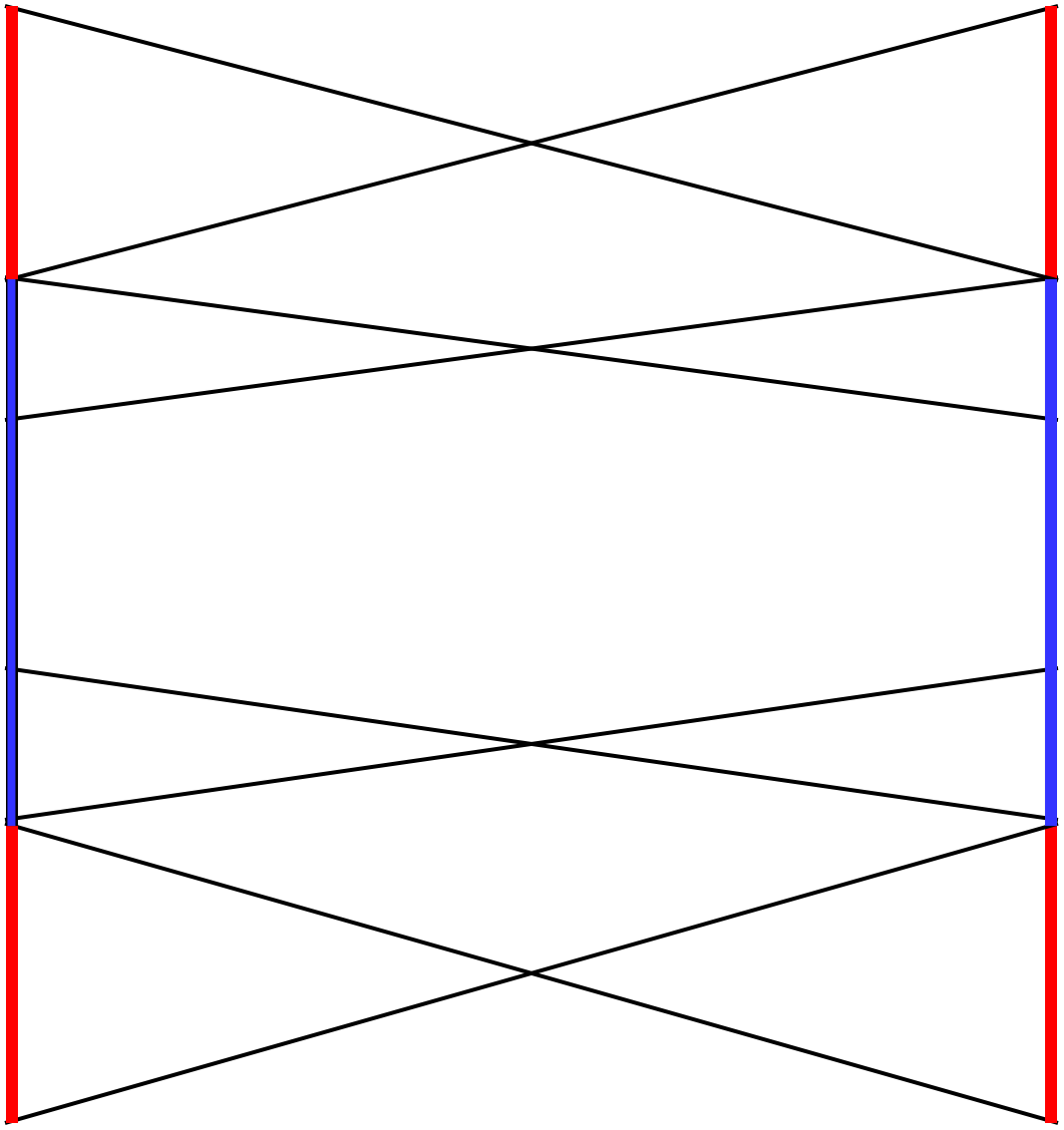



Meta-layers
Cortex
Prediction
Goals
Actions
Physiology
Actions
errors

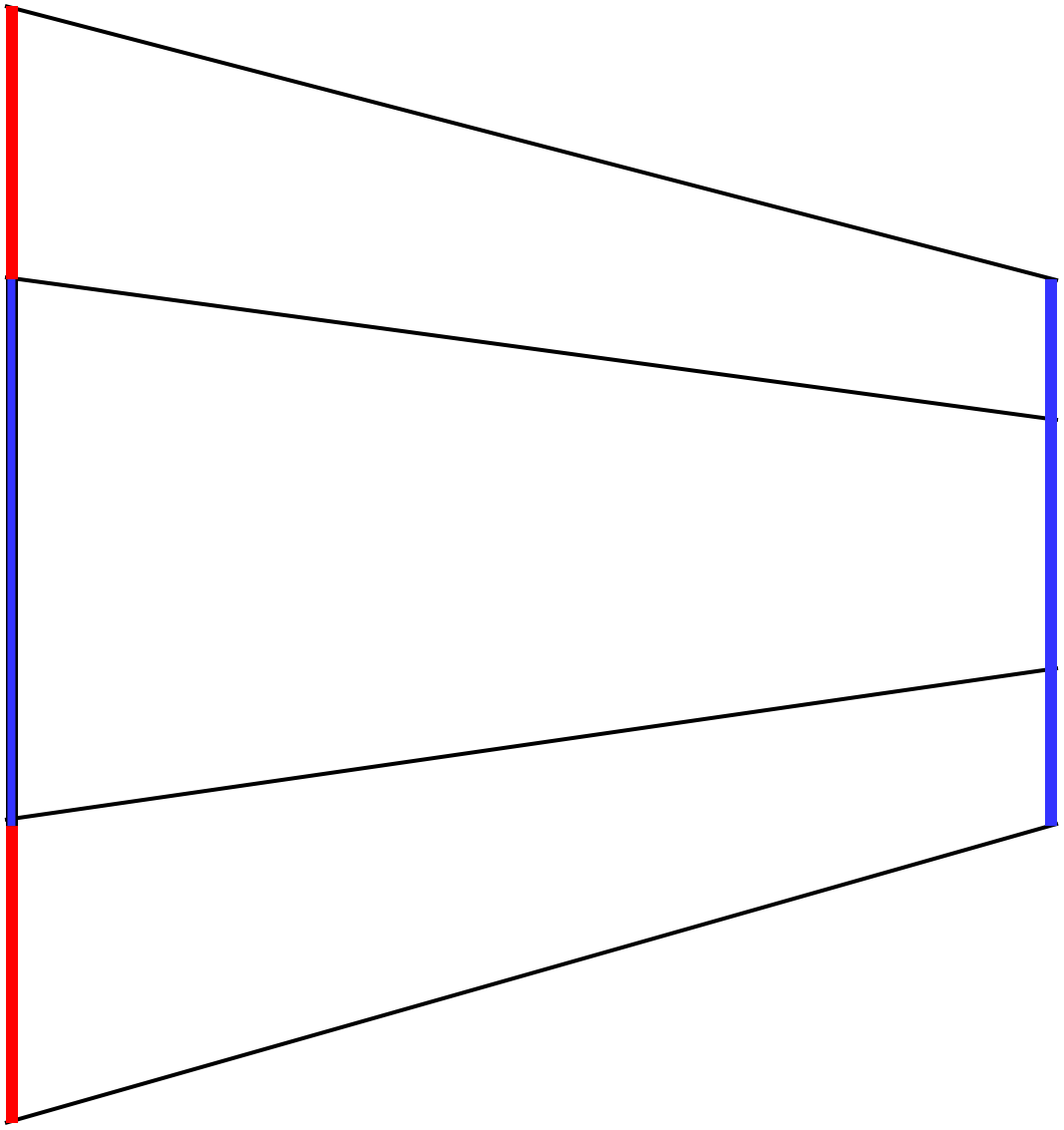
Which blue line is longer?

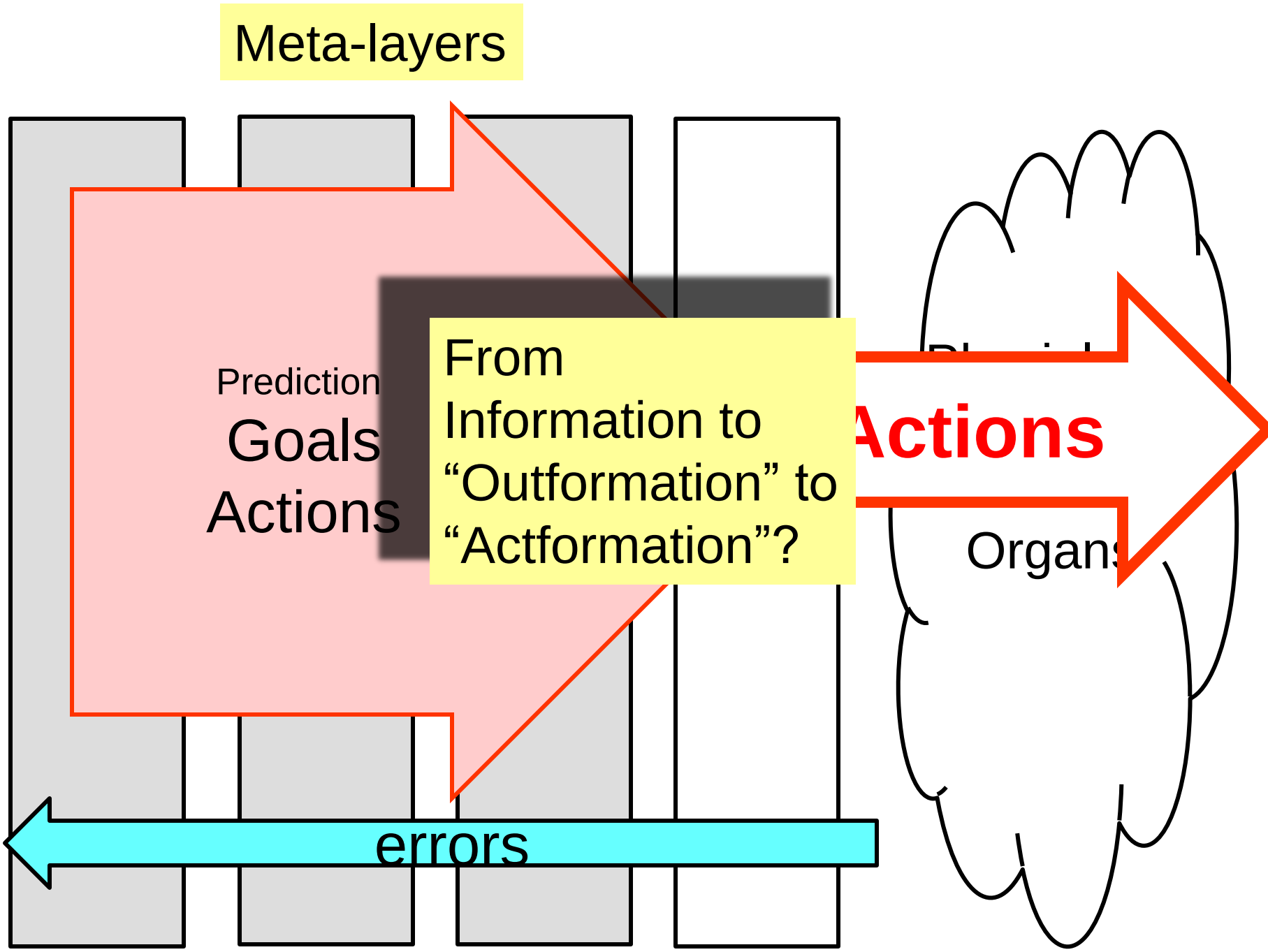


Which blue line is longer?

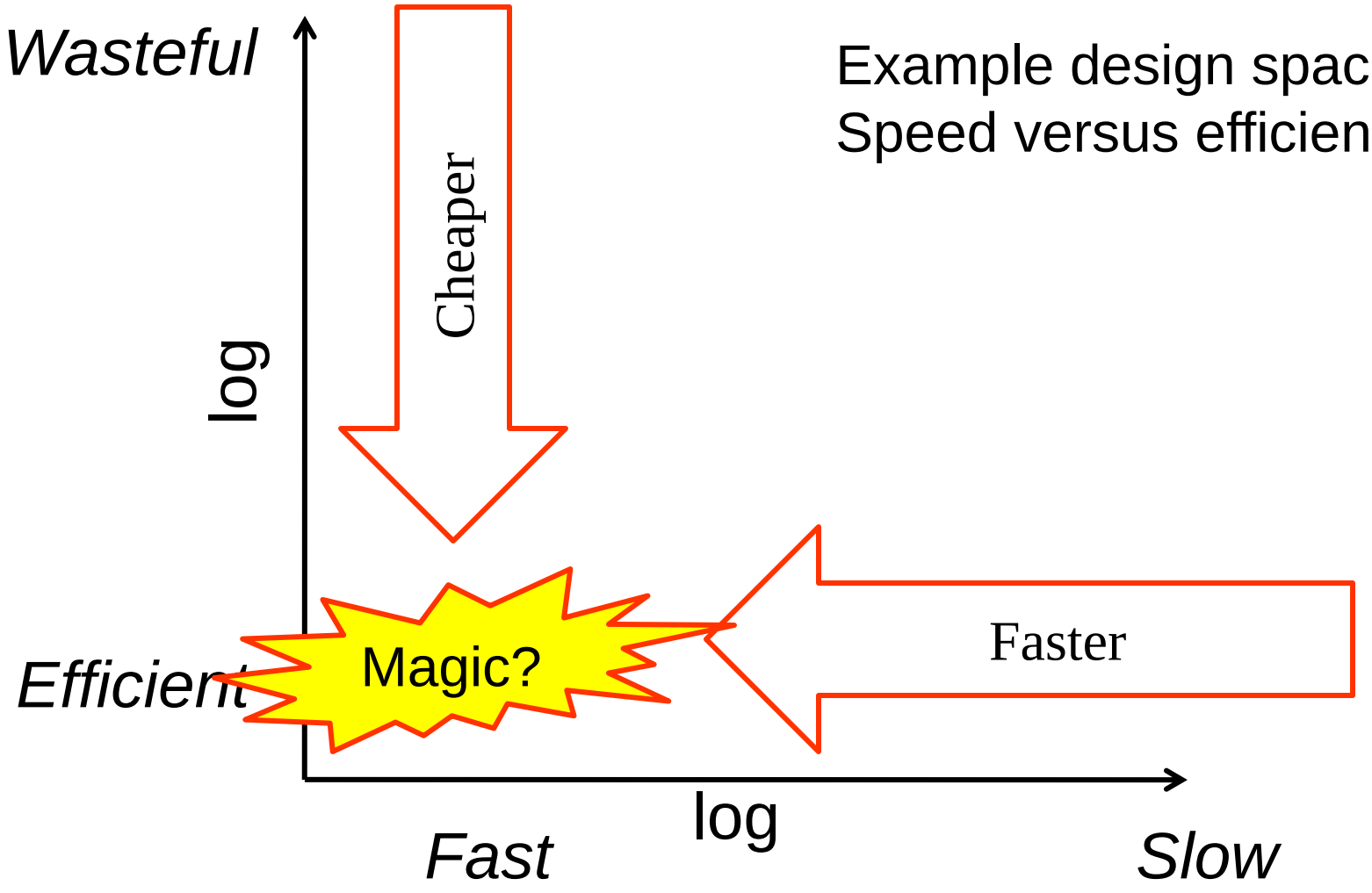


Which blue line is longer?

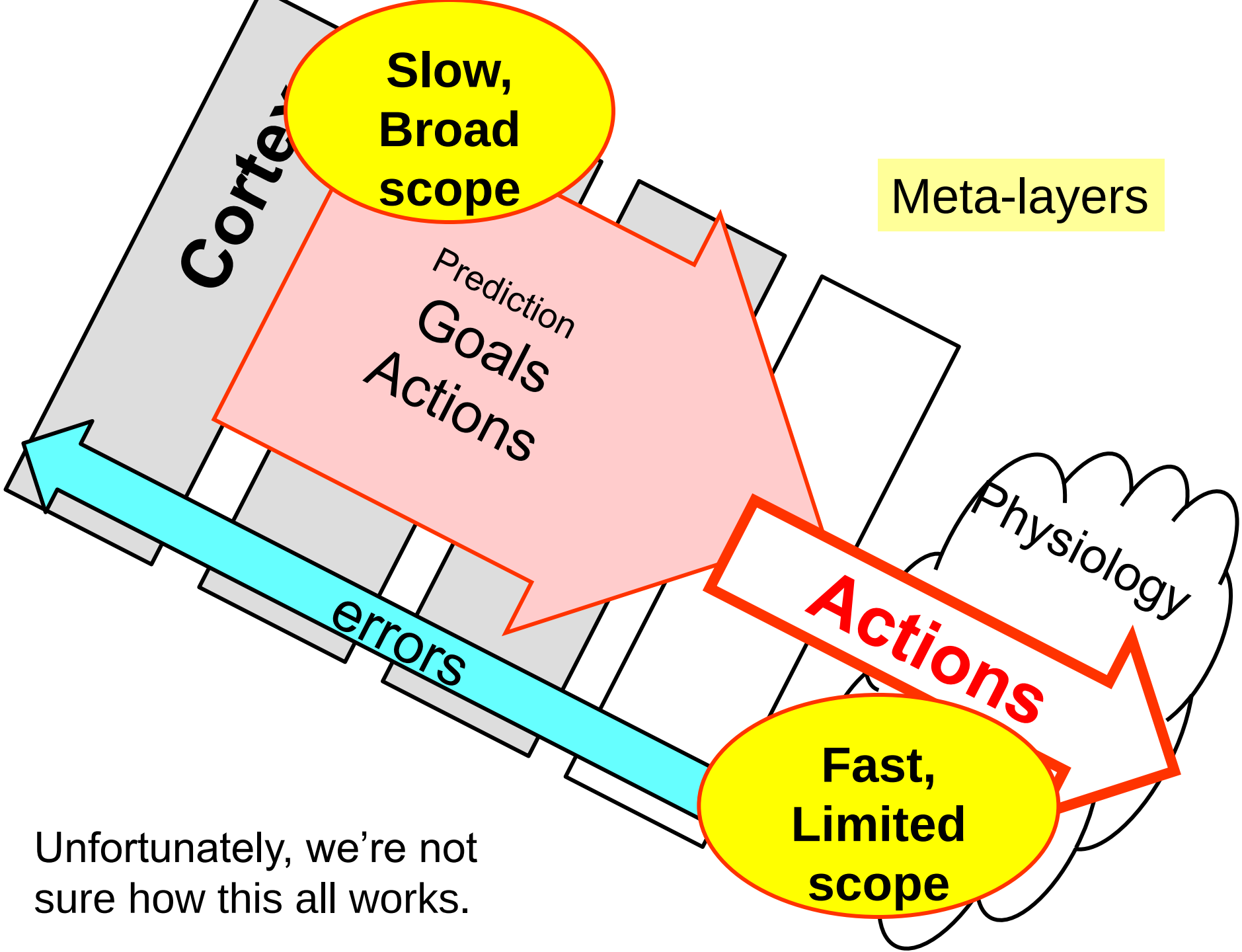



Meta-layers
Prediction
Goals
Actions
From
Information to
“Outformation” to
“Actformation”?
Actions
Organs
errors

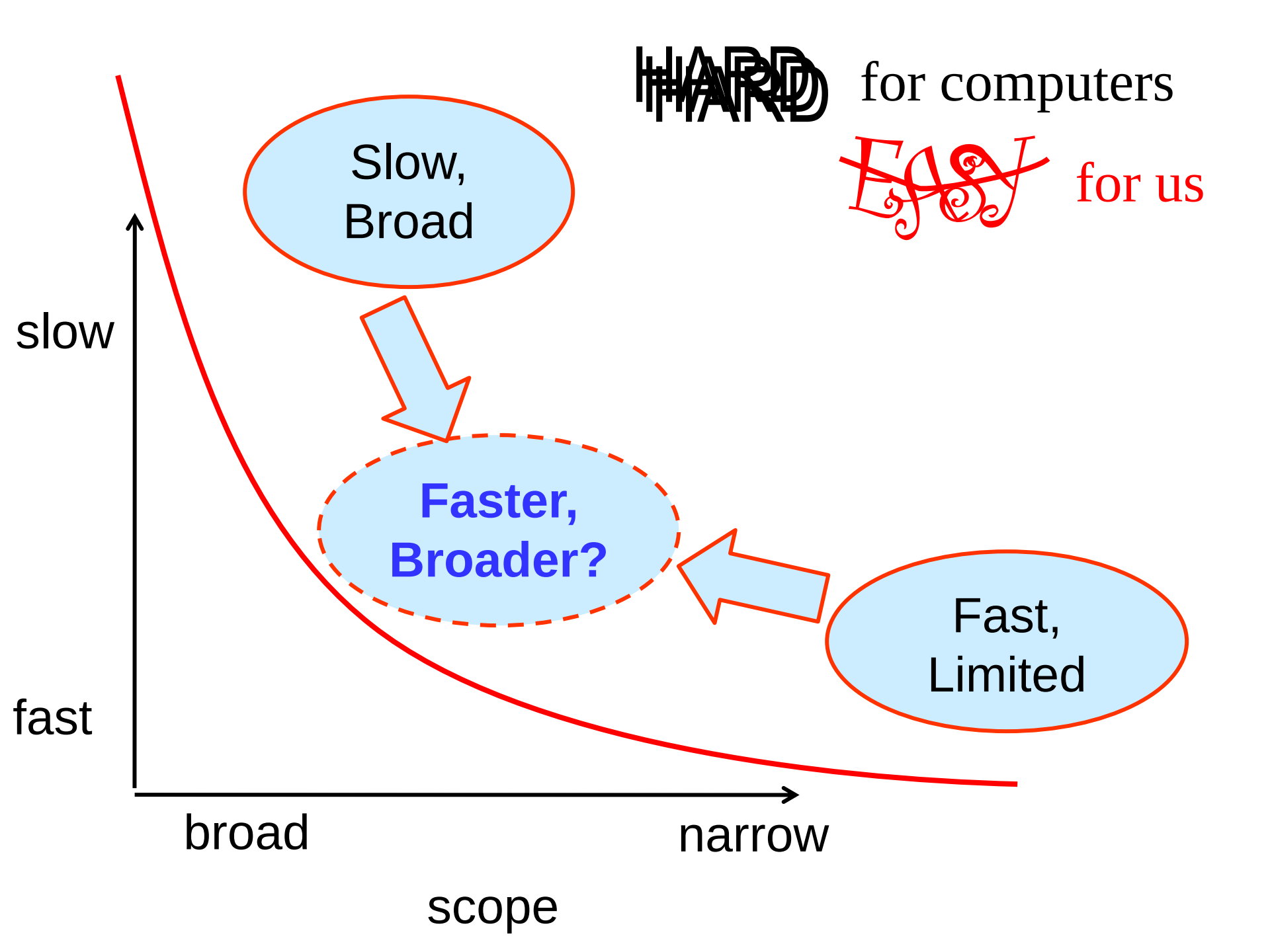
Design tradeoffs



Example design space:
Speed versus efficiency

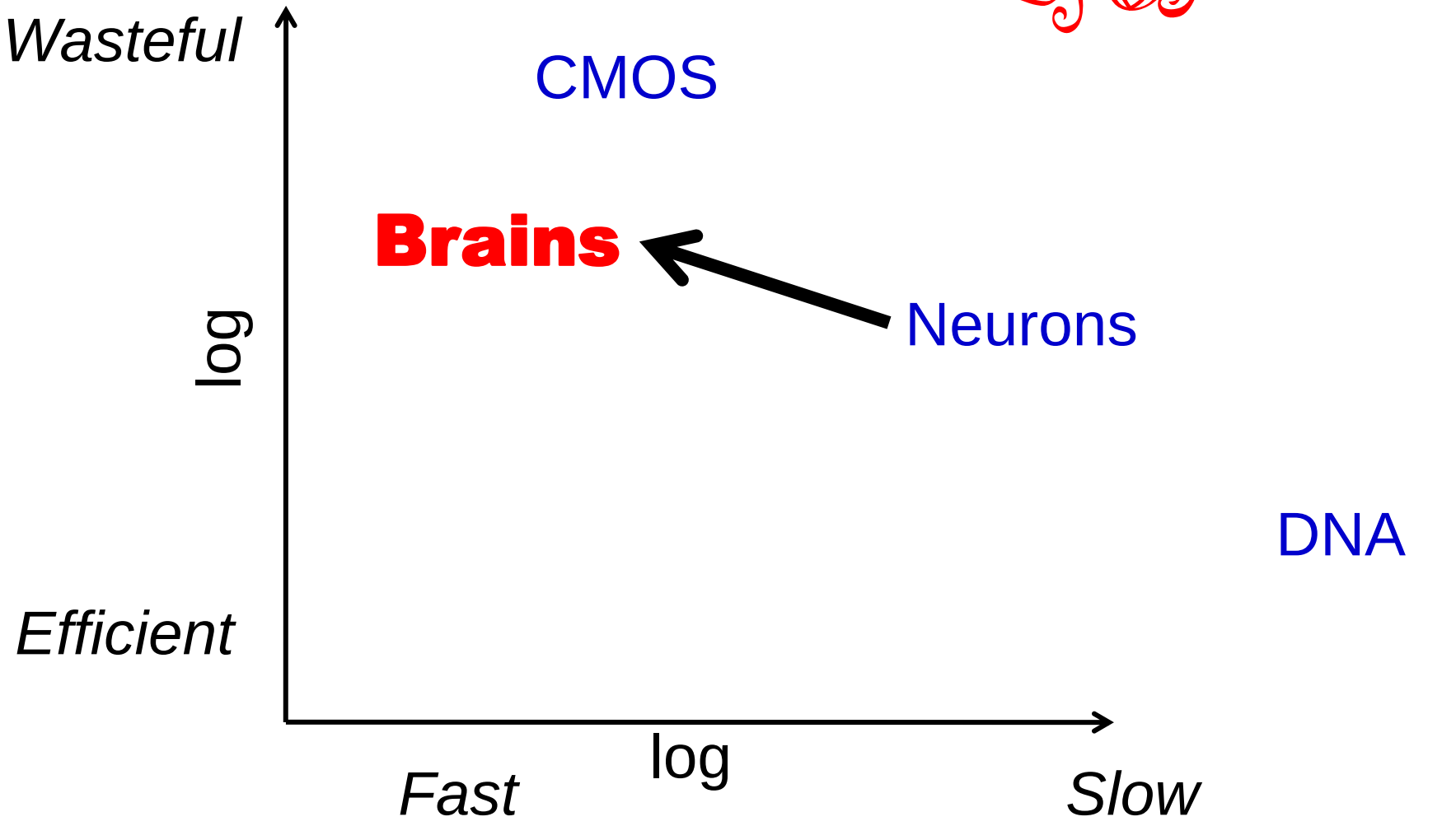


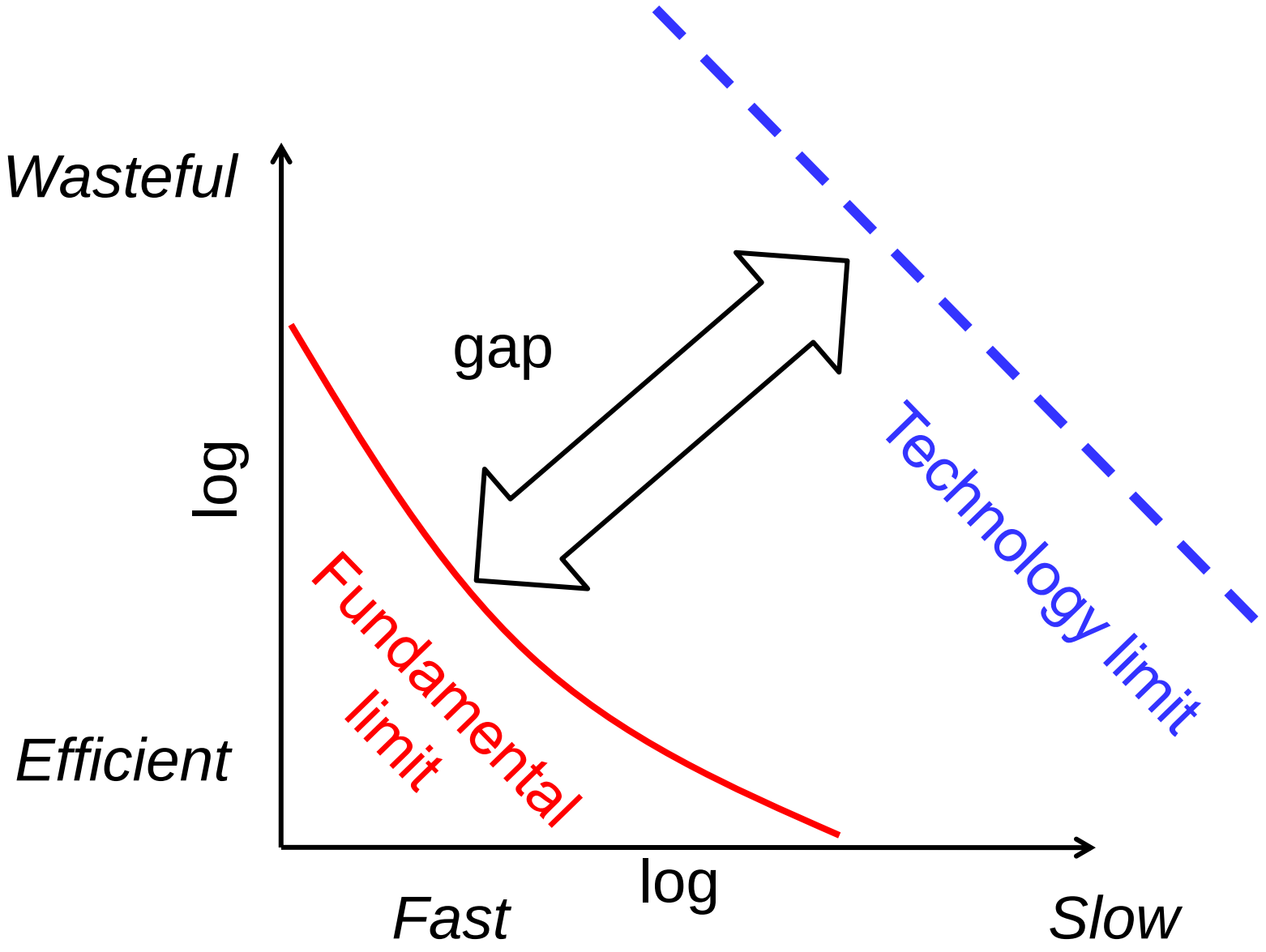
Unfortunately, we're not sure how this all works.

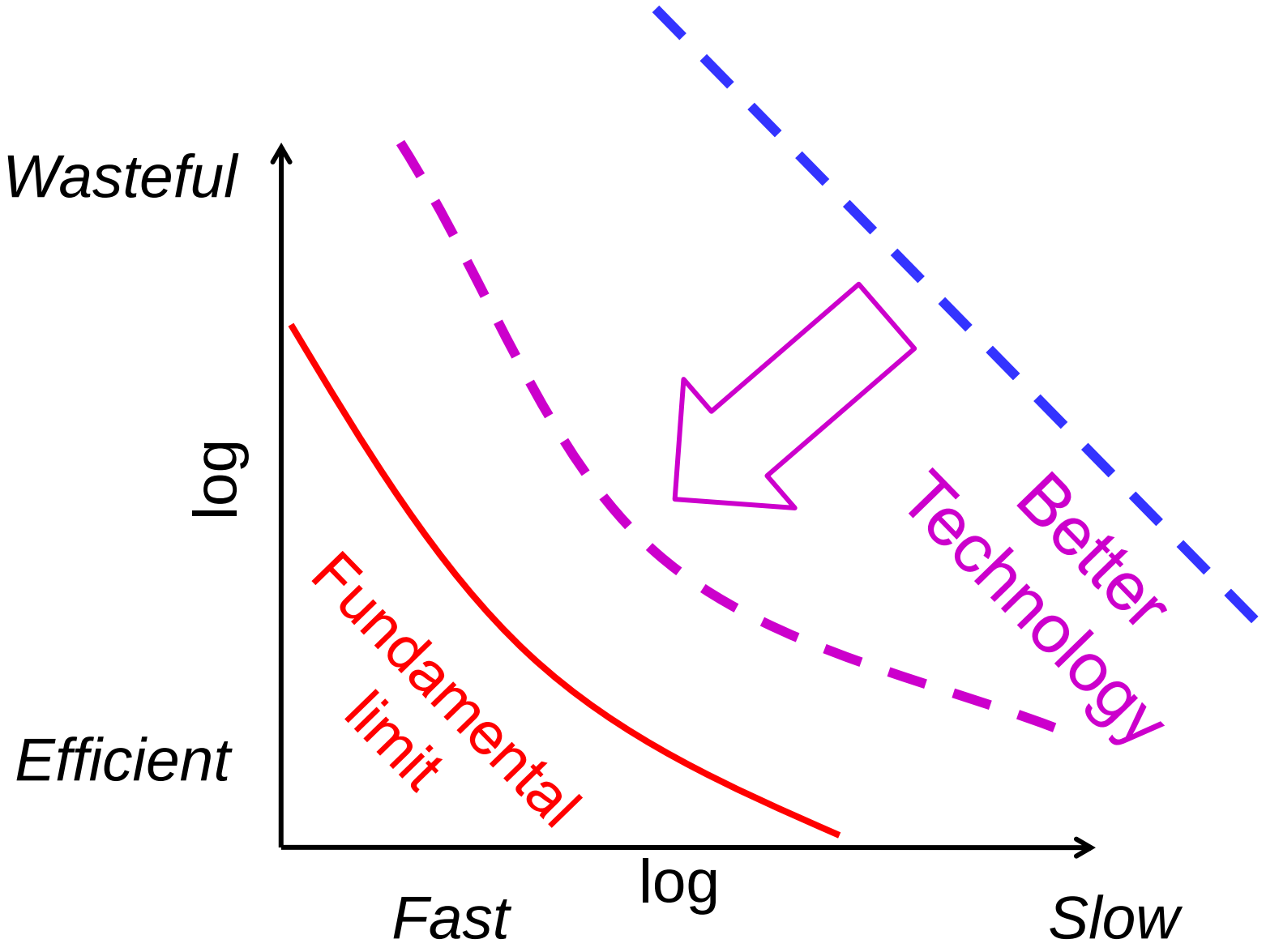

HARD for computers
EASY for us
Slow,
Broad
slow
Faster,
Broader?
Fast,
Limited
fast
broad
narrow
scope

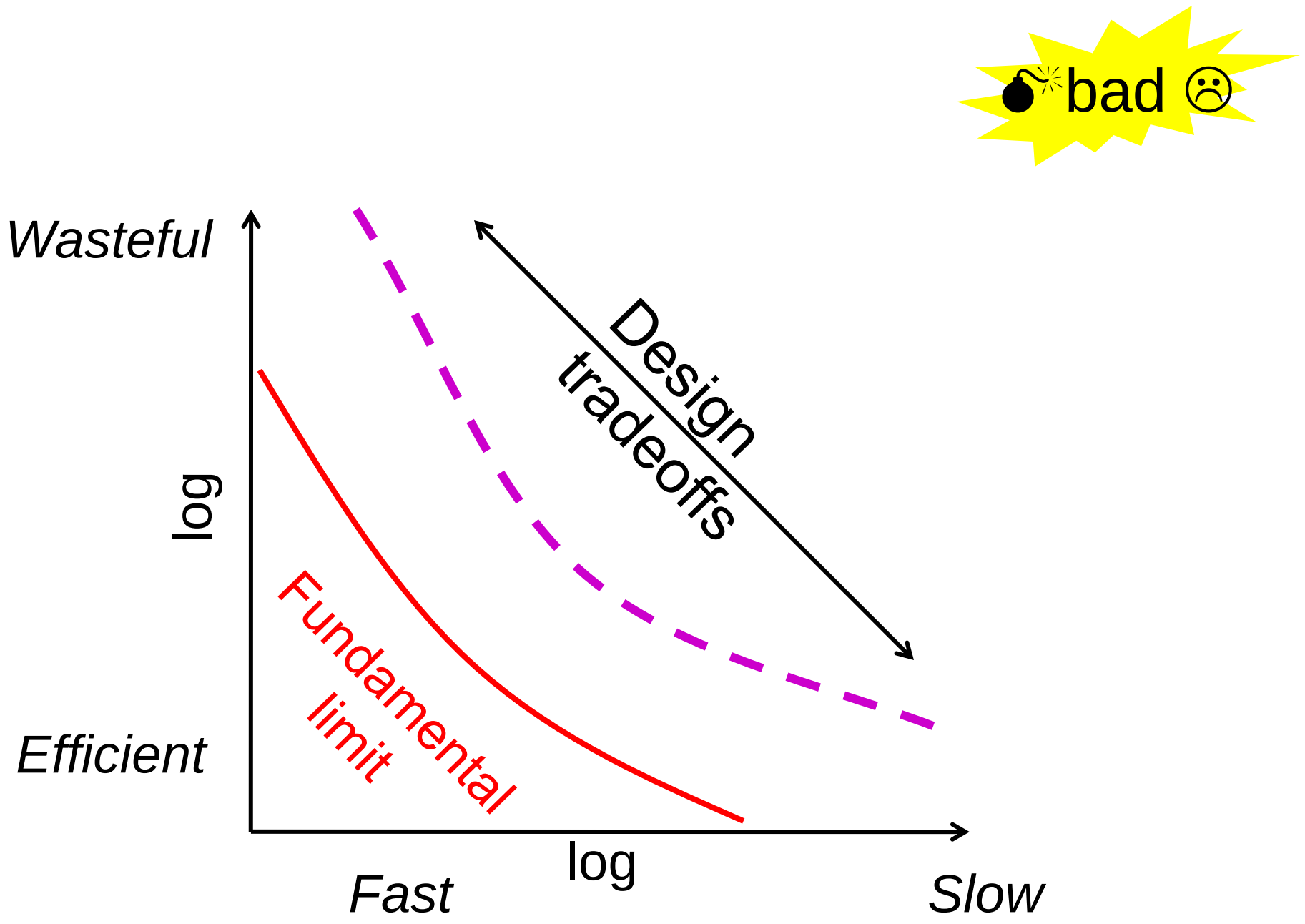
Some tasks: HARD for computers

EASY for us




Wasteful
log
Efficient
gap
Technology limit
Fundamental limit
Fast
log
Slow

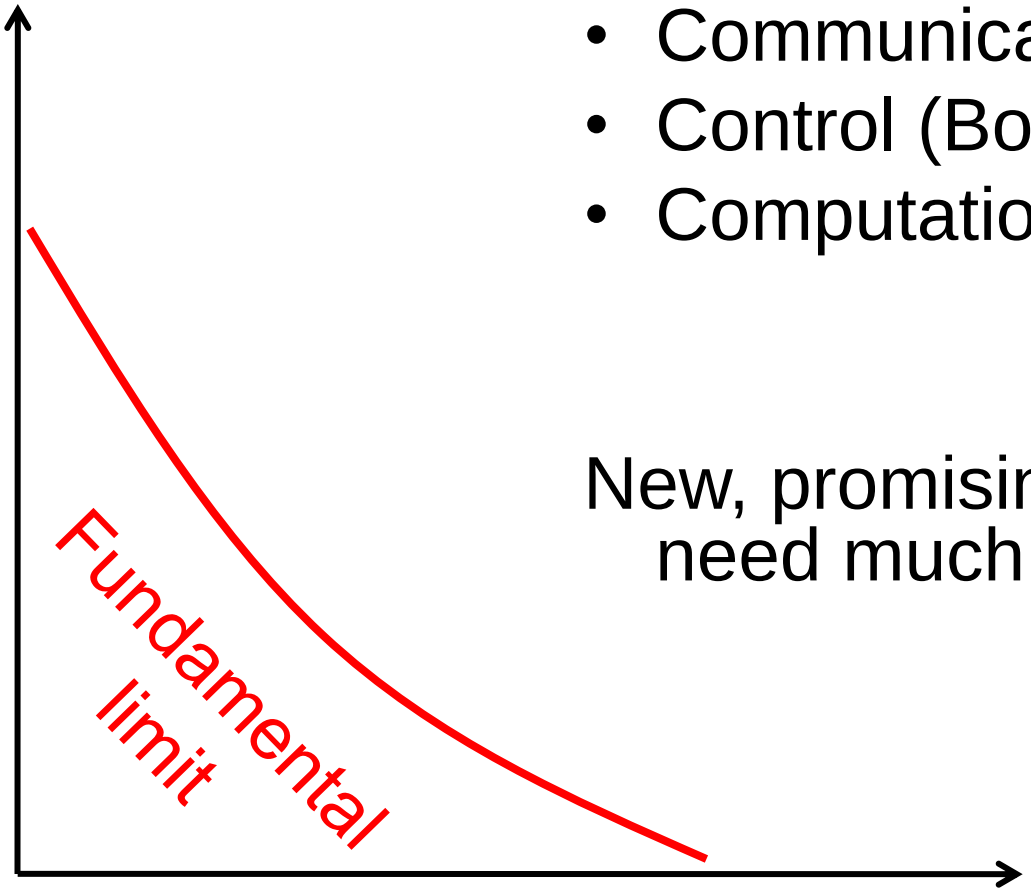

Wasteful
log
Efficient
Fundamental limit
Better Technology
log
Fast
Slow


bad ☹
Wasteful
log
Efficient
Design
tradeoffs
Fundamental
limit
log
Fast
Slow

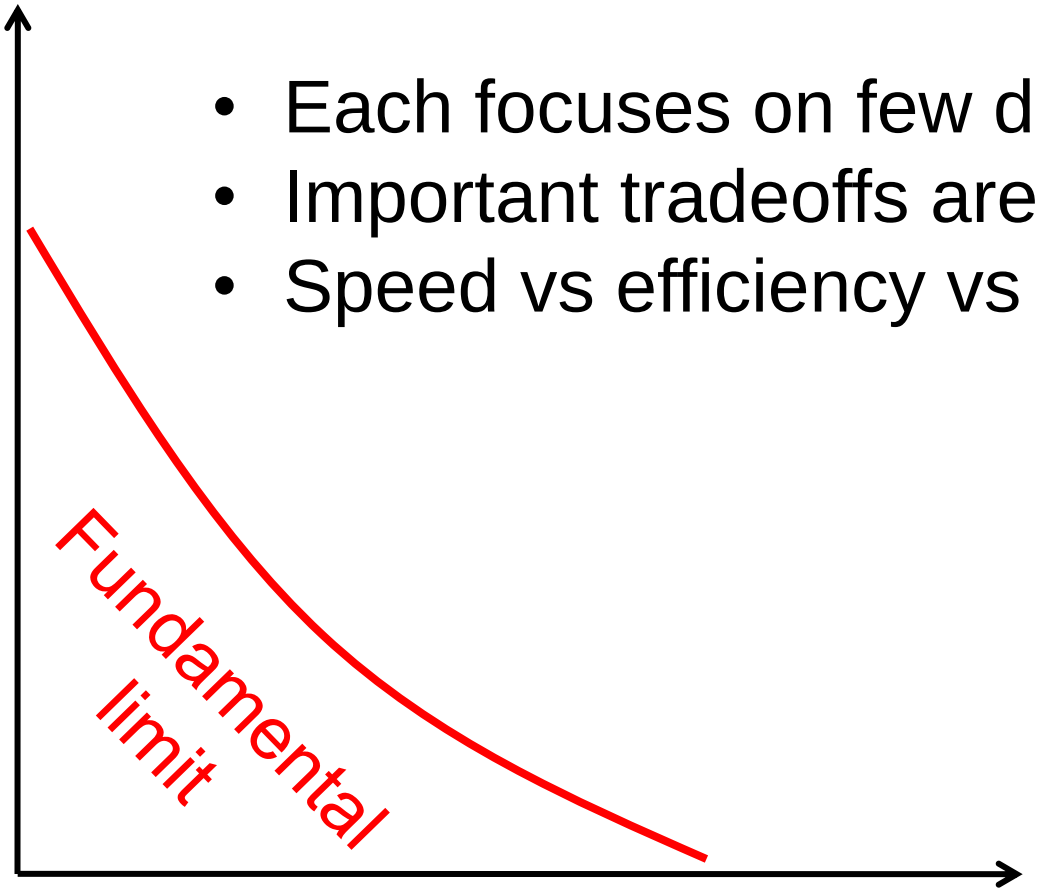
Existing hard limits have restrictive assumptions and few dimensions

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

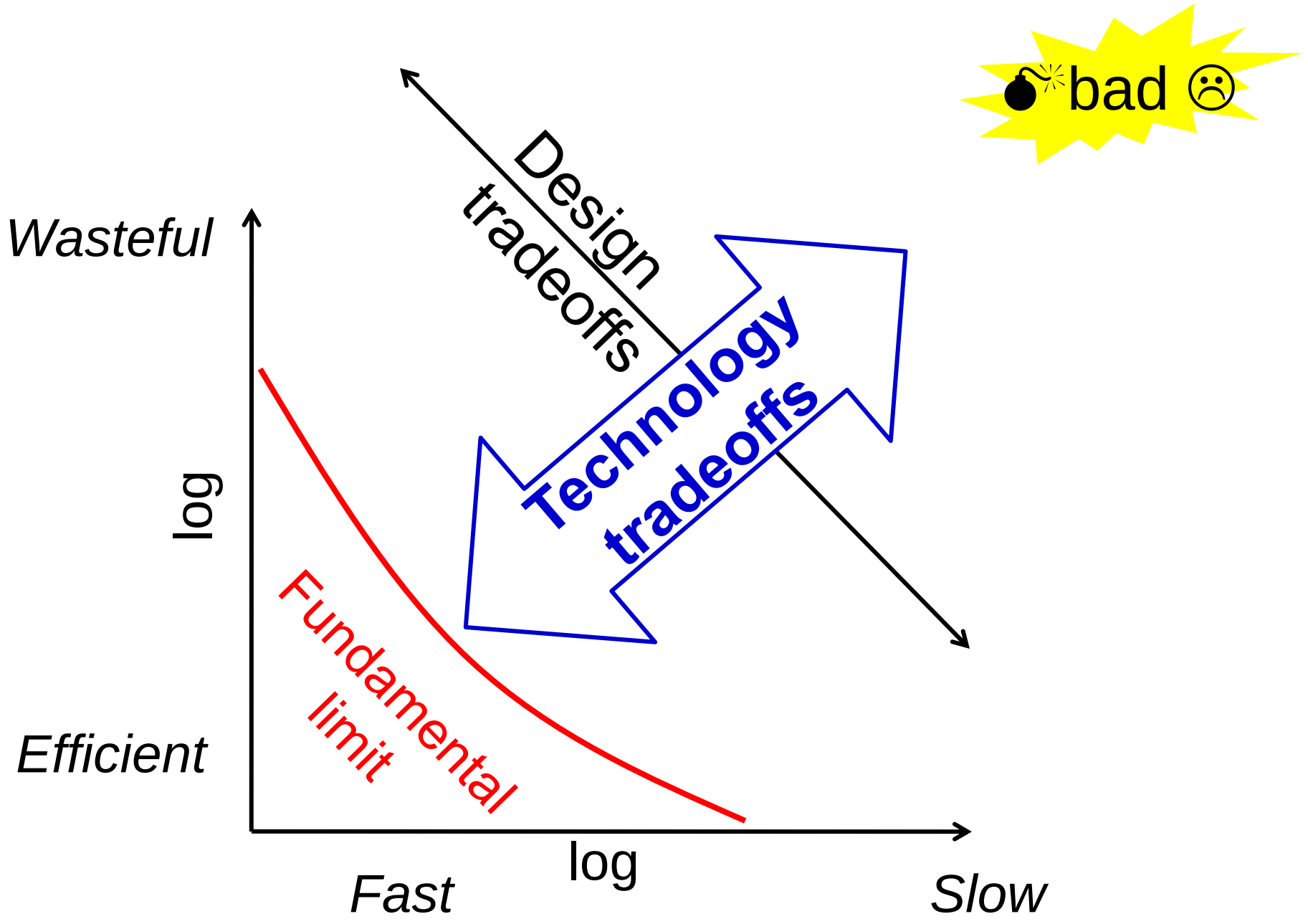
New, promising unifications but need much more

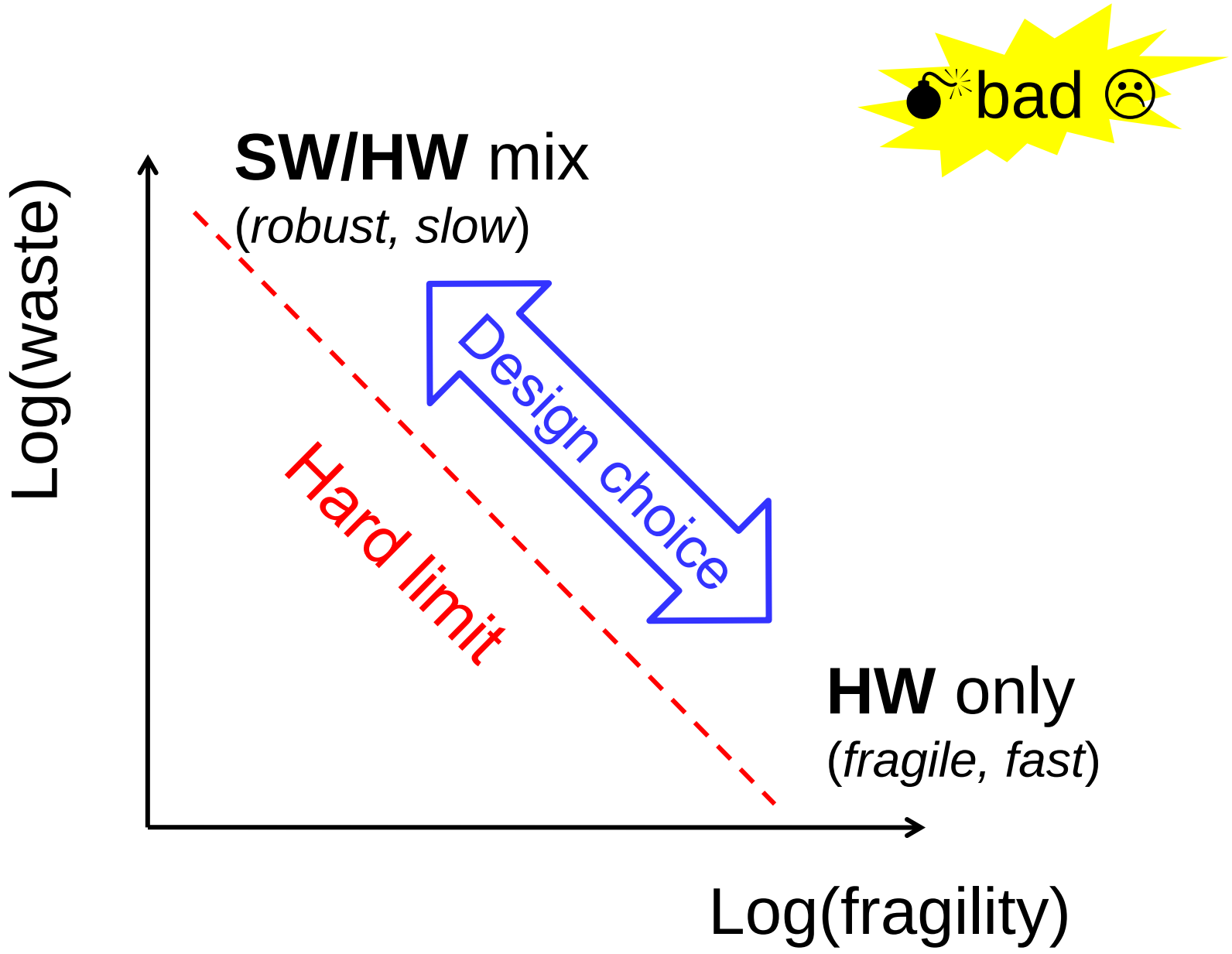


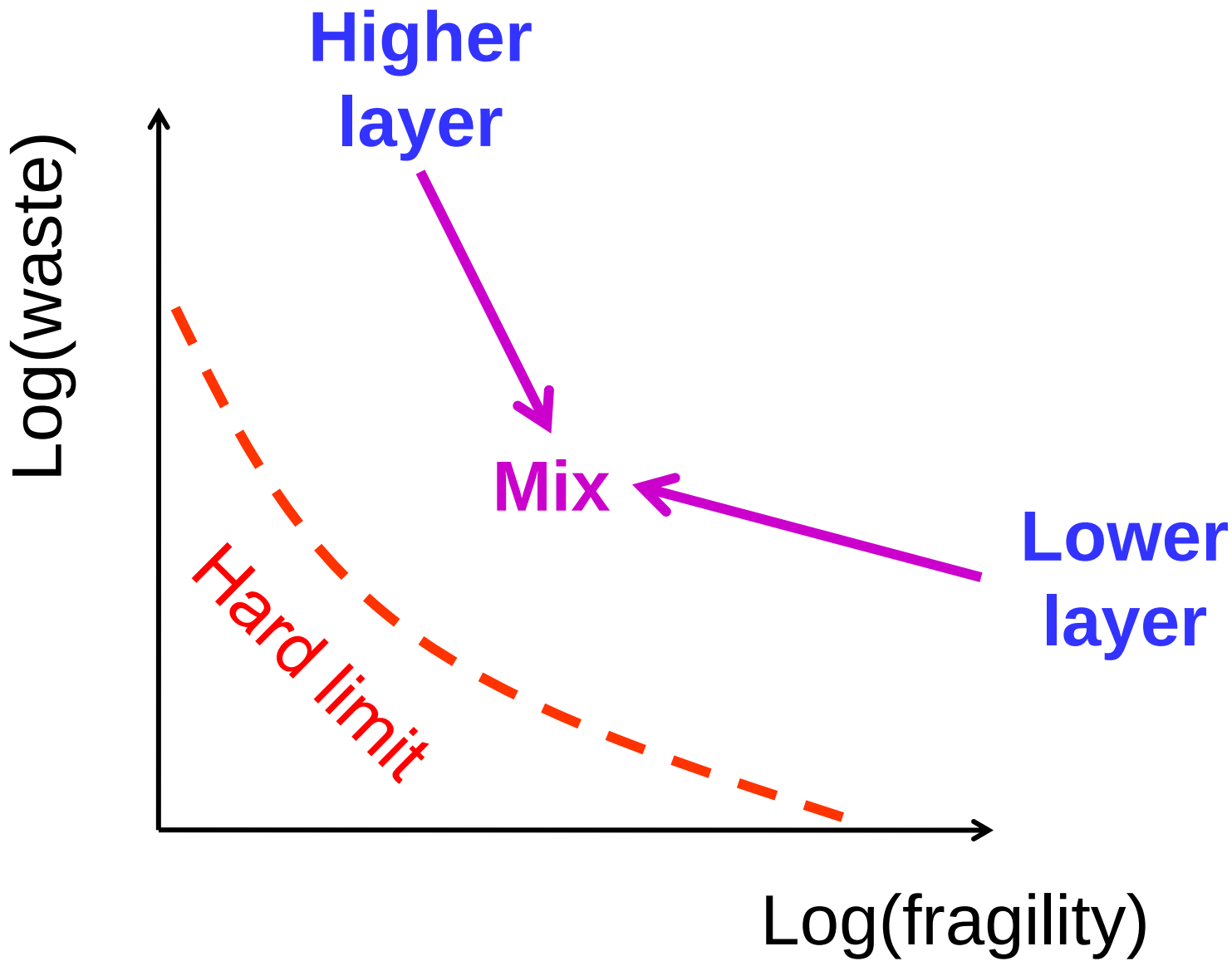
- Thermodynamics (Carnot)
- Communications (Shannon)
- Control (Bode)
- Computation (Turing)

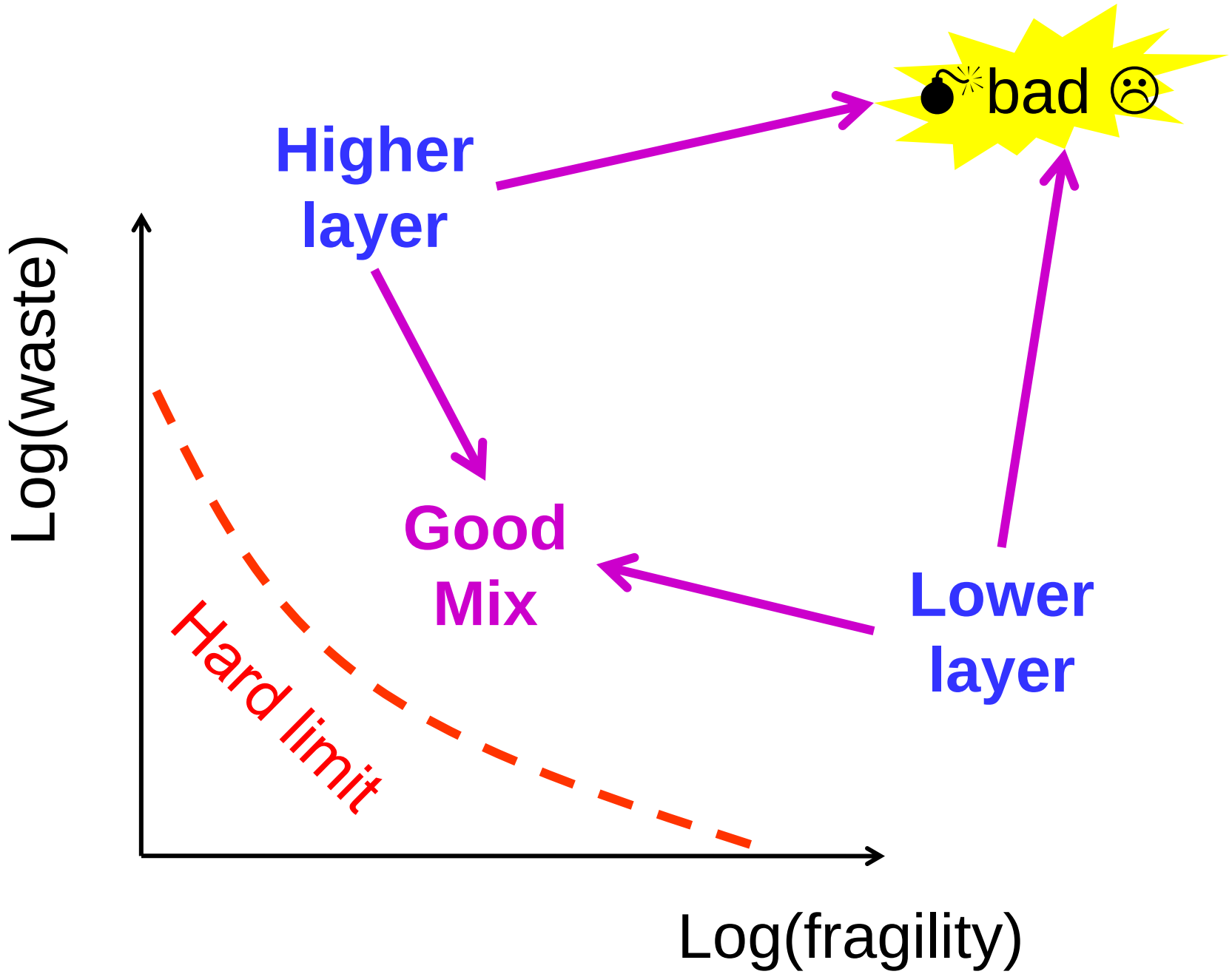


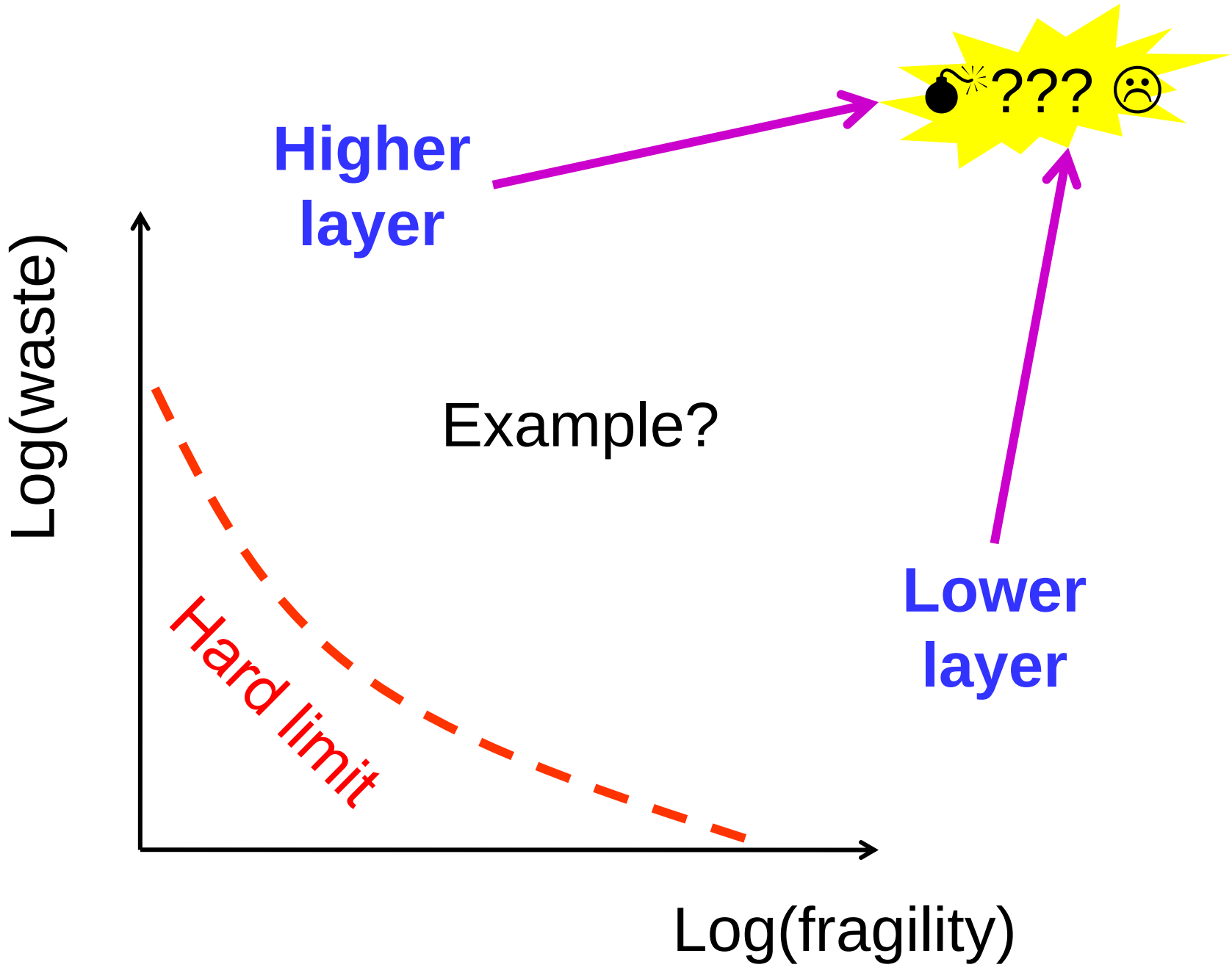
- Each focuses on few dimensions
- Important tradeoffs are across these areas
- Speed vs efficiency vs robustness vs …


bad ☹
Design tradeoffs
Technology tradeoffs
Wasteful
Efficient
log
Fundamental limit
log
Fast
Slow


bad ☹
SW/HW mix
(robust, slow)
Design choice
Hard limit
HW only
(fragile, fast)
Log(waste)
Log(fragility)

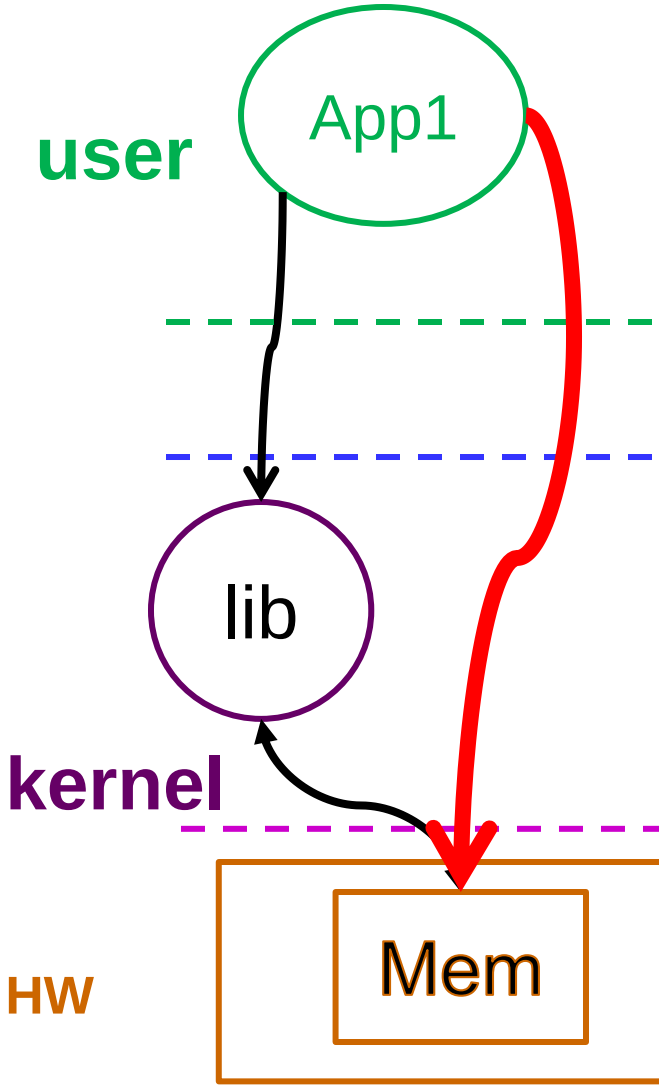

Higher layer
Log(waste)
Mix
Lower layer
Hard limit
Log(fragility)


bad ☹
Higher layer
Log(waste)
Good Mix
Hard limit
Lower layer
Log(fragility)


???
Higher layer
Example?
Lower layer
Log(waste)
Hard limit
Log(fragility)

Don’t cross layers

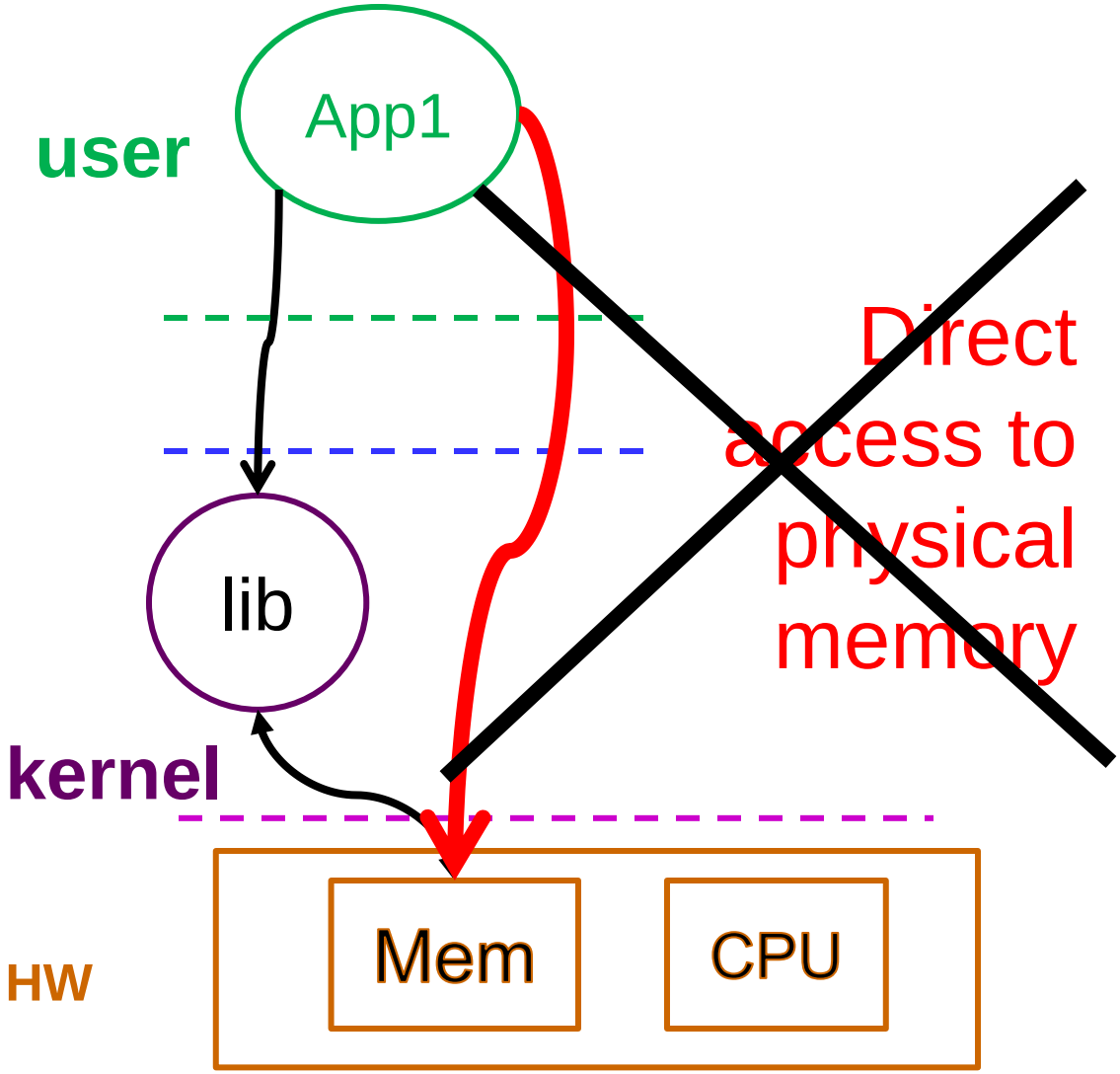
~~Robust~~
- ~~Secure~~
- ~~Scalable~~
- ~~Verifiable~~
- ~~Evolvable~~
- ~~Maintainable~~
- ~~Designable~~
- ~~…~~

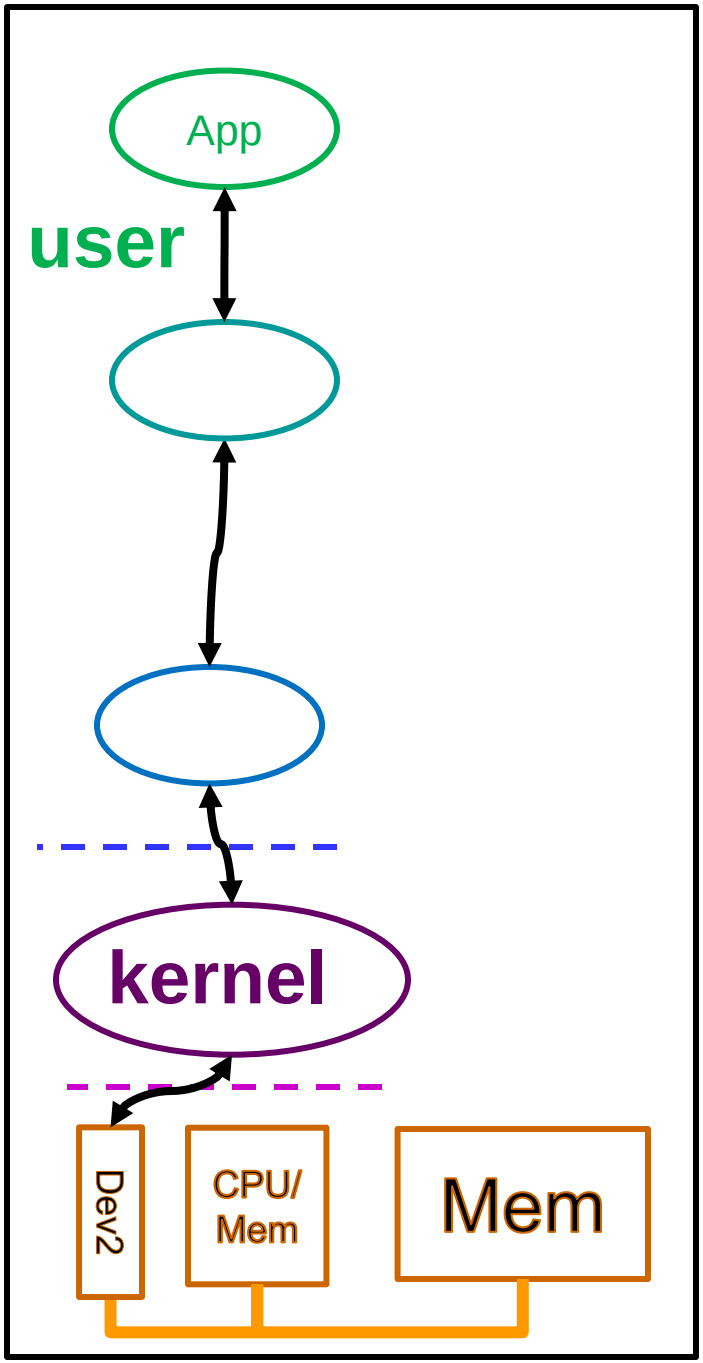


Direct access to physical memory

Separate logical names and physical addresses

~~Robust~~
- ~~Secure~~
- ~~Scalable~~
- ~~Verifiable~~
- ~~Evolvable~~
- ~~Maintainable~~
- ~~Designable~~
- ~~…~~





In programming:
No global variables

In operating systems:
Don’t cross layers

Naming and addressing

- Names to locate objects
- 2.5 ways to resolve a name
  1. Exhaustive search, table lookup
  2. Name gives hints
- Extra ½ is for indirection
- Address = name that involves locations

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
- Local variables and addresses

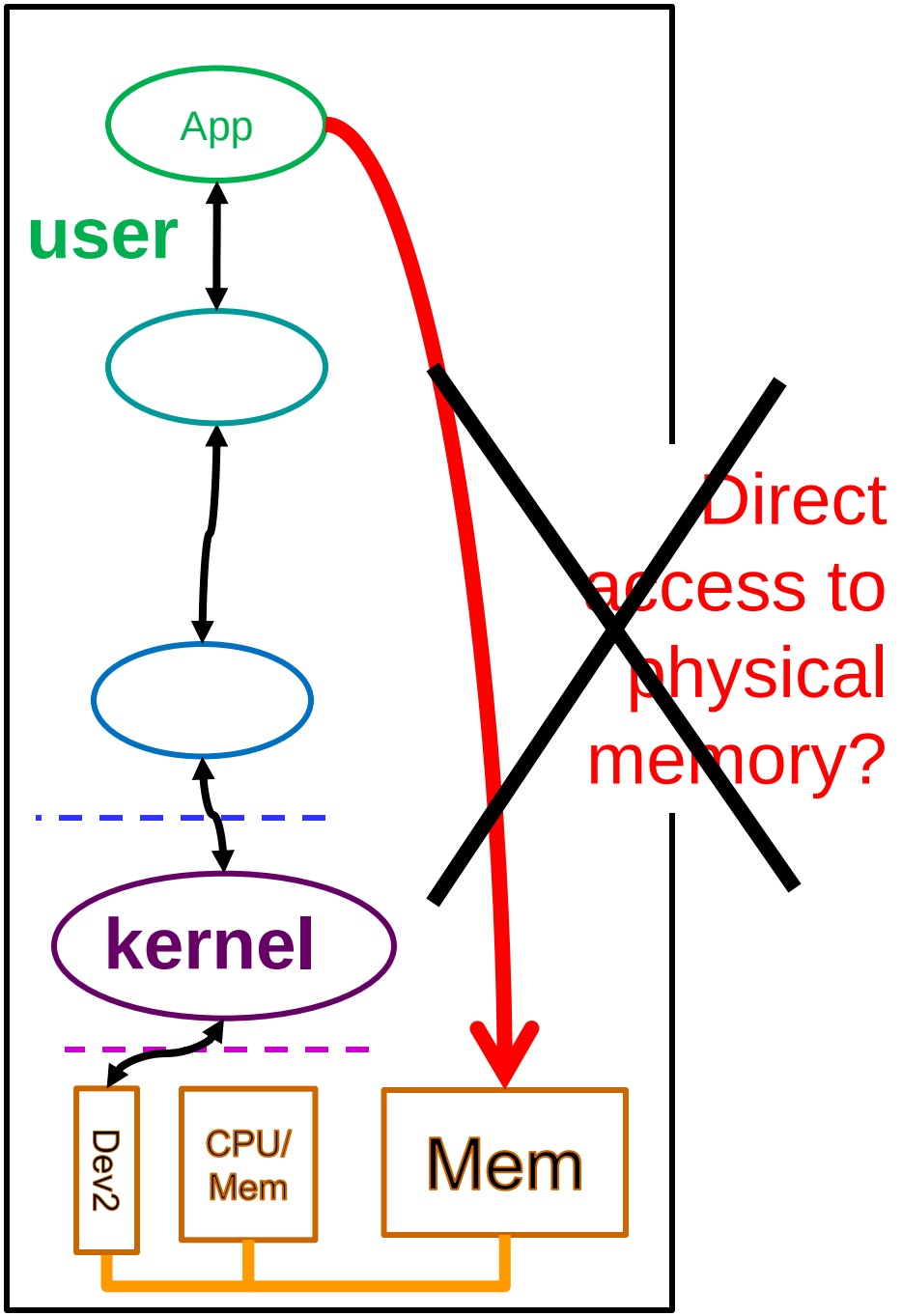
- Optimization/control by duality?

Problems with incomplete layering

"Black box" benefits are lost

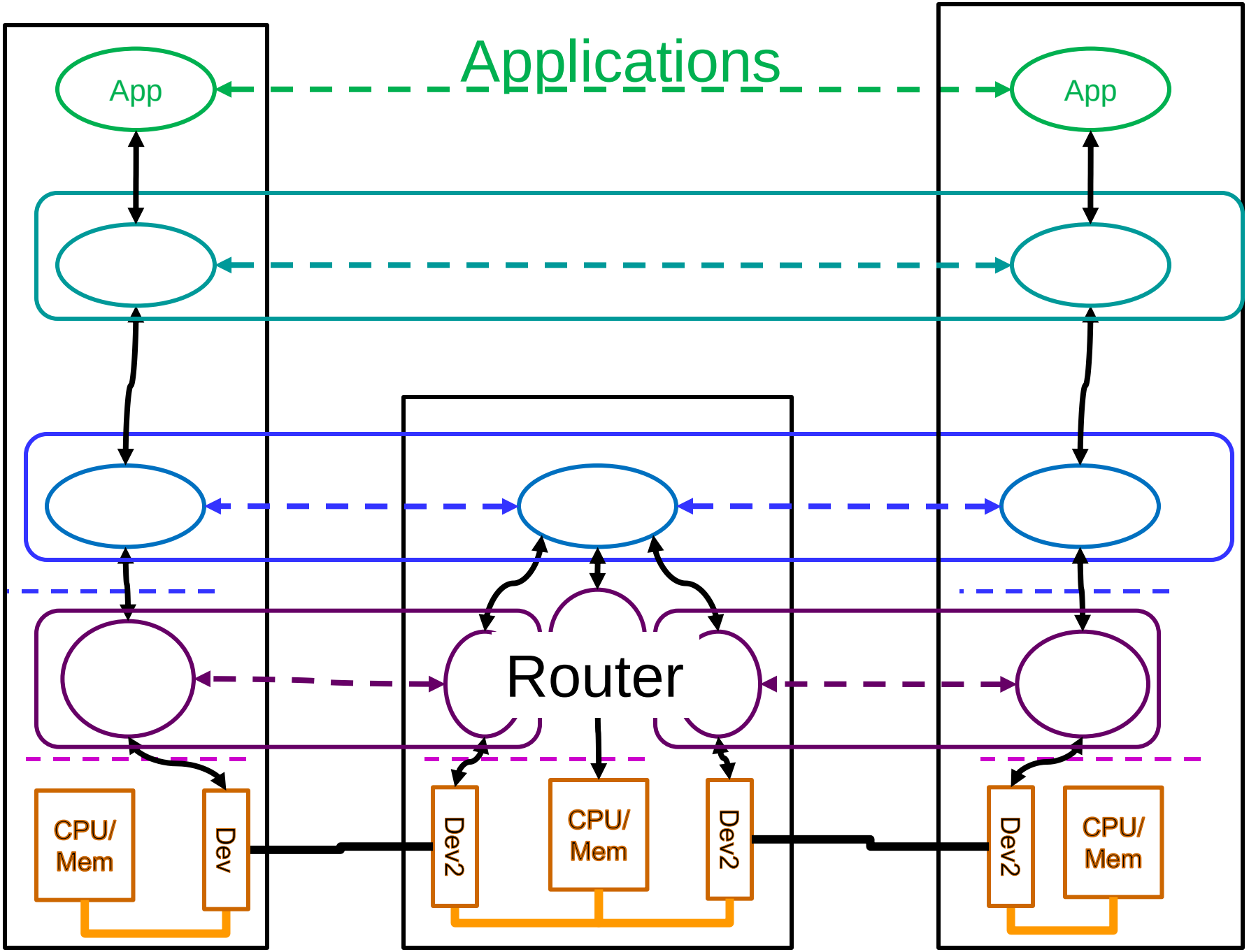
- Global variables? @$%*&!^%@&
- Poor portability of applications
- Insecurity of physical address space
- Fragile to application crashes
- No scalability of virtual/real addressing

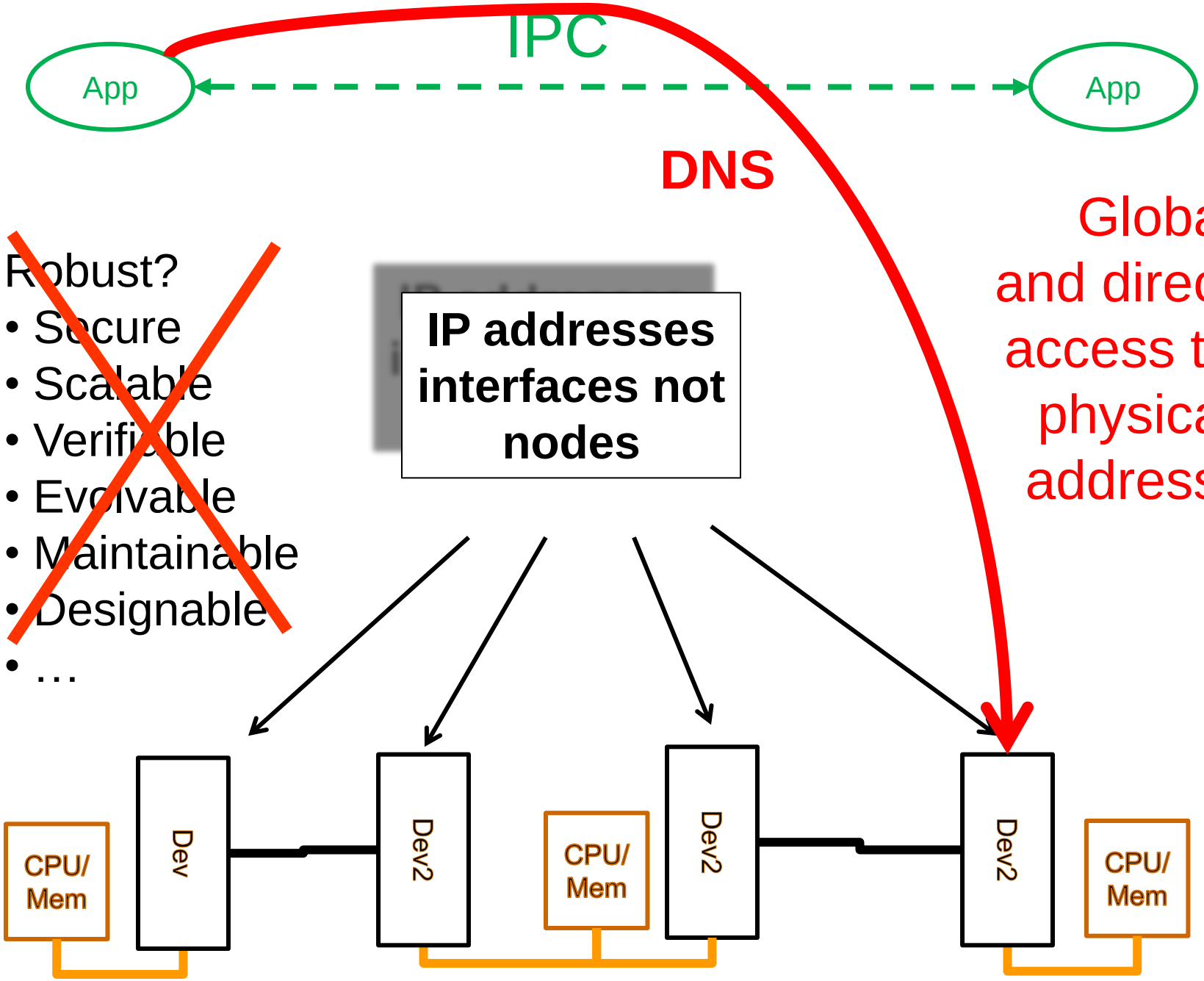
- Limits optimization/control by duality?



In programming:
No global variables

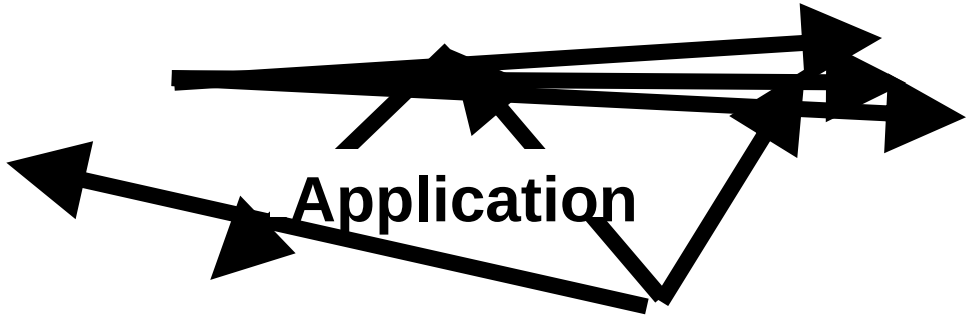
In operating systems:
Don’t cross layers
(rings)

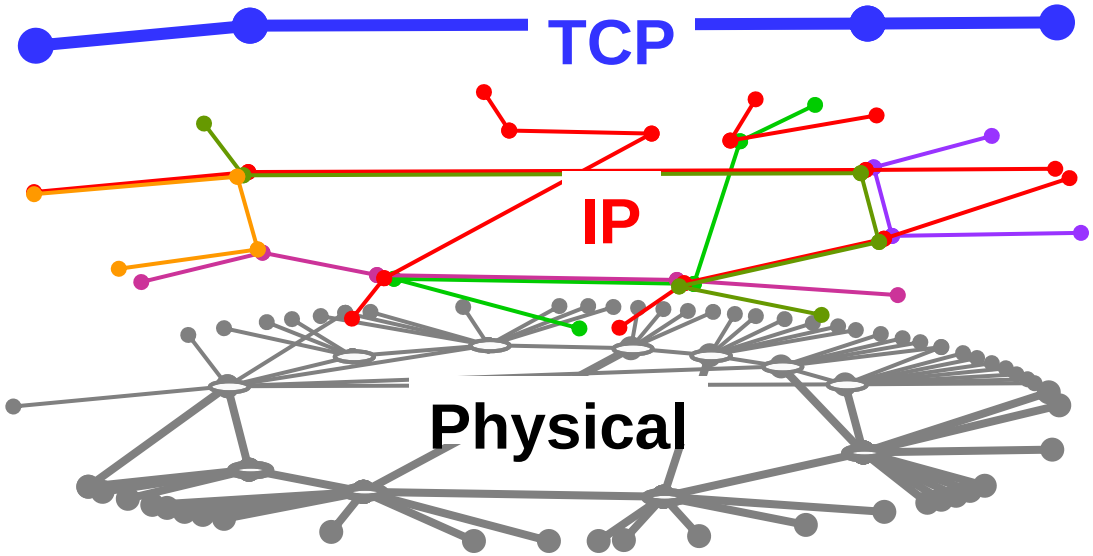

Applications
App
App
Router
CPU/
Mem
Dev
Dev2
CPU/
Mem
Dev2
Dev2
CPU/
Mem


IPC
App
App
DNS
Global and direct access to physical address!
Robust?
• Secure
• Scalable
• Verifiable
• Evolvable
• Maintainable
• Designable
• …
IP addresses interfaces not nodes
CPU/ Mem
Dev
Dev2
CPU/ Mem
Dev2
Dev2
CPU/ Mem

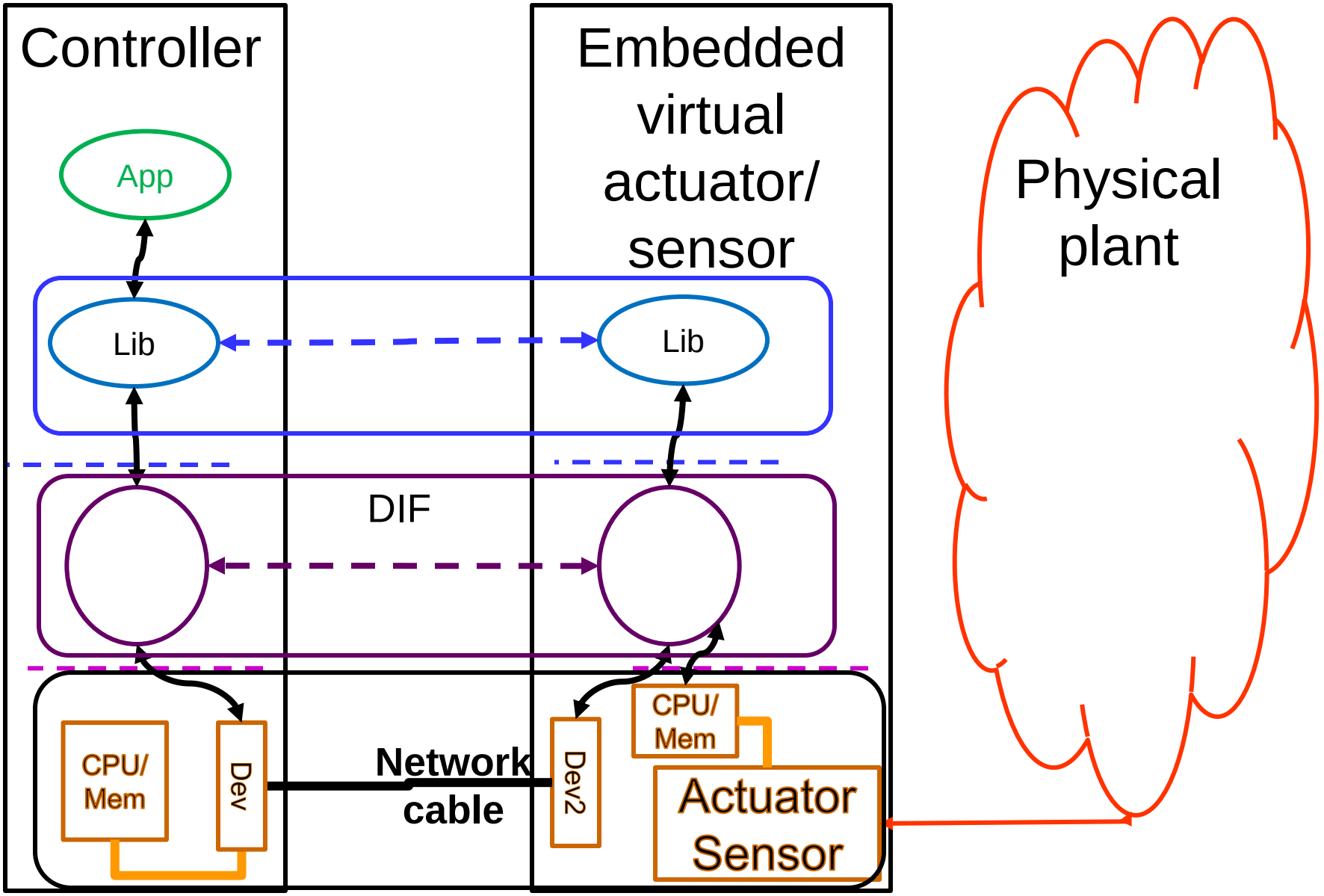
Naming and addressing need to be
- resolved within layer
- translated between layers
- not exposed outside of layer

Related issues
- DNS
- NATS
- Firewalls
- Multihoming
- Mobility
- Routing table size
- Overlays
- …

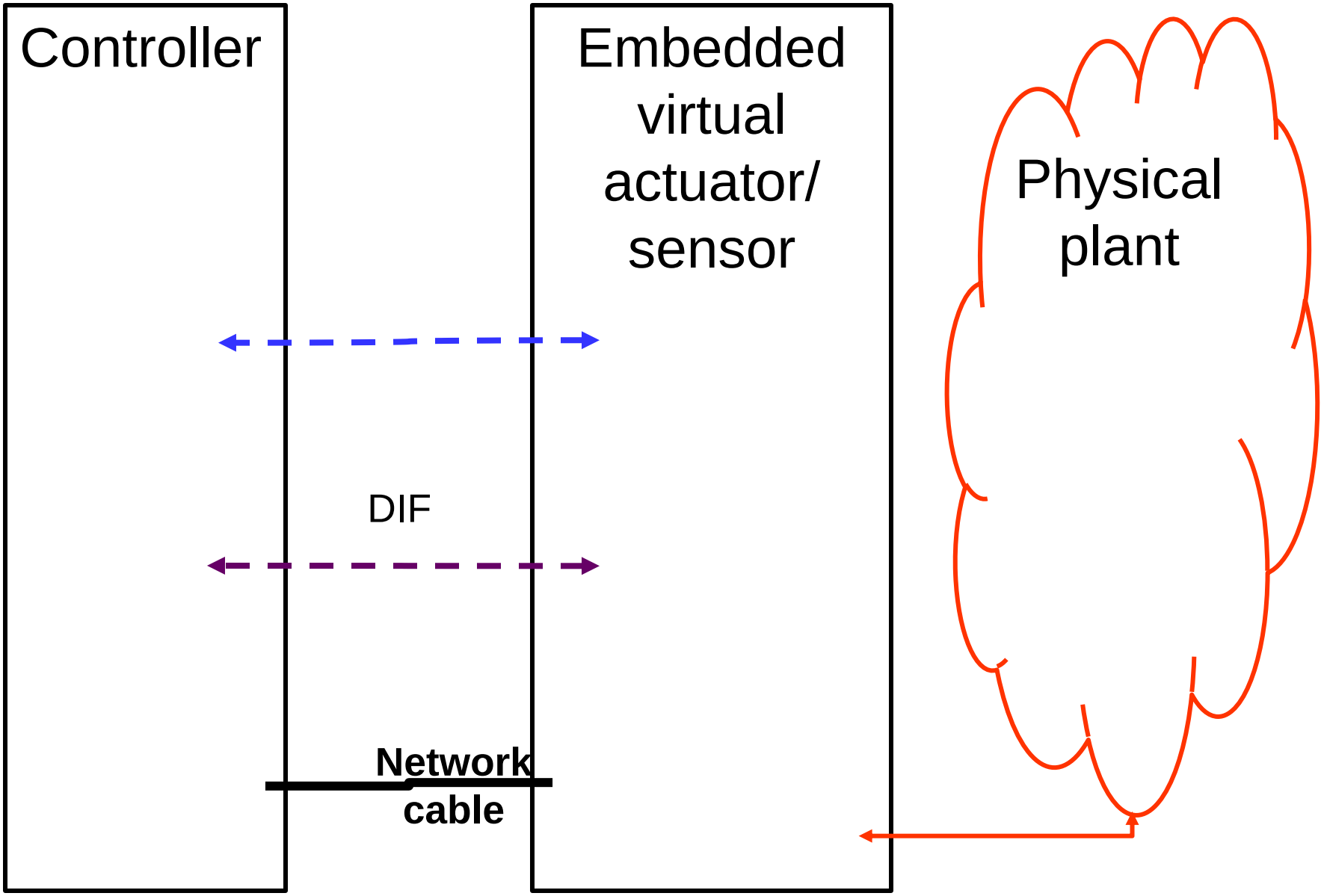




Networked/embedded/layered

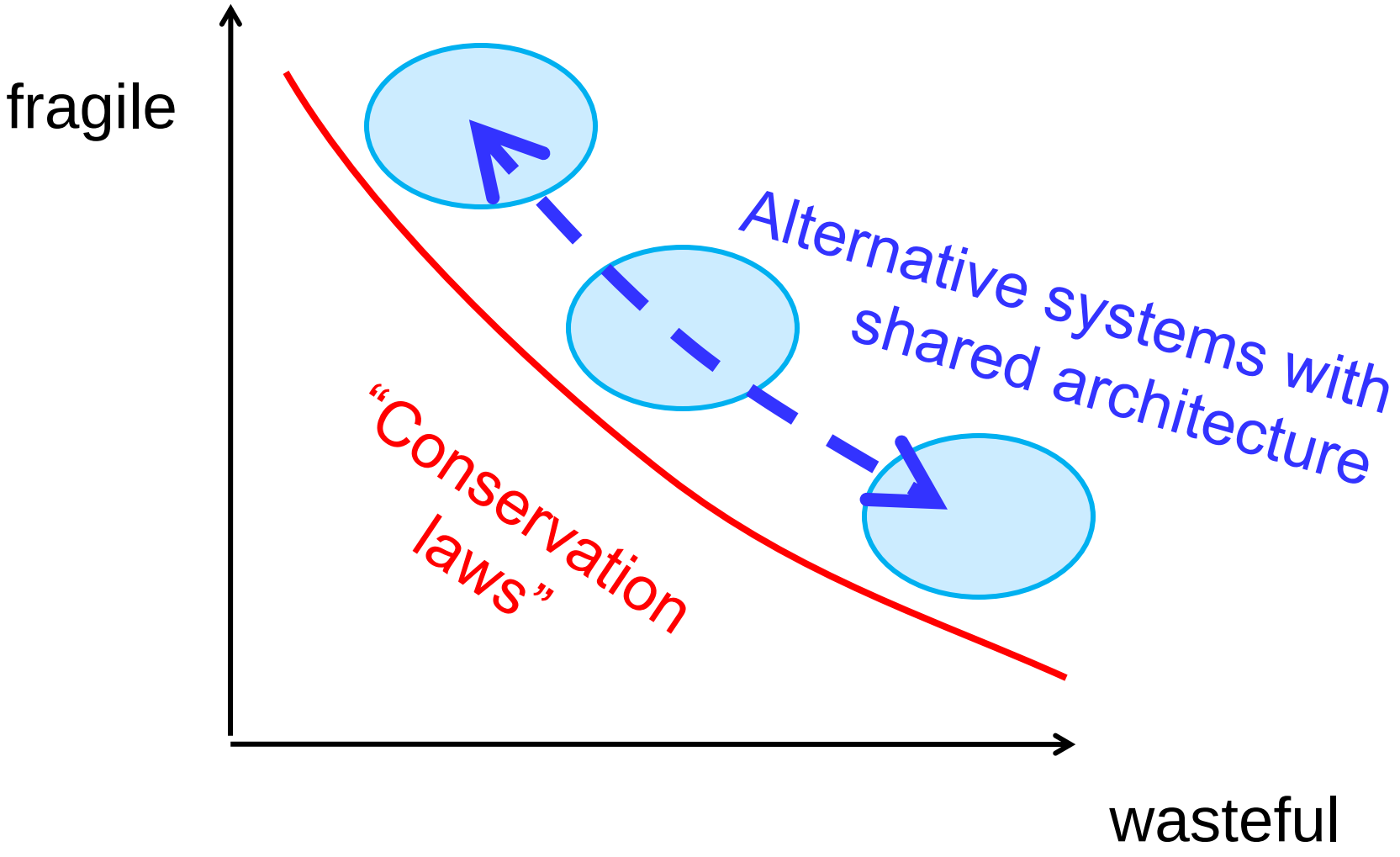


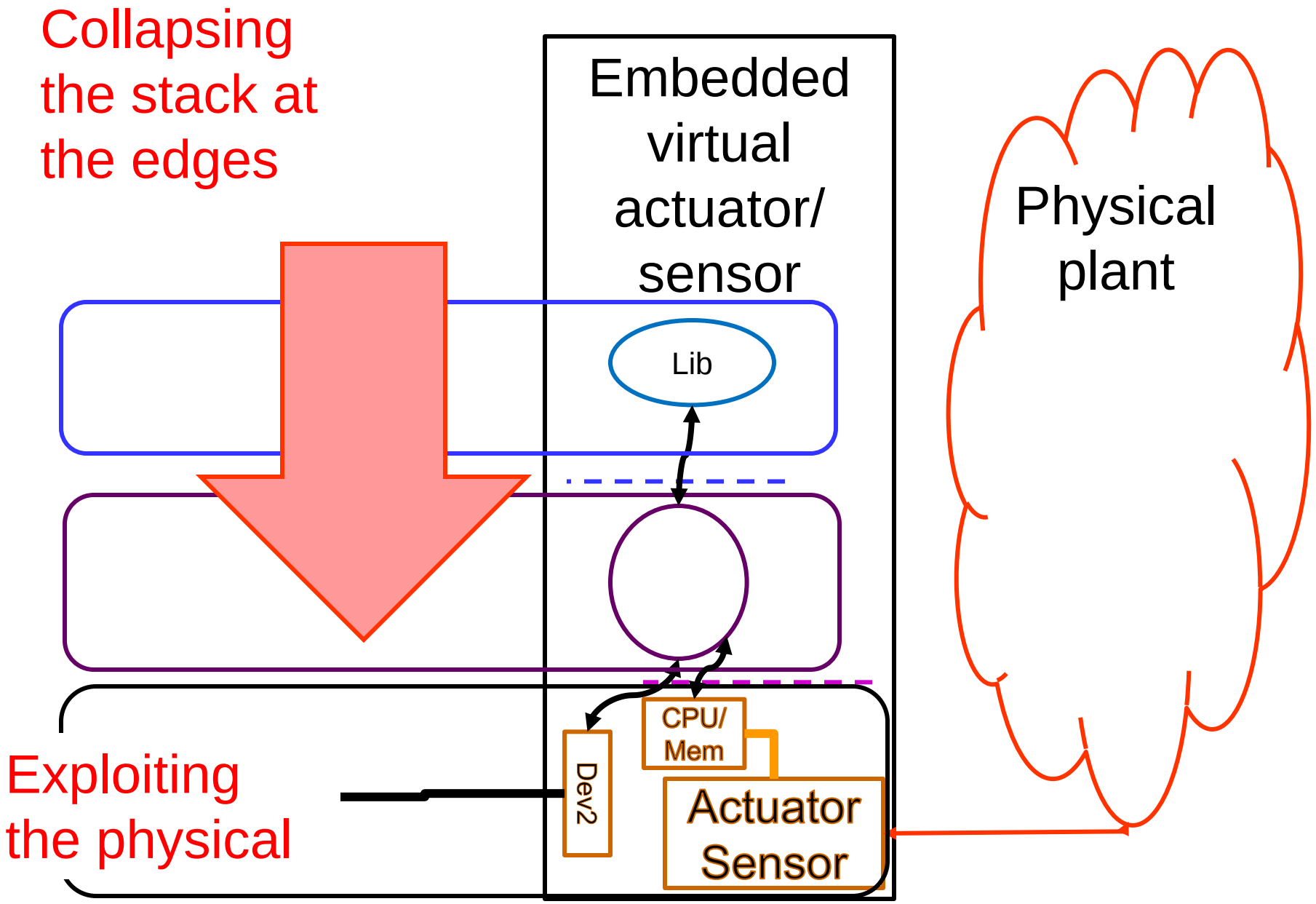
Meta-layering of cyber-phys control



Architecture

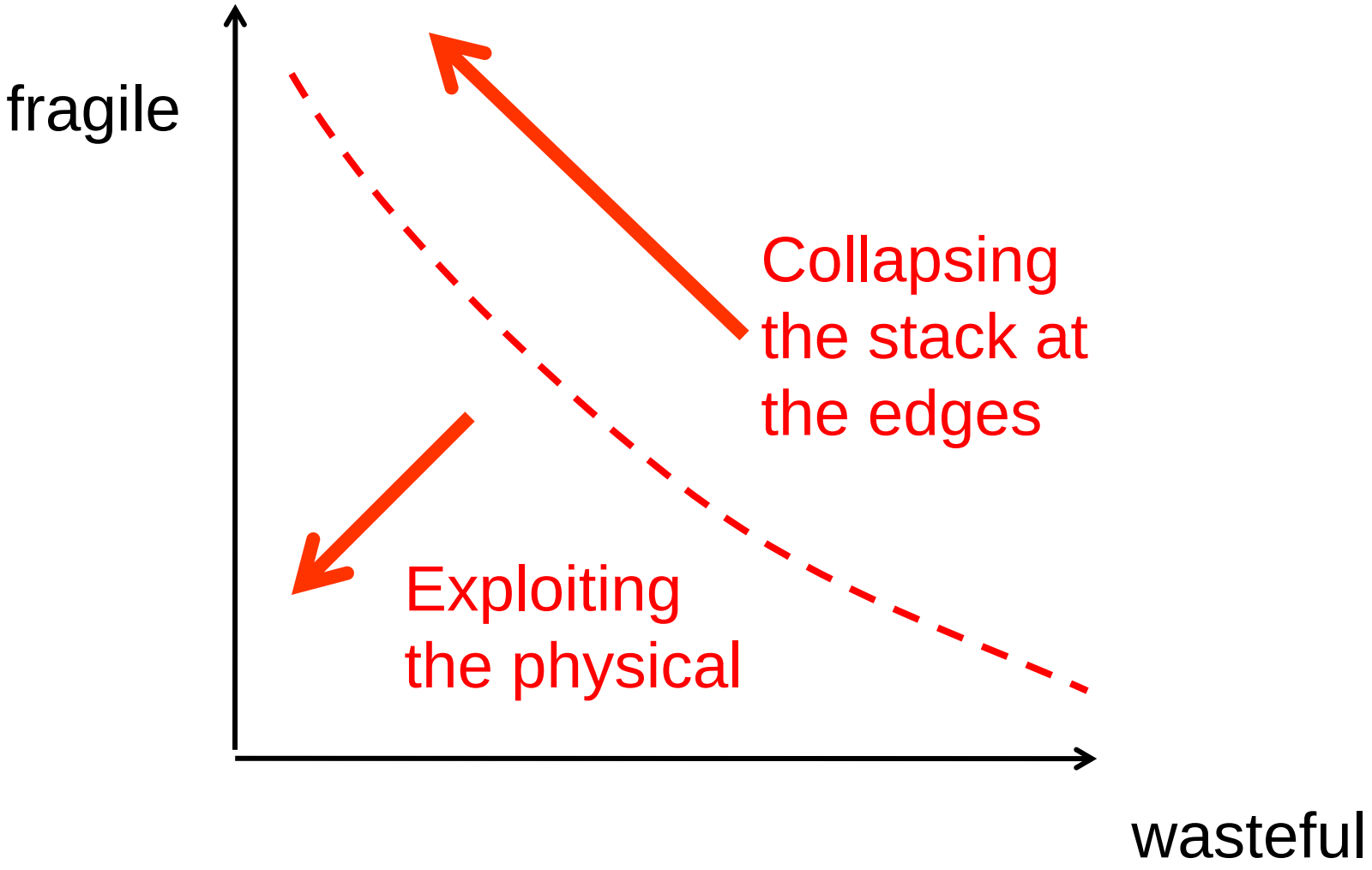
Good architectures allow for effective tradeoffs



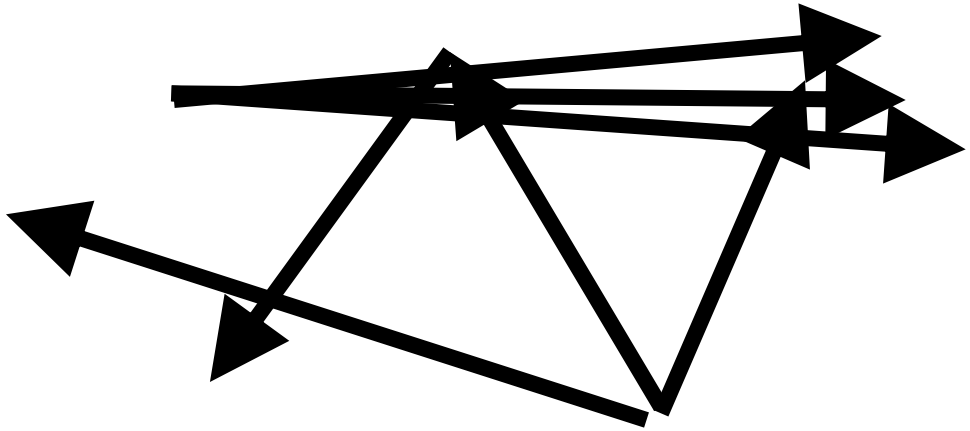

Collapsing
the stack at
the edges
Embedded
virtual
actuator/
sensor
Physical
plant
Lib
CPU/
Mem
Dev2
Actuator
Sensor
Exploiting
the physical

Architecture

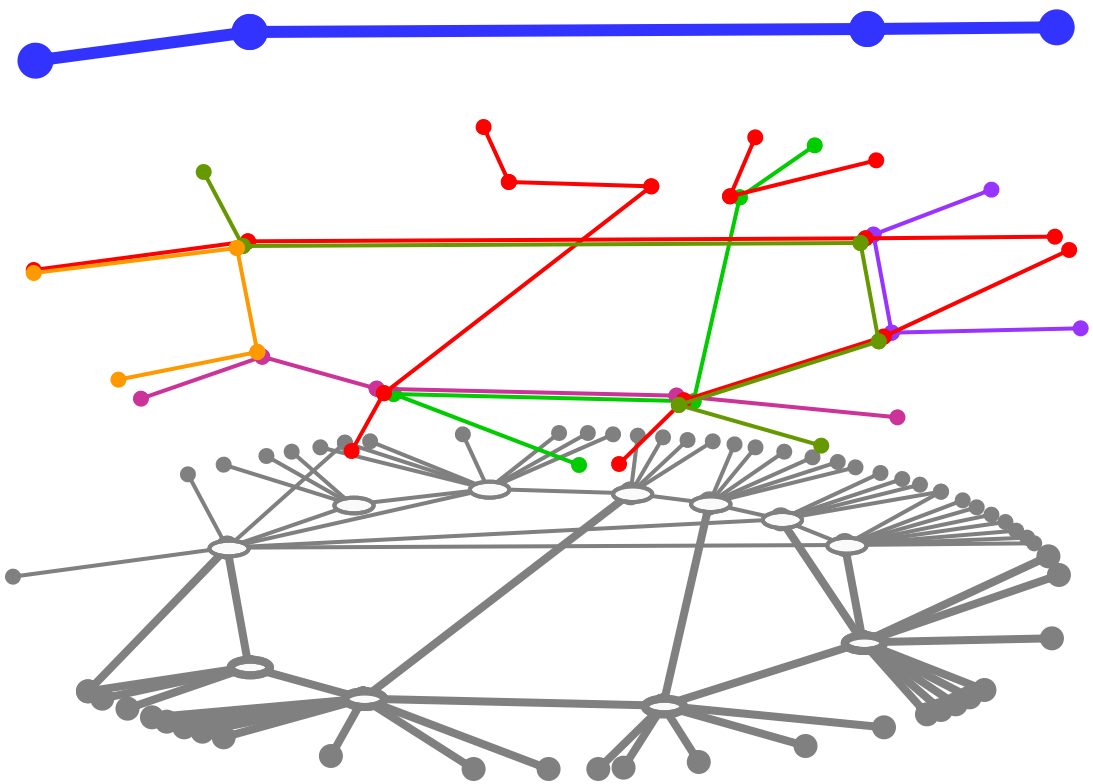
Good architectures allow for effective tradeoffs



Persistent errors and confusion.

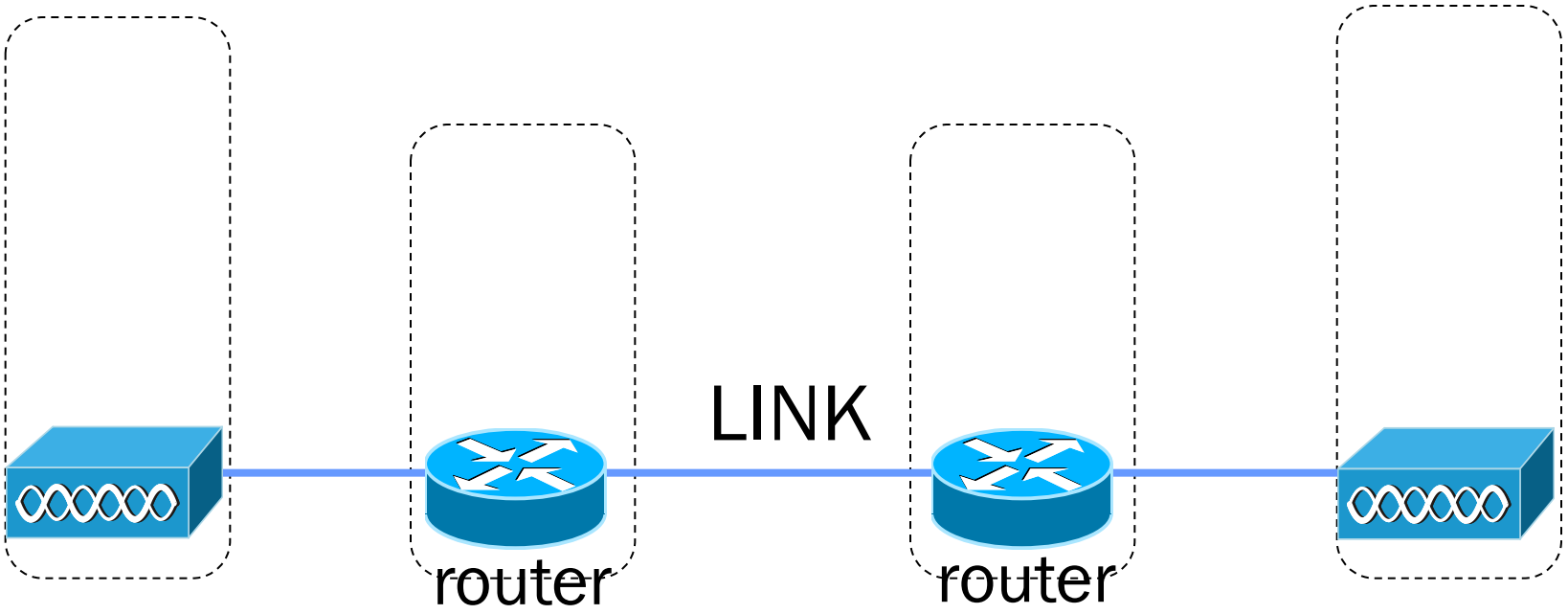


Architecture is ***not*** graph topology.

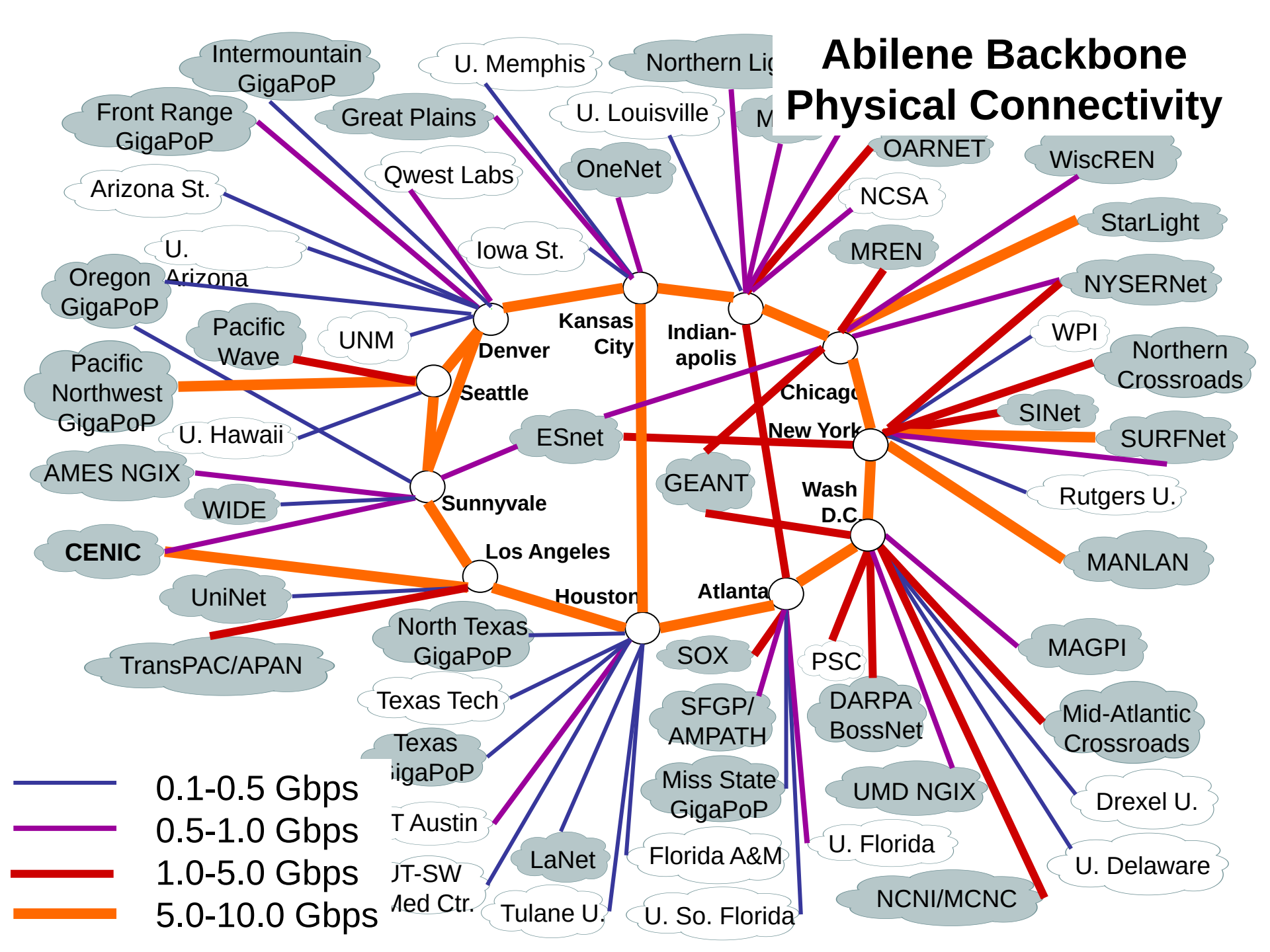


Architecture facilitates arbitrary graphs.

A layered view:
Diverse but not arbitrary

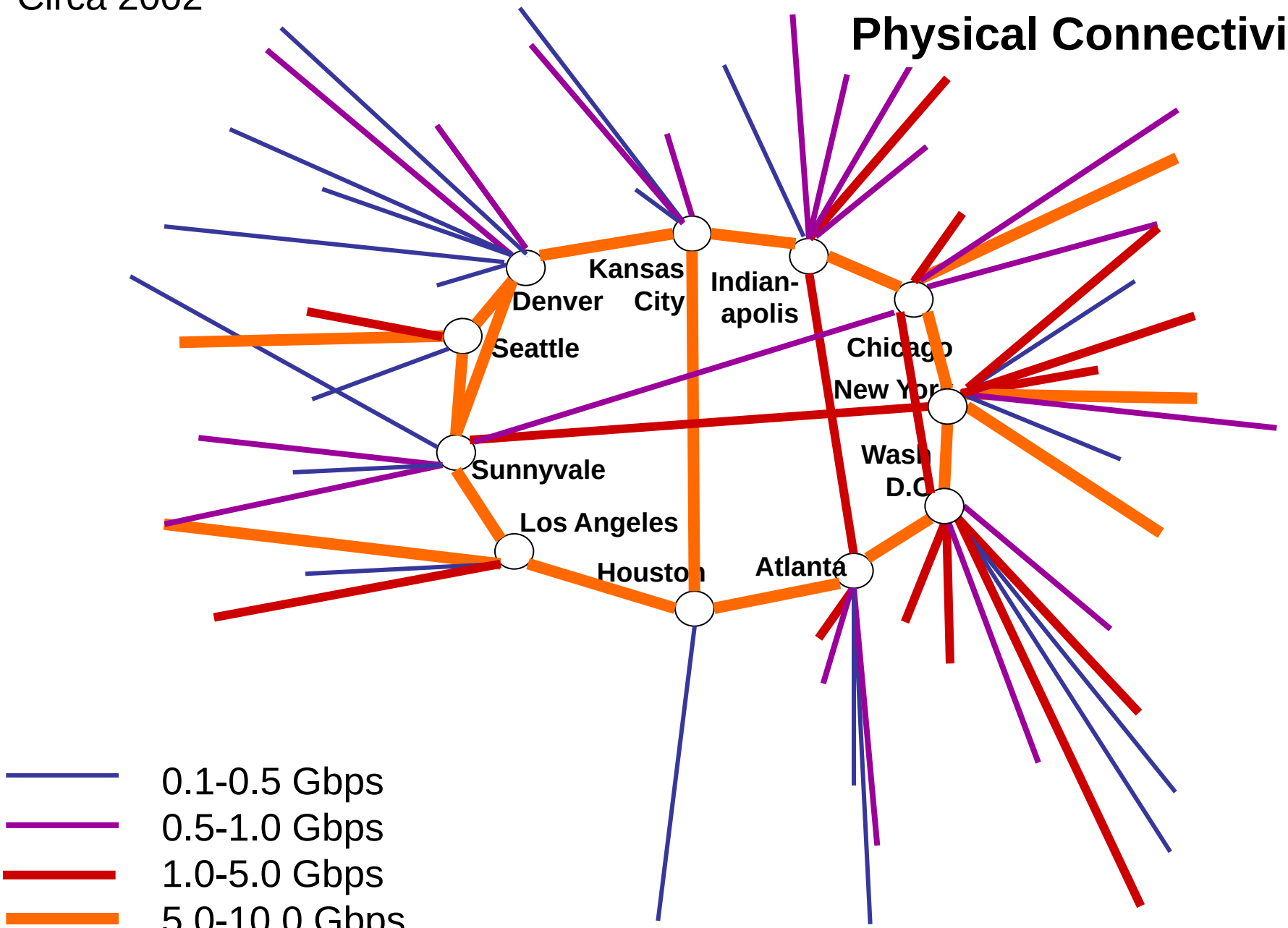


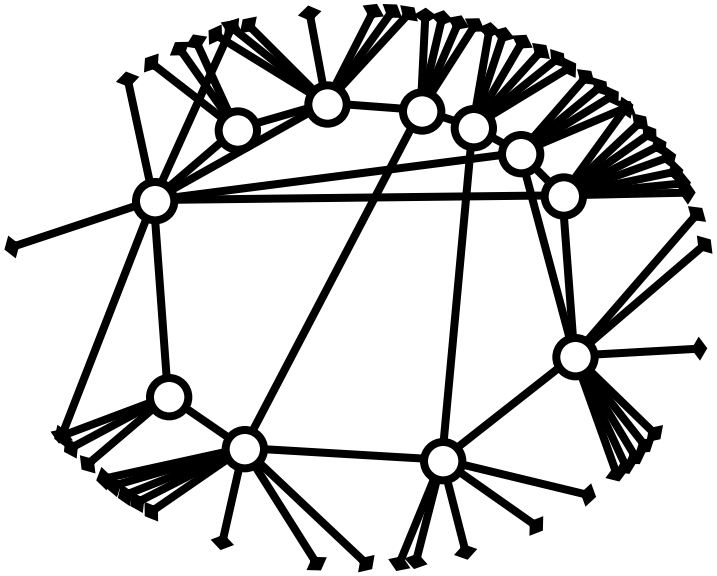
Diverse


Abilene Backbone
Physical Connectivity
Intermountain GigaPoP
U. Memphis
Northern Lig
Front Range GigaPoP
Great Plains
U. Louisville
OARNET
WiscREN
Qwest Labs
OneNet
NCSA
Arizona St.
StarLight
Iowa St.
MREN
U. Arizona
Oregon GigaPoP
NYSERNet
Pacific Wave
UNM
Kansas City
Indian-apolis
WPI
Denver
Northern Crossroads
Pacific Northwest GigaPoP
Seattle
Chicago
SINet
U. Hawaii
ESnet
New York
SURFNet
AMES NGIX
GEANT
Wash D.C
Rutgers U.
WIDE
Sunnyvale
CENIC
Los Angeles
MANLAN
UniNet
Houston
Atlanta
North Texas GigaPoP
MAGPI
TransPAC/APAN
SOX
PSC
Texas Tech
SFGP/ AMPATH
DARPA BossNet
Mid-Atlantic Crossroads
Texas
Miss State GigaPoP
UMD NGIX
Drexel U.
T Austin
LaNet
Florida A&M
U. Florida
U. Delaware
Tulane U.
U. So. Florida
NCNI/MCNC
0.1-0.5 Gbps
0.5-1.0 Gbps
1.0-5.0 Gbps
5.0-10.0 Gbps

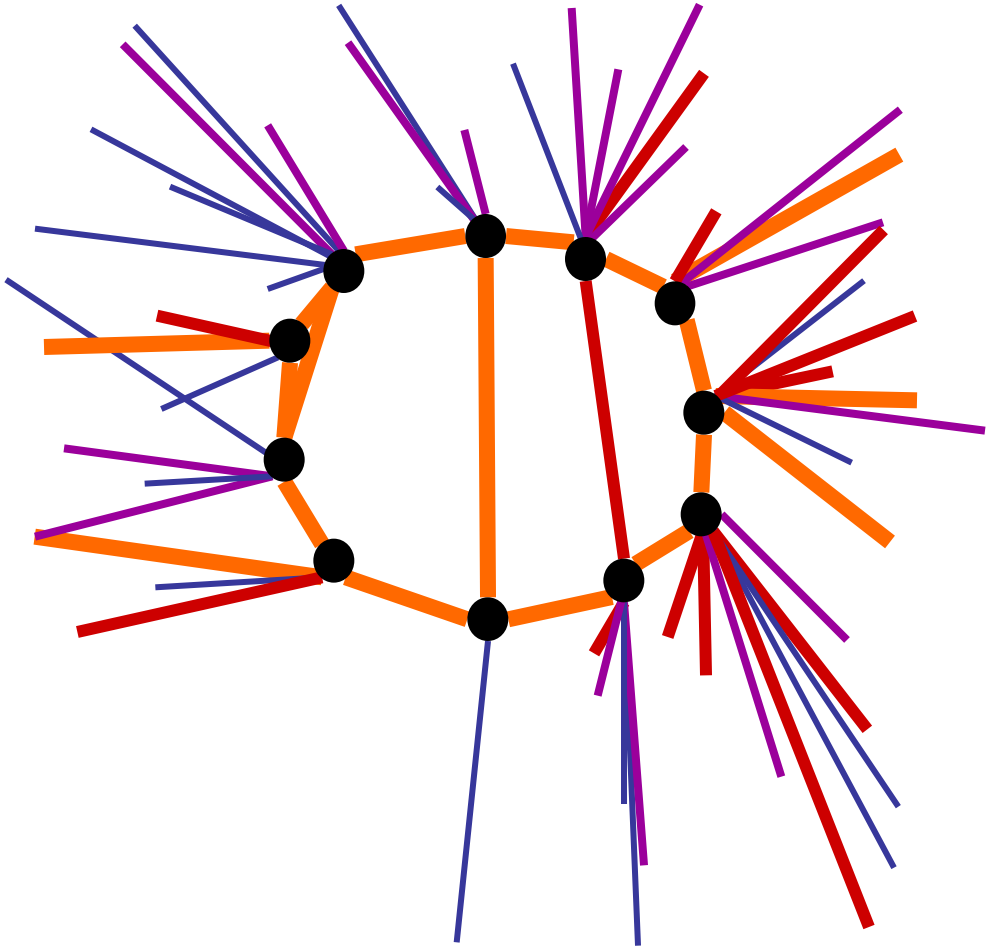
Geography not to scale
Circa 2002

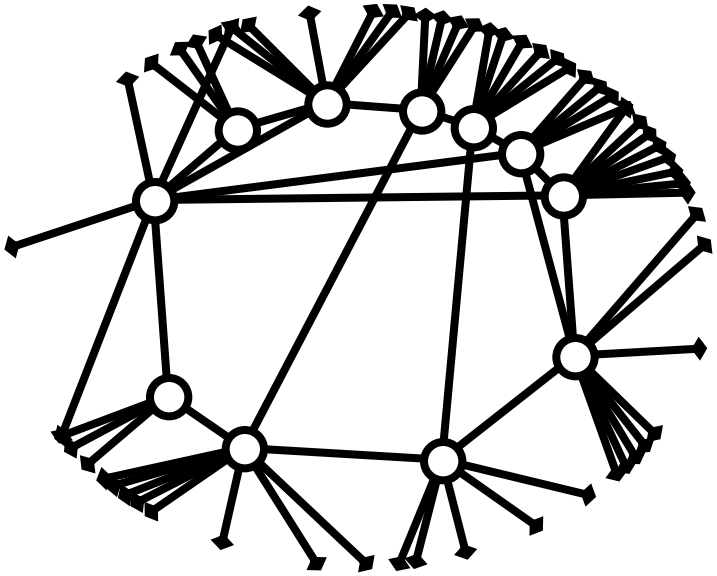
Abilene Backbone Physical Connectivity



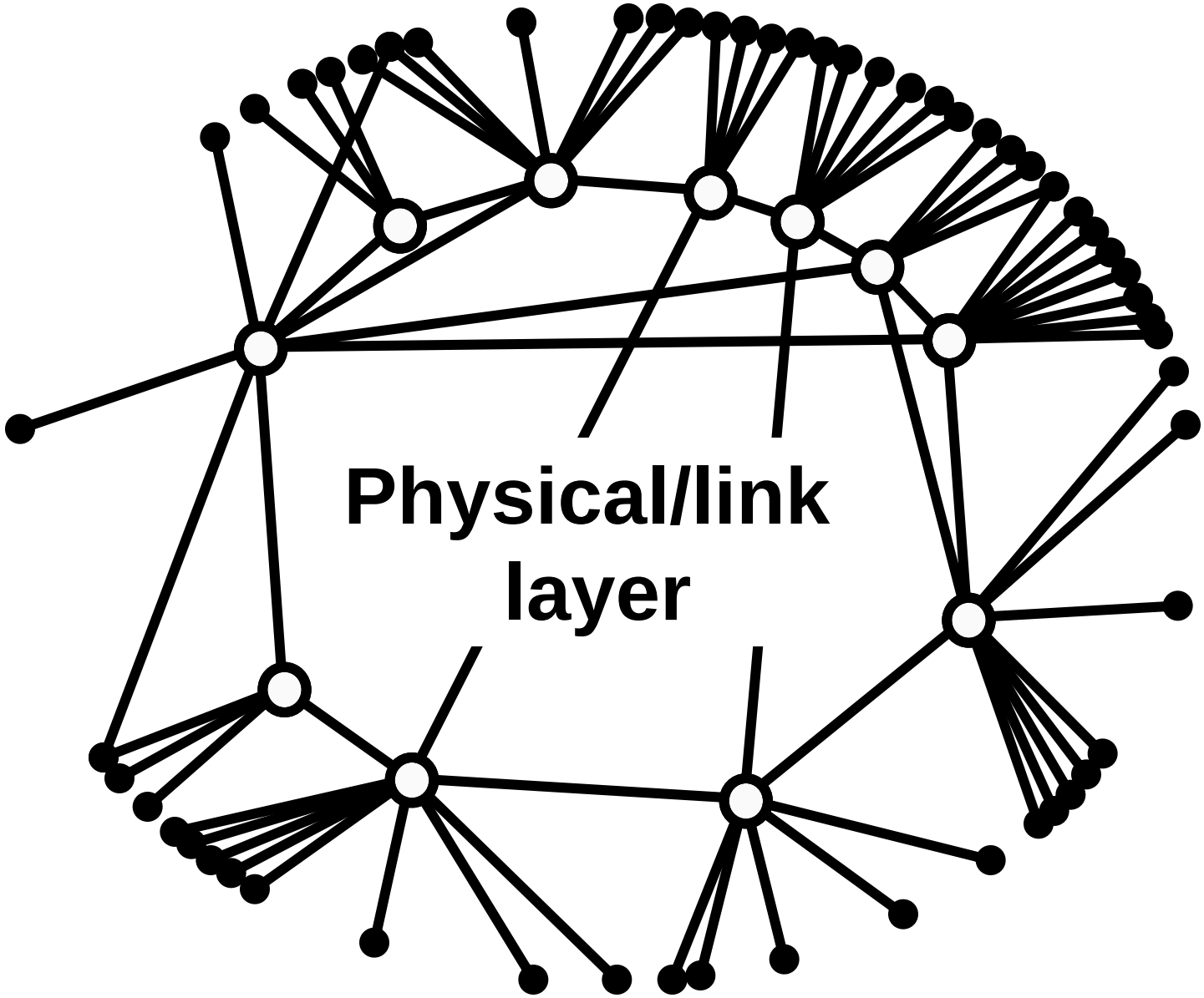


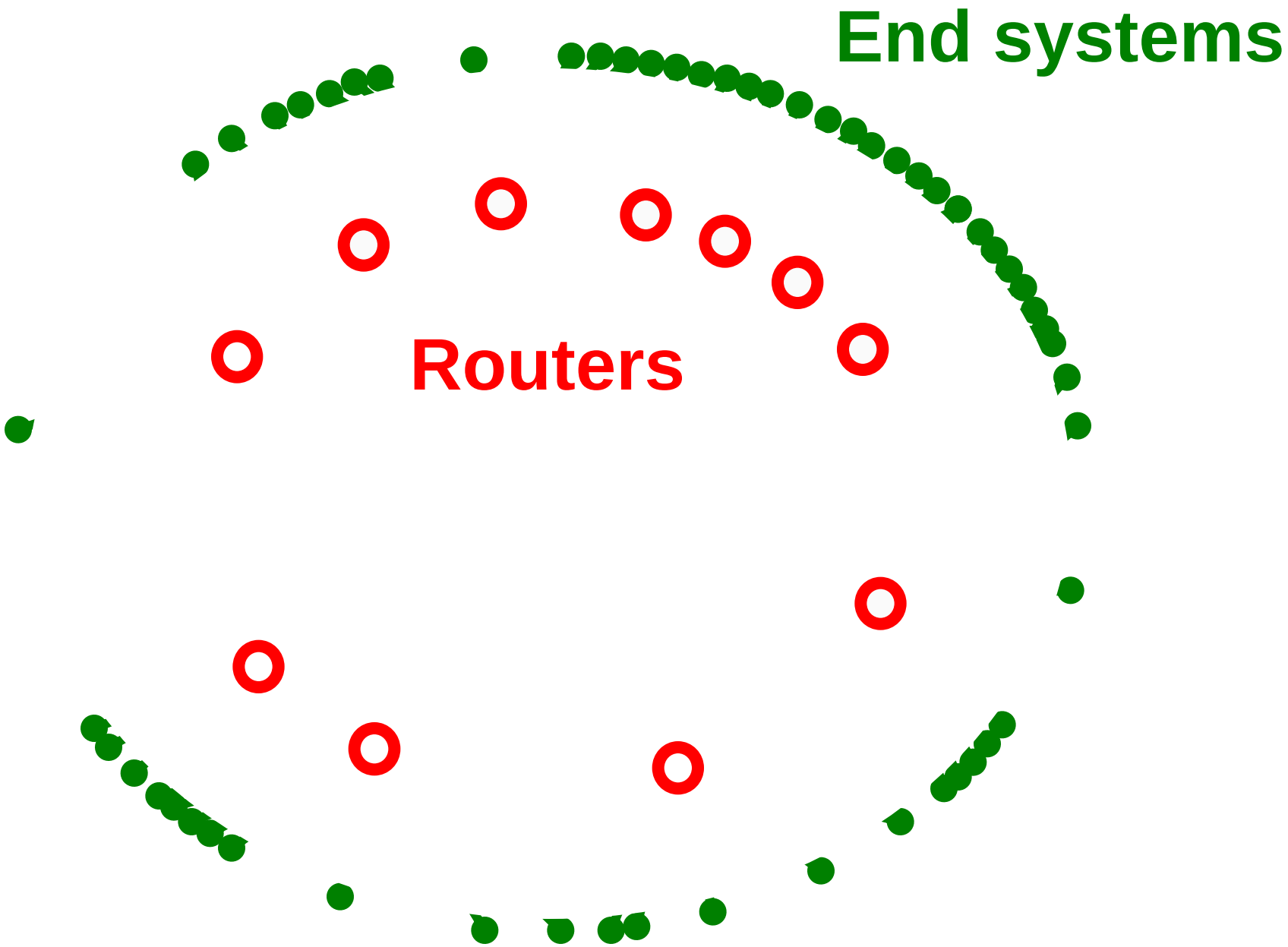
Ignore
bandwidths

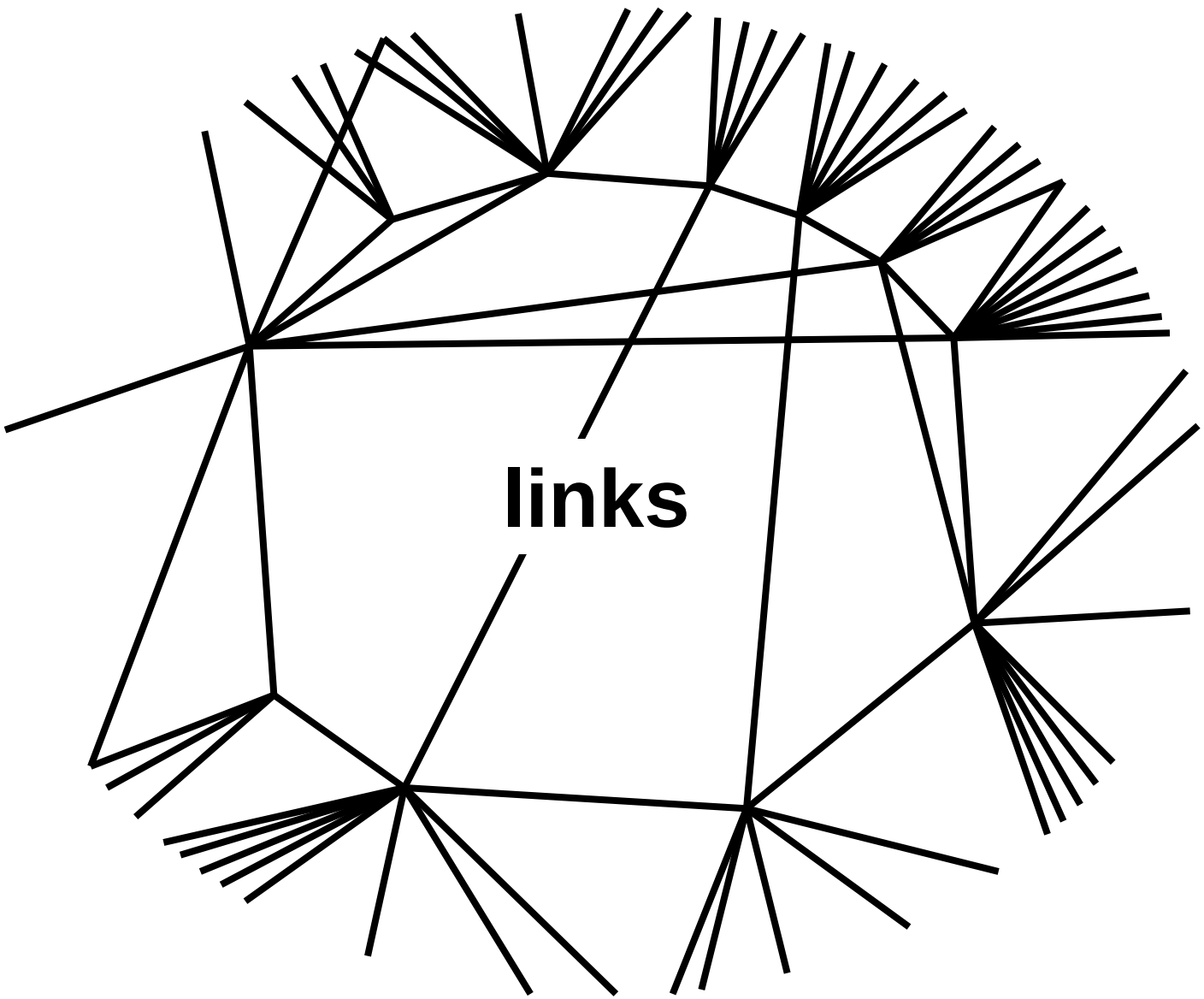


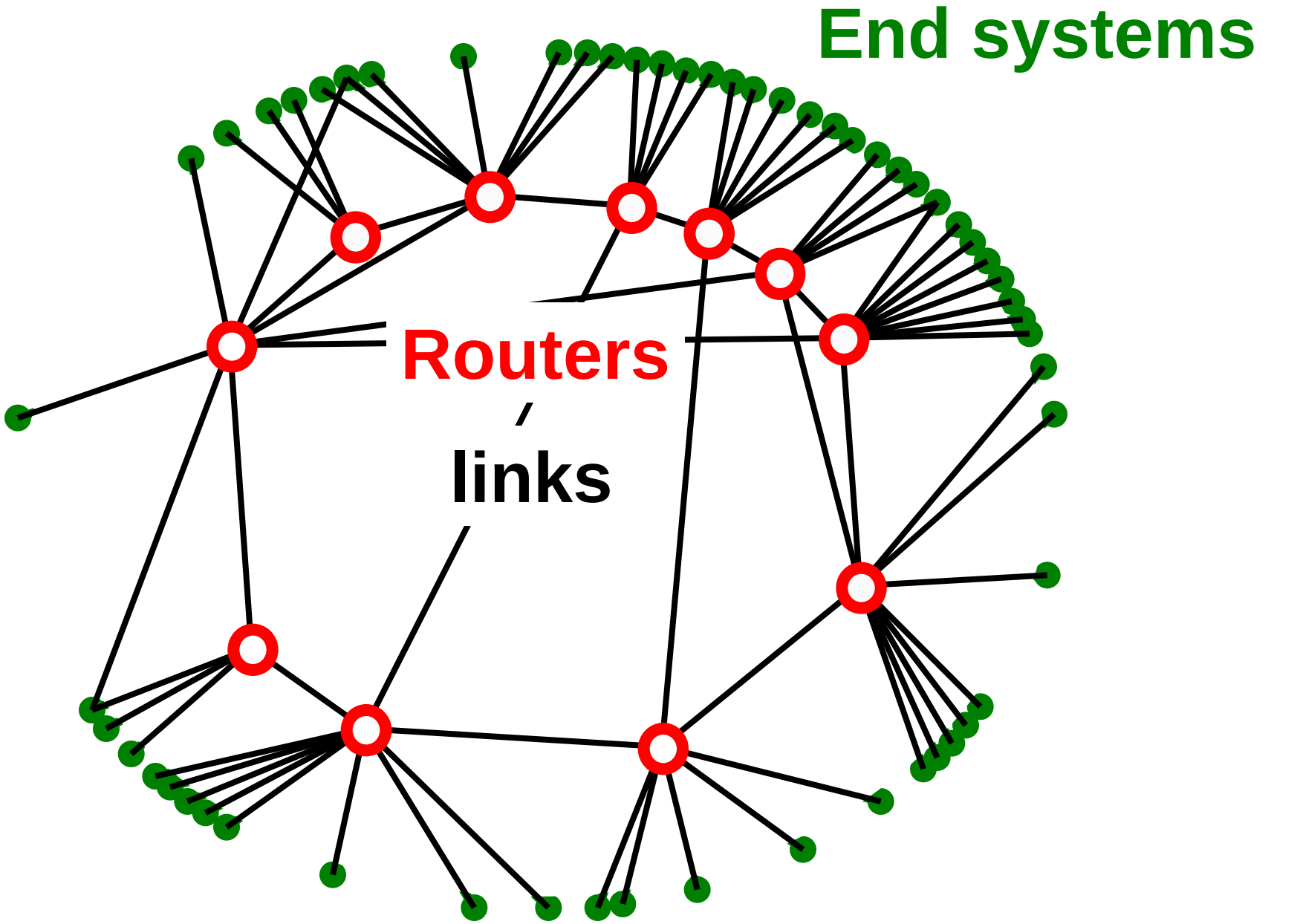


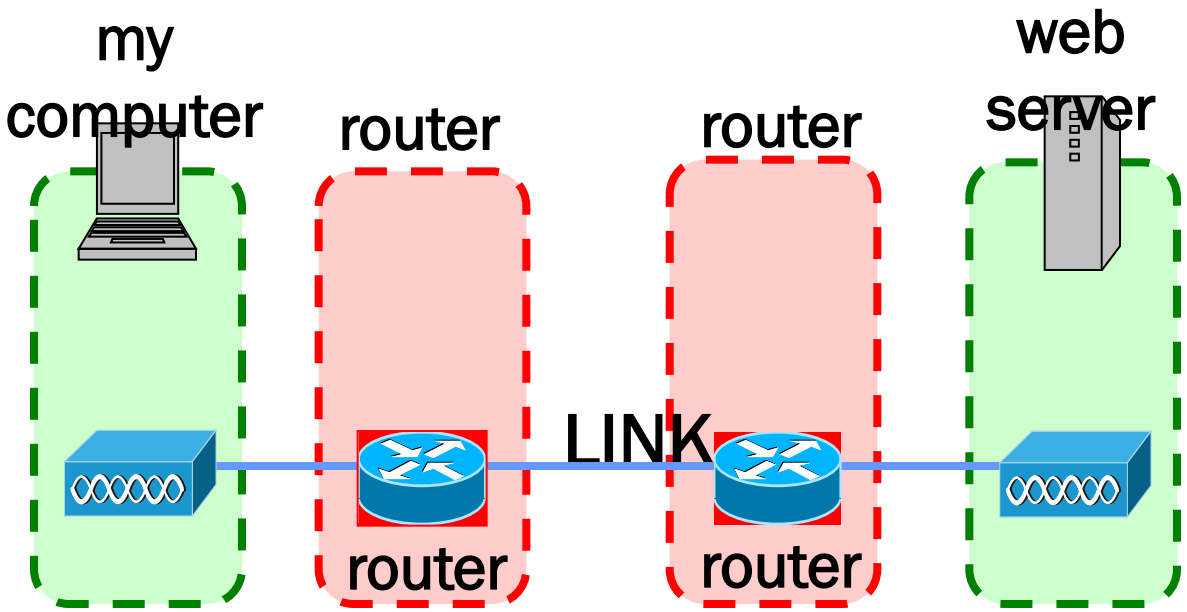
Diverse

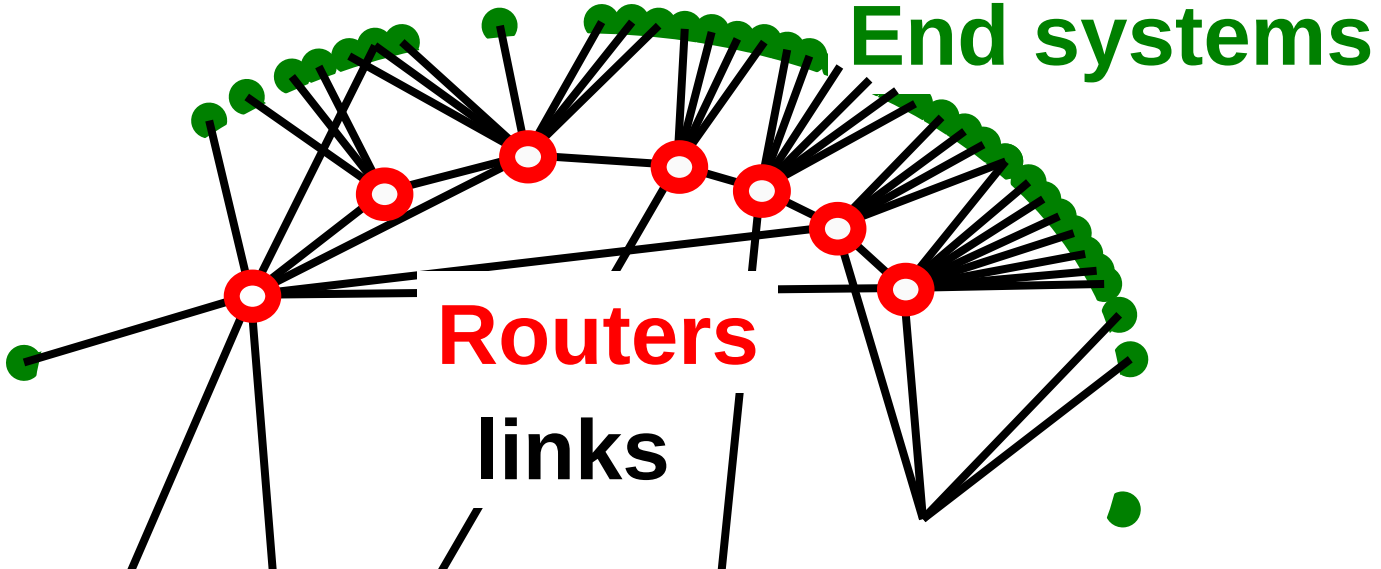

Physical/link
layer

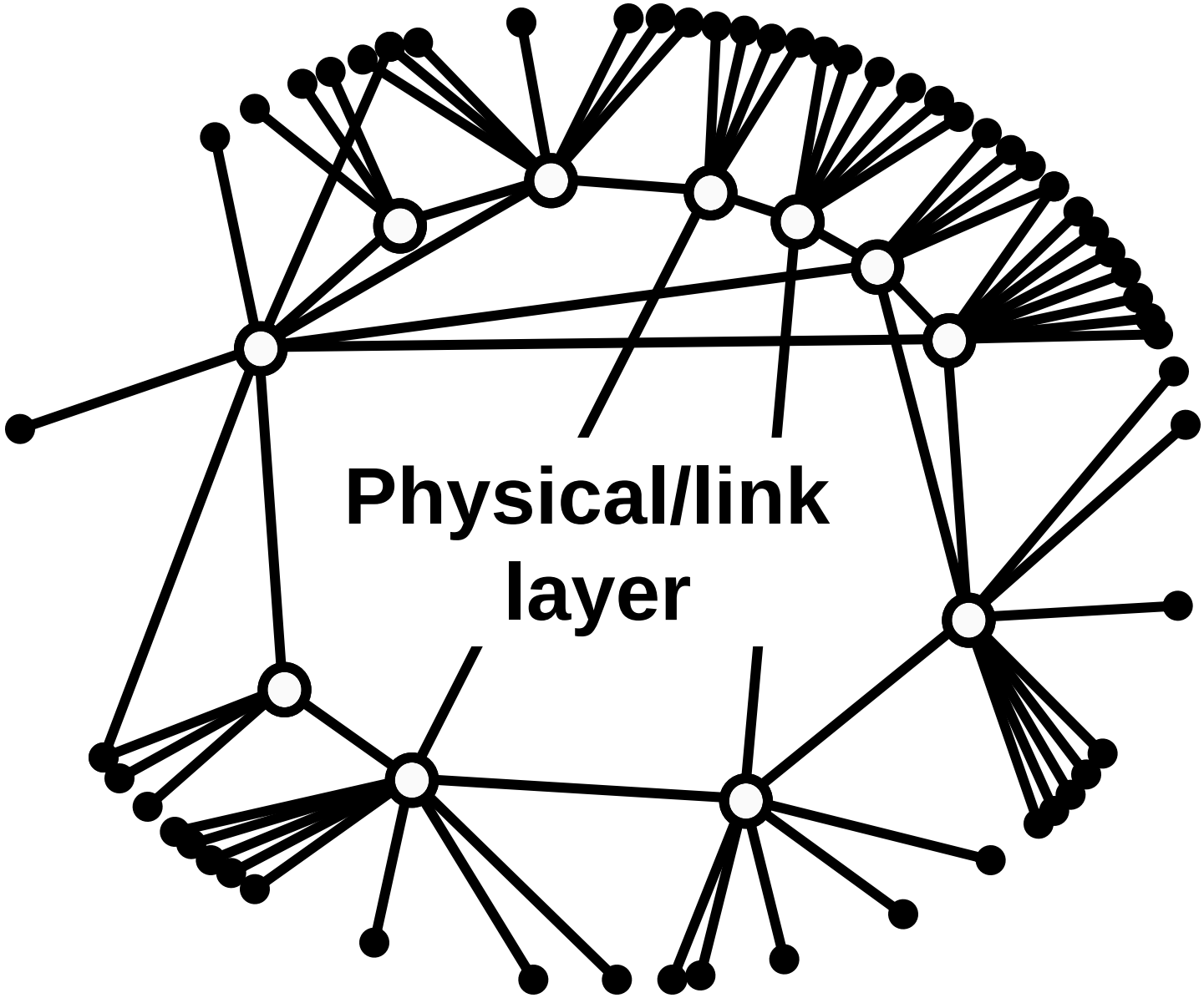

End systems
Routers

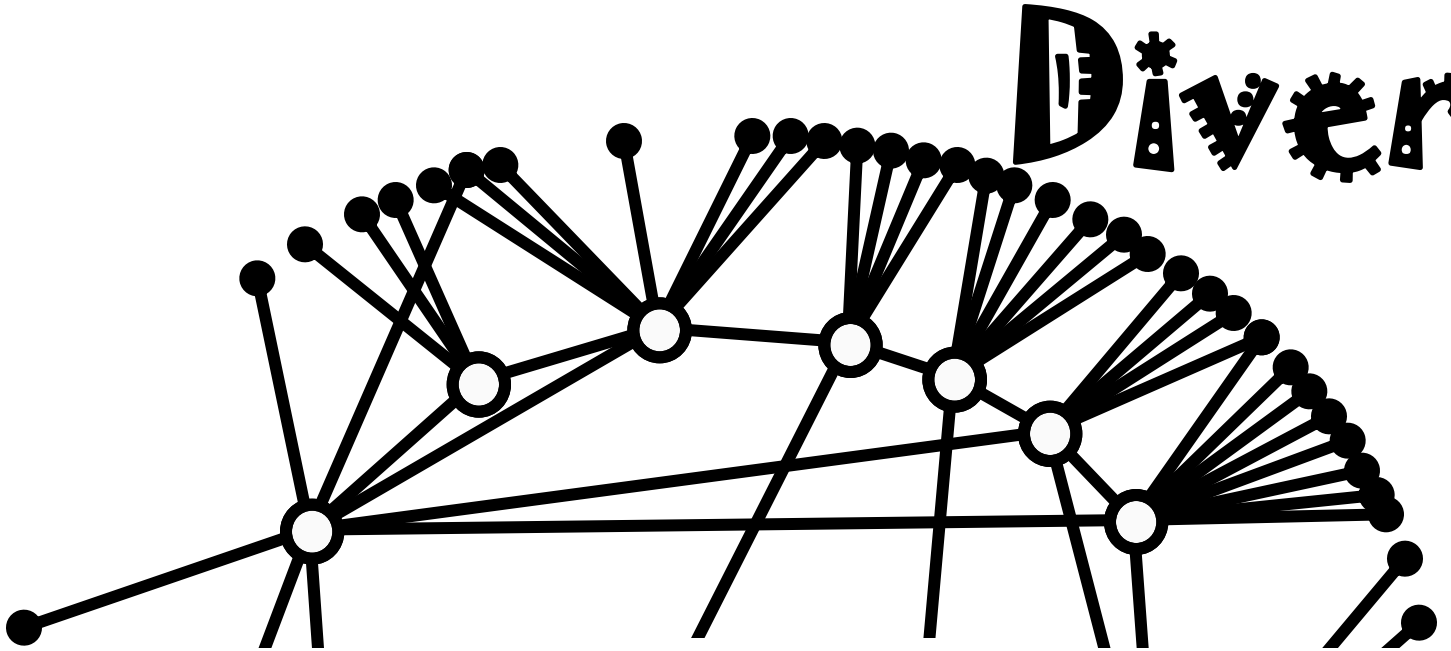

links


End systems
Routers
links


my
computer
router
router
web
server
LINK
router
router

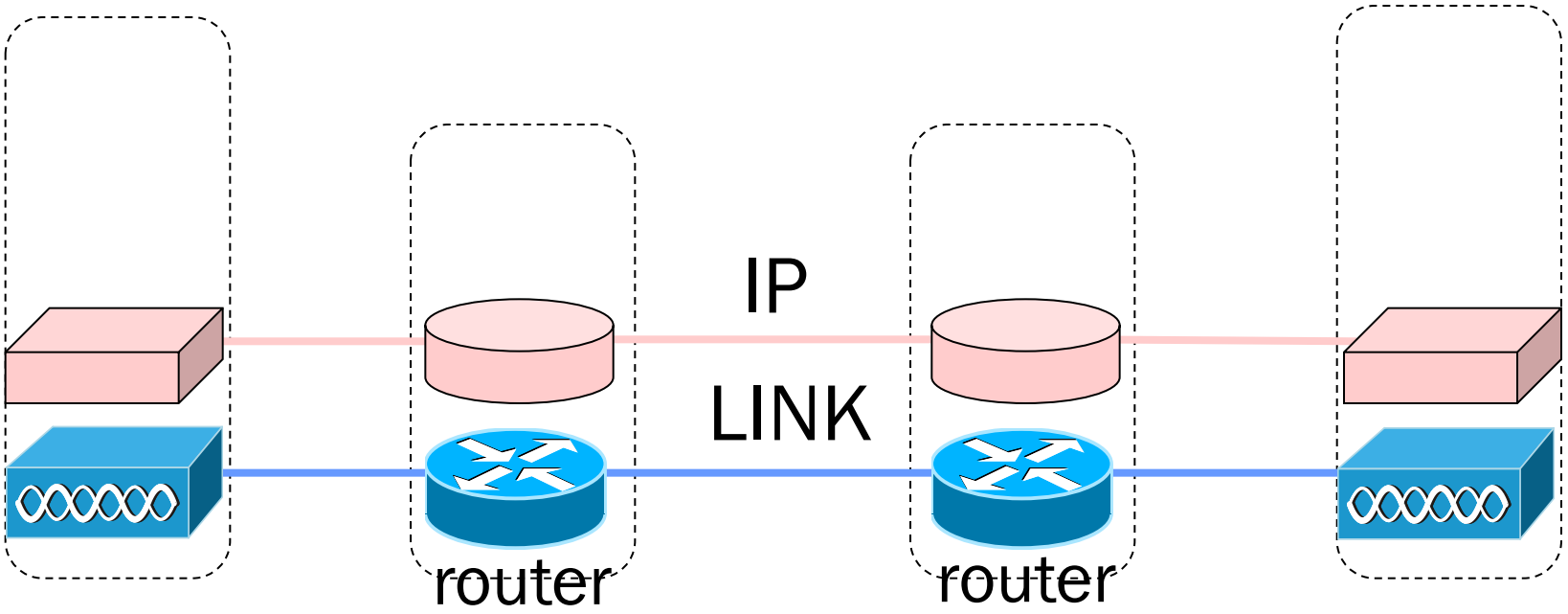

End systems
Routers
links


Physical/link
layer



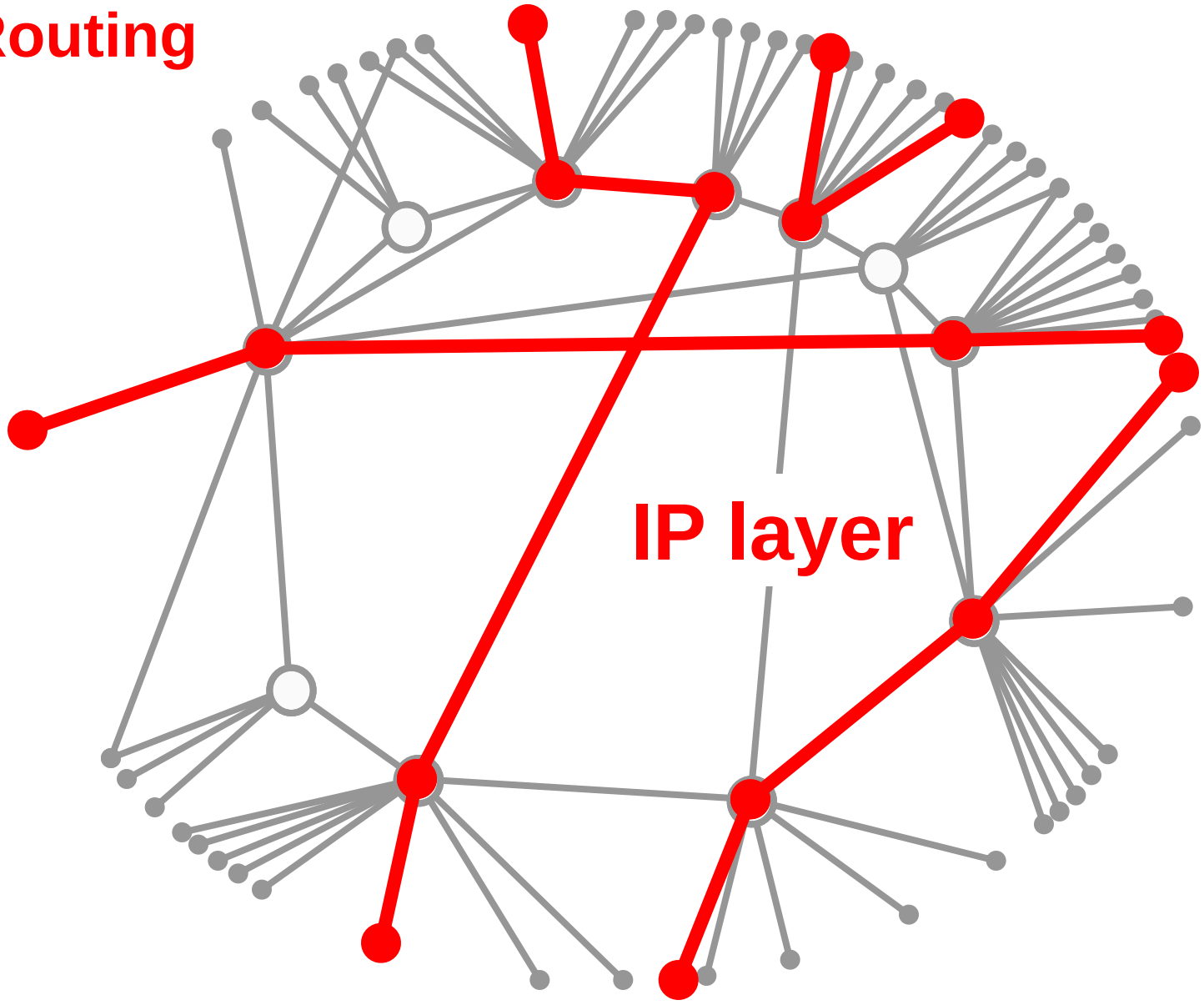
Physical/link layer

IP layer

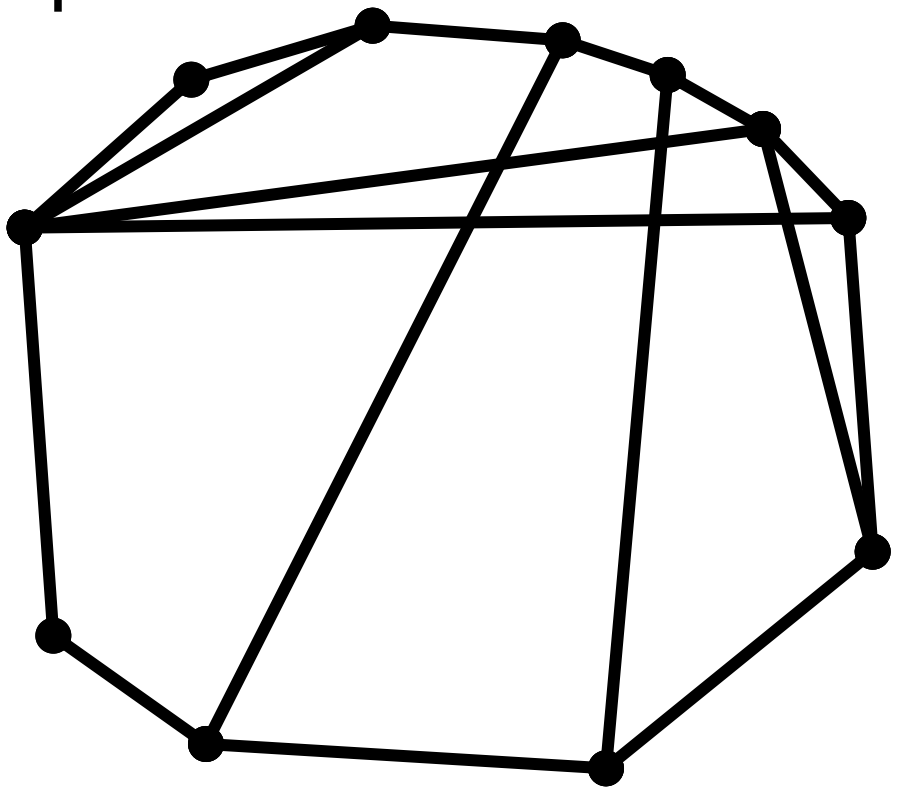


Control:

- **Routing**



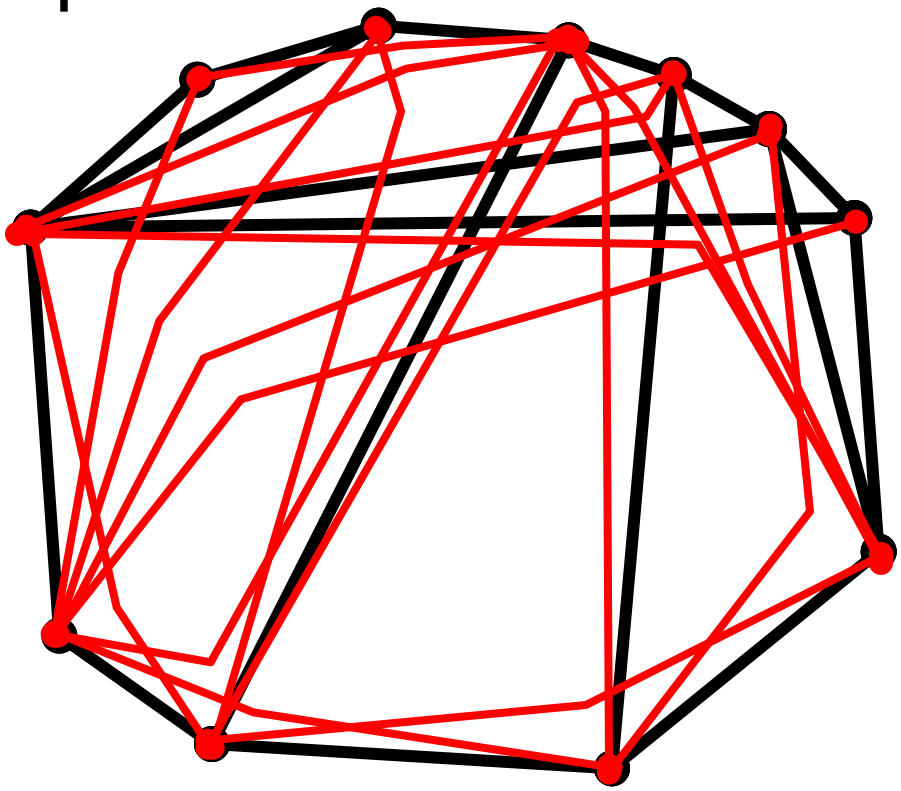
1 hop



IP layer

1 hop

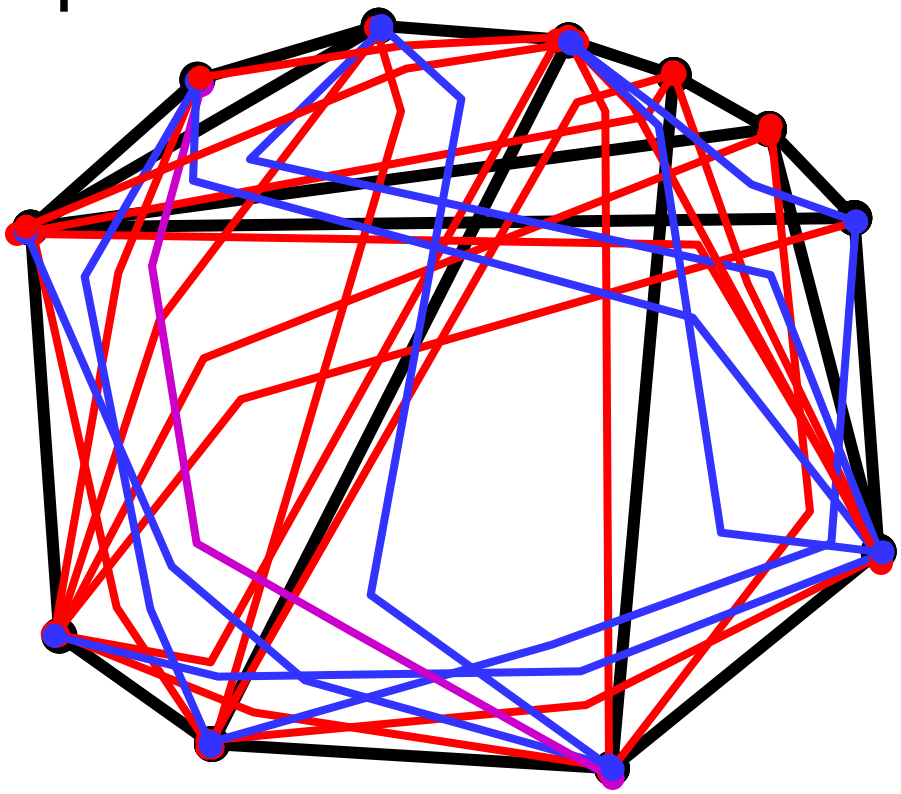
2 hops



IP layer

1 hop

2 hops

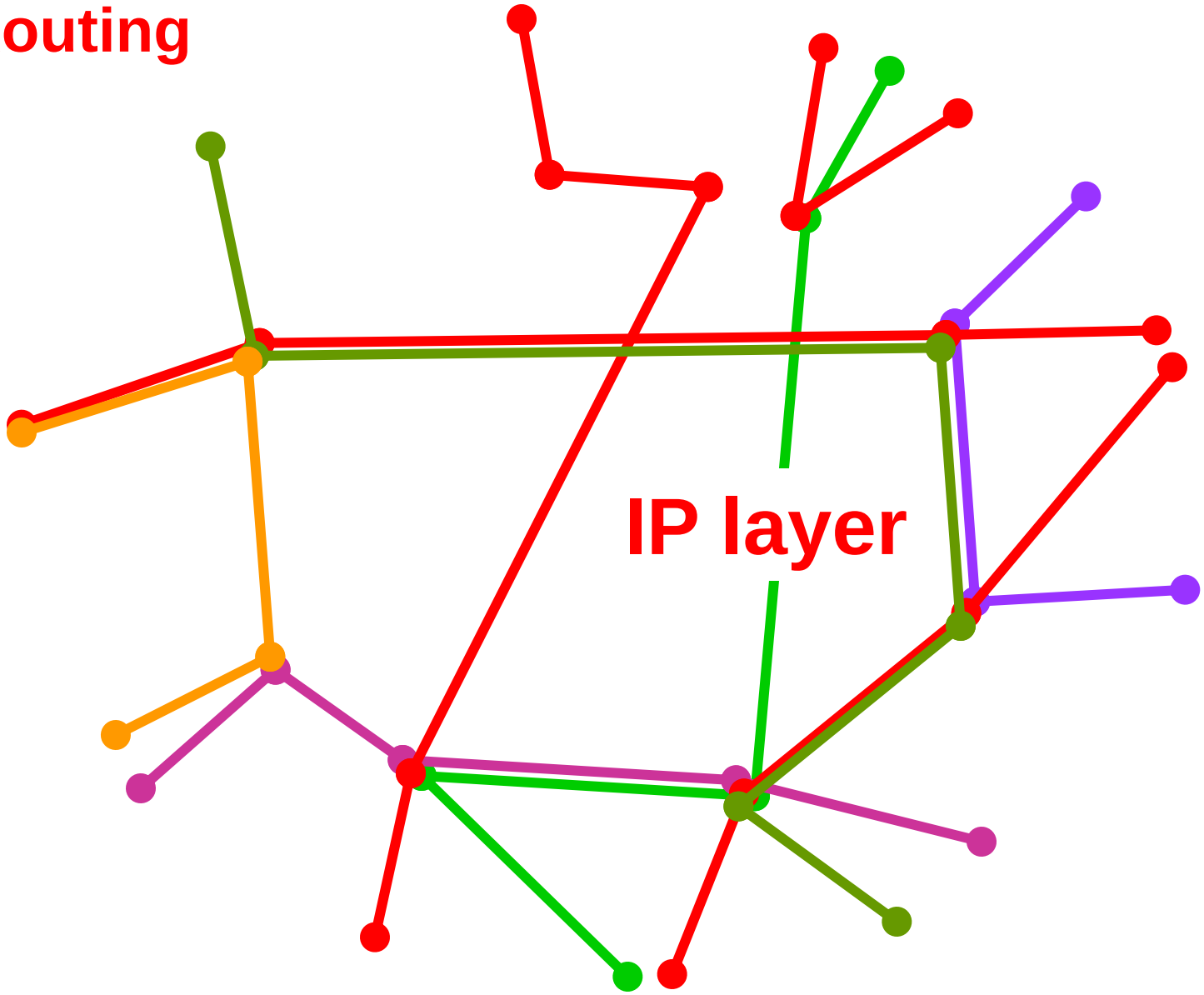


3 hops

IP layer

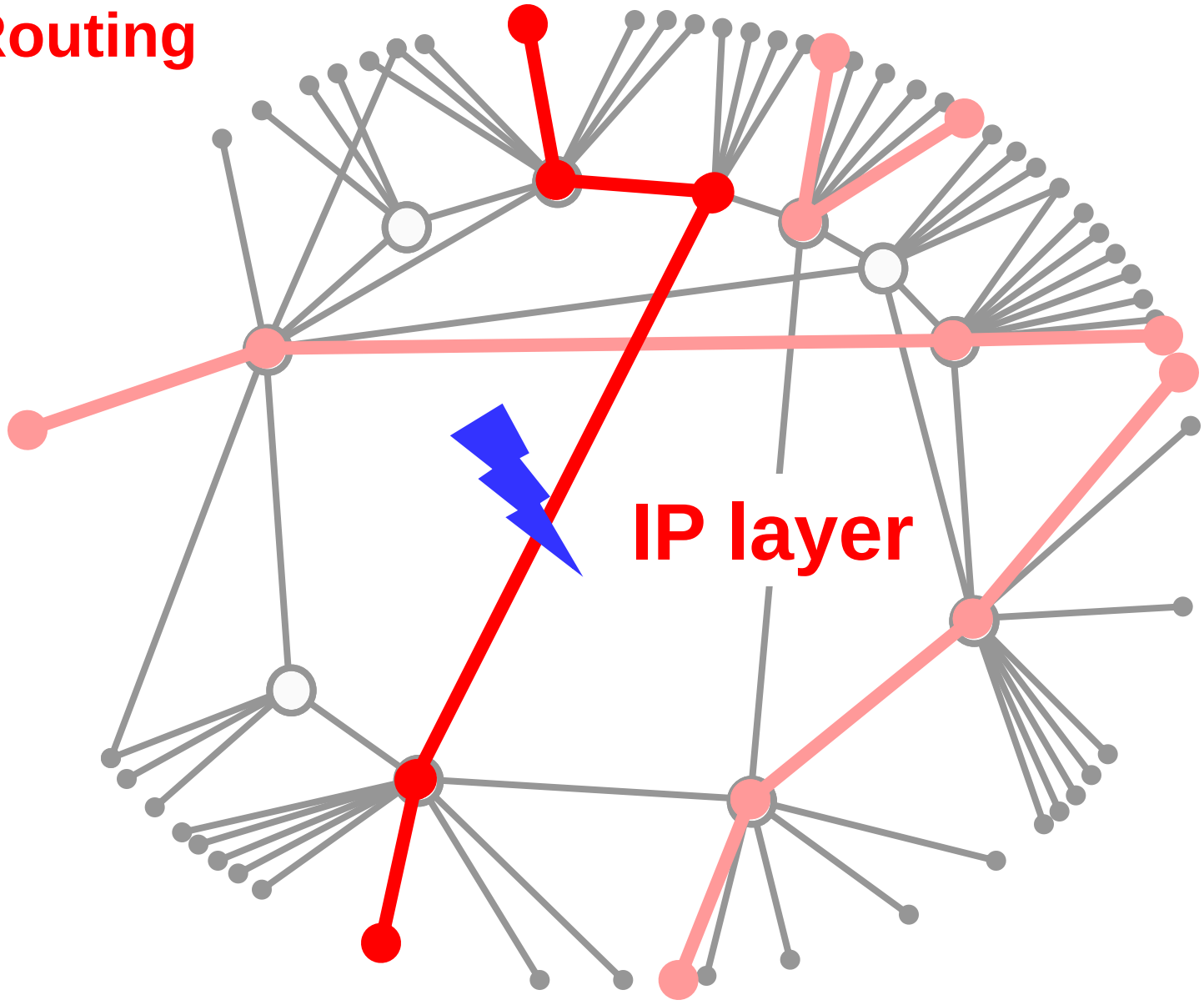
Control:

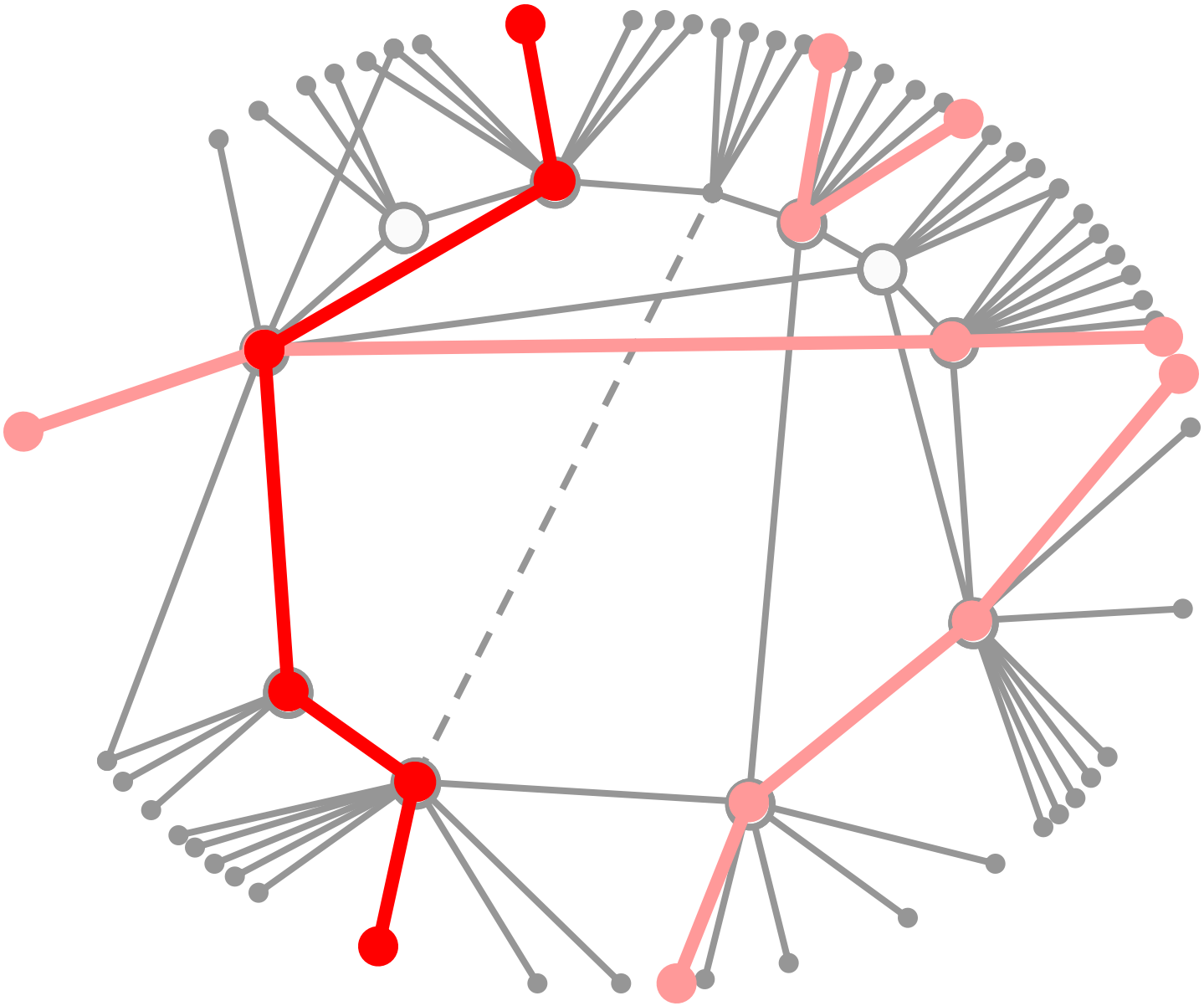
- **Routing**

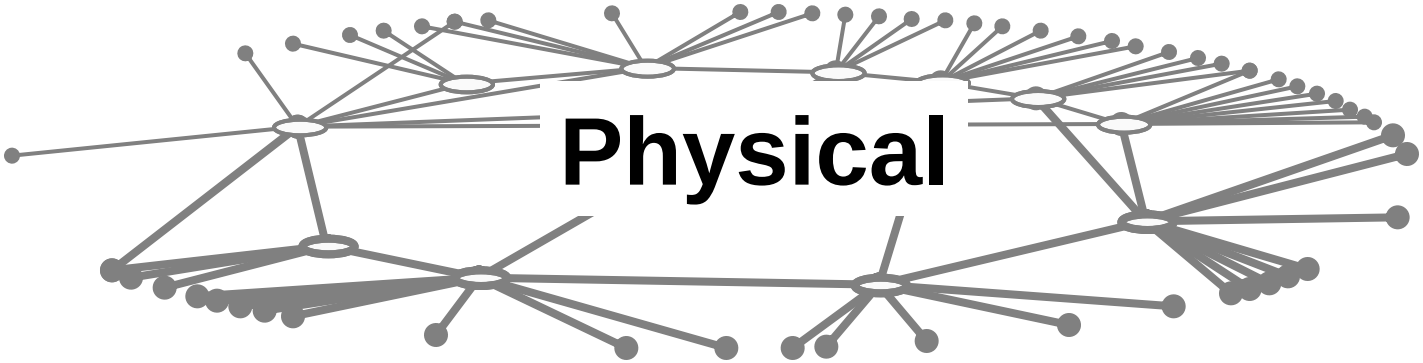


Control:

- **Routing**

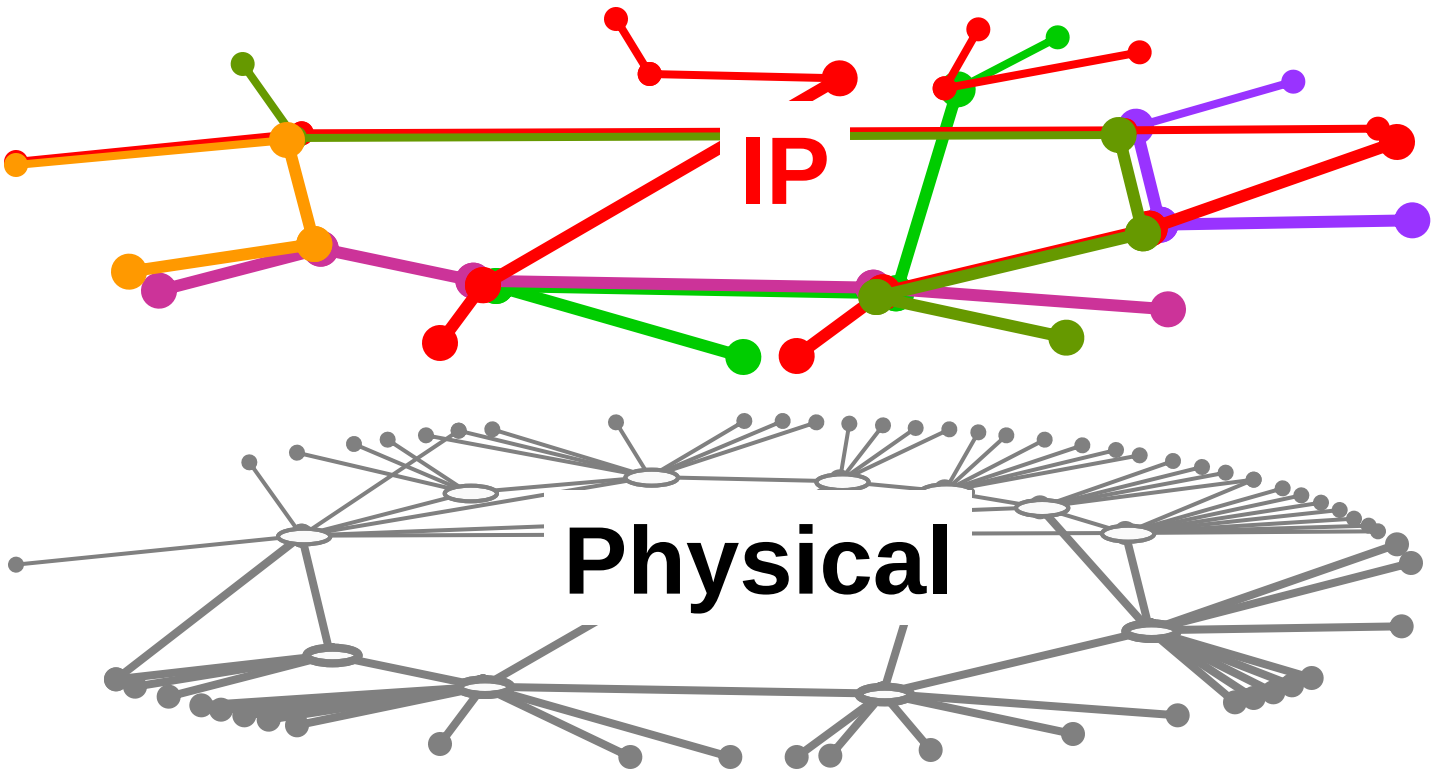


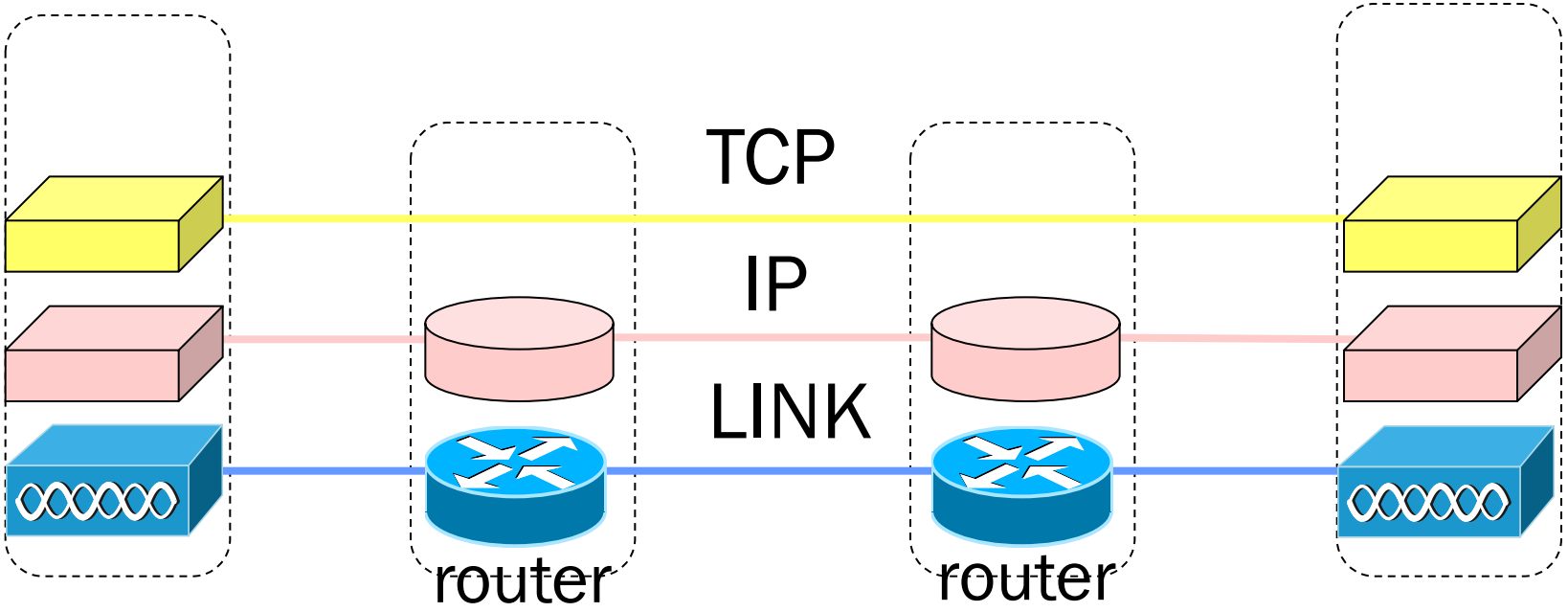



Physical

Control:

- **Routing**

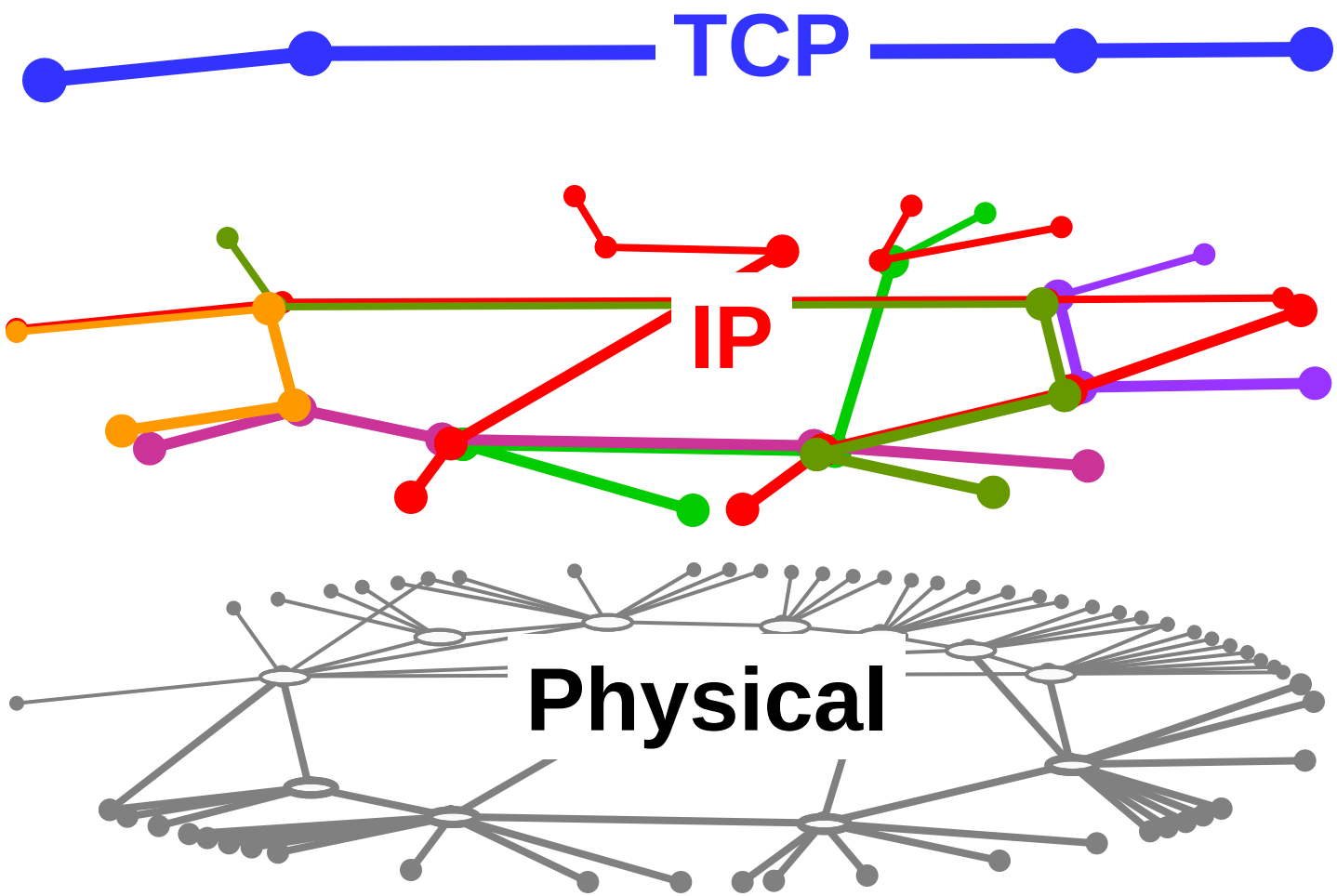




Diverse

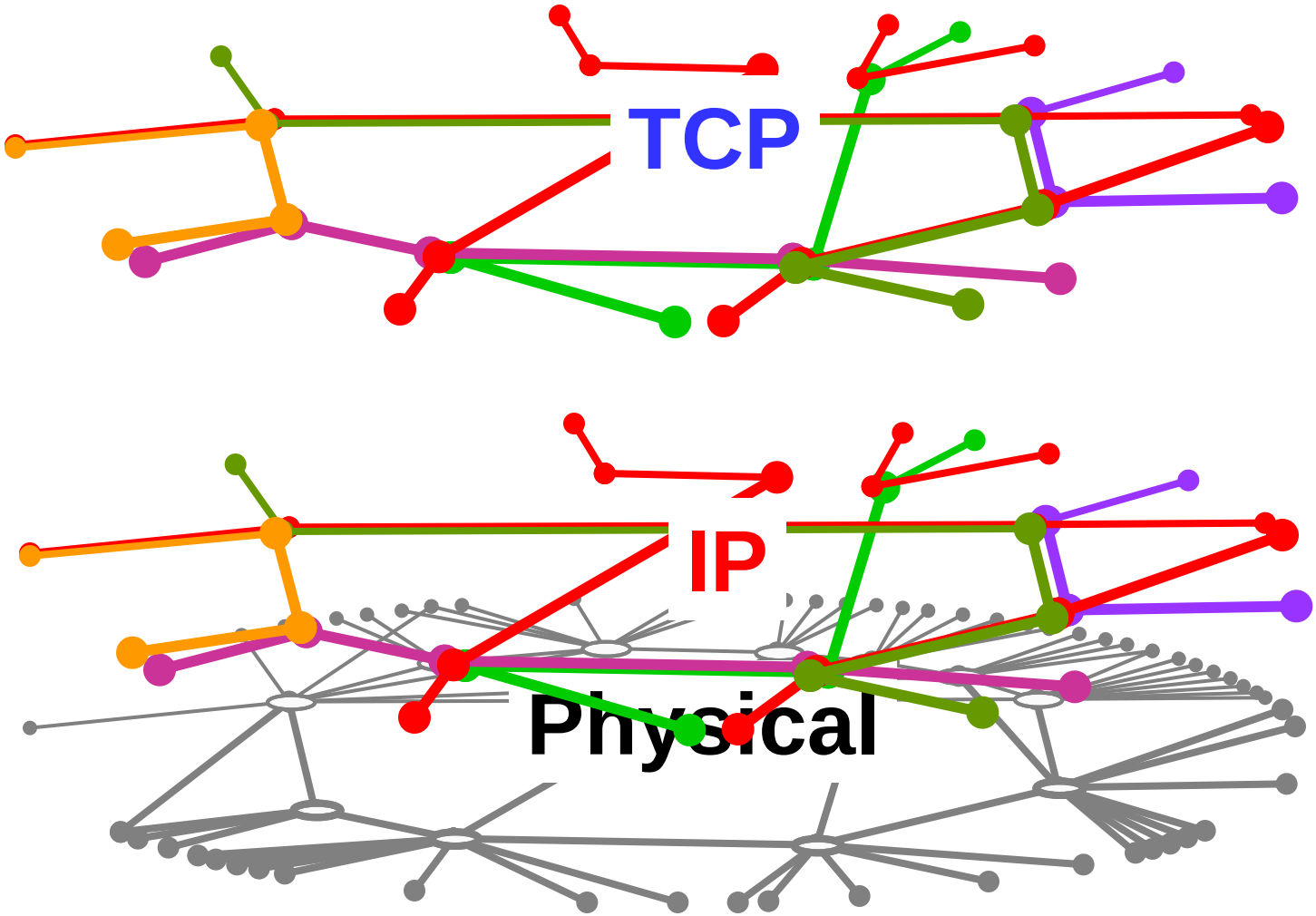
Control:

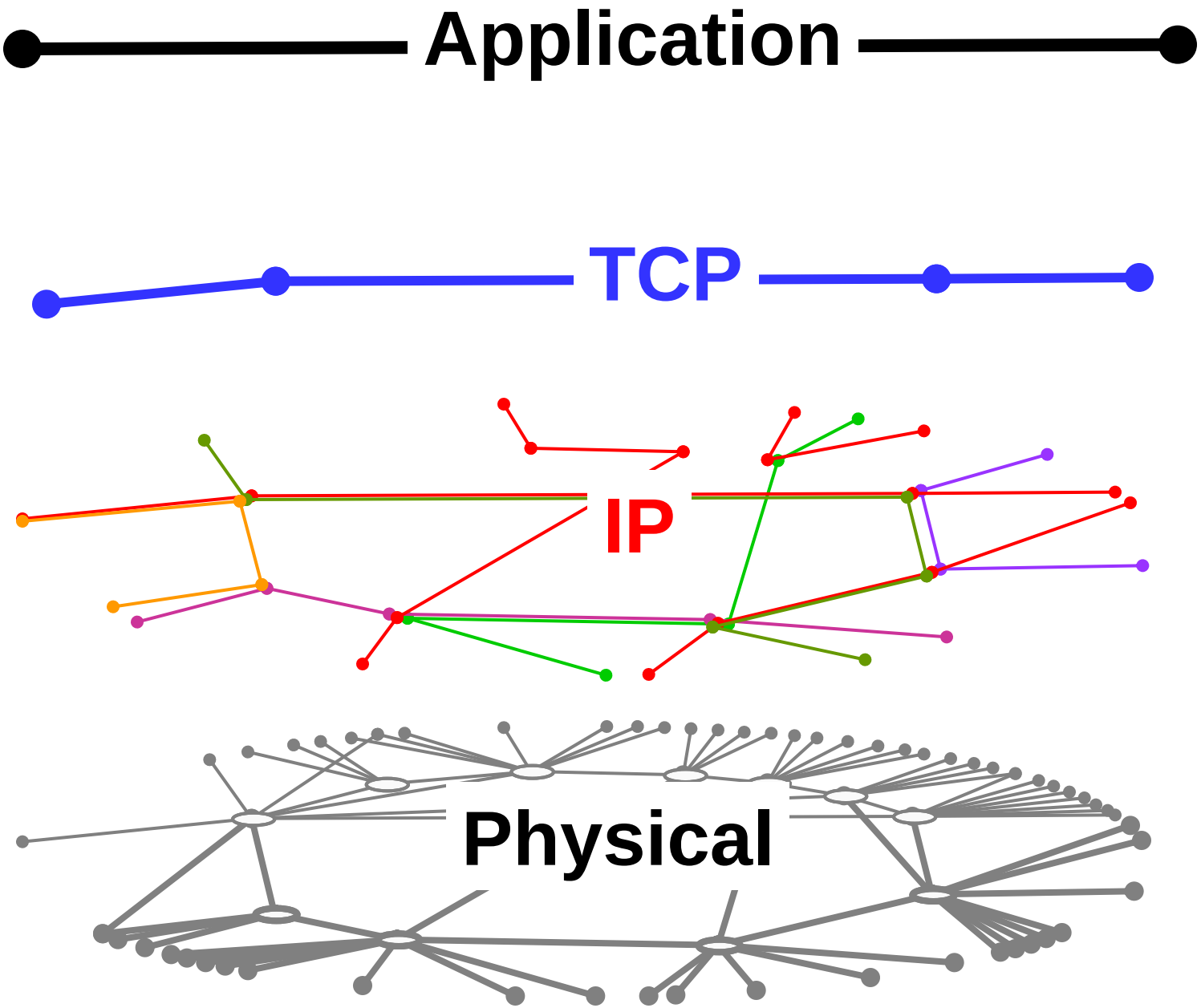
- **Congestion (window)**
- **Loss (retransmission)**

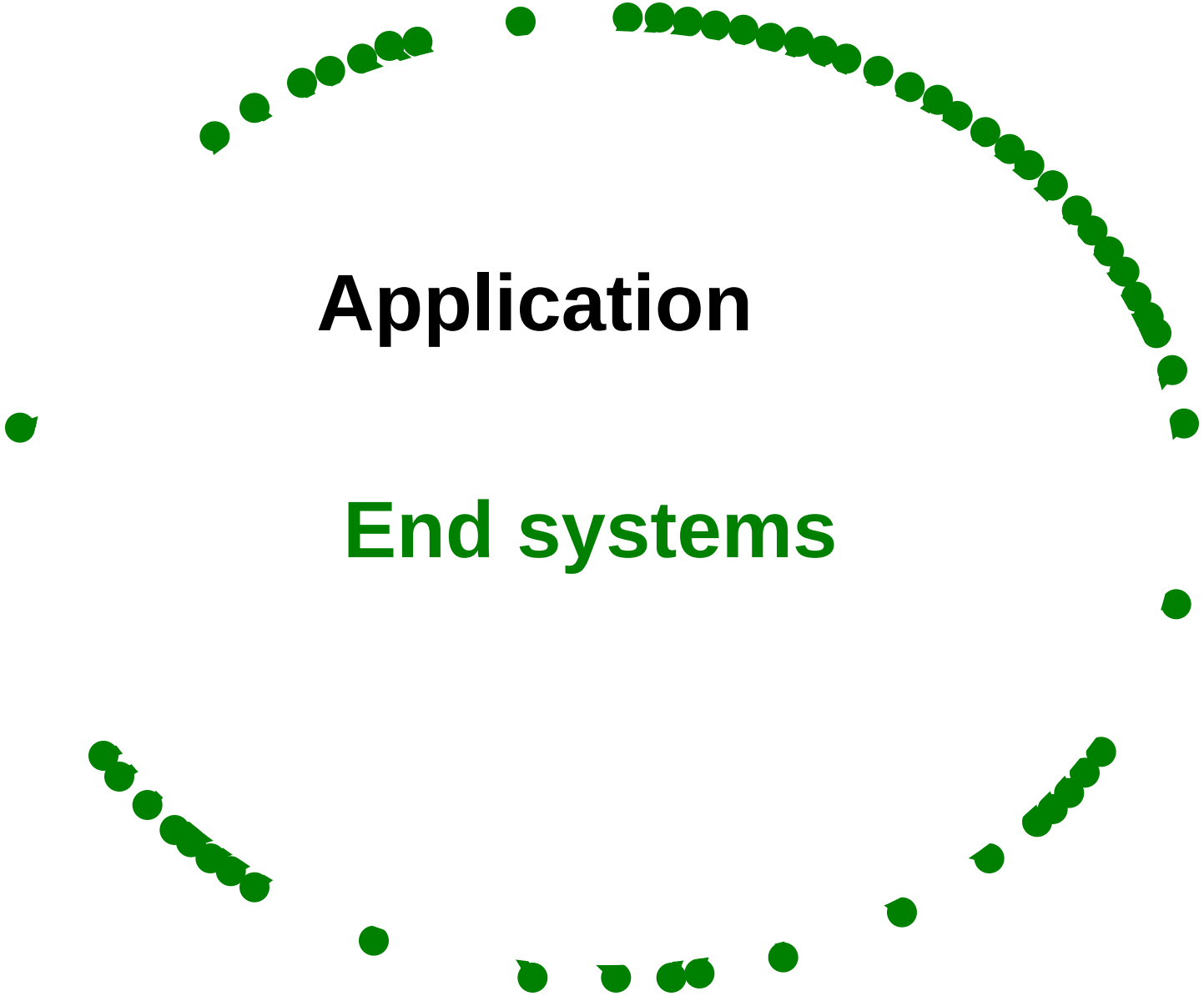


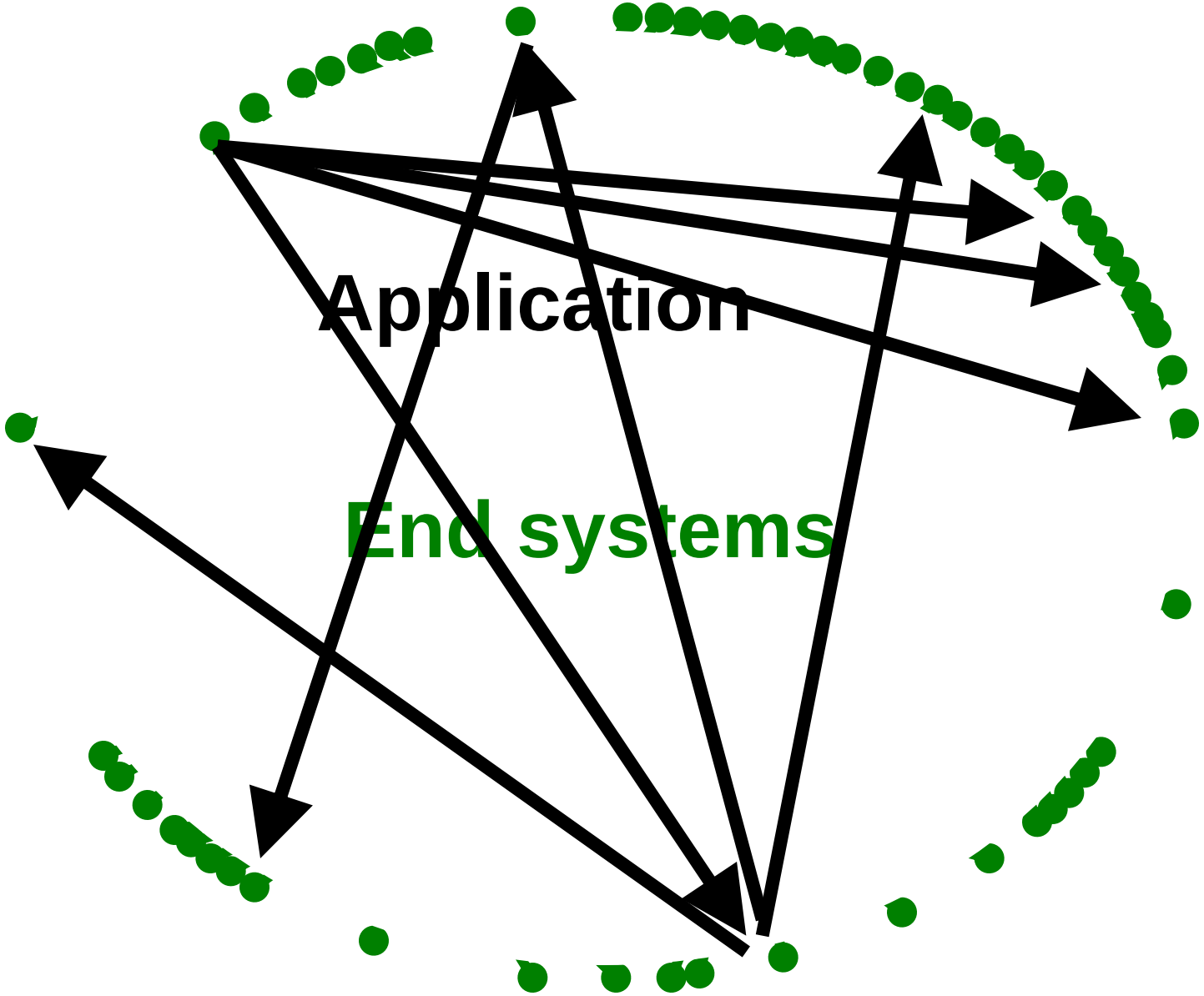
Control:

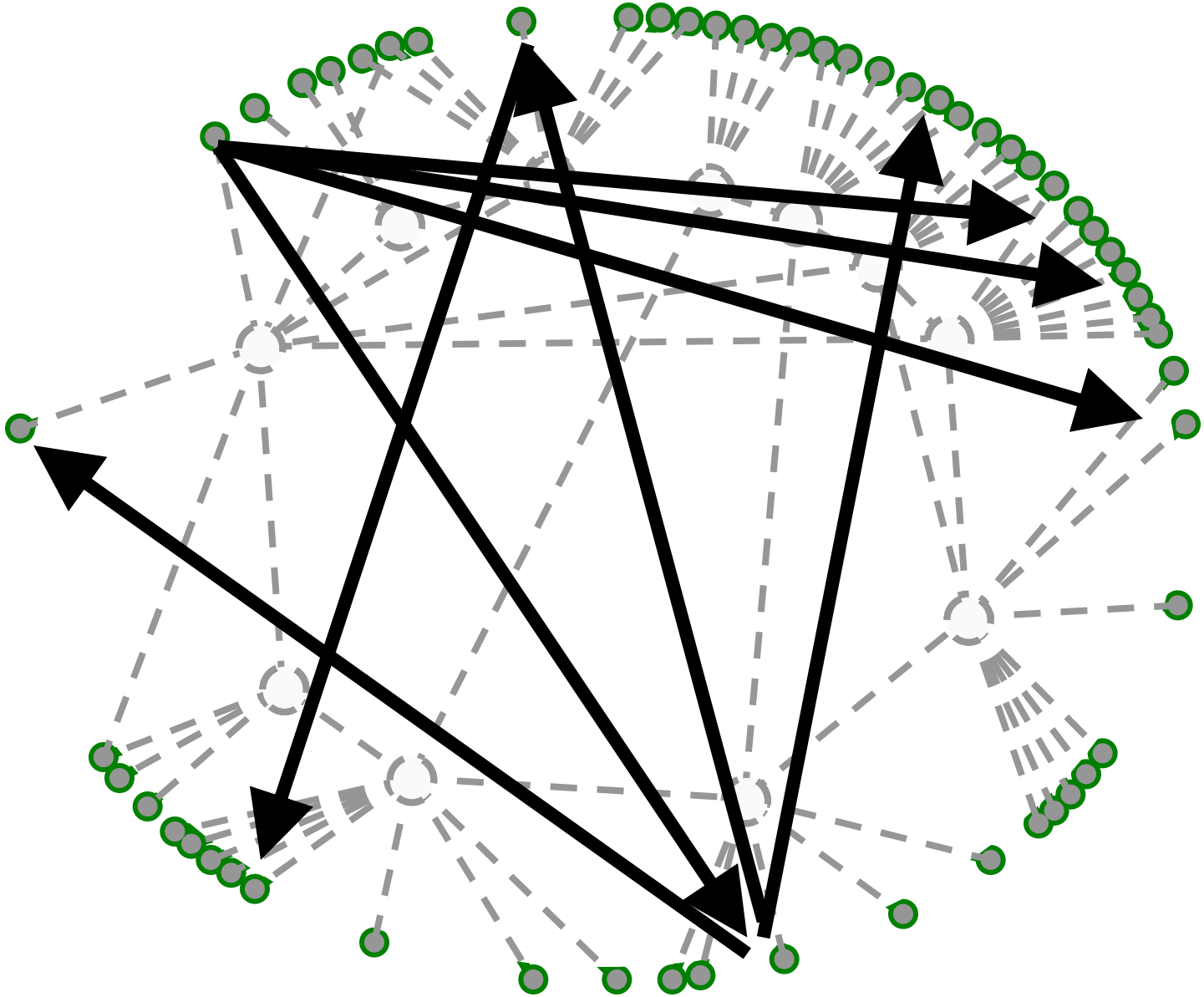
- **Congestion (window)**
- **Loss (retransmission)**

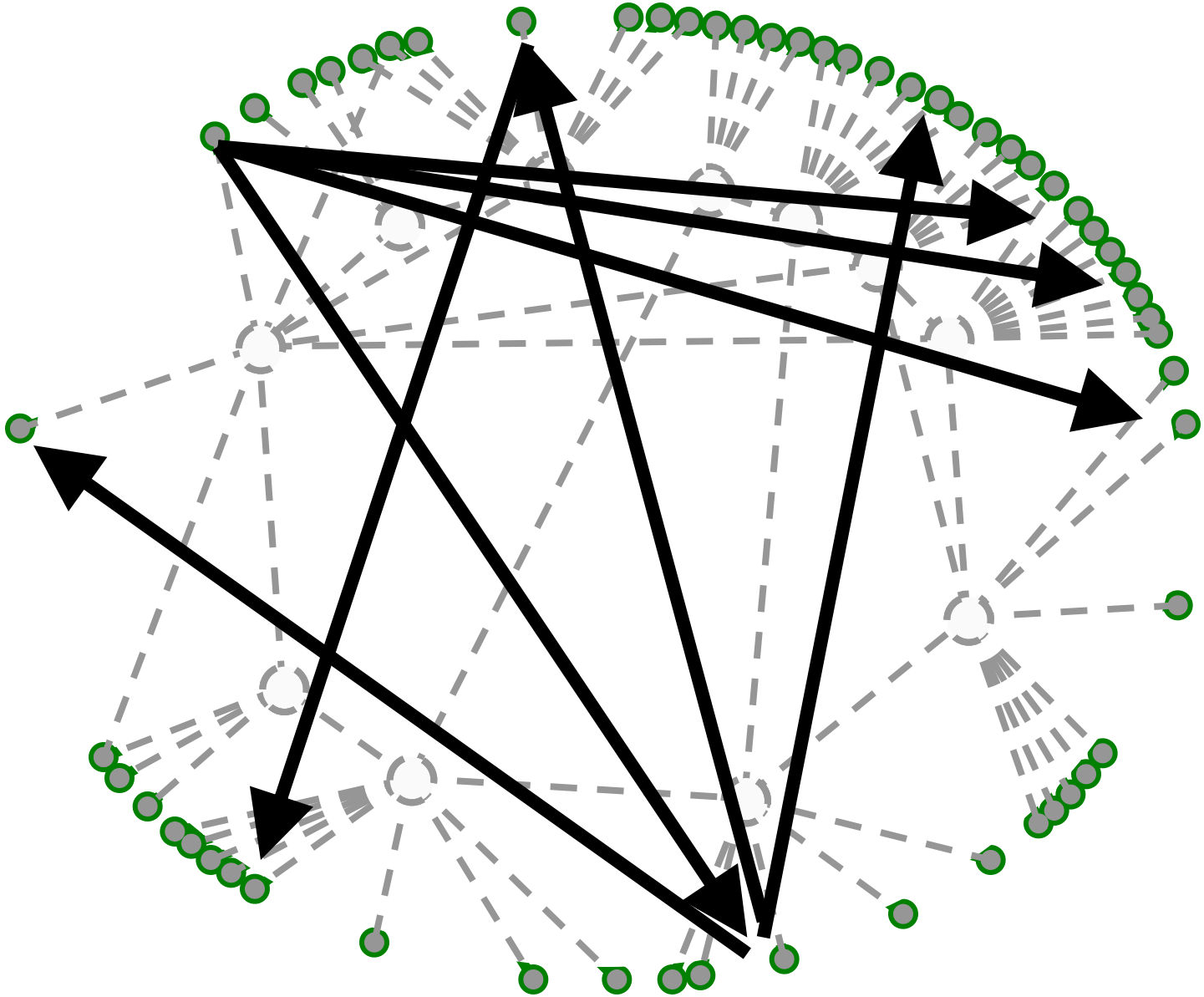


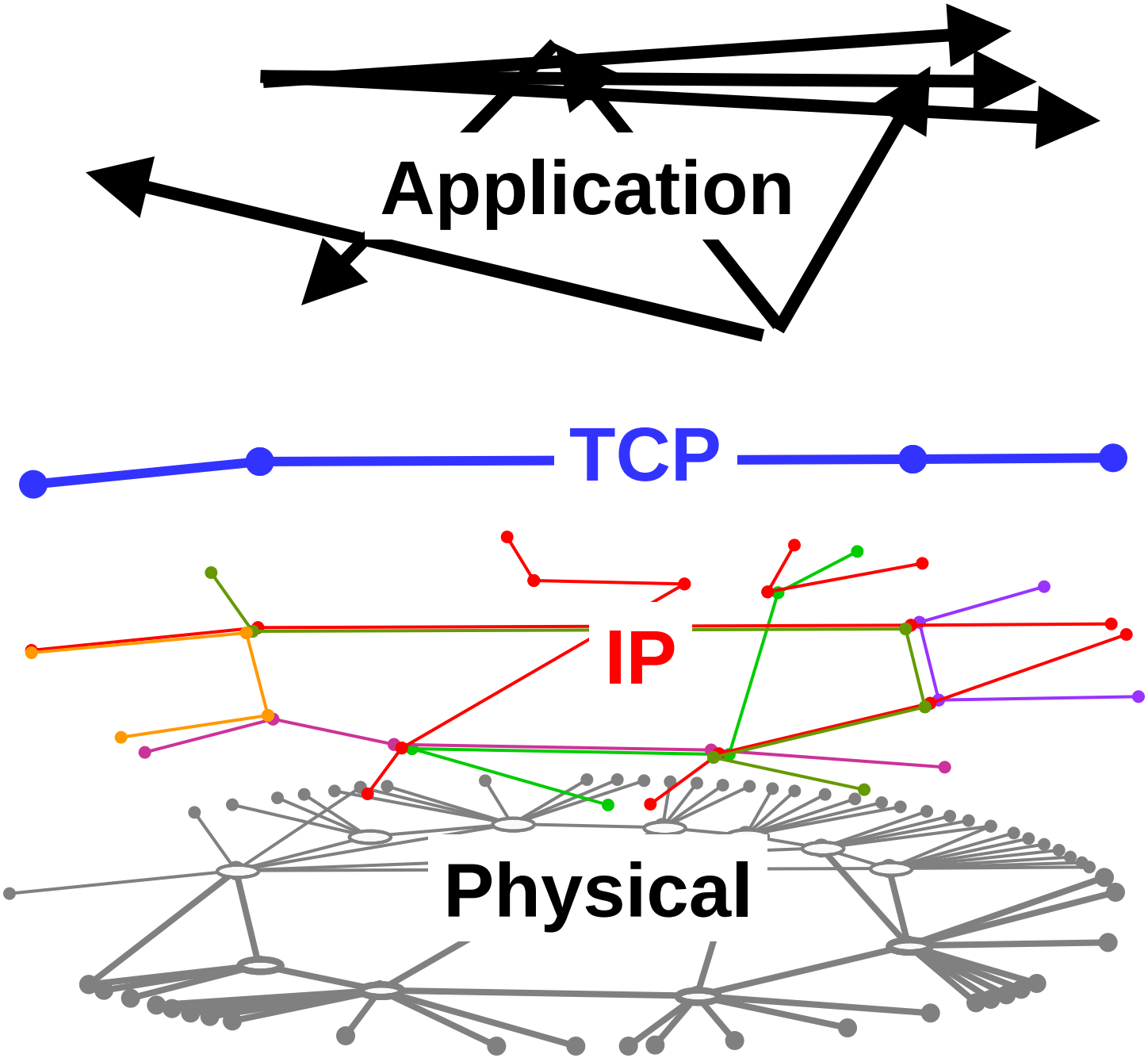

Application
TCP
IP
Physical


Application
End systems


Application
End systems

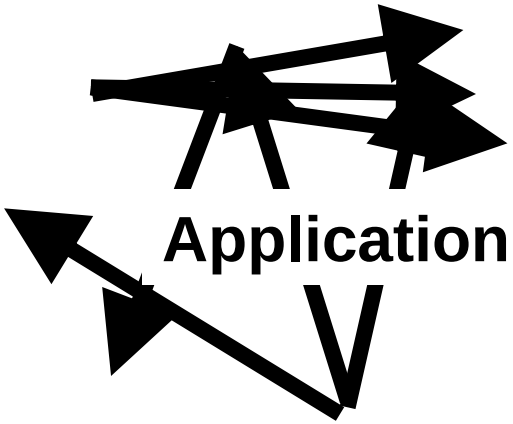


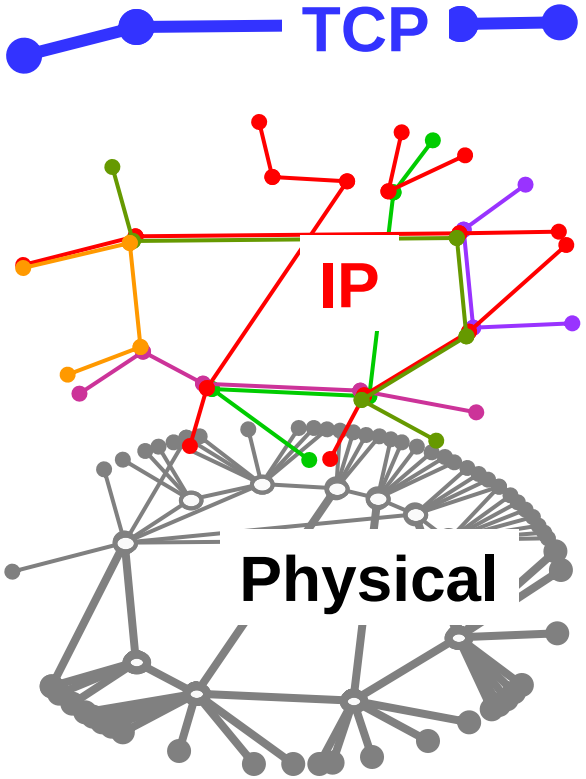


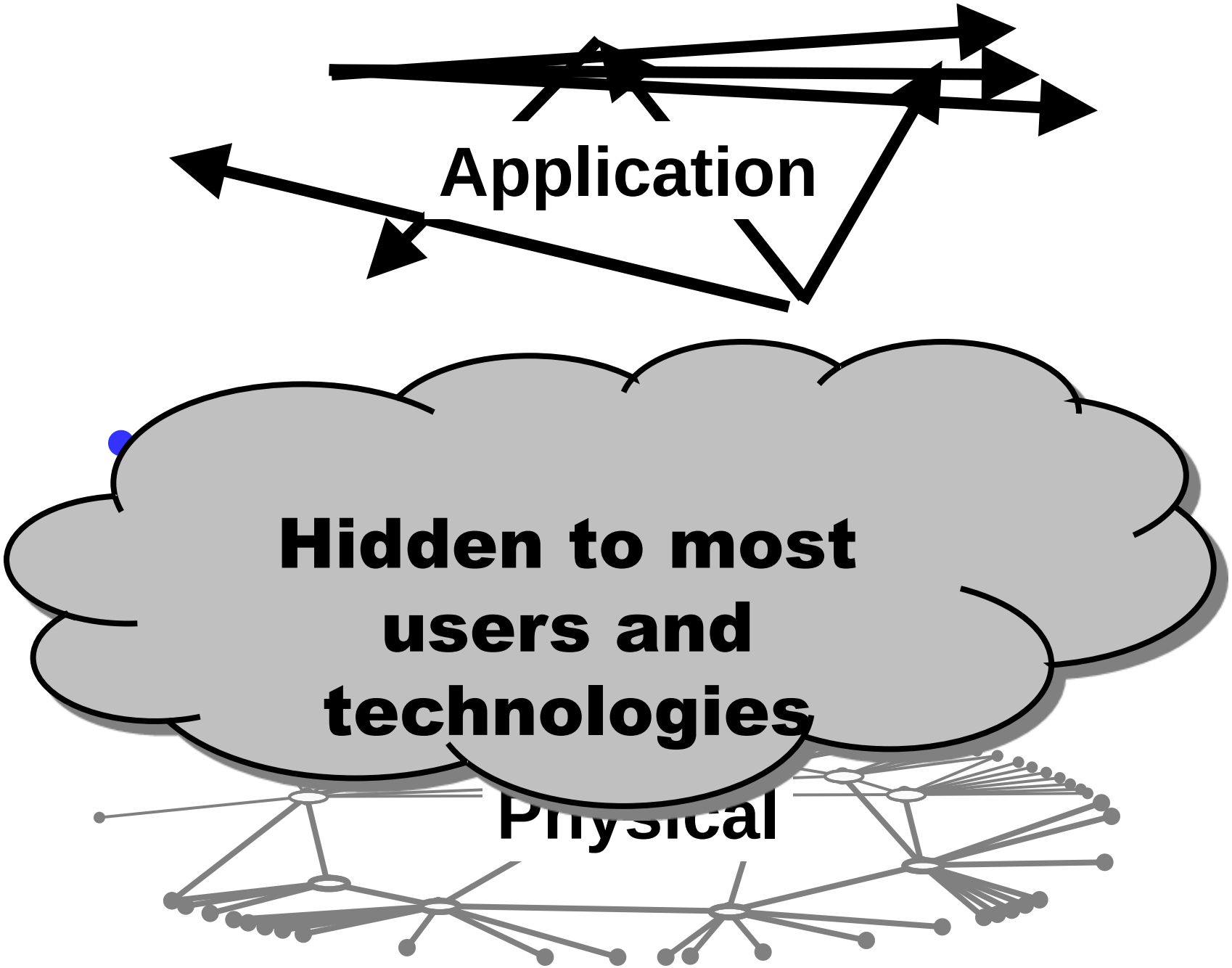

Application
TCP
IP
Physical

What is the graph of the Internet?

Wrong question.






Application
Hidden to most users and technologies
Physical

Application

Diverse

Physical

Diverse

One of
the most-read
papers ever on
the Internet!

PERSPECTIVE

Scale-Free Networks: A Decade and Beyond

Albert-László Barabási

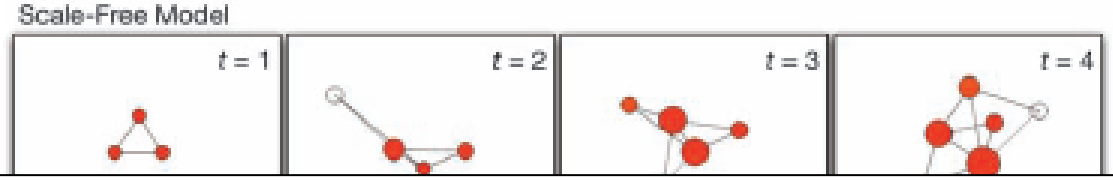
For decades, we tacitly assumed that the components of such complex systems as the cell, the society, or the Internet are randomly wired together. In the past decade, an avalanche of research has shown that many real networks, independent of their age, function, and scope, converge to similar architectures, a universality that allowed researchers from different disciplines to embrace network theory as a common paradigm. The decade-old discovery of scale-free networks was one of those events that had helped catalyze the emergence of network science, a new research field with its distinct set of challenges and accomplishments.

Nature, society, and many technologies are sustained by numerous networks that are not only too important to fail but paradoxically for decades have also proved too complicated to understand. Simple models, like the one introduced in 1959 by mathematicians Pál Erdős and Alfréd Rényi (*1*), drove much of our thinking about interconnected systems. They assumed that complex systems are wired randomly together, a hypothesis that was adopted by sociology, biology, and computer science. It had considerable predictive power, explaining for example why everybody is only six handshakes from anybody else (*2*–*5*), a phenomenon observed as early as 1929 (*2*) but which resonated

suspected that the scale-free property (*6*) might not be unique to the WWW. The main purpose of the 1999 *Science* paper was to report this unexpected similarity between networks of quite different nature and to show that two mechanisms, growth and preferential attachment, are the underlying causes (Fig. 1).

When we concluded in 1999 that we "expect that the scale invariant state [...] is a generic property of many complex networks" (*7*), it was more of a prediction than a fact, because nature could have chosen as many different architectures as there are networks. Yet, probably the most surprising discovery of modern network theory is the universality of the network topology: Many real networks, from the cell to the Internet, independent of their age, function, and scope, converge to similar architectures. It is this universality that allowed researchers from different disciplines to embrace network theory as a common paradigm.

Today, the scale-free nature of networks of key scientific interest, from protein interactions to social networks and from the network of interlinked documents that make up the WWW to the interconnected hardware behind the Internet, has been established beyond doubt. The evidence comes not only from better maps and data sets but also from the agreement between empirical data and analytical models that predict the network structure (*10*, *11*). Yet, the early euphoria was not without negative side effects, prompting some researchers to label many systems scale-free, even when the evidence was scarce at best. However, the net result was to force us to better understand the factors that shape network structure. For ex-



- For decades, we tacitly assumed that the components of such complex systems as the cell, the society, or the Internet are **randomly wired** together.
- In the past decade, an avalanche of research has shown that many real networks, independent of their age, function, and scope, converge to similar **architectures**,
- a **universality** that allowed researchers from different disciplines to embrace network theory as a common paradigm.
- The decade-old discovery of scale-free networks was one of those events that had helped catalyze the **emergence of network science**, a new research field with its distinct set of challenges and accomplishments.

24 JULY 2009 VOL 325 SCIENCE www.sciencemag.org

Fantasy

rare
organized

Reality

"order
for free"

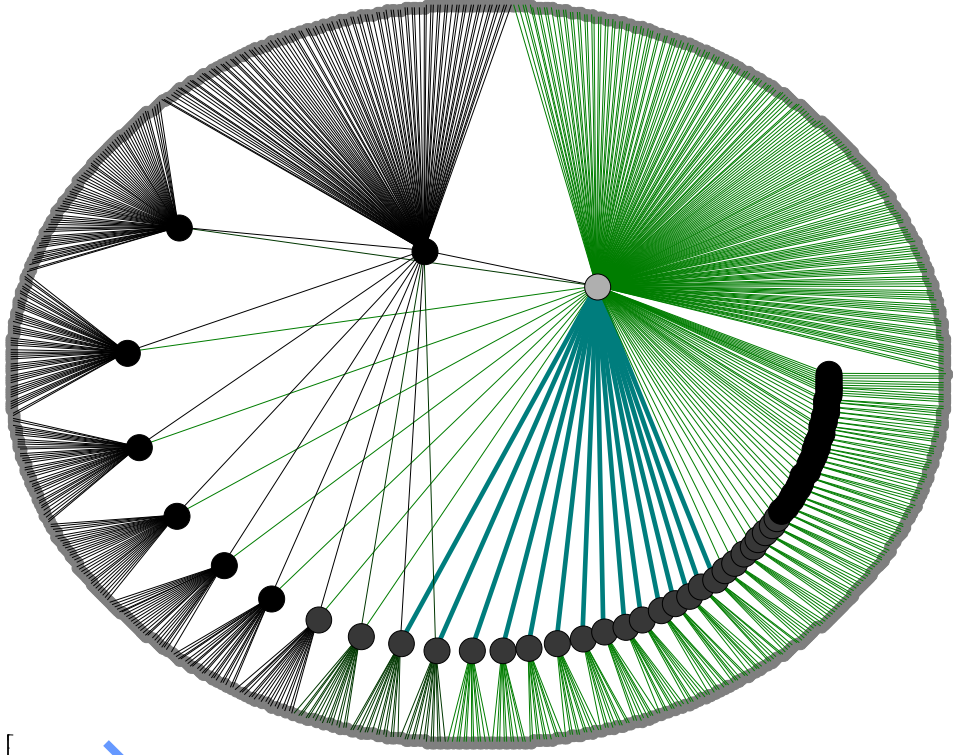
Fantasy

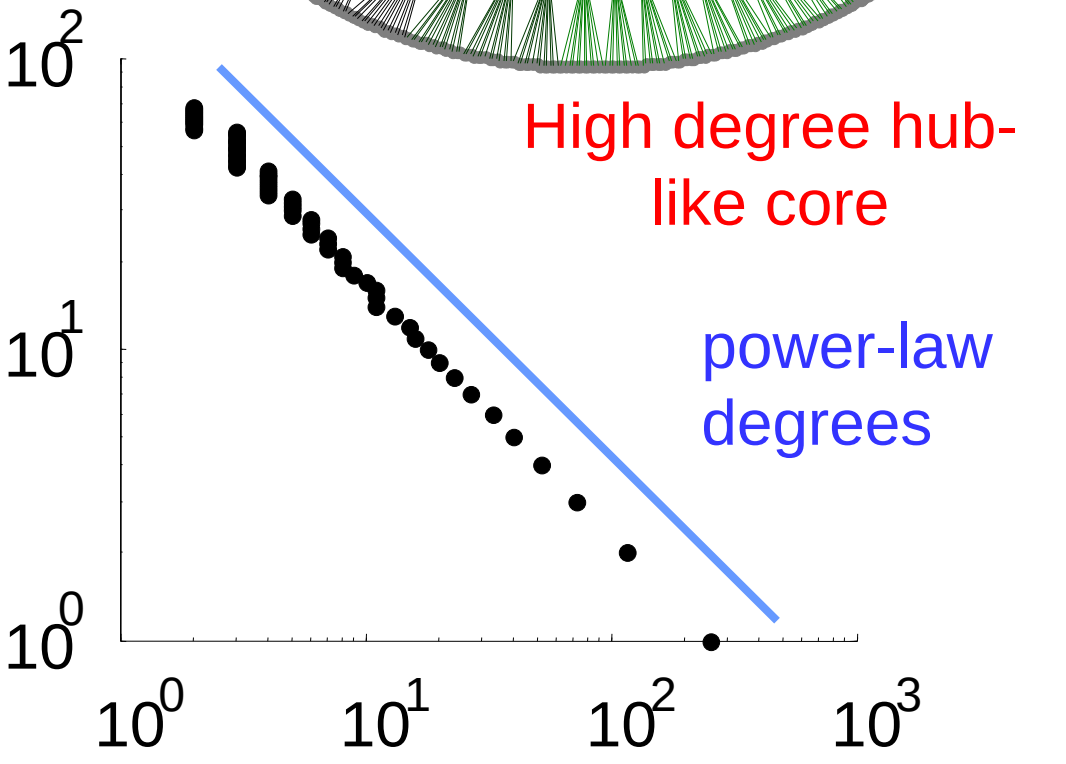
likely
random

robust
efficient

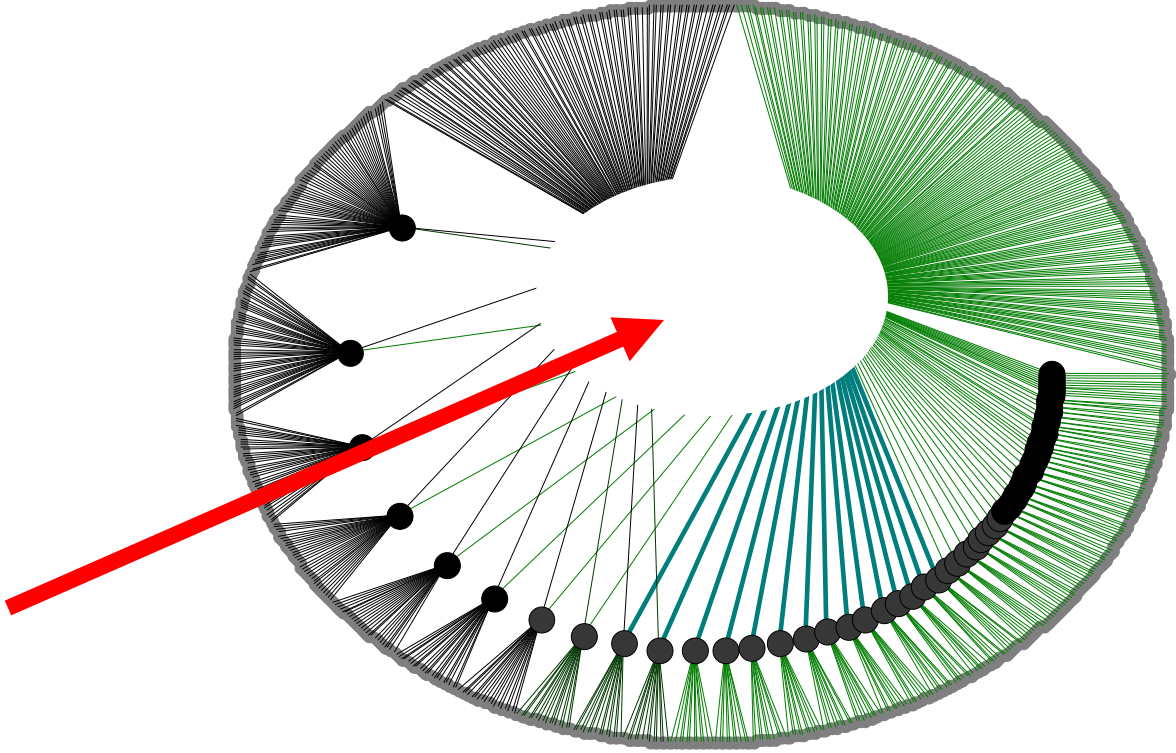
fragile
wasteful

“Scale-free” networks and the “Achilles’ heel” of the Internet





High degree
hub-like core



Delete these “hubs” and the network disconnects!

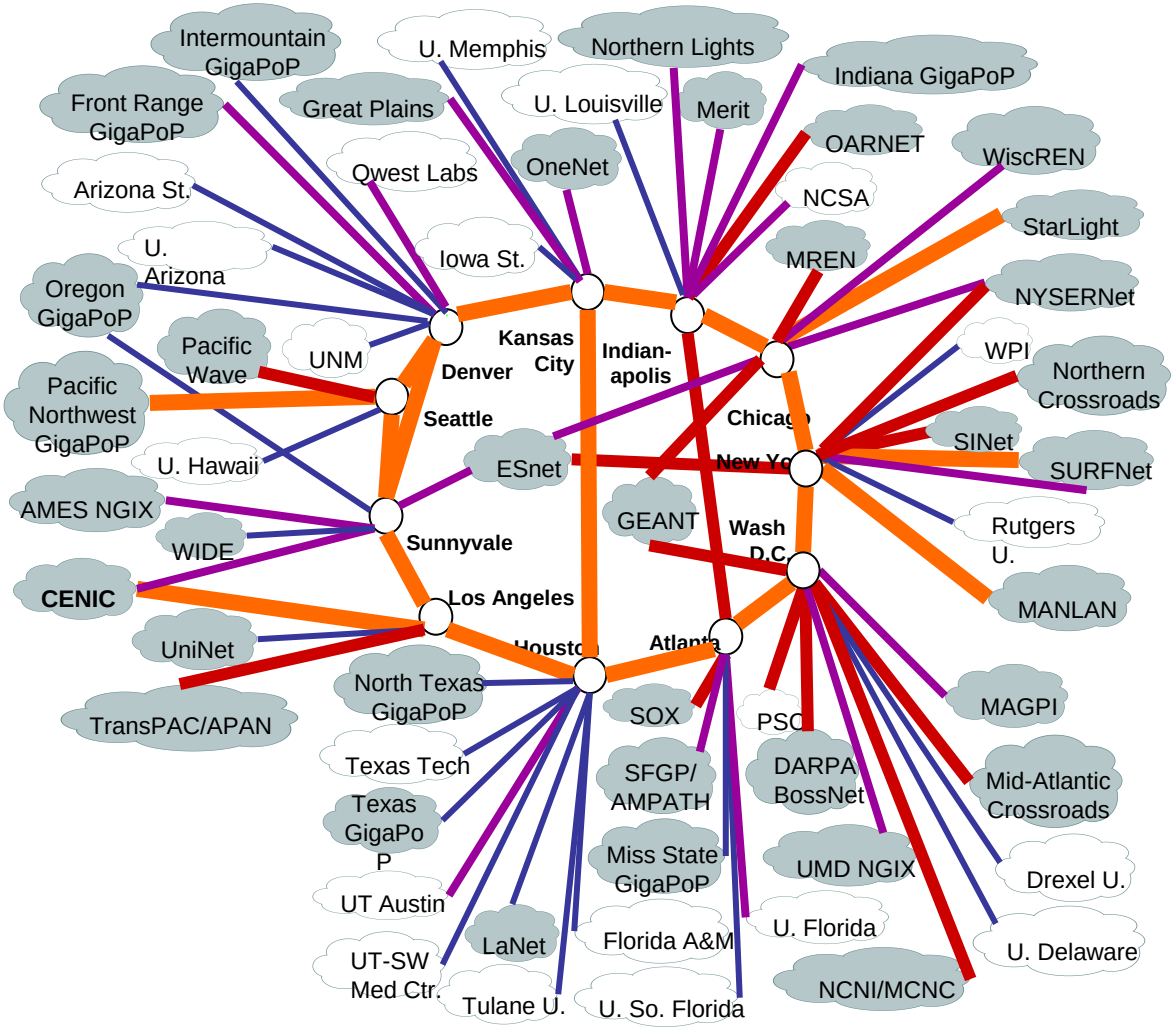
Delete “non-hubs” with little effect!

Robust yet fragile!?!?!?

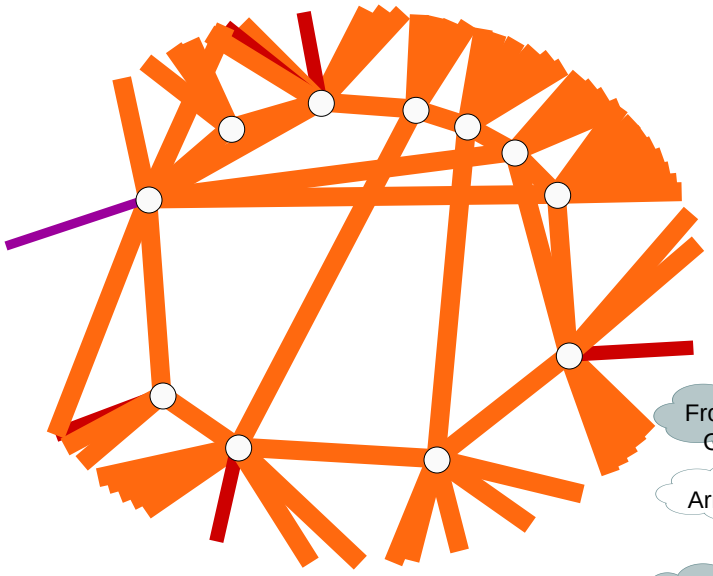
The real Internet?

(circa 2002)

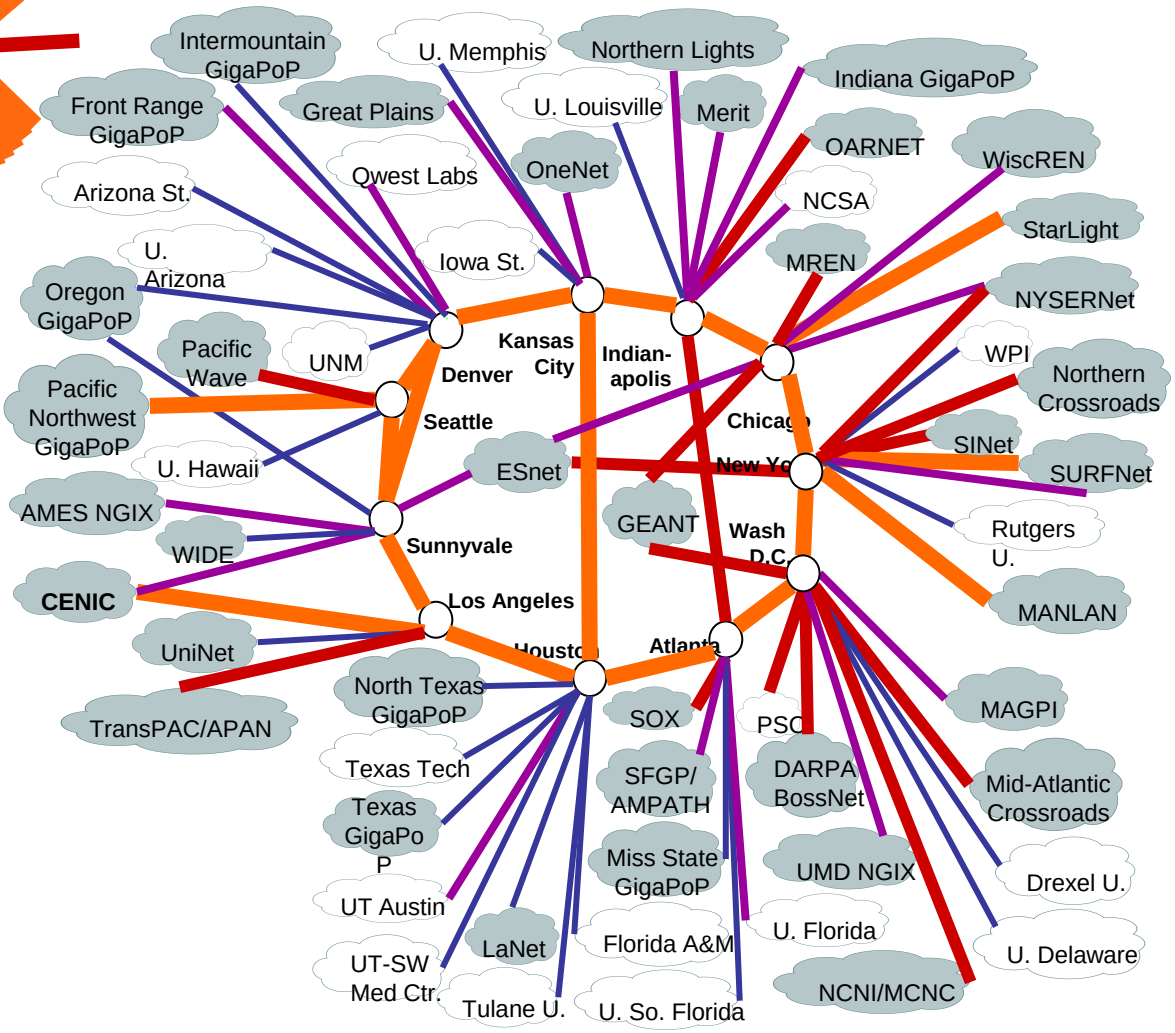
Internet router-level topology



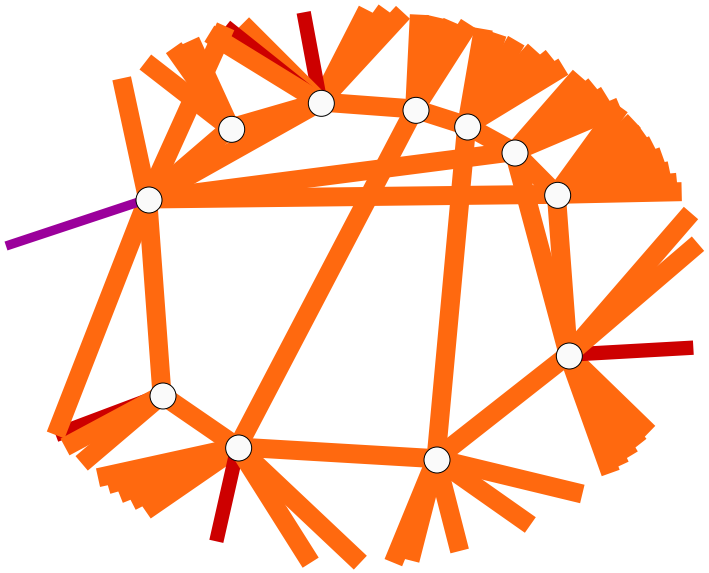
Abilene Backbone Physical Connectivity



Internet router-level topology

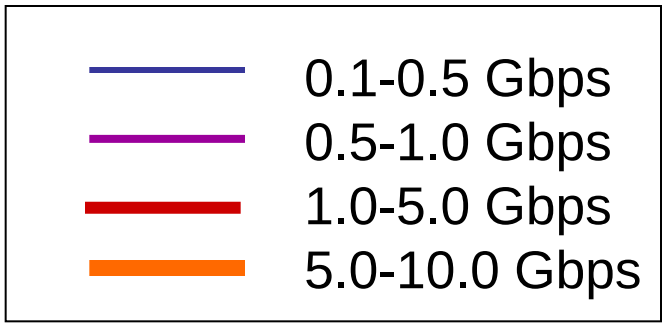


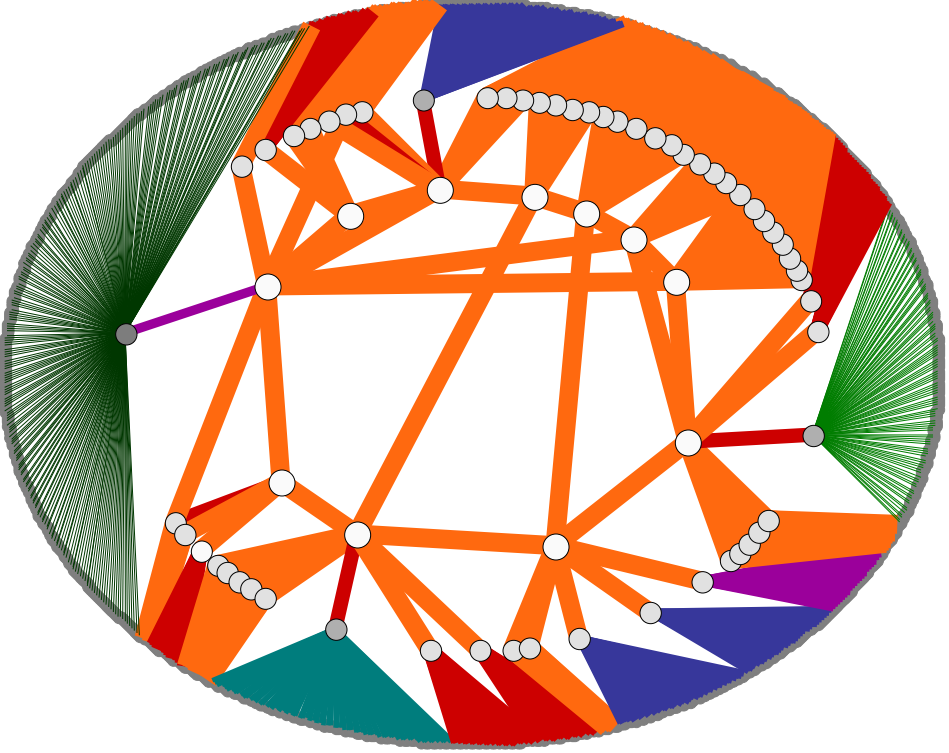
0.1-0.5 Gbps
0.5-1.0 Gbps
1.0-5.0 Gbps
5.0-10.0 Gbps



Start with Internet2 backbone

Internet router-level topology





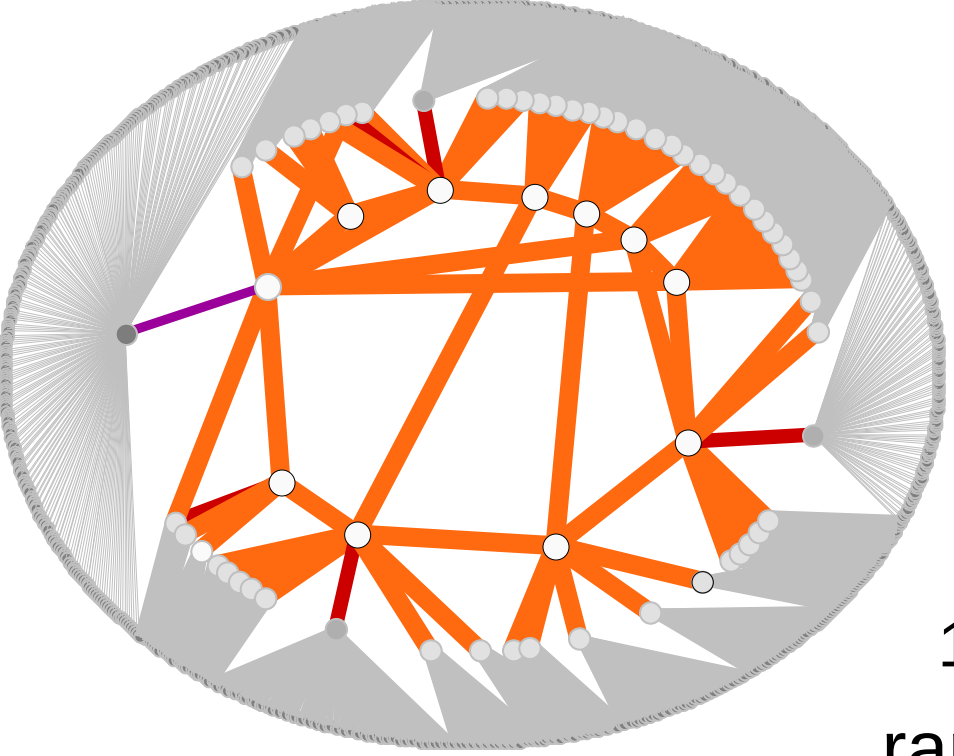
Add gateway routers
and end users

Consistent with
technological
constraints on
routers and users

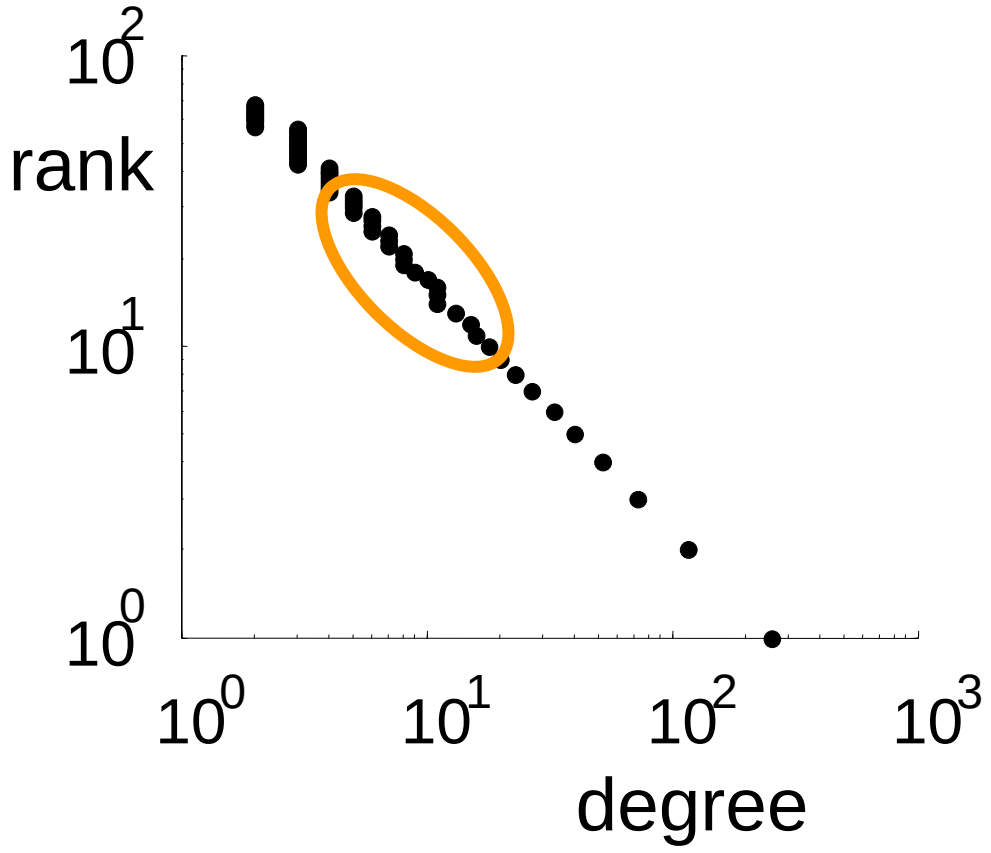
High throughput,
efficiency, economy

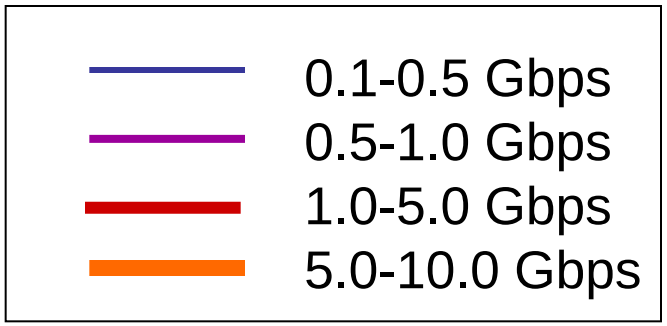
0.1-0.5 Gbps
0.5-1.0 Gbps
1.0-5.0 Gbps
5.0-10.0 Gbps

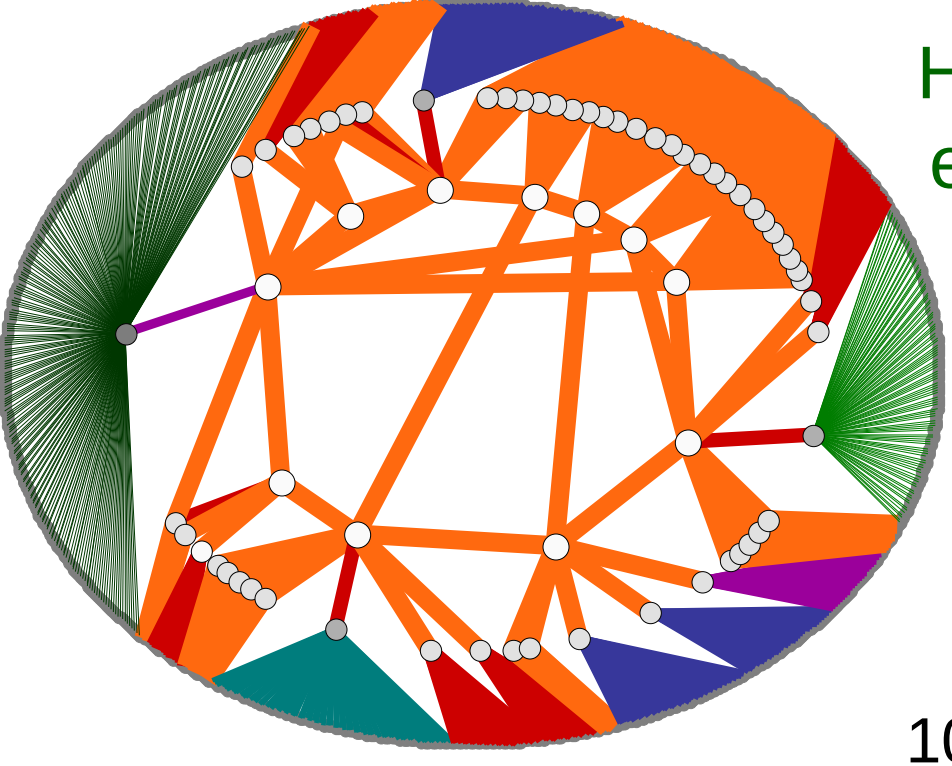
“HOT model”



Low degree
mesh-like core

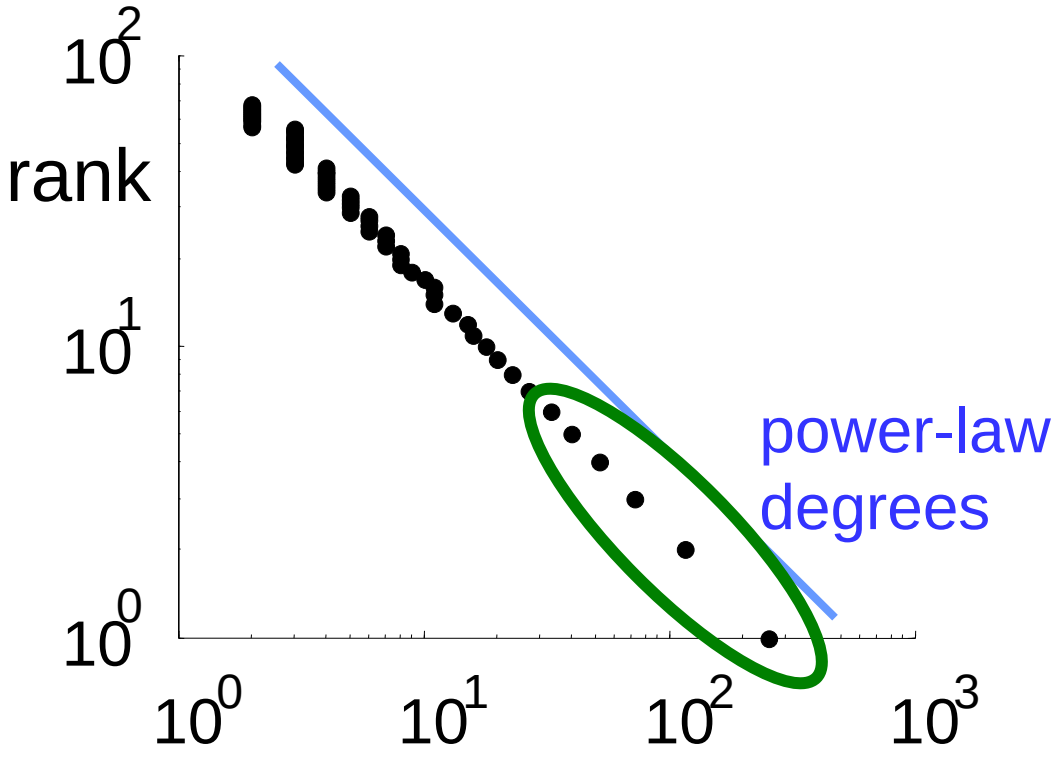


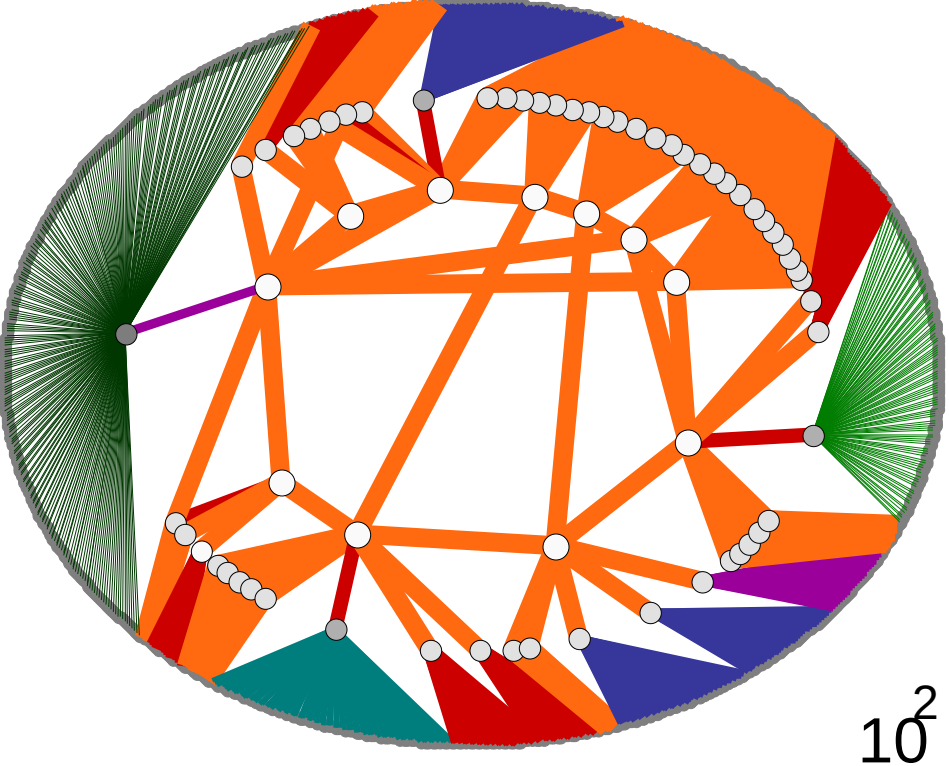




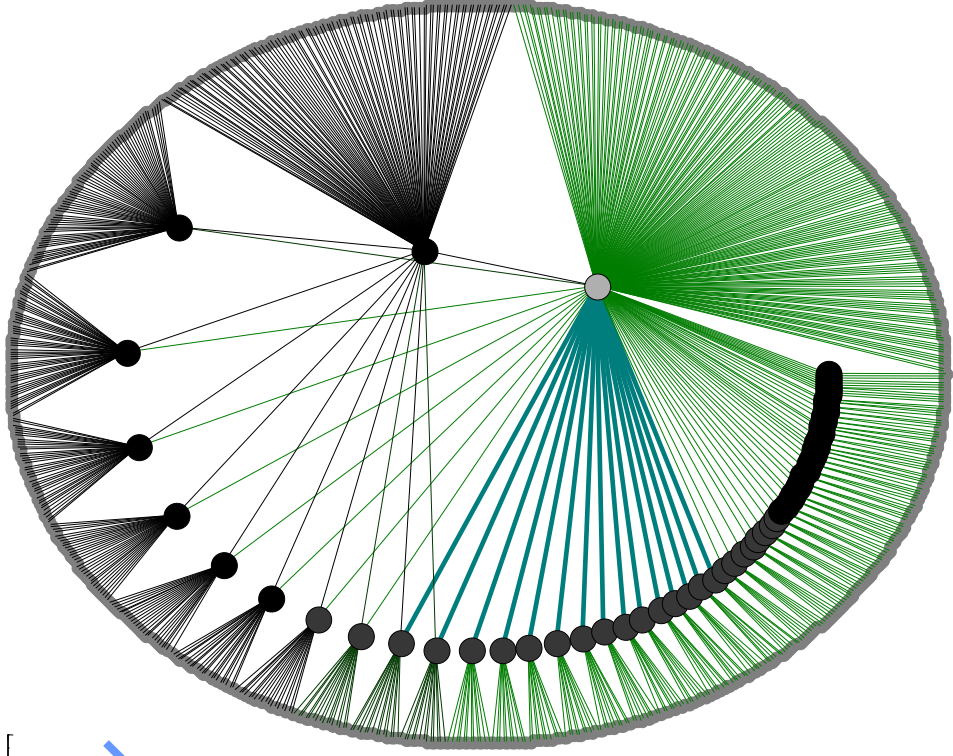
High variability
edge systems

Low degree
mesh-like core

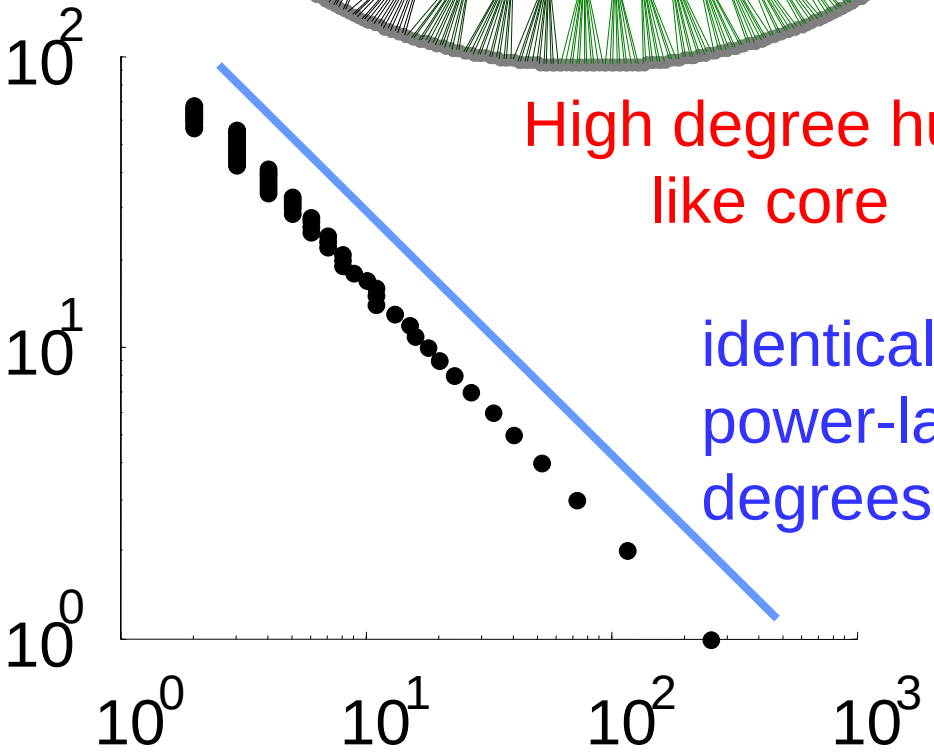




Low degree
mesh-like core

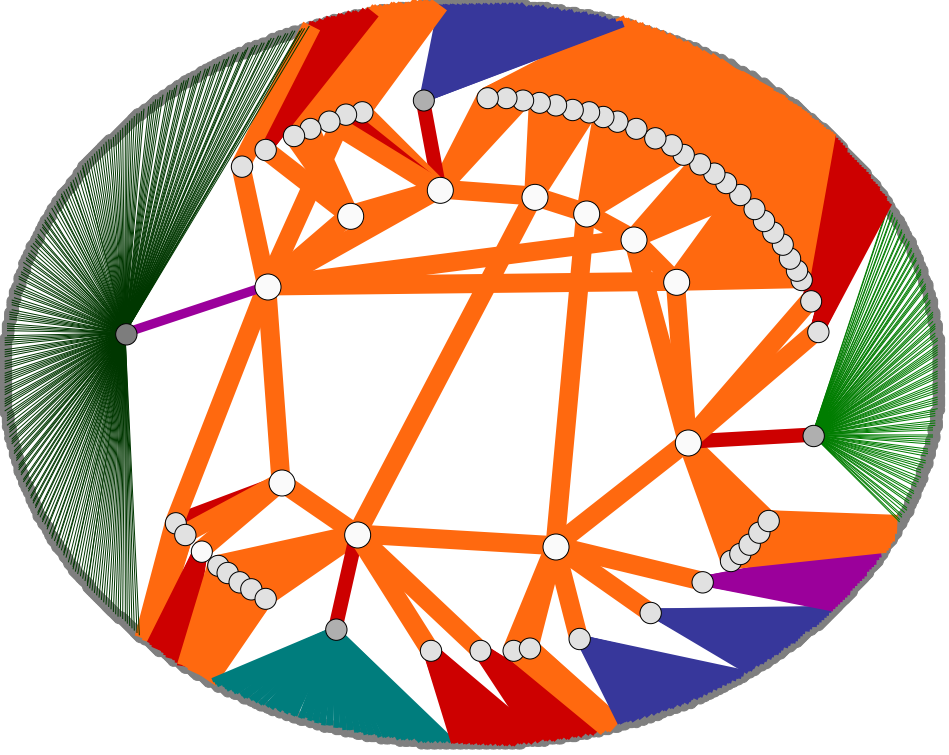


High degree hub-like core

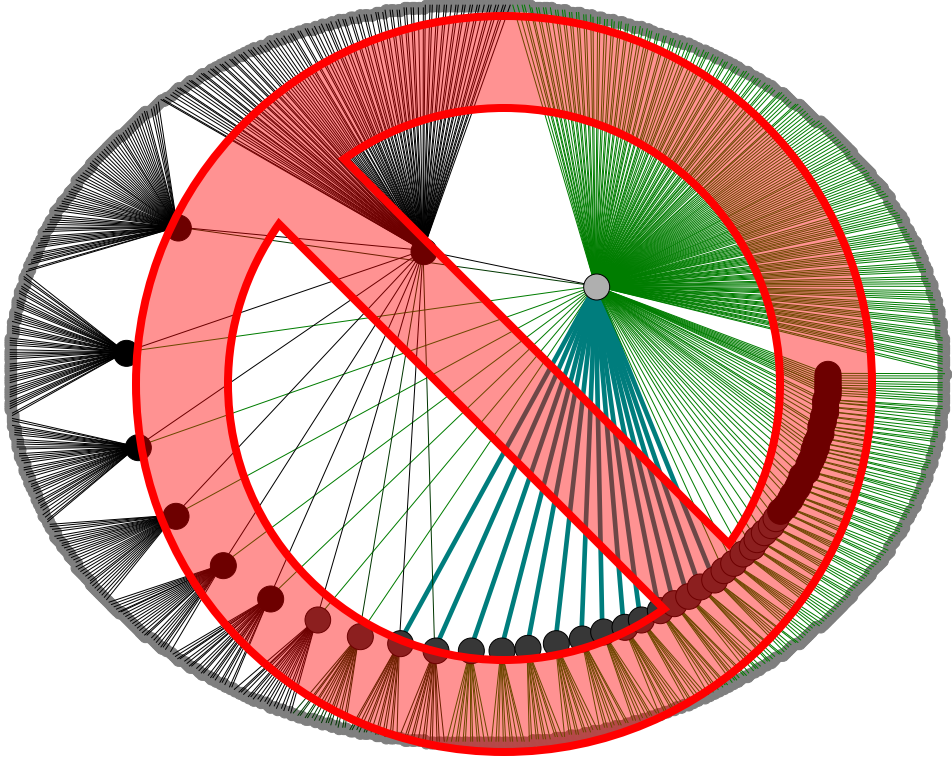


identical power-law degrees

Completely different networks can have the same node degrees.



- Low degree core
- High performance and robustness
- Efficient, economic

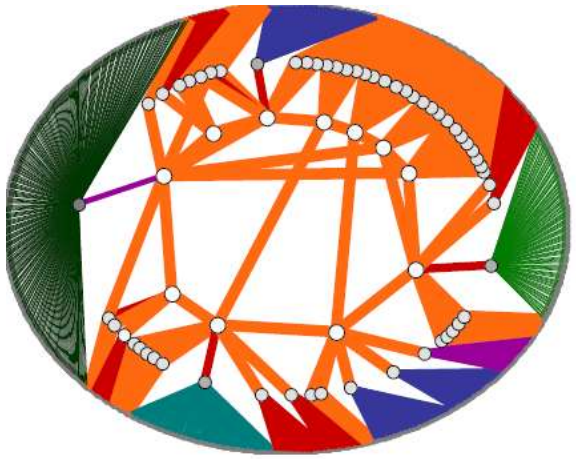


- High degree “hubs”
- Poor performance and robustness
- Wasteful, expensive

Nothing like the real Internet.

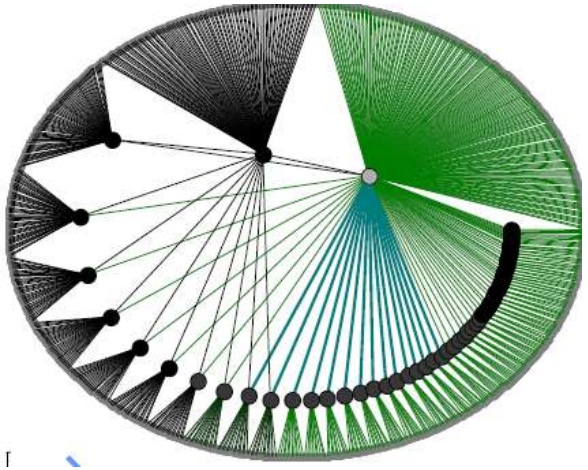
See PNAS, Sigcomm, TransNet papers for details.

rare
organized



robust
efficient

likely
random

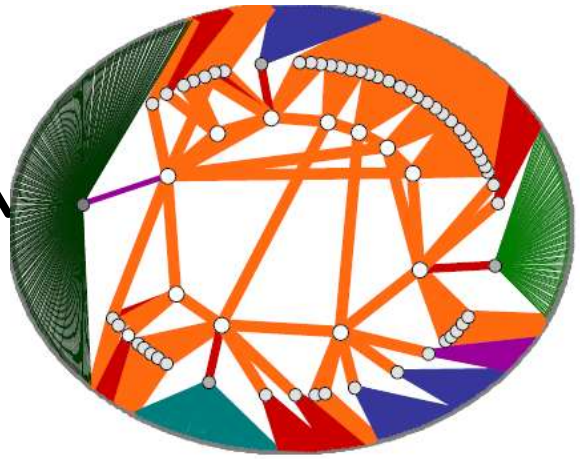


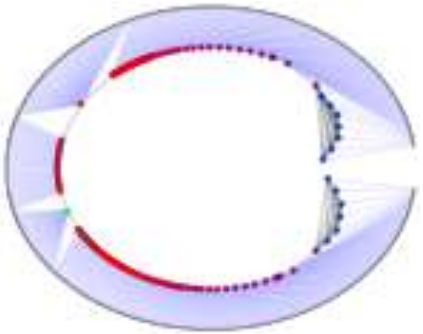
fragile
wasteful

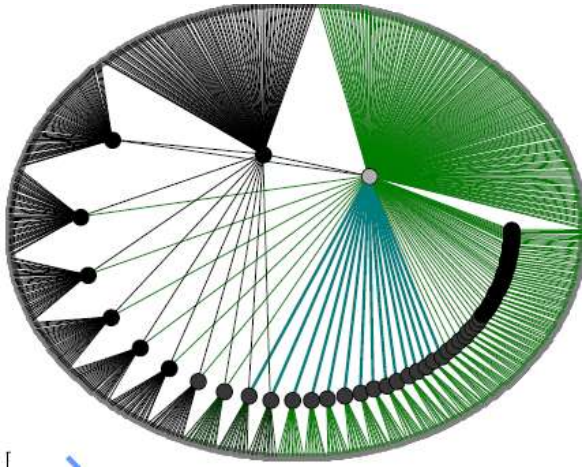
Two separate worlds, can we view them together?

rare
organized

likely
random



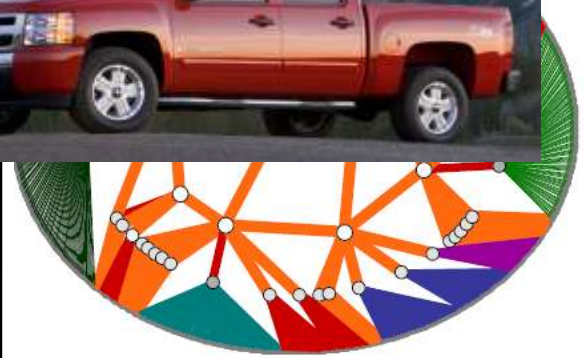




robust
efficient

fragile
wasteful

rare
organized



likely
random

“order
for free”

robust
efficient

fragile
wasteful

Fantasy

rare
organized

Reality

"order
for free"

likely
random

Fantasy

robust
efficient

fragile
wasteful

- “new sciences”
- statistical physics

“order for free”

Fantasy

likely
random

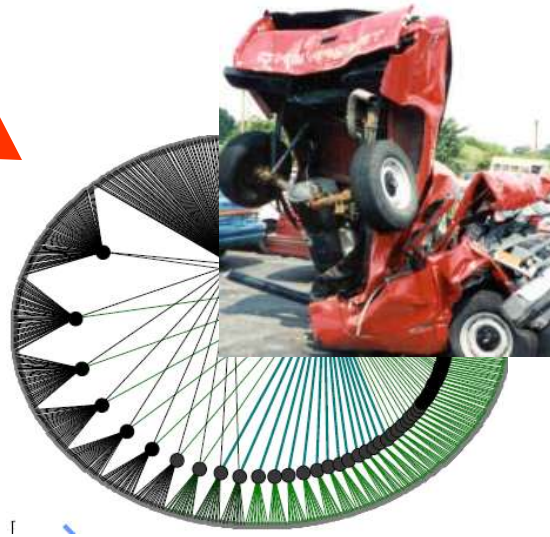
robust
efficient

fragile
wasteful

- “new sciences”
- statistical physics

randomize

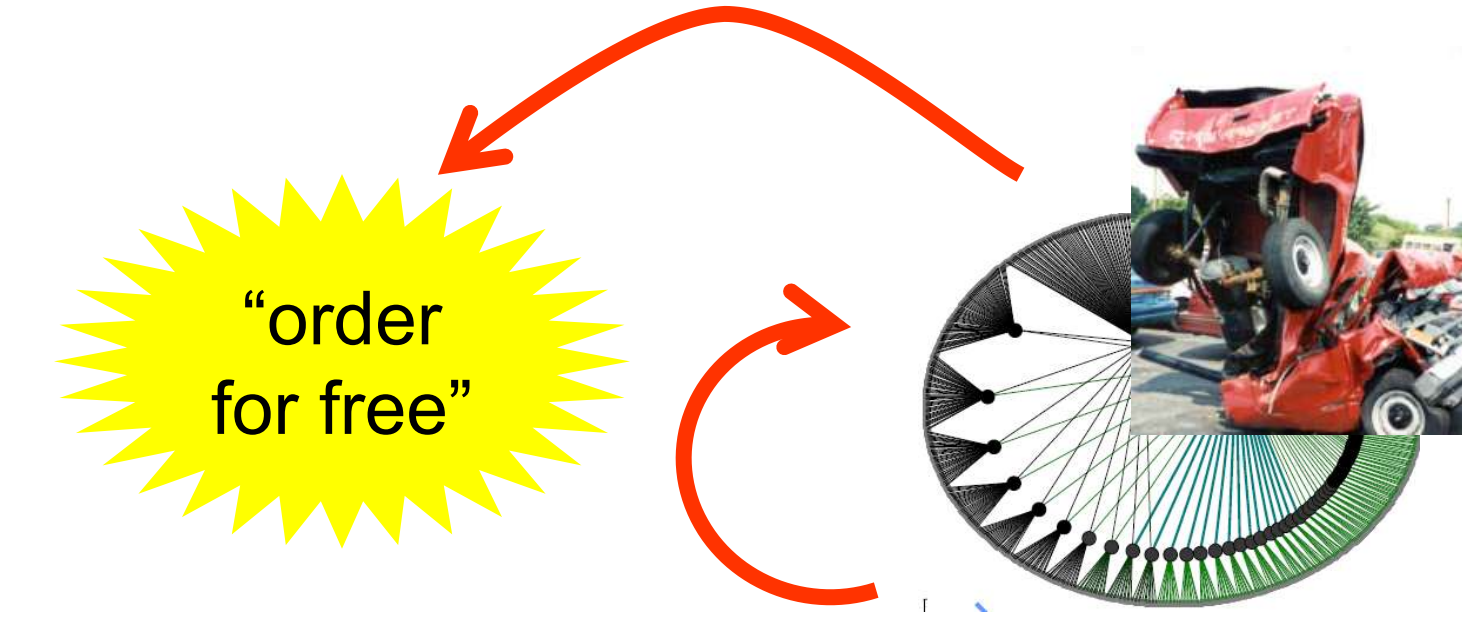
likely
random



fragile
wasteful

- universality
- phase transition
- edge of chaos
- self-organized criticality
- scale-free networks

order parameter



Fantasy?

rare
organized

Reality

"order
for free"

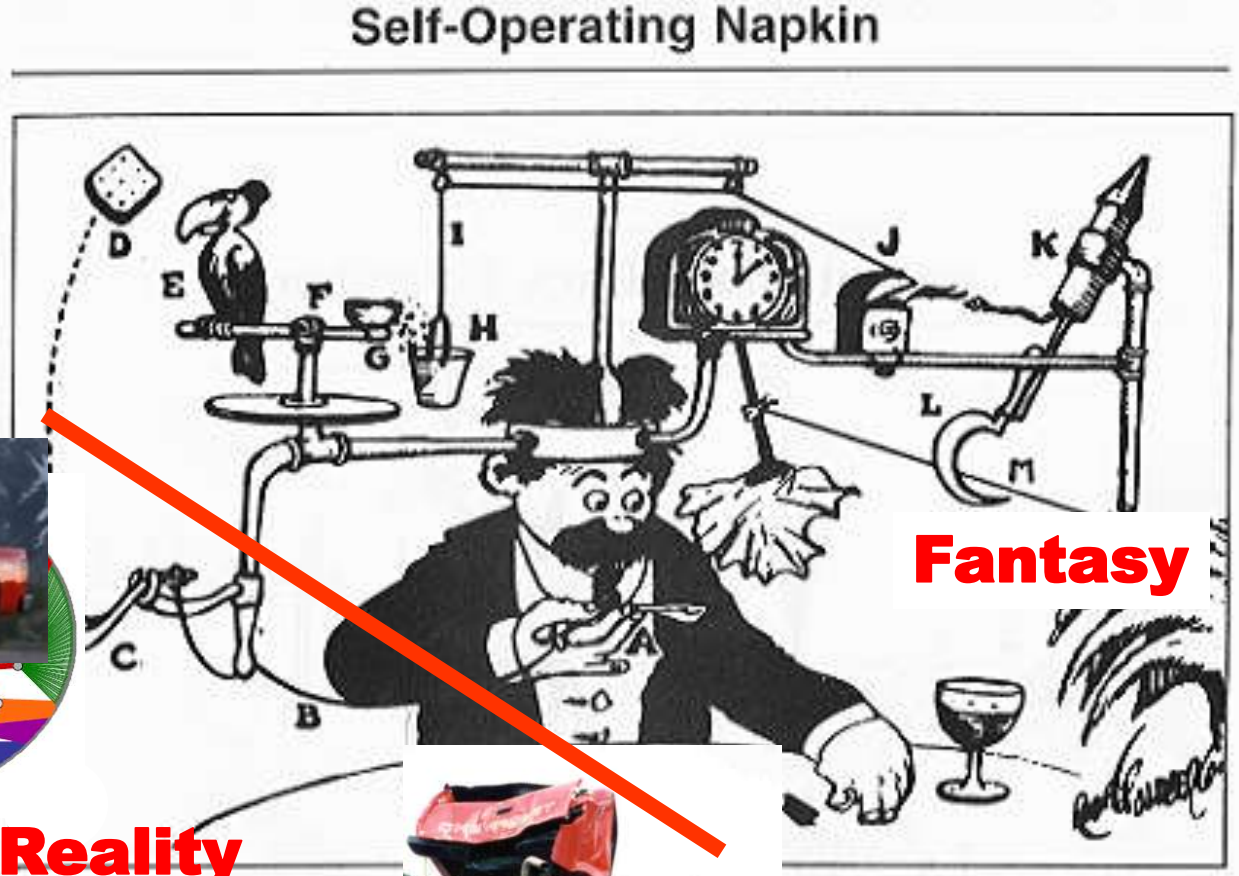
likely
random

Fantasy

robust
efficient

fragile
wasteful

Rube Goldberg



rare
organized

likely
random

robust
efficient

fragile
wasteful

Fantasy

Reality

Fantasy

"order
for free"

Fantasy

rare
organized

Reality

"order
for free"

Fantasy

likely
random

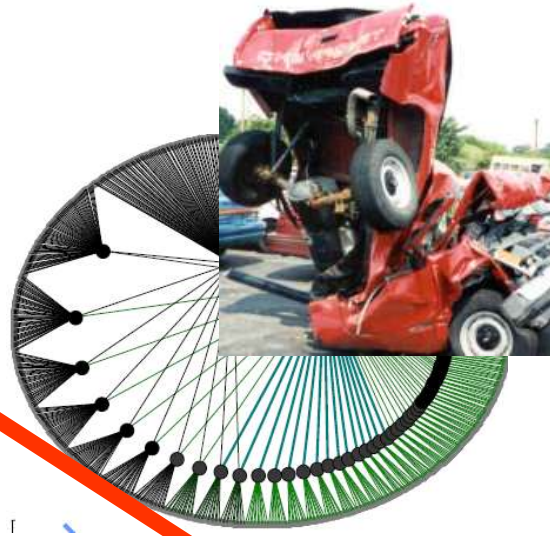
robust
efficient

fragile
wasteful

This is a fake tradeoff

rare
organized

likely
random



robust
efficient

fragile
wasteful

Much
"network science"
and
"complex systems"
literature
is equally
specious

Similar errors in “high impact” journals

Nature

- Human physiological variability
- Protein-Protein Interaction (PPI) networks
- Metabolic networks

Science

- Forest fires
- Power grid
- WWW “graph”

Physical Review Letters

- Almost any paper with power laws

Persistent source of errors and confusion

Pushing Networks to the Limit

PERSPECTIVE

Scale-Free Networks: A Decade and Beyond

Today, the scale-free nature of networks of key scientific interest, from protein interactions to social networks and from the network of interlinked documents that make up the WWW to the interconnected hardware behind the Internet, has been established beyond doubt.

property of many complex networks" (*7*), it was more of a prediction than a fact, because nature could have chosen as many different architectures as there are networks. Yet, probably the most surprising discovery of modern network theory is the universality of the network topology: Many real networks, from the cell to the Internet, independent of their age, function, and scope, converge to similar architectures. It is this uni- lity that allowed researchers from different nes to embrace network theory as a com-

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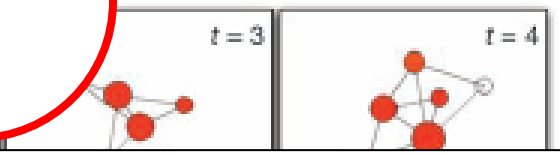


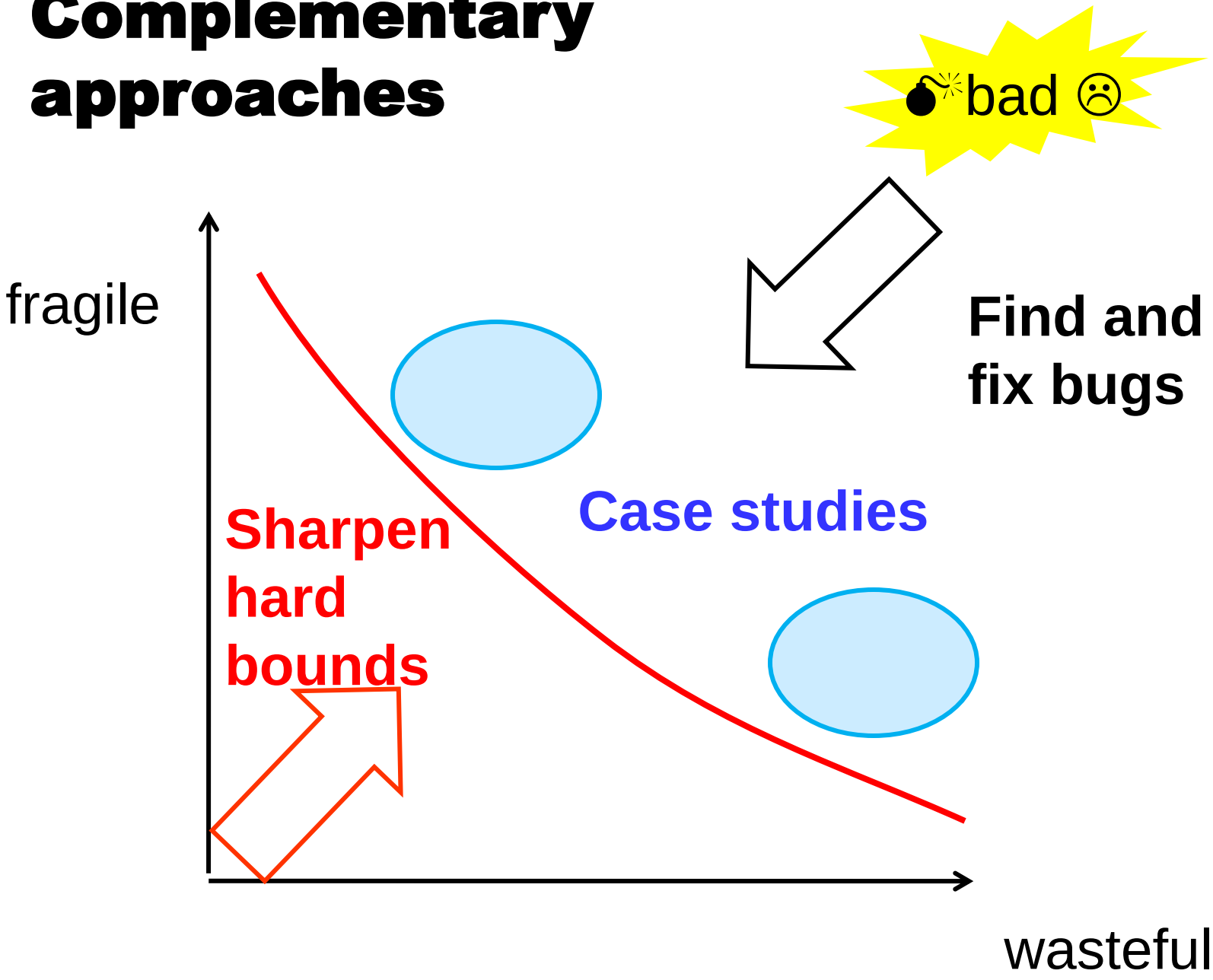
Power laws: main reading

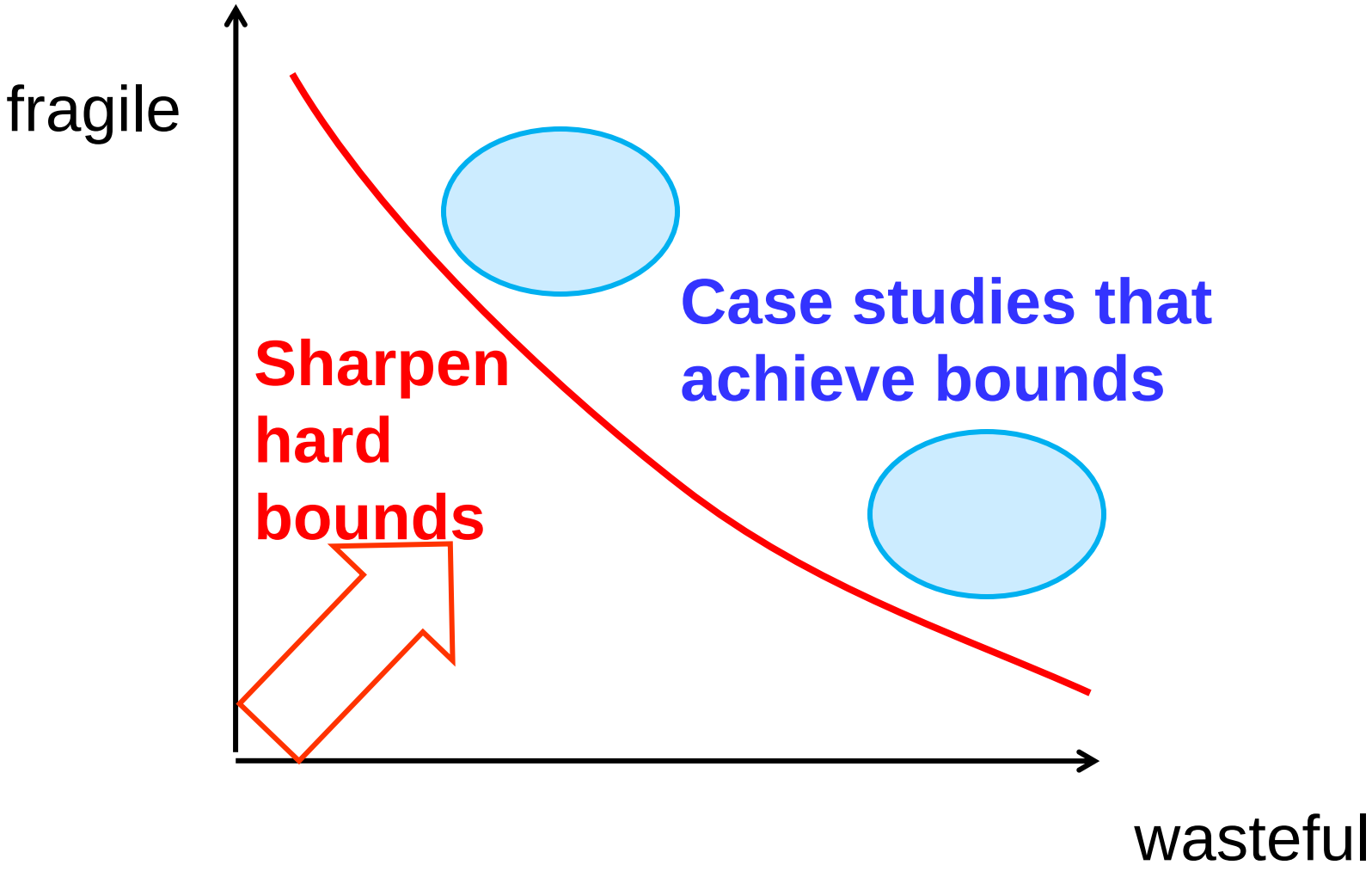
1. Carlson JM, Doyle J, Complexity and robustness, *PNAS*, USA 99: 2538-2545 Suppl. 1 FEB 19 2002
2. Willinger, W, D. Alderson, J.C. Doyle, and L.Li., 2004. More ``Normal'' Than Normal: Scaling Distributions and Complex Systems. Proceedings of the 2004 Winter Simulation Conference.
3. R. Tanaka, T-M Yi, and J. Doyle (2005) Some protein interaction data do not exhibit power law statistics, FEBS letters, 579 (23): 5140-5144 SEP 26 2005
4. Doyle et al, (2005), The "Robust Yet Fragile" Nature of the Internet, *PNAS* 102 (41), October 11, 2005
5. R. Tanaka, M. Csete and J. Doyle, Highly optimised global organisation of metabolic networks, IEE Proc.-Syst. Biol., Vol. 152, No. 4, December 2005
6. MA Moritz, ME Morais, LA Summerell, JM Carlson, J Doyle (2005) Wildfires, complexity, and highly optimized tolerance, *PNAS*, 102 (50) December 13, 2005;
7. L Li, D Alderson, JC Doyle, W Willinger (2006) Towards a Theory of Scale-Free Graphs: Definition, Properties, and Implications, *Internet Math*, Vol. 2, No. 4, 2006

Additional reading

1. http://www.physics.ucsb.edu/~complex/
2. http://linkage.rockefeller.edu/wli/zipf/index_ru.html
3. M. Mitzenmacher, A Brief History of Generative Models for Power Law and Lognormal Distributions, *Internet Mathematics*, vol 1, No. 2, pp. 226-251, 2004.
4. Csete M.E. and J.C. Doyle, (2004), Bow ties, metabolism, and disease, Trends in Biotechnology, Vol 22, Issue 9, pg. 446-450
5. Manning M, Carlson JM, Doyle J (2005) Highly optimized tolerance and power laws in dense and sparse resource regimes PHYSICAL REVIEW E 72 (1): Art. No. 016108 Part 2 JUL 2005
6. Brookings, T, Carlson, JM & Doyle, J Three mechanisms for power laws on the Cayley tree (2005) Phys. Rev. E 72
7. Doyle J, and Csete M, Rules of engagement. NATURE 446 (7138): 860-860 APR 19 2007 (PMID: 17443168)

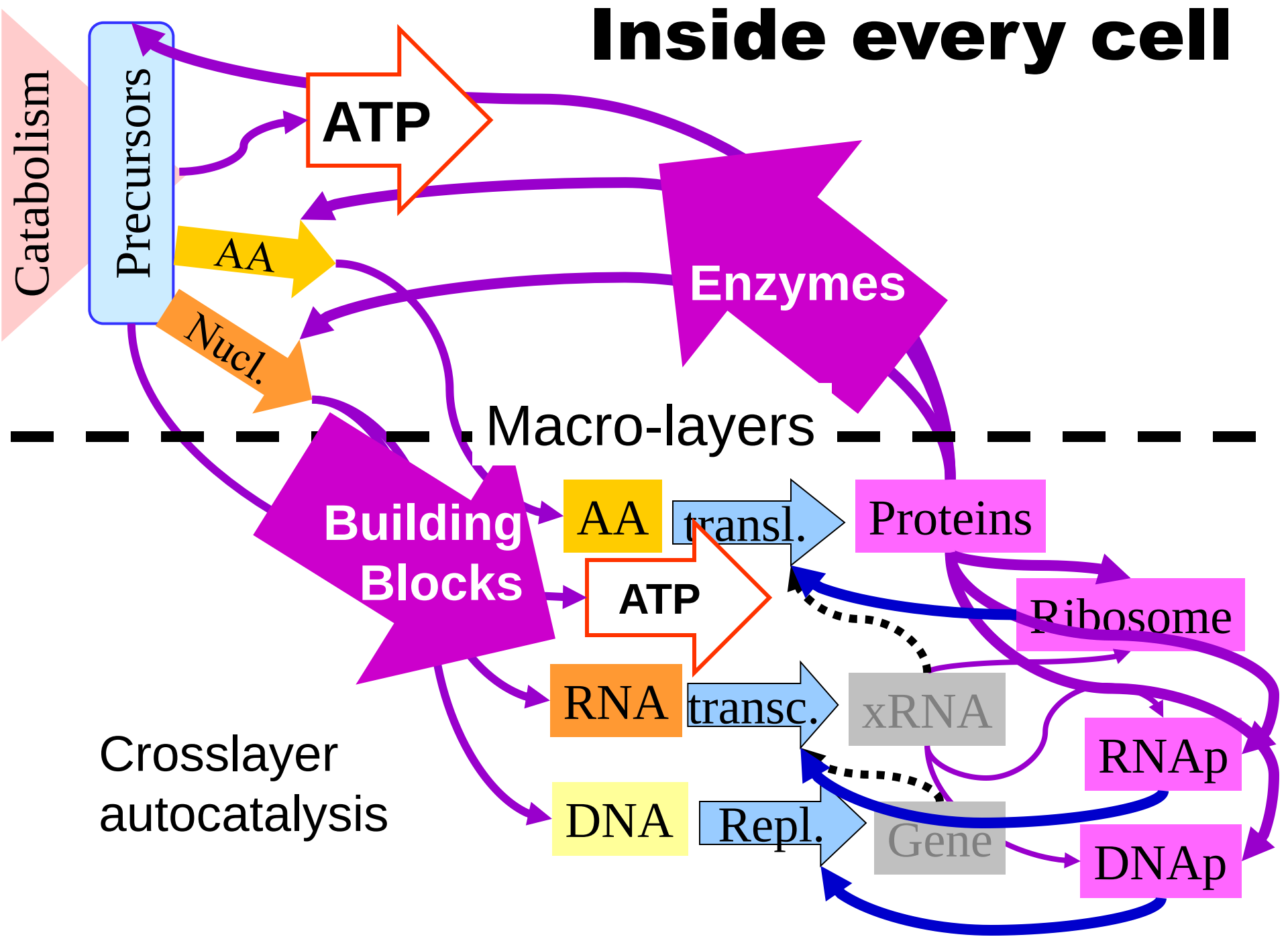
Complementary approaches




fragile
Case studies that achieve bounds
Sharpen hard bounds
wasteful

Bacterial architecture

- More complex macro-layering of function
  - Upper: Metabolism, envelope, signaling, building blocks
  - Lower: Proteins & macromolecule synthesis, replication
- Cleaner layering of control
  - Transcription factors
  - 2 component signal transduction
- Name/address resolution
  - Global, exhaustive by fast diffusion within layers
  - Highly structured interactions between layers
- Limited scalability
  - Limited to small volumes
  - Control proteins scale super-linearly with enzyme numbers

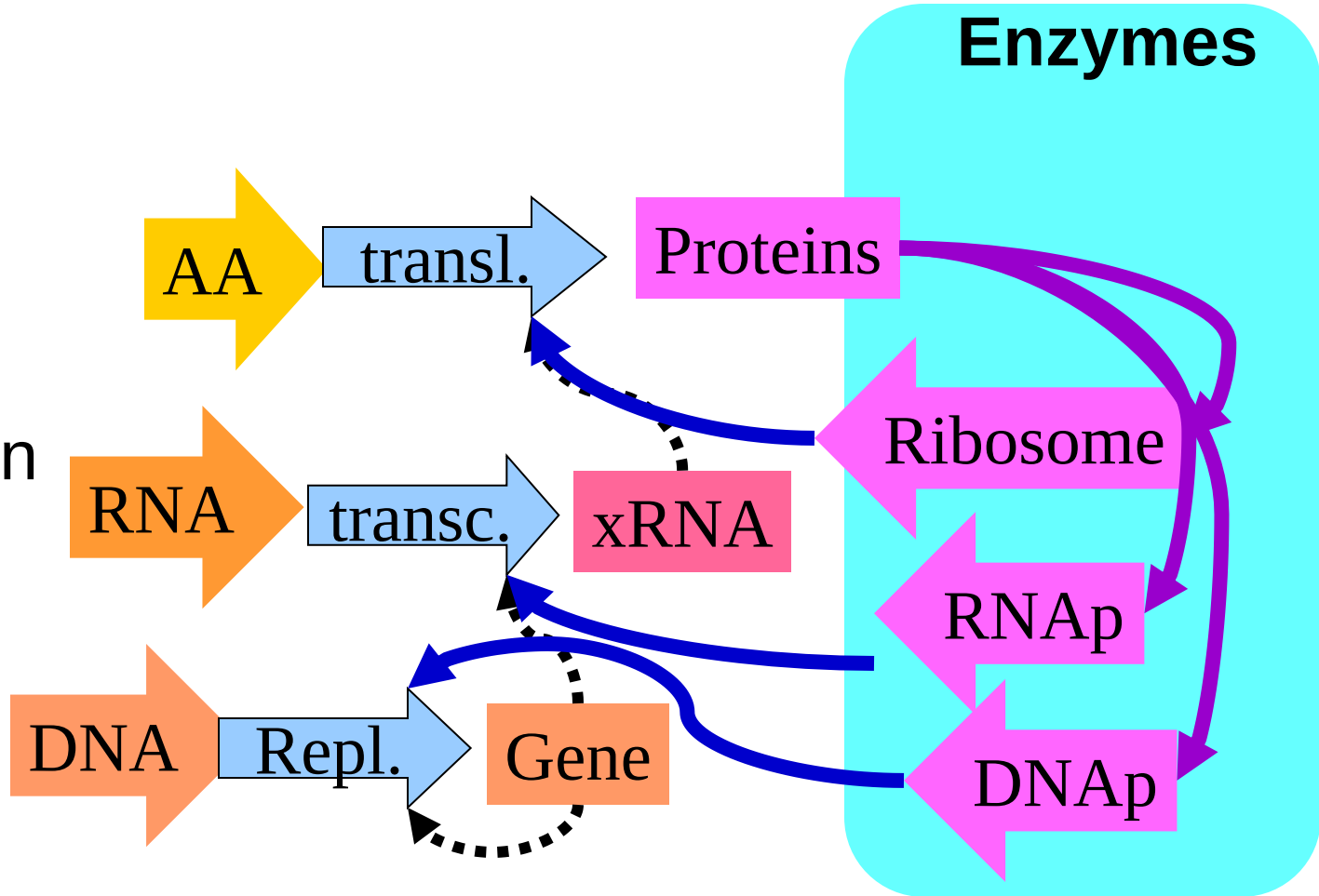

Inside every cell
Catabolism
Precursors
ATP
AA
Nucl.
Enzymes
Macro-layers
Building Blocks
AA
transl.
Proteins
ATP
Ribosome
RNA
transc.
xRNA
RNAp
DNA
Repl.
Gene
DNAp
Crosslayer autocatalysis

Lower layer autocatalysis

Macromolecules making …

Three lower layers? Yes:

- Translation
- Transcription
- Replication



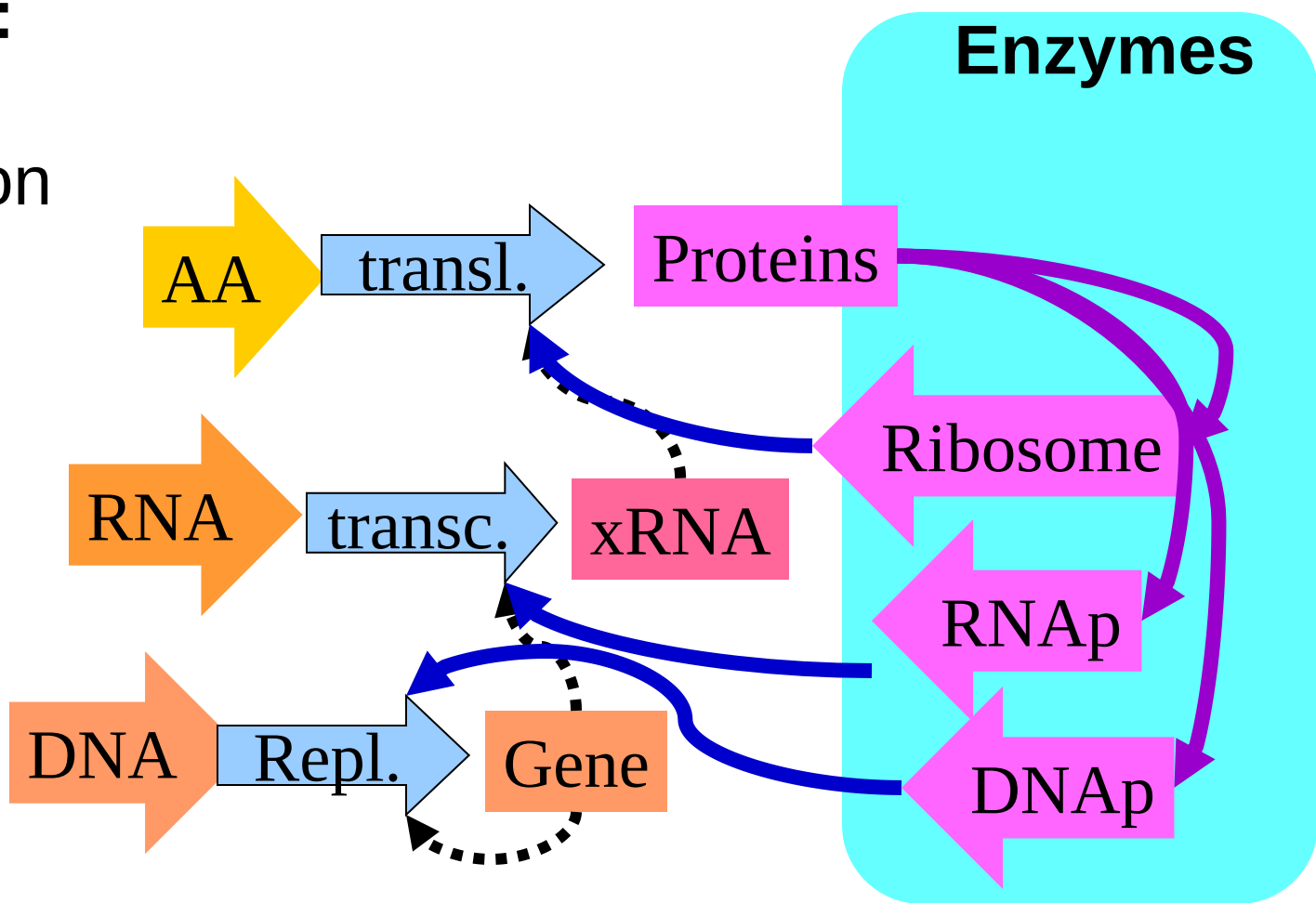
Autocatalytic within lower layers

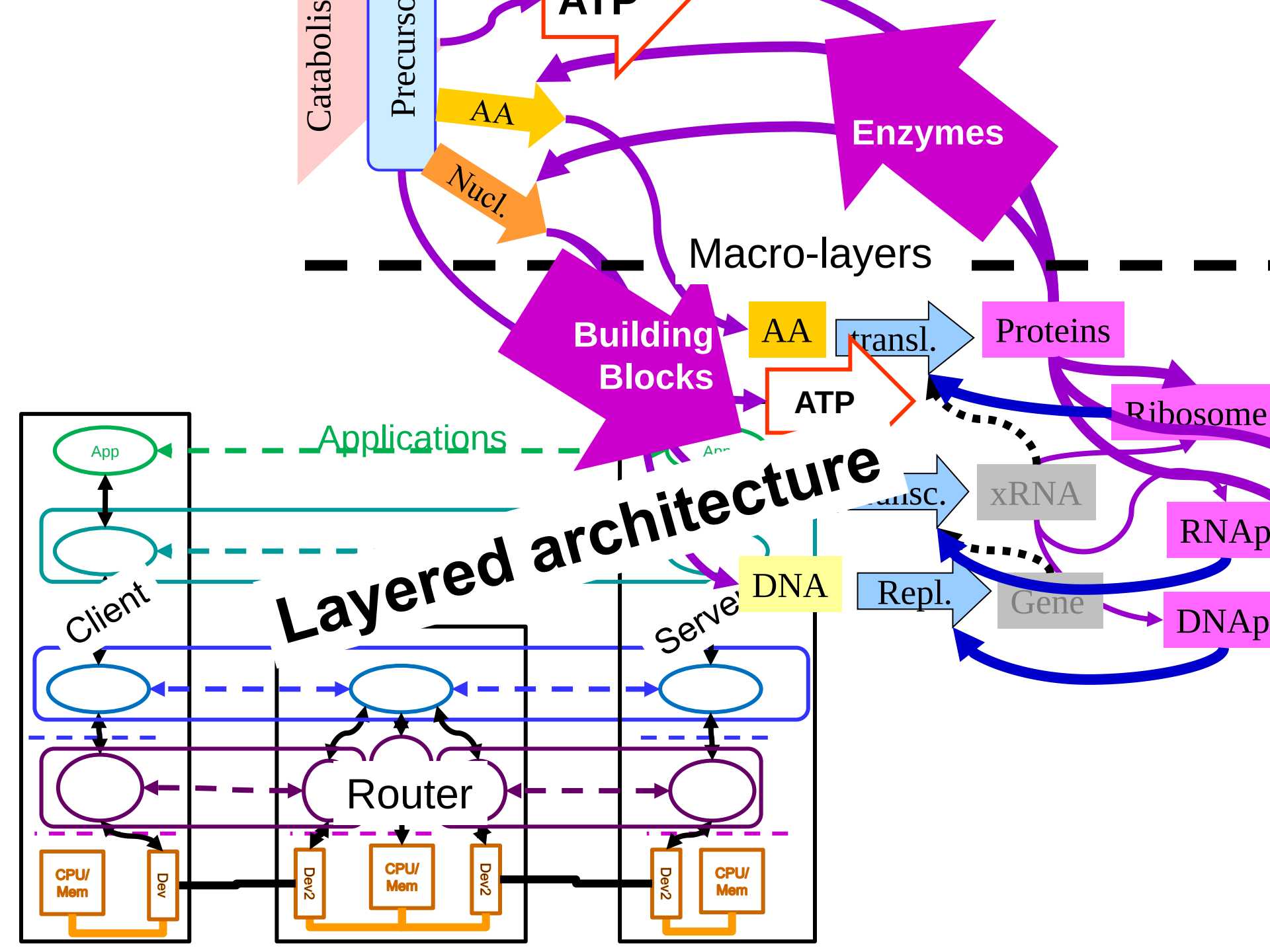
- Collectively self-replicating
- Ribosomes make ribosomes, etc

Three lower layers? Yes:

- Translation
- Transcription
- Replication

Naturally recursive




Catabolism
Precursors
ATP
AA
Nucl.
Enzymes
Macro-layers
Building Blocks
AA
transl.
Proteins
ATP
Ribosome
Applications
xRNA
RNAp
DNA
Repl.
Gene
DNAp
Layered architecture
App
Client
Server
Router
CPU/ Mem
Dev
Dev2
CPU/ Mem
Dev2
Dev2
CPU/ Mem

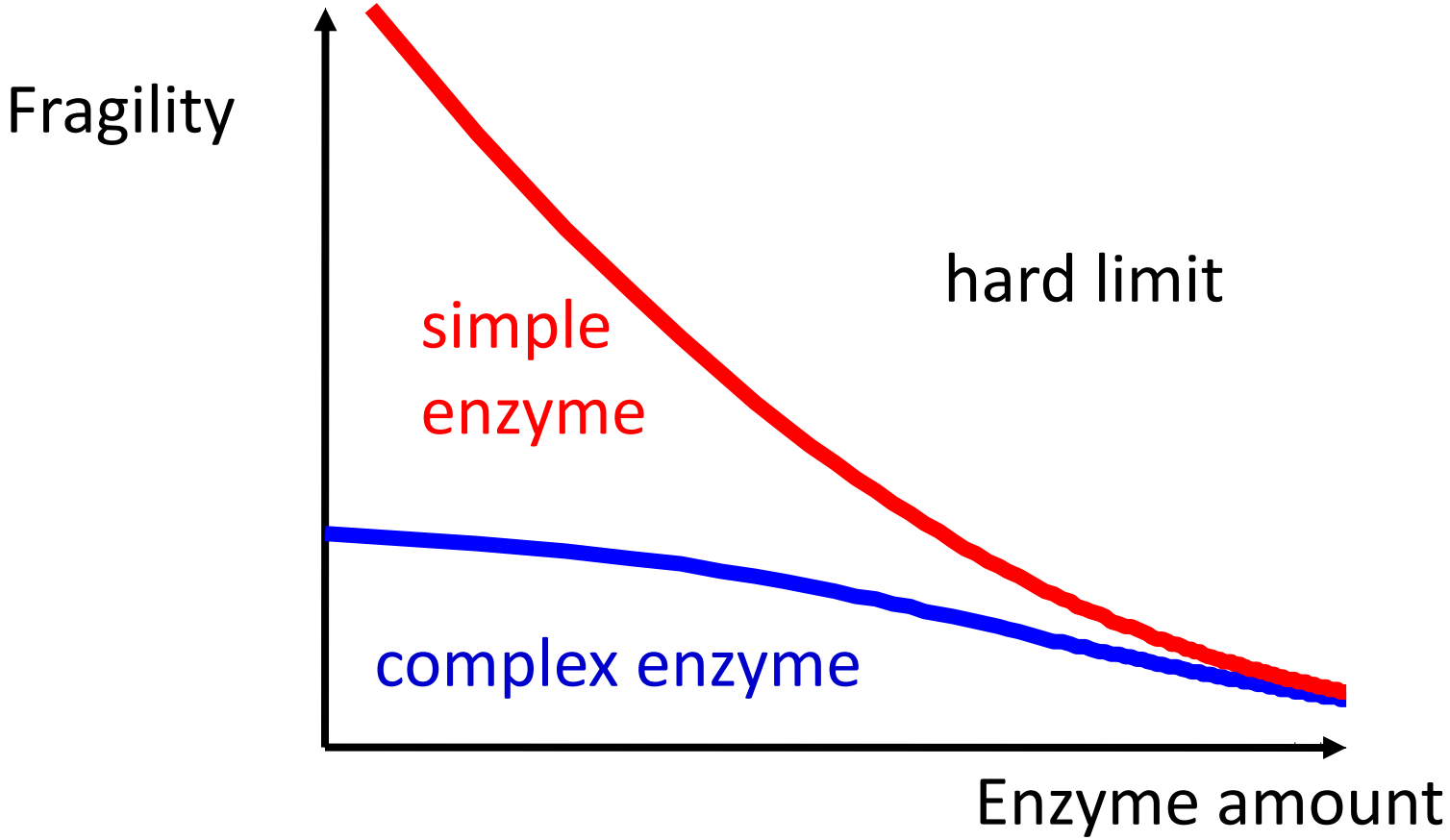
Theory plus biology case study

Hard tradeoffs between

- Fragility (disturbance rejection)
- Metabolic overhead
  - Amount (of enzymes)
  - Complexity (of enzymes)

- Glycolytic oscillations
- Most ubiquitous and studied “circuit” in science or engineering
- New insights and experiments
- Resolves longstanding mysteries
- Biology component funded by NIH and Army ICB

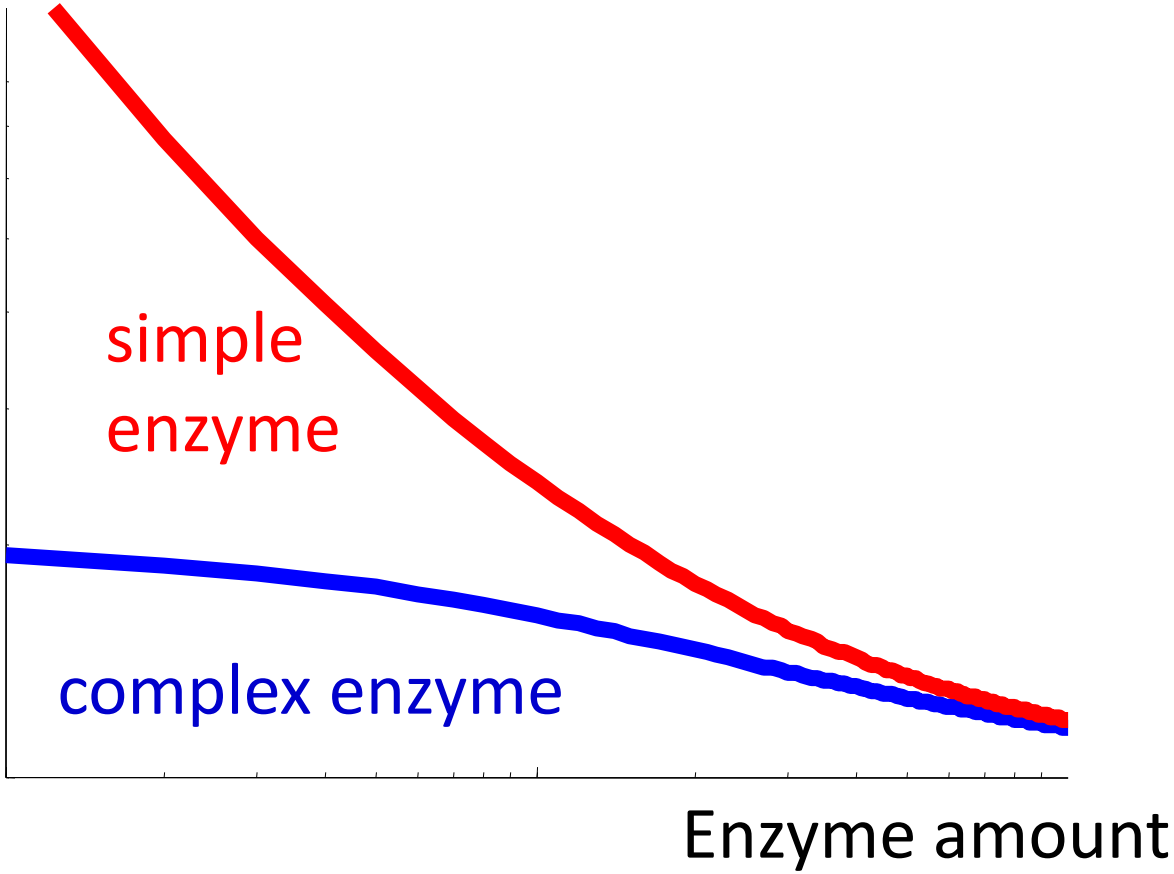
- Fragility (disturbance rejection)
- Metabolic overhead
  - Amount (of enzymes)
  - Complexity (of enzymes)



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

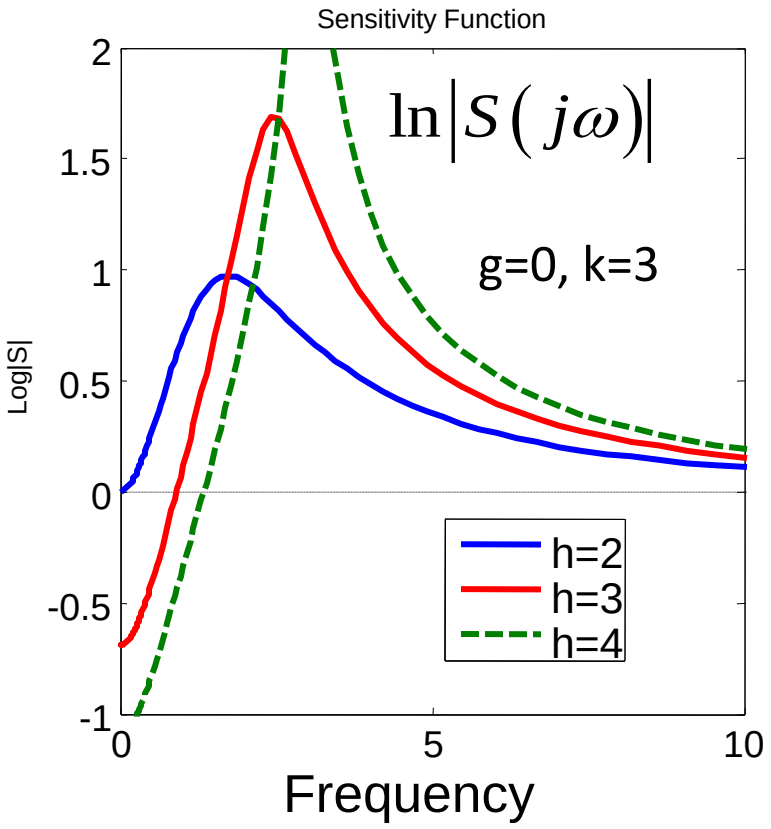
Fragility

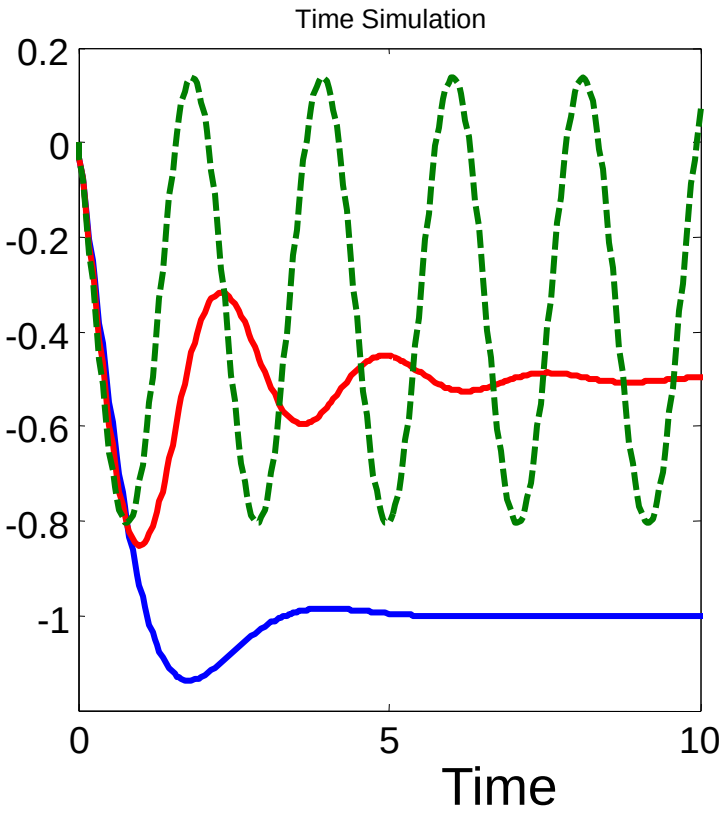
$$\ln\left|\frac{z+p}{z-p}\right|$$



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

Fragility (standard control theory) rigorous, first-principles.



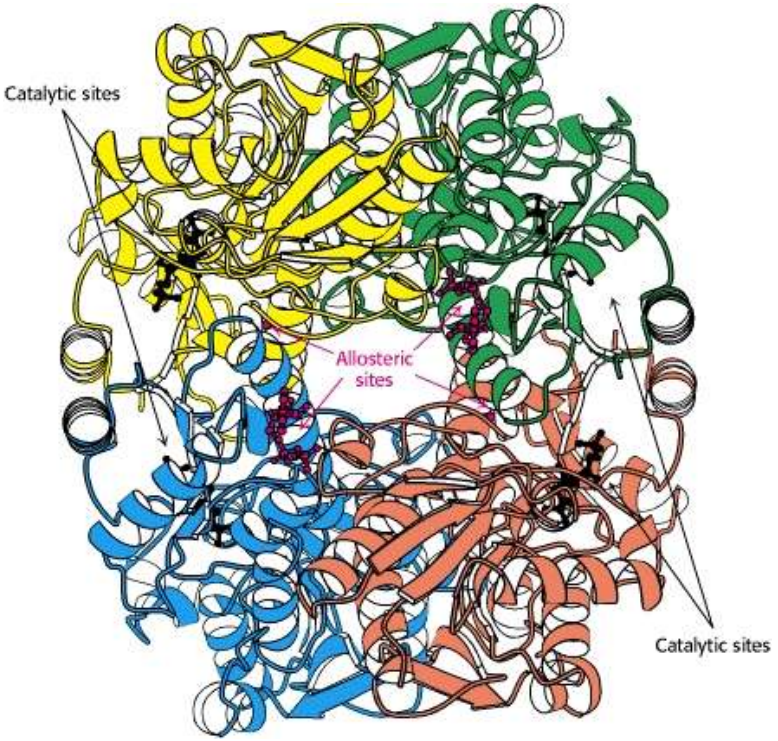


Theorem $$\frac{1}{\pi}\int_0^{\infty} \ln\left|S(j\omega)\right|\left(\frac{z}{z^2+\omega^2}\right)d\omega \geq \ln\left|\frac{z+p}{z-p}\right|$$

- z and p are functions of enzyme complexity and amount
- standard biochemistry models
- phenomenological
- first principles?

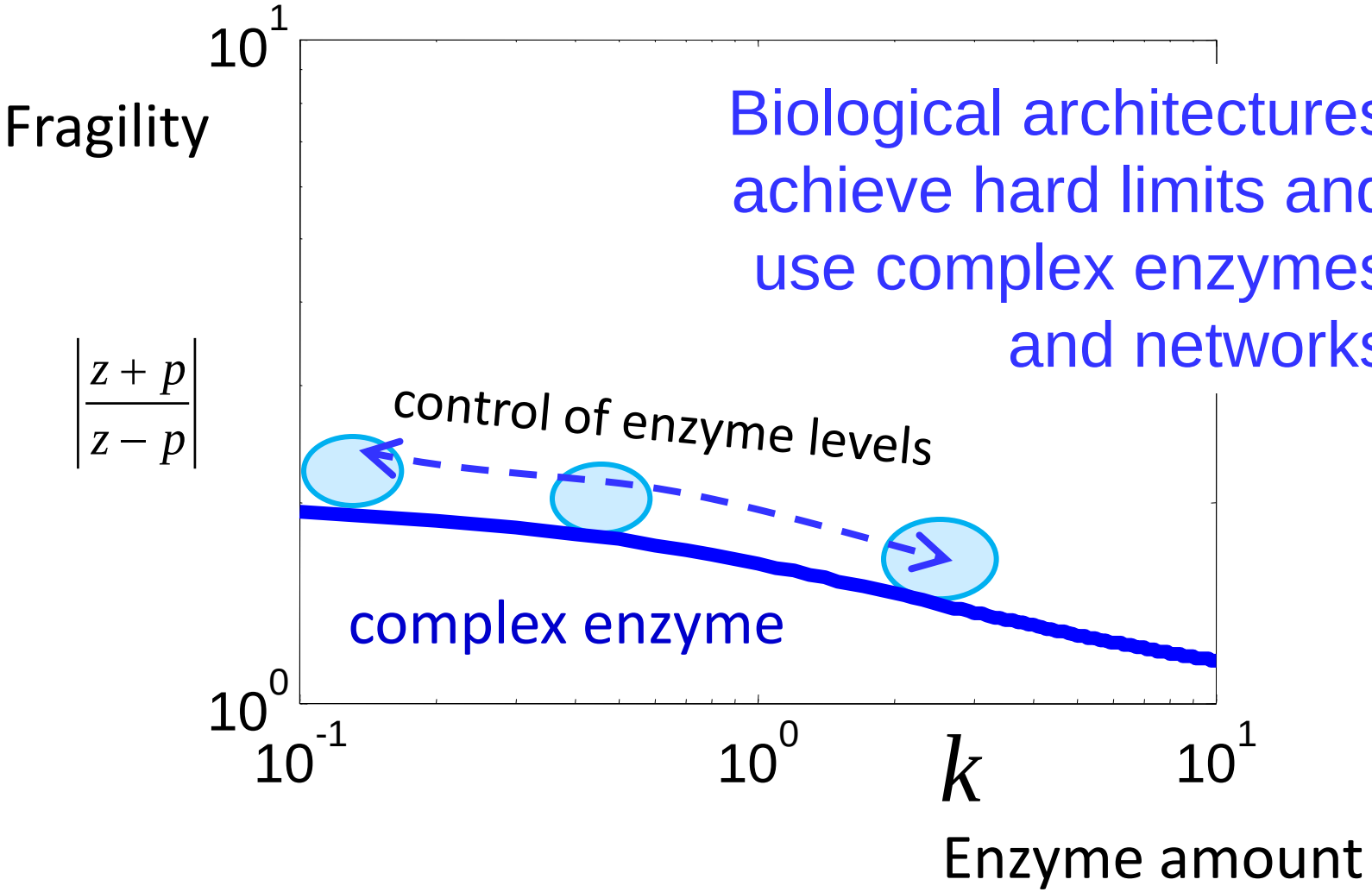
simple enzyme

complex enzyme



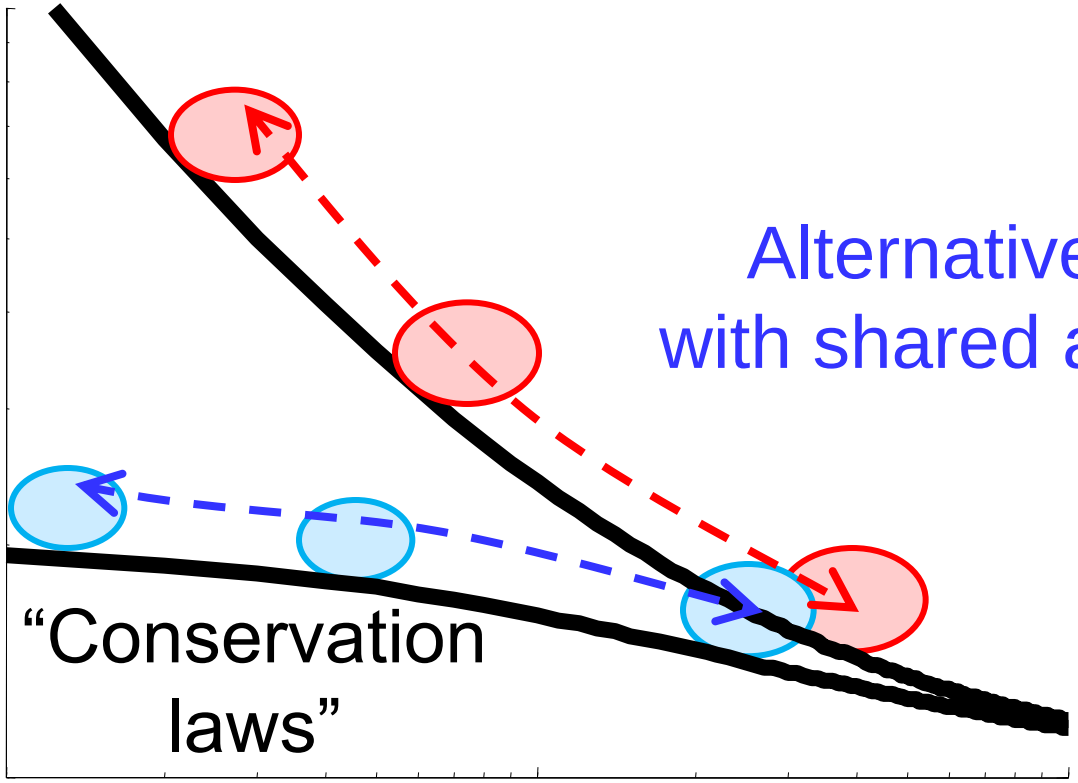
Enzyme amount

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



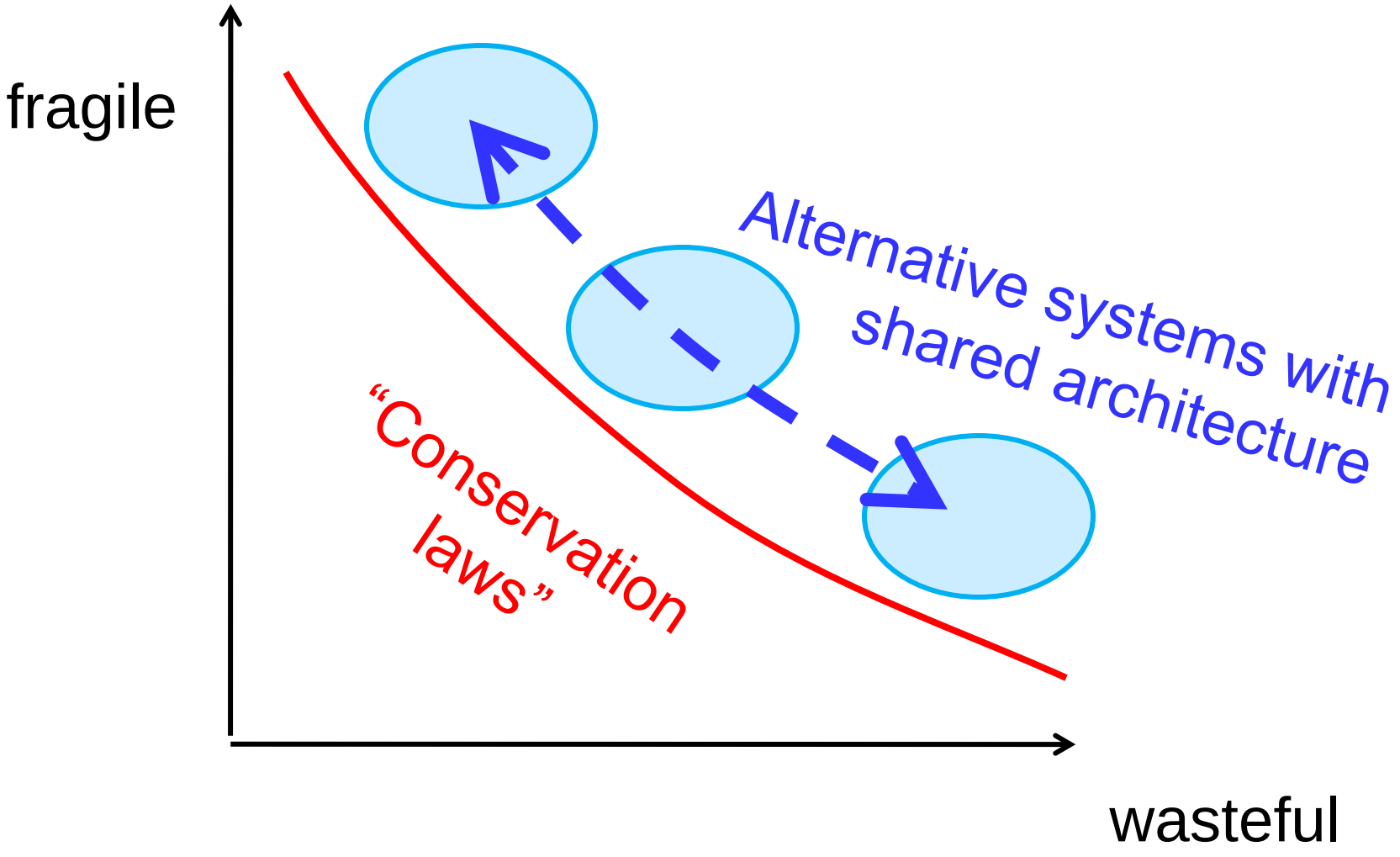
Architecture

Good architectures allow for effective tradeoffs



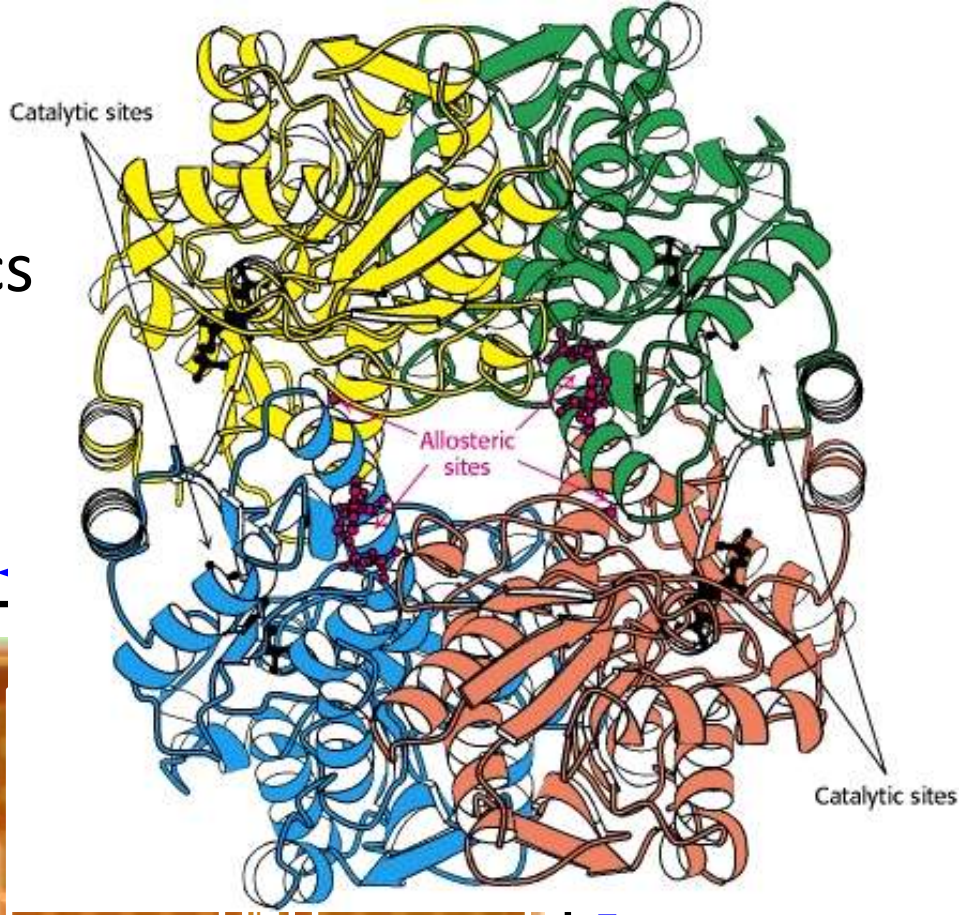
Architecture

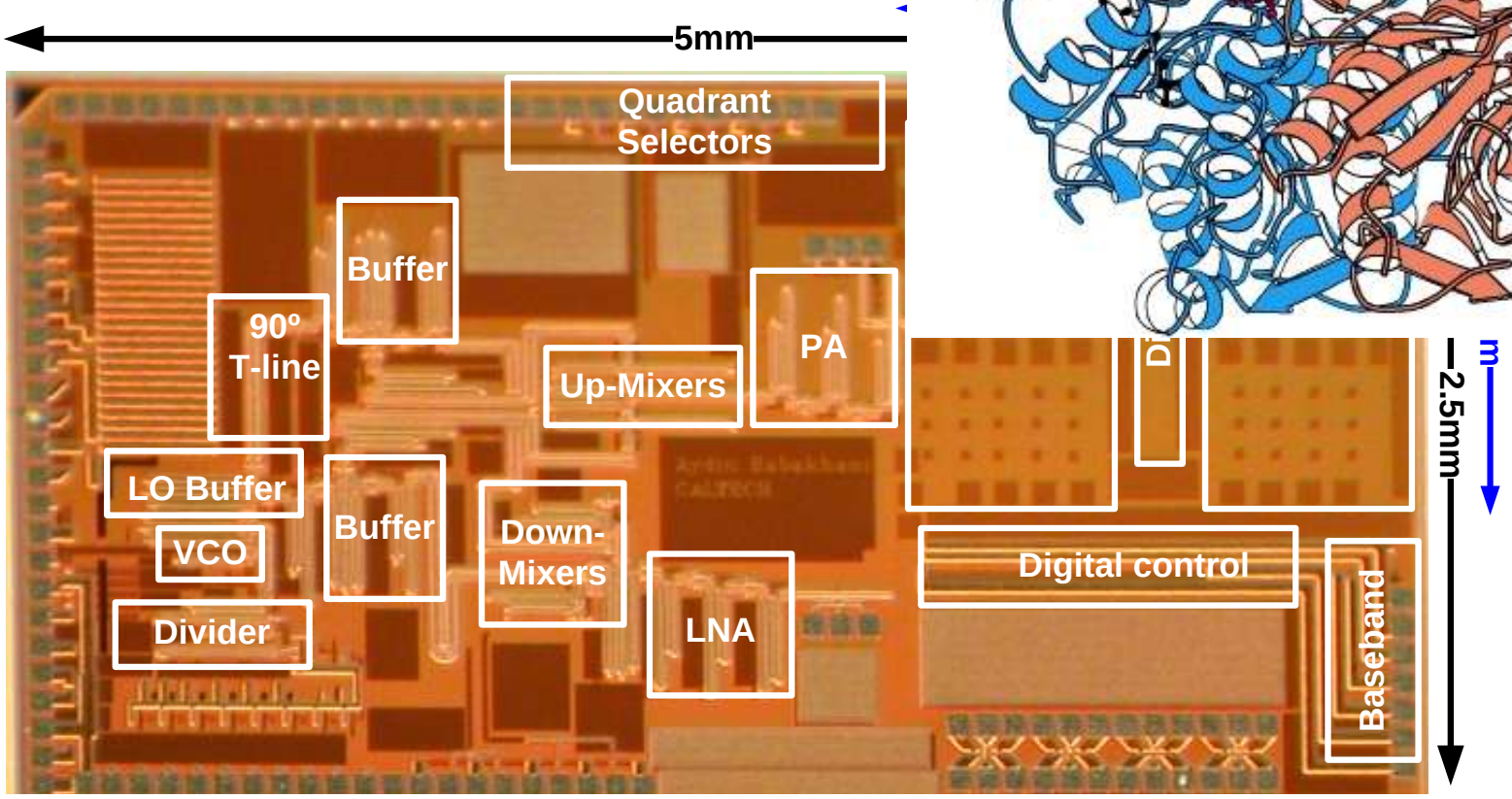
Good architectures allow for effective tradeoffs

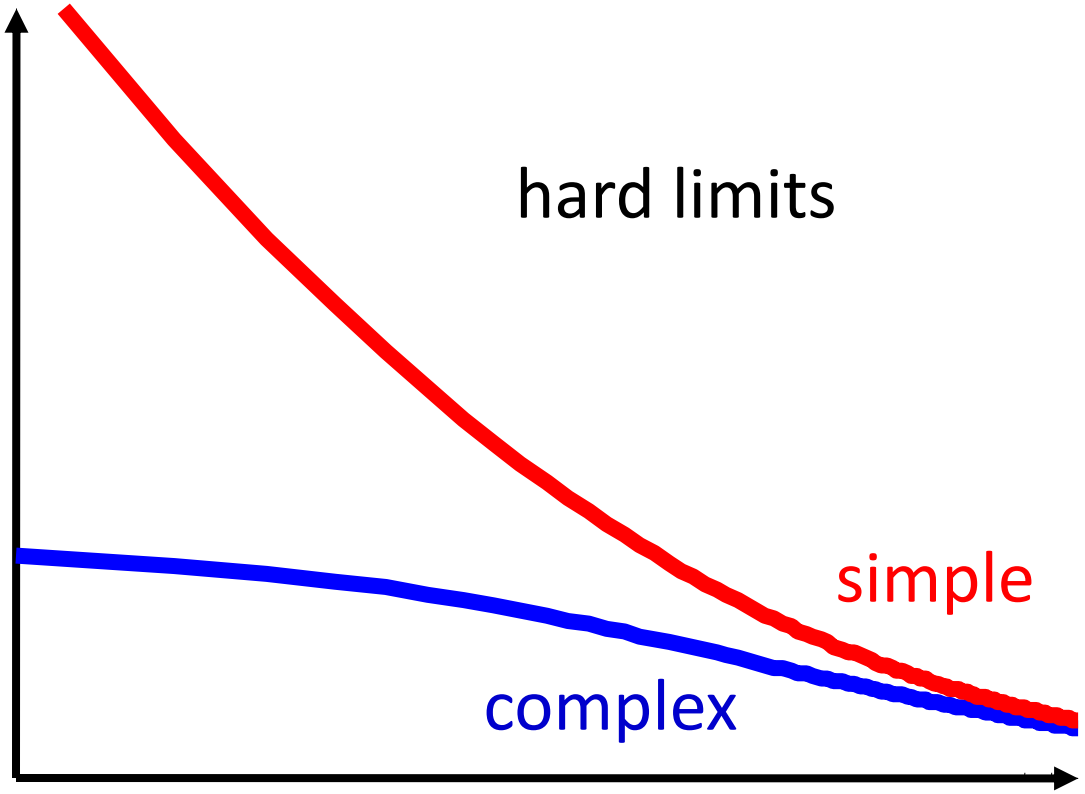


Phenomenology

1. Incorporate domain specifics
2. First principles models







- General
- Rigorous
- First principle

?

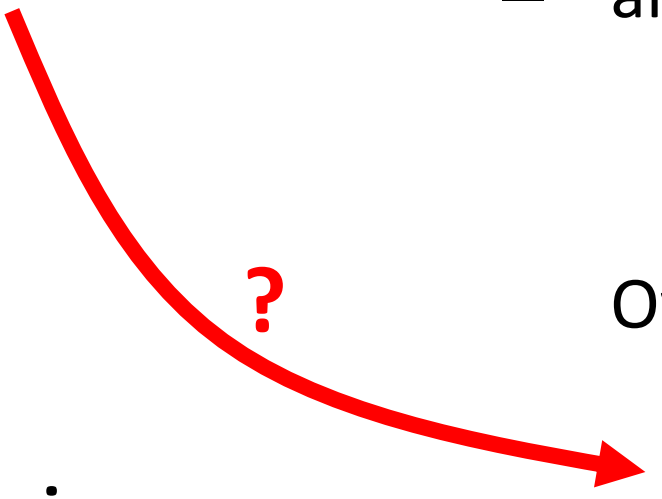
- Domain specific
- Ad hoc
- Phenomenological

Plugging in domain details

- Fundamental multiscale physics
- Start classically
- Foundations, origins of
  - noise
  - dissipation
  - amplification

Fragility

- General
- Rigorous
- First principle



Overhead, waste

- Domain specific
- Ad hoc
- Phenomenological

Plugging in domain details

IEEE TRANS ON AUTOMATIC CONTROL,
to appear, FEBRUARY, 2011
Sandberg, Delvenne, and Doyle

http://arxiv.org/abs/1009.2830

On Lossless Approximations, the Fluctuation-Dissipation Theorem, and Limitations of Measurements

Henrik Sandberg, Jean-Charles Delvenne, and John C. Doyle

Abstract—**In this paper, we take a control-theoretic approach to answering some standard questions in statistical mechanics, and use the results to derive limitations of classical measurements. A central problem is the relation between systems which appear macroscopically dissipative but are microscopically lossless. We show that a linear system is dissipative if, and only if, it can be approximated by a linear lossless system over arbitrarily long time intervals. Hence lossless systems are in this sense dense in dissipative systems. A linear active system can be approximated by a nonlinear lossless system that is charged with initial energy. As a by-product, we obtain mechanisms explaining the Onsager relations from time-reversible lossless approximations, and the fluctuation-dissipation theorem from uncertainty in the initial state of the lossless system. The results are applied to measurement devices and are used to quantify limits on the so-called observer effect, also called *back action*.**

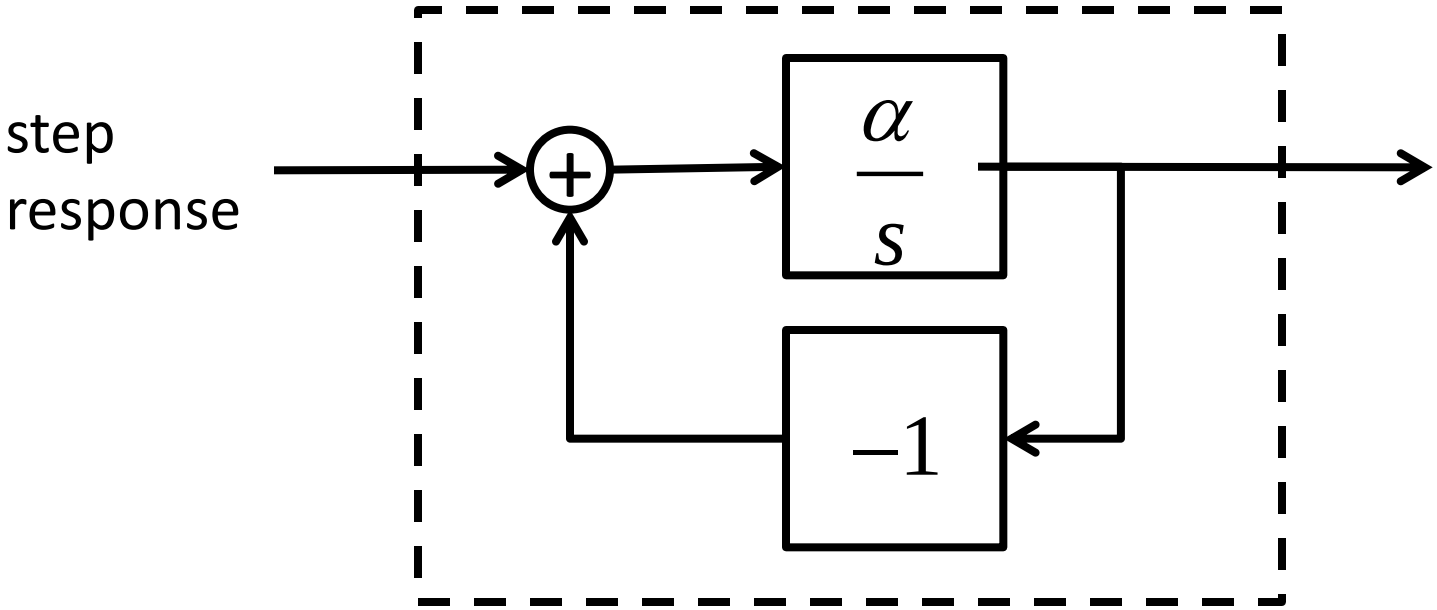
Derivation of limitations is also at the core of physics. Well-known examples are the laws of thermodynamics in classical physics and the uncertainty principle in quantum mechanics [6]–[8]. The exact implications of these physical limitations on the performance of control systems have received little attention, even though all components of a control system, such as actuators, sensors, and computers, are built from physical components which are constrained by physical laws. Control engineers discuss limitations in terms of location of unstable plant poles and zeros, saturation limits of actuators, and more recently channel capacity in feedback loops. But how does the amount of available energy limit the possible bandwidth of a control system? How does the ambient temperature affect the

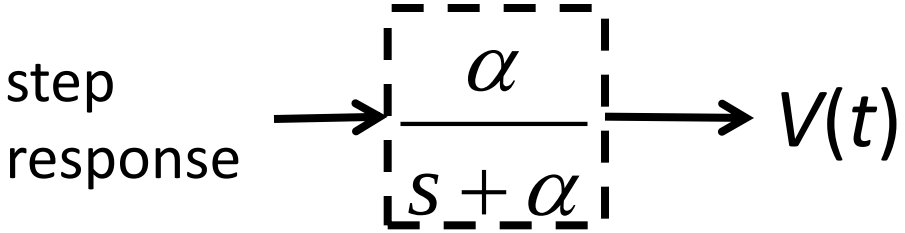
Layers in hardware

So well-known as to be taken for granted

- **Digital** abstraction and modularity
- **Analog** substrate is active and lossy
- **Microscopic** world is lossless

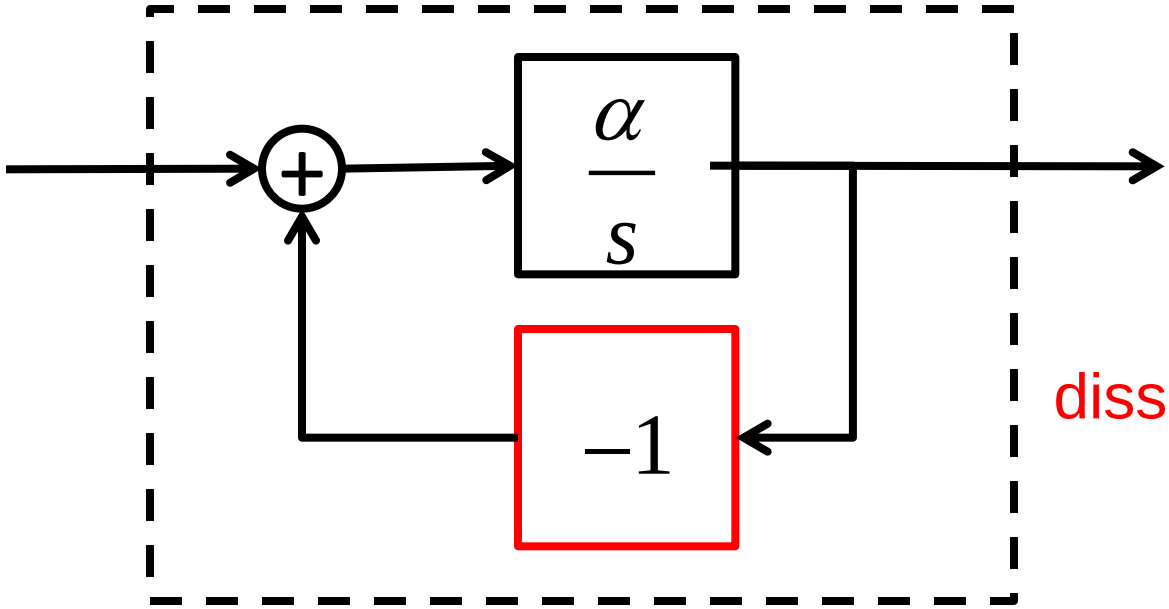
- Reconcile these in a clear and coherent way
- Exploit designable physical layer more


step
response
+
$\frac{\alpha}{s}$
-1

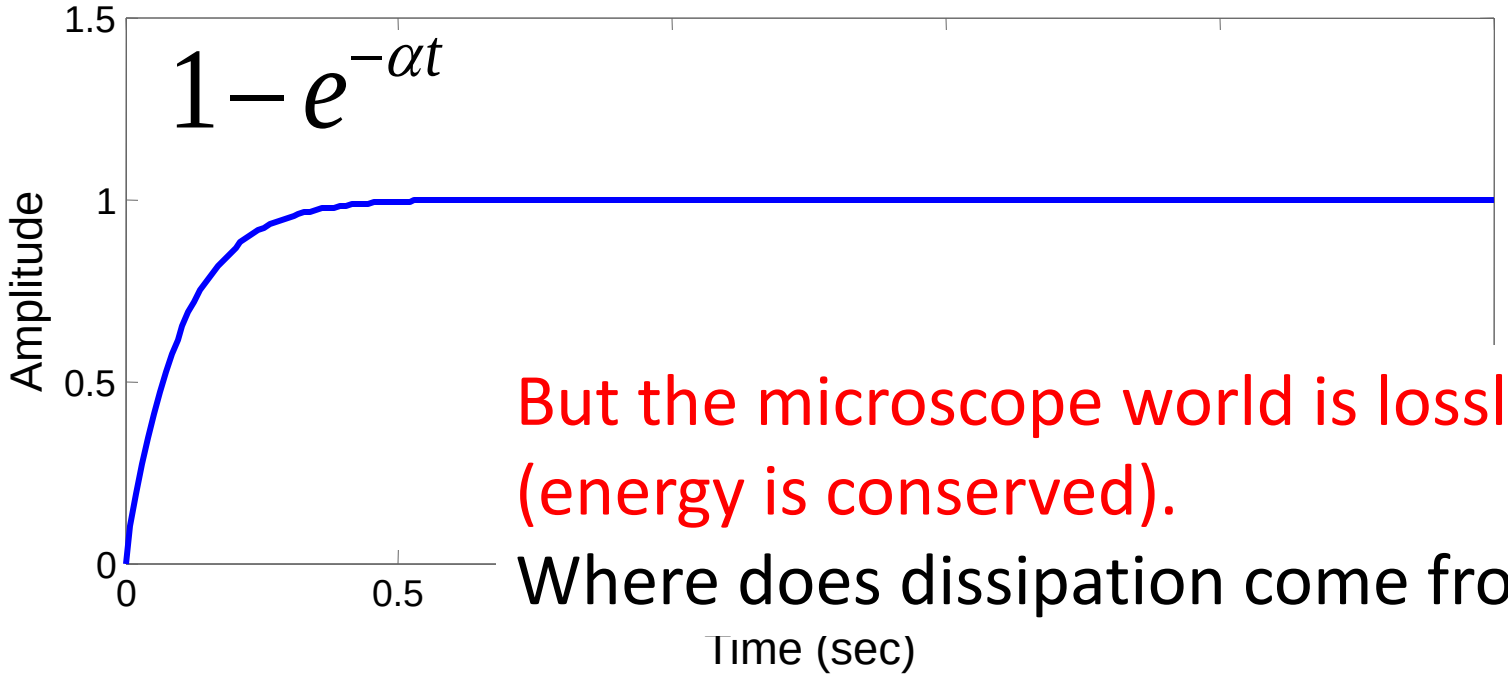

step
response
$\frac{\alpha}{s+\alpha}$
$V(t)$

step response

$\alpha = 10$

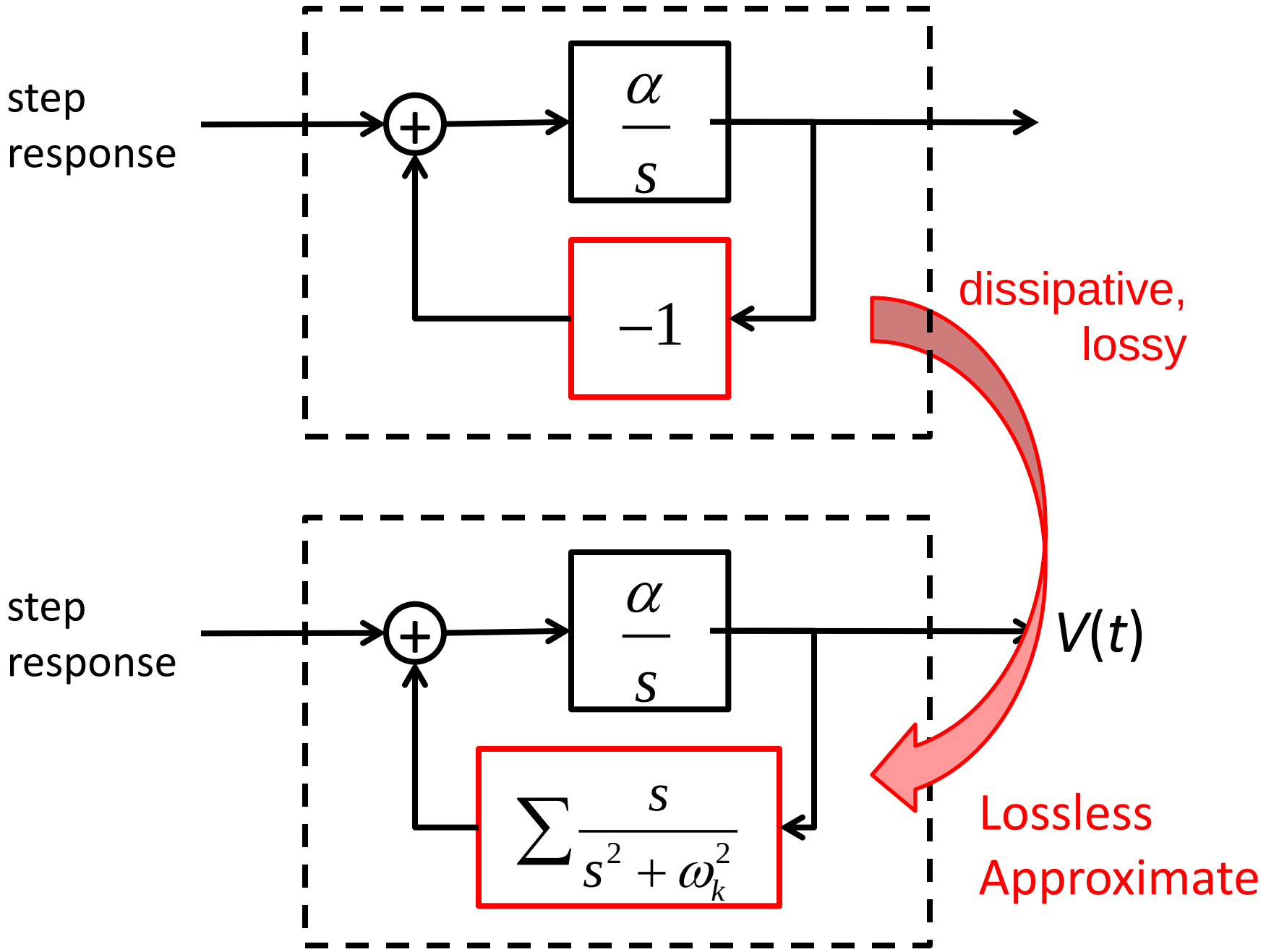


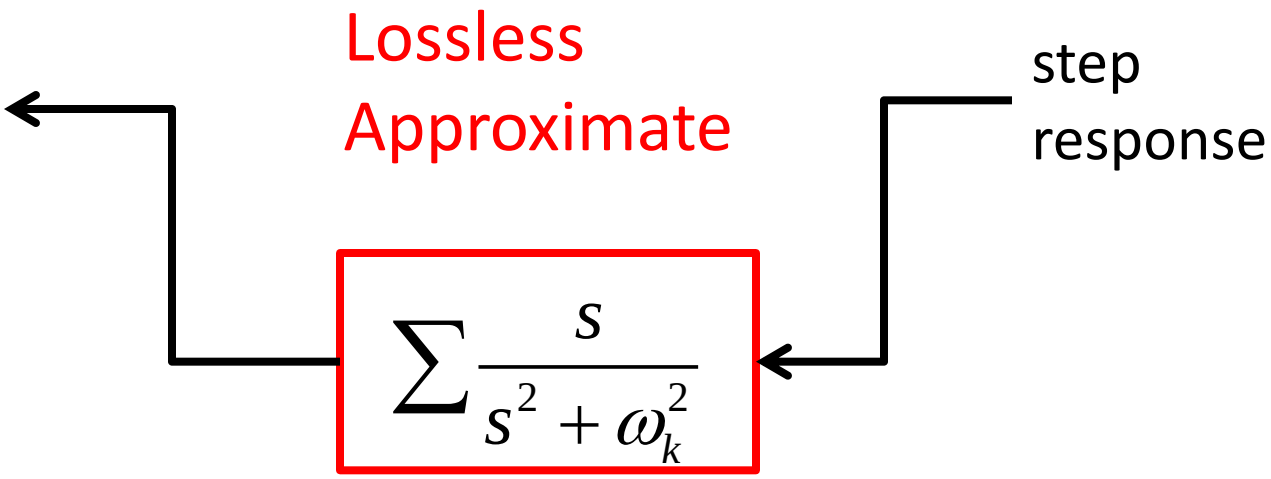
dissipative, lossy

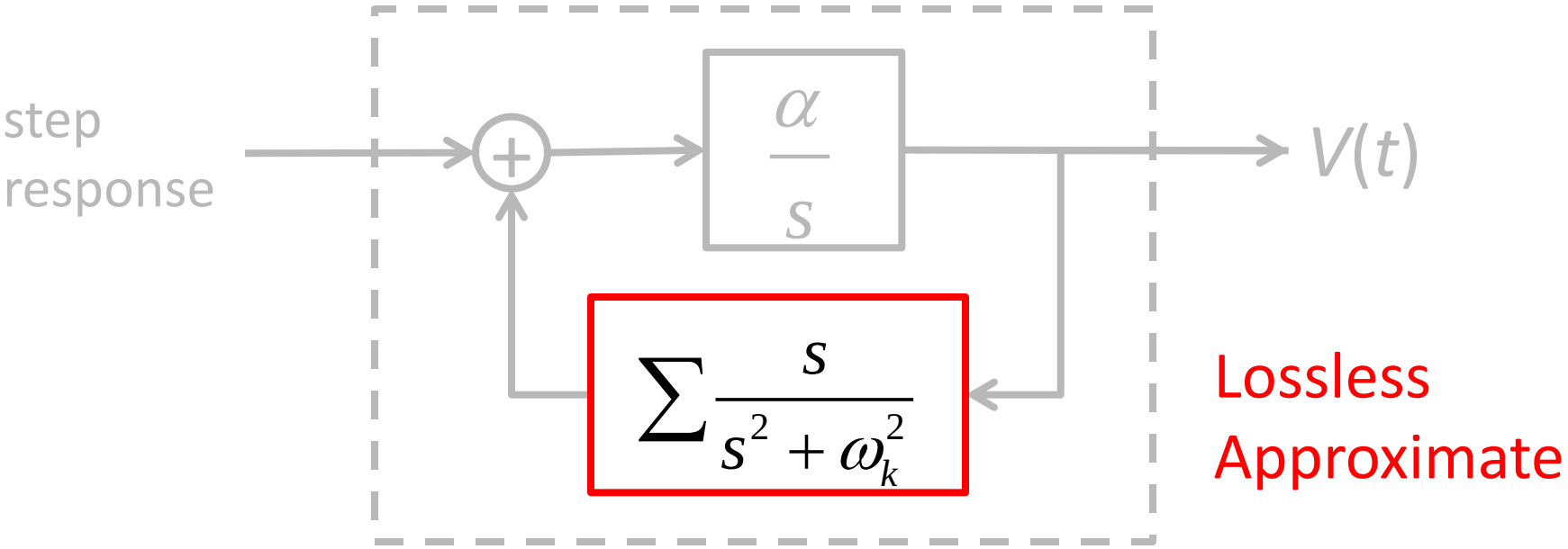


But the microscope world is lossless (energy is conserved).

Where does dissipation come from?


step
response
$\frac{\alpha}{s}$
-1
dissipative,
lossy
step
response
$\frac{\alpha}{s}$
$V(t)$
$\sum \frac{s}{s^2+\omega_k^2}$
Lossless
Approximate


Lossless
Approximate
step
response
$\sum \frac{s}{s^2+\omega_k^2}$

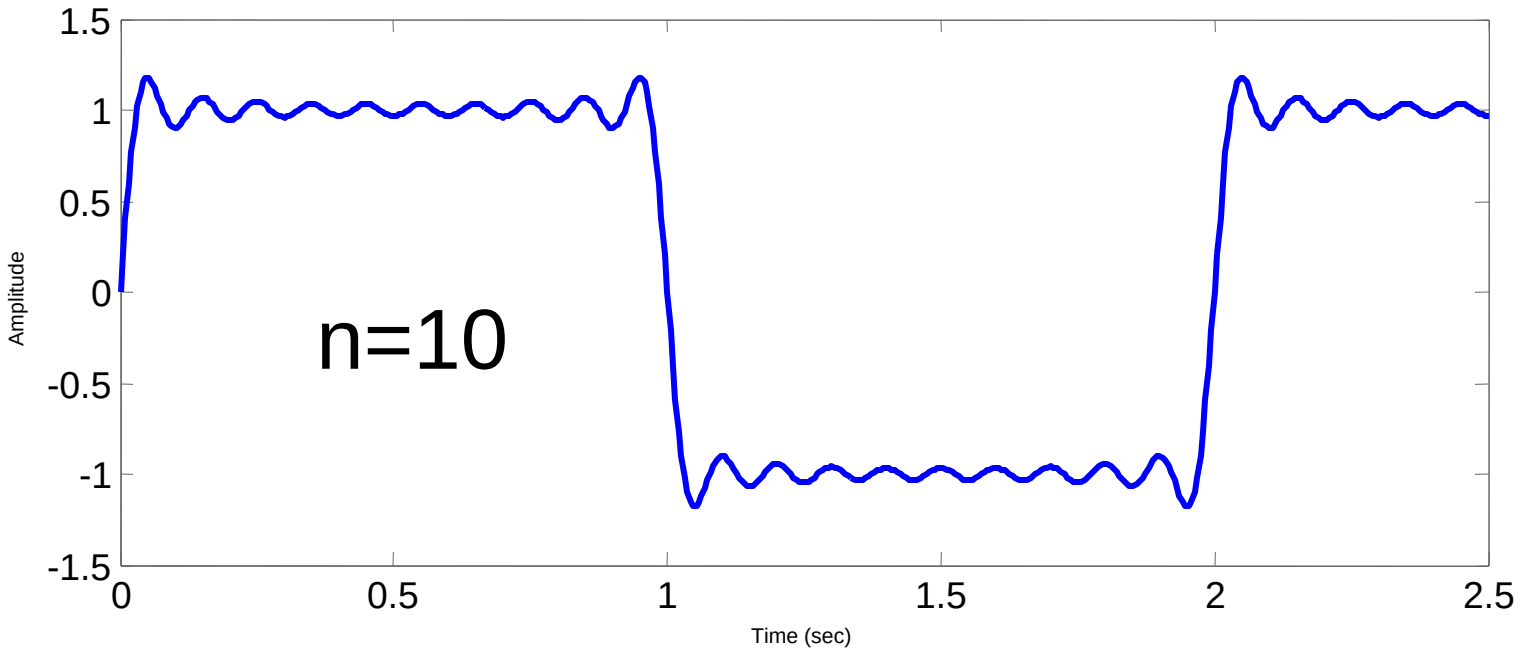

step
response
$\frac{\alpha}{s}$
$V(t)$
$\sum \frac{s}{s^2+\omega_k^2}$
Lossless
Approximate

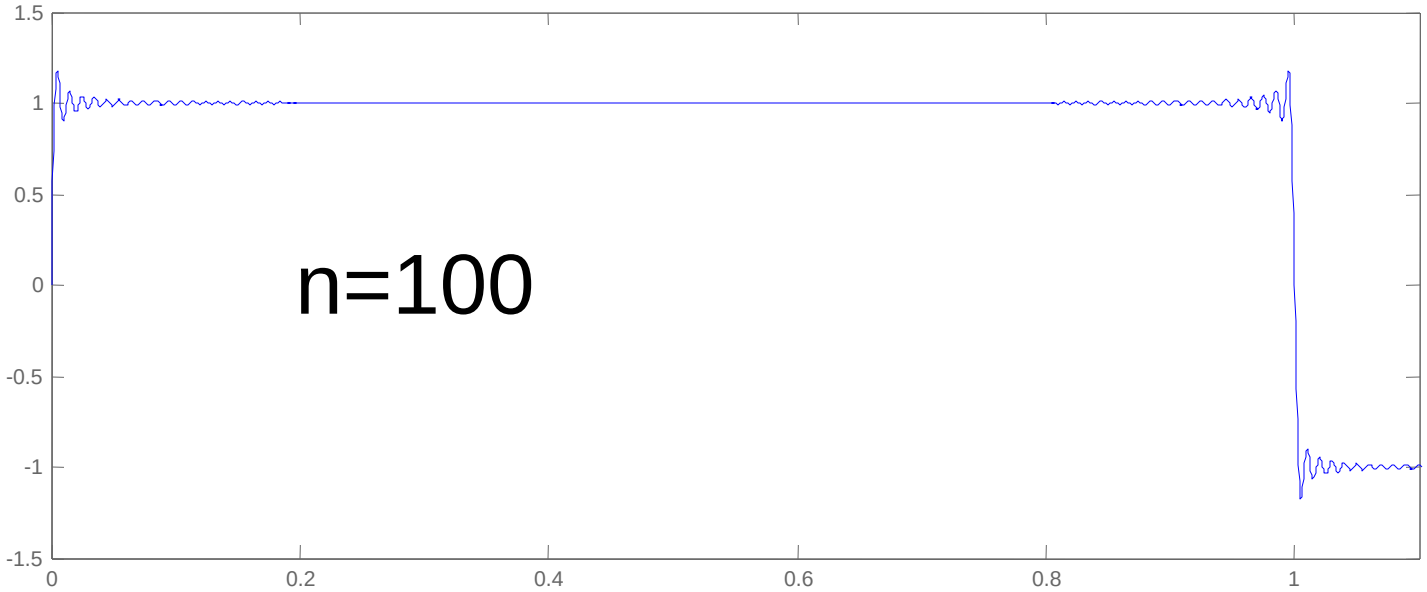
Lossless
Approximate

step
response

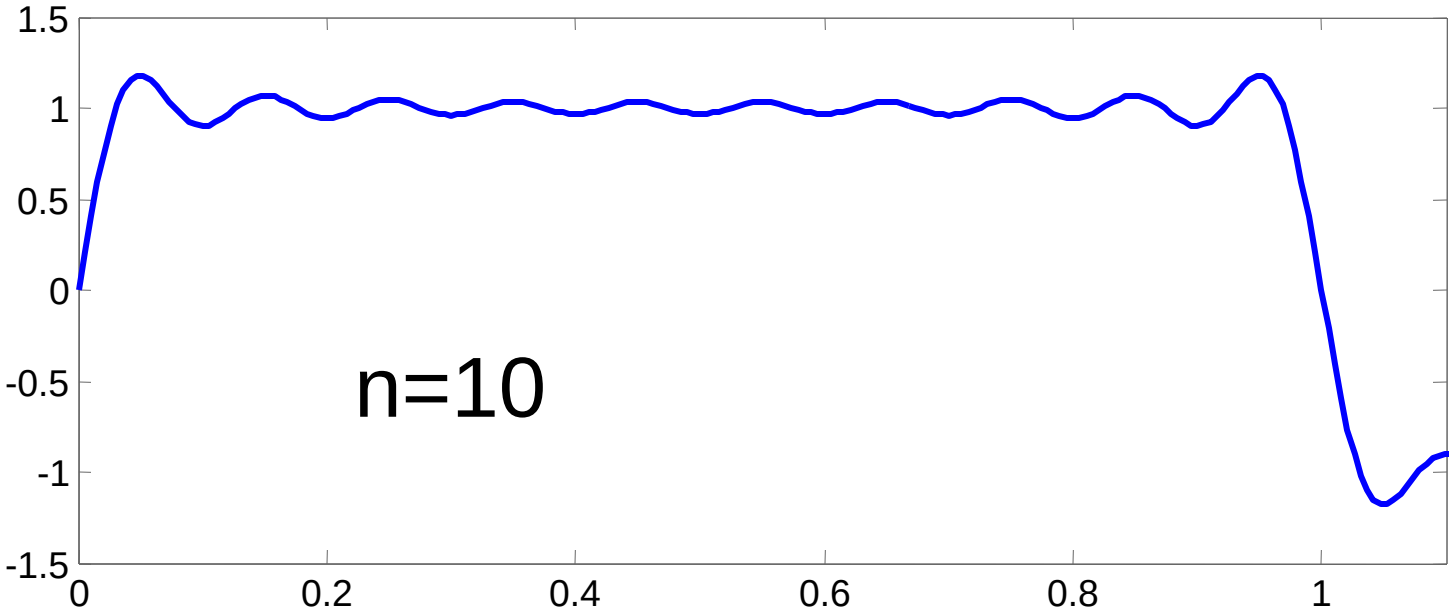
$$\sum \frac{s}{s^2 + \omega_k^2}$$

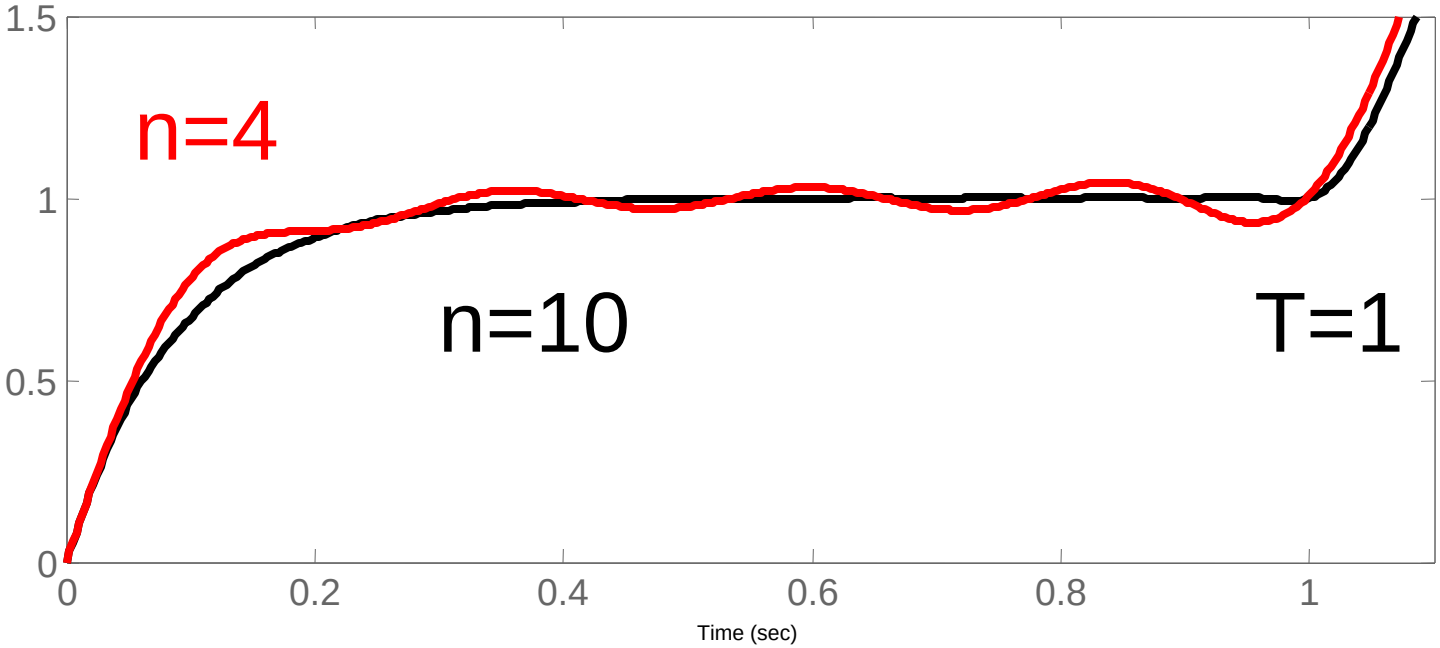
T=1

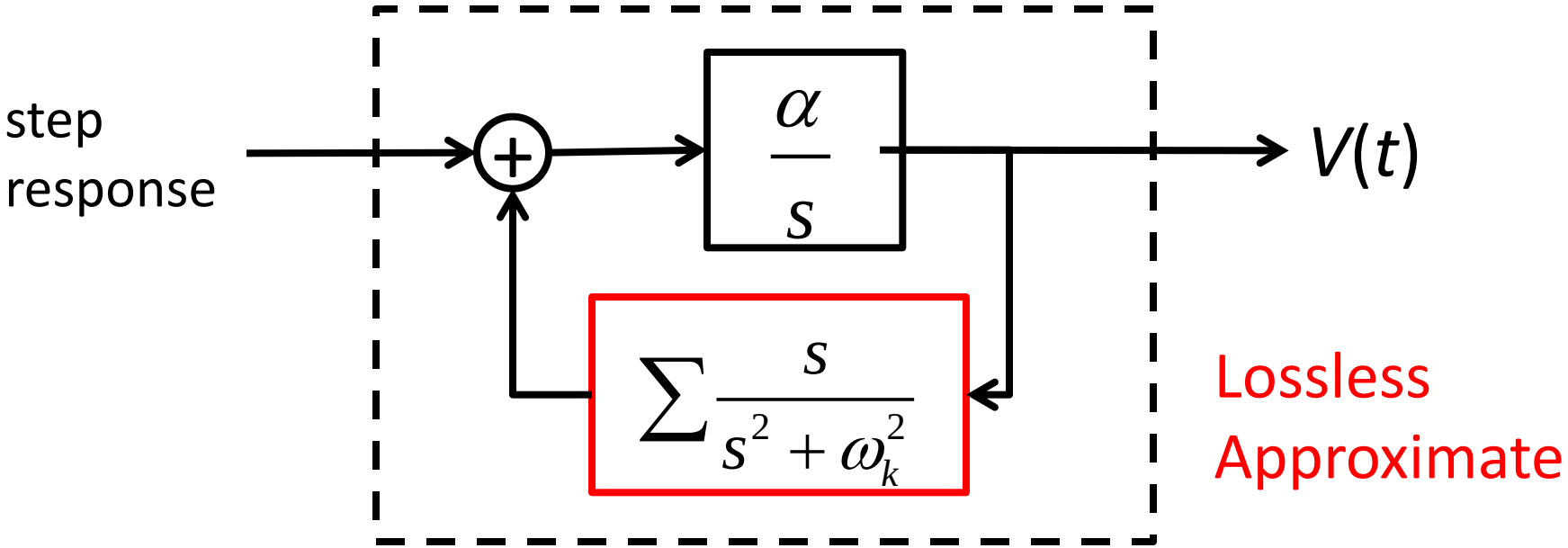


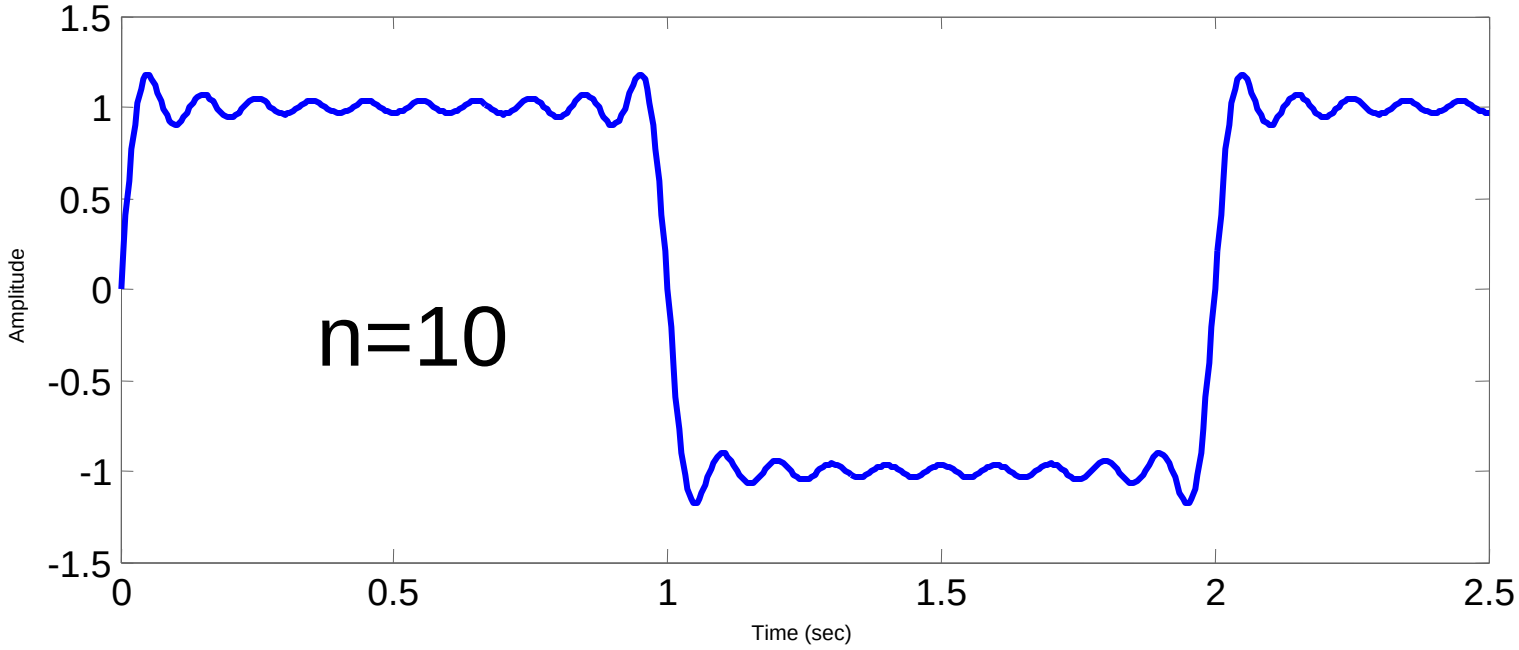


T=1




n=4
n=10
T=1
1.5
1
0.5
0
0
0.2
0.4
0.6
0.8
1
Time (sec)

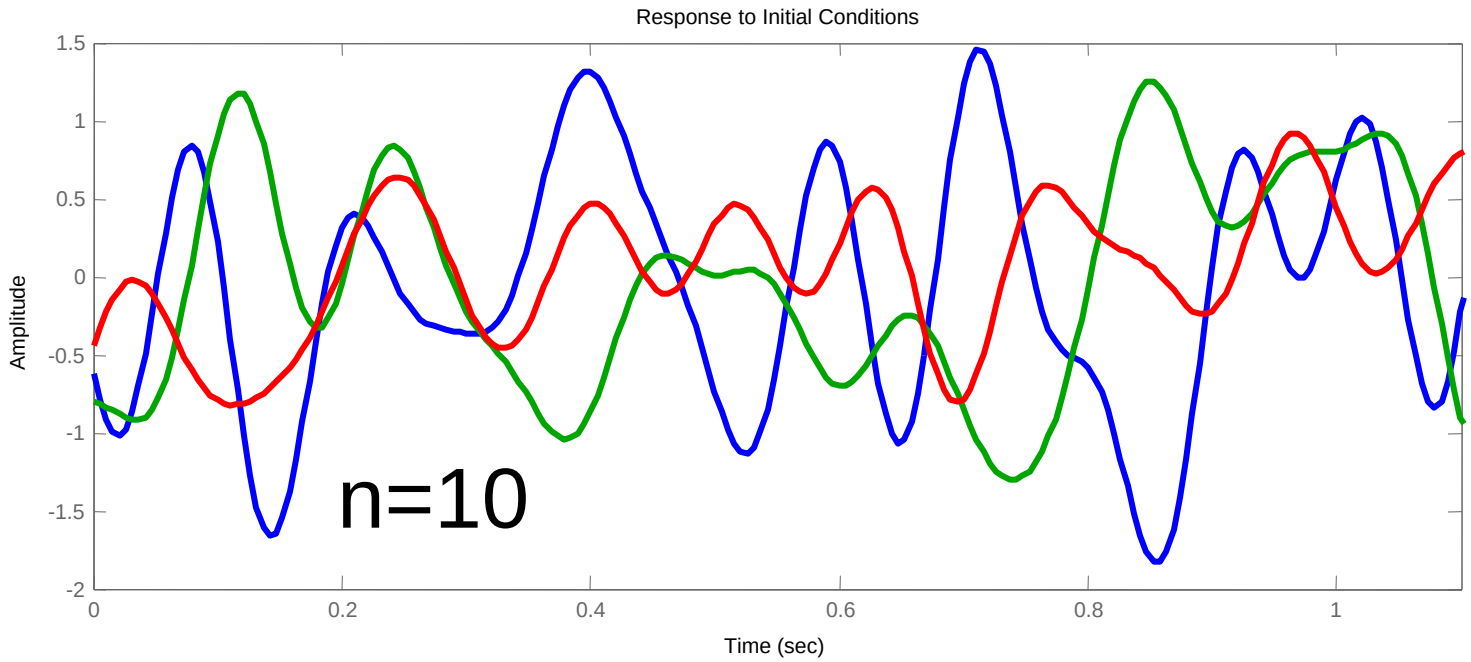

step
response
$\frac{\alpha}{s}$
$V(t)$
$\sum \frac{s}{s^2+\omega_k^2}$
Lossless
Approximate



Lossless
Approximate

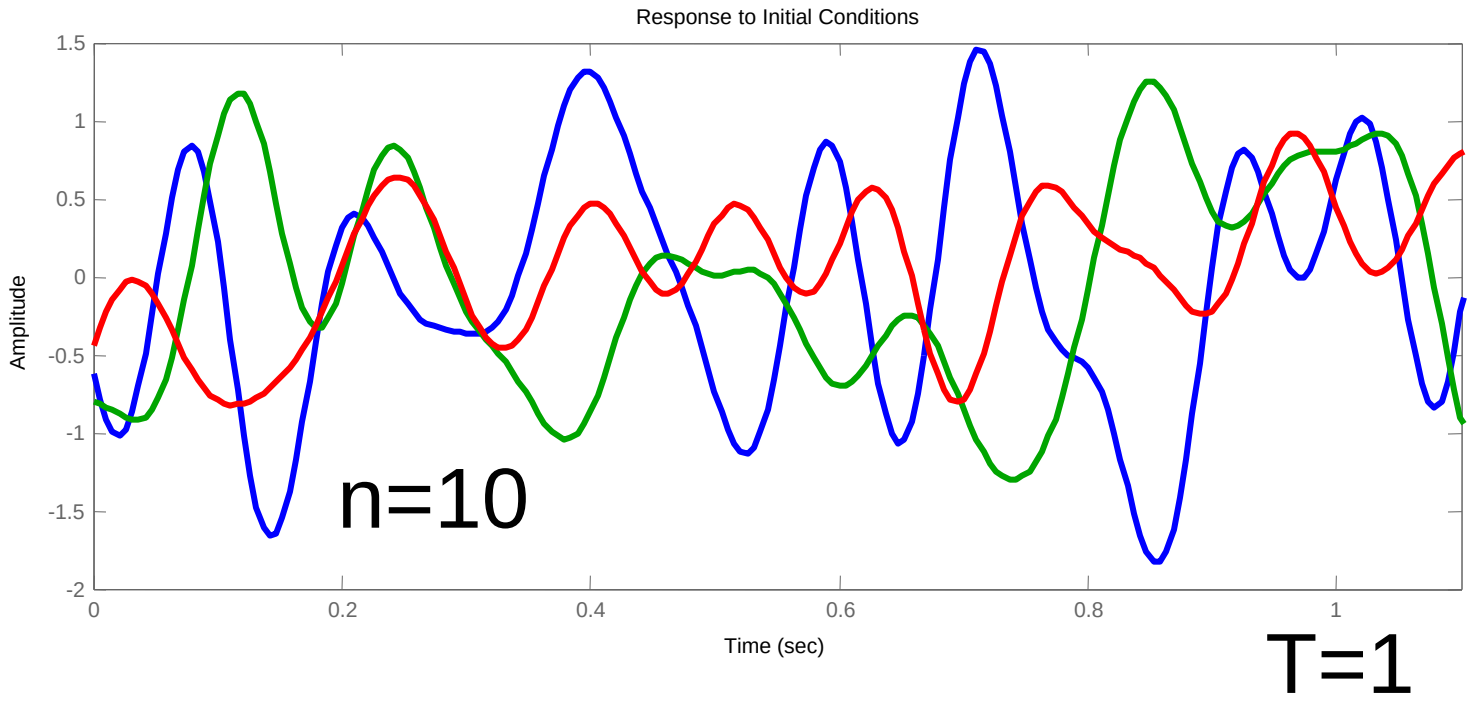
step
response

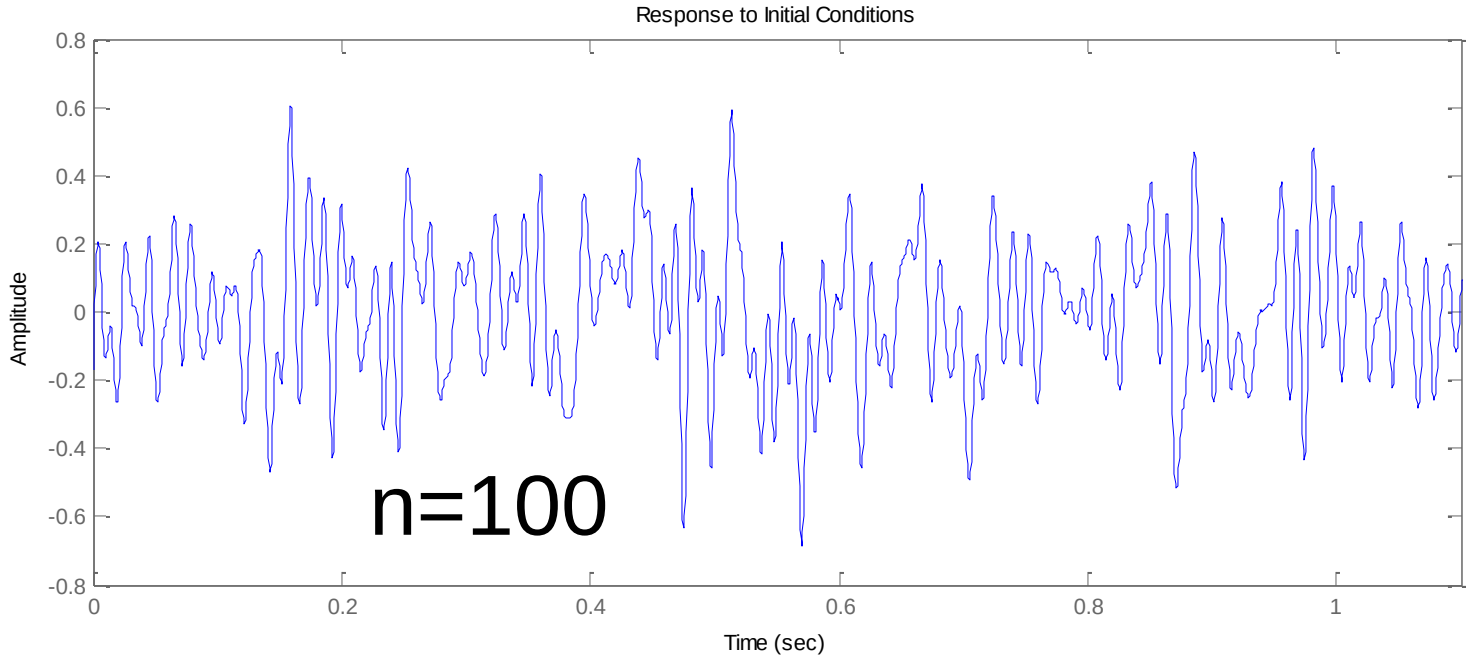
$$\sum \frac{s}{s^2 + \omega_k^2}$$

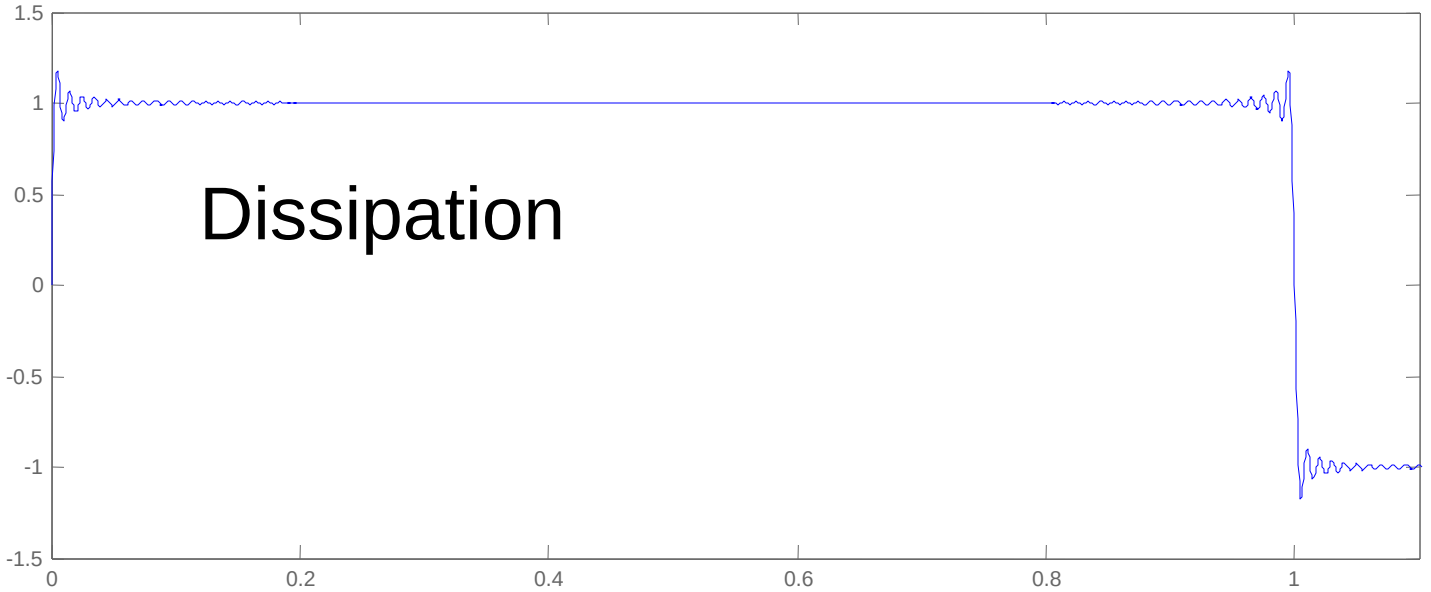


random initial conditions

$$\sum \frac{s}{s^2 + \omega_k^2}$$

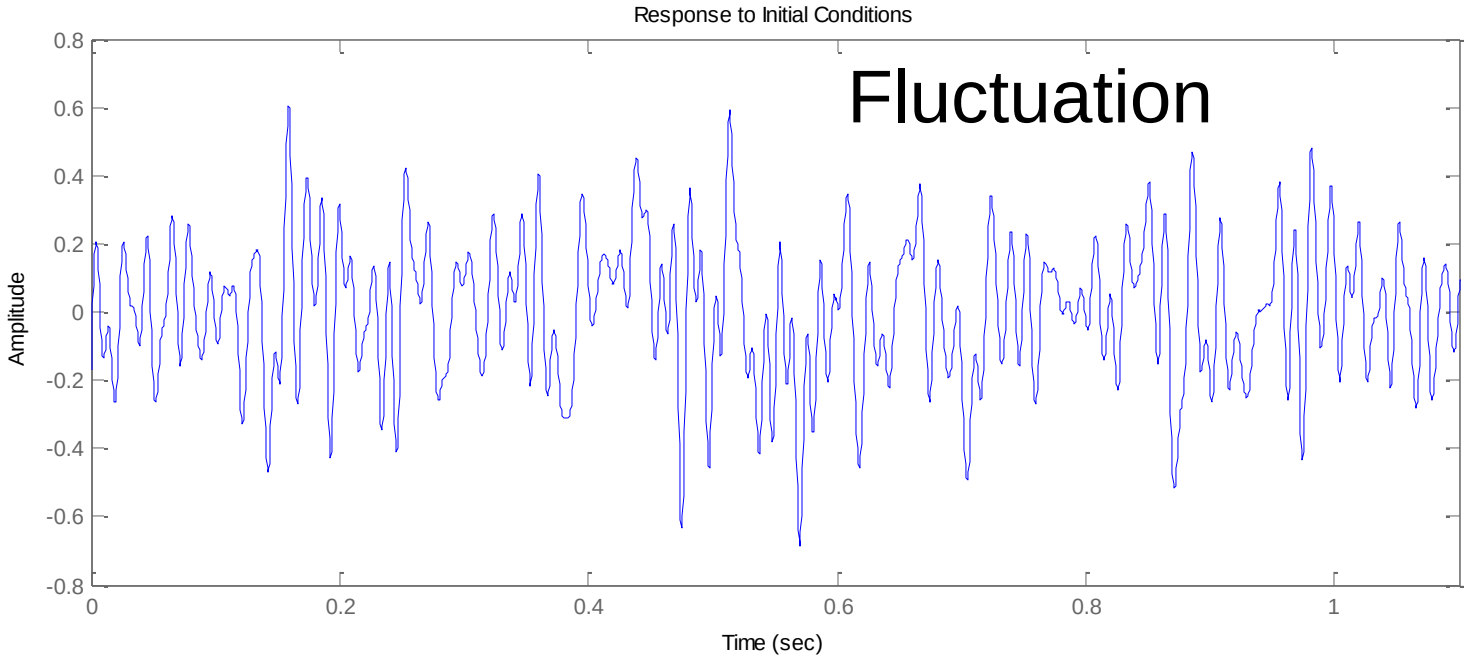

Response to Initial Conditions
Amplitude
Time (sec)
n=10
T=1


Response to Initial Conditions
Amplitude
Time (sec)
n=100



Theorem: Fluctuation $\Leftrightarrow$ Dissipation

T=1

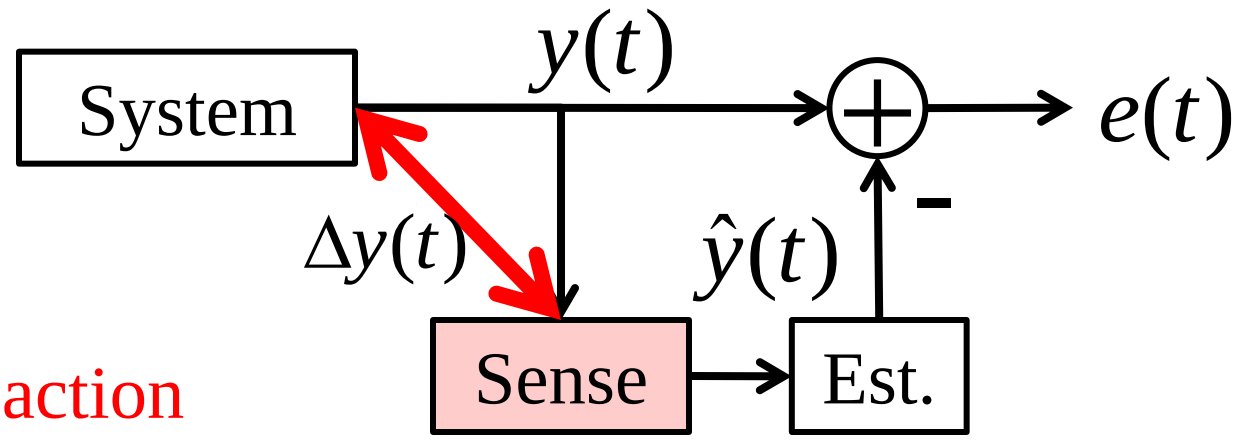


Theorem: Fluctuation $\Leftrightarrow$ Dissipation

Theorem: Linear passive ***iff***
linear lossless approximation

Theorem: Linear *active* needs
*non*linear lossless approximation

Consequences

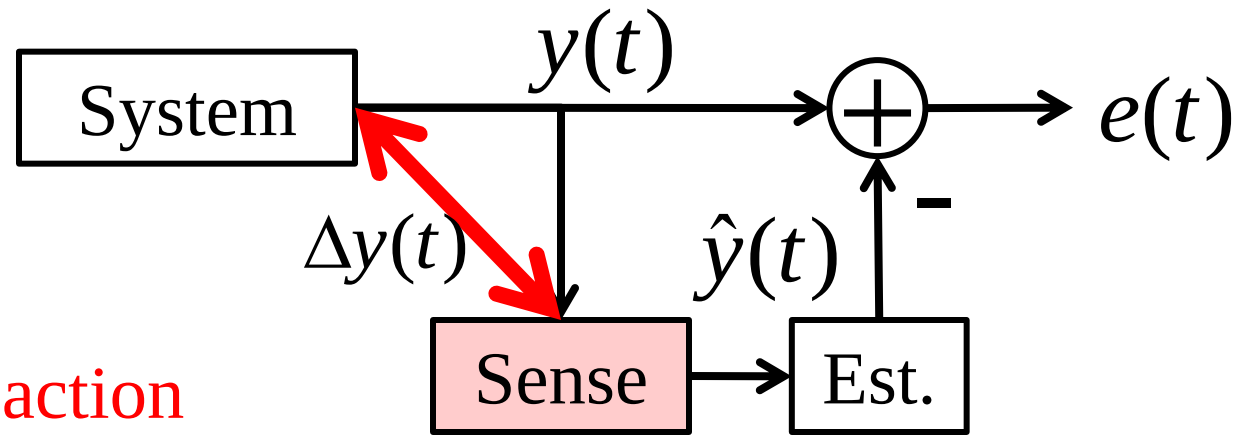


Back action

Sensor “noise”

“Physical” implementation

- Sensor at temp T
- Short interval $(0,t)$



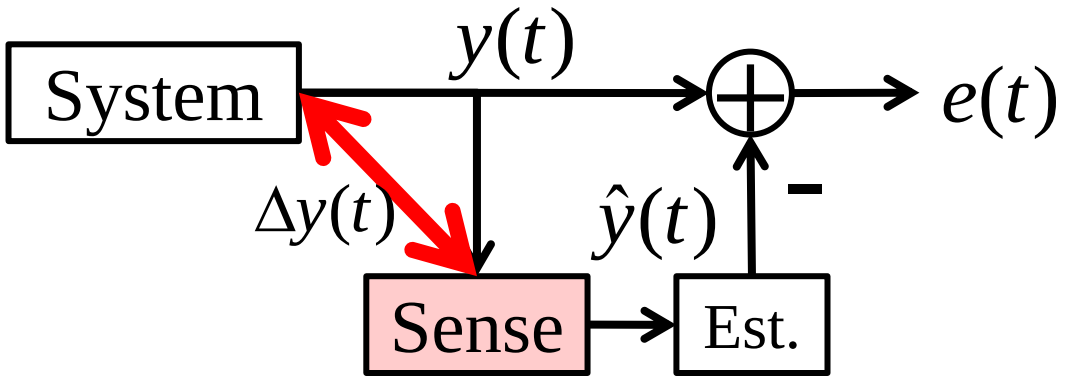
Back action

$$E\left(\Delta y^2(t)\right) \geq kTt + O\left(t^2\right)$$

Sensor "noise"

$$E\left(e^2(t)\right) \geq \frac{kT}{t} + O(1)$$

Theorem



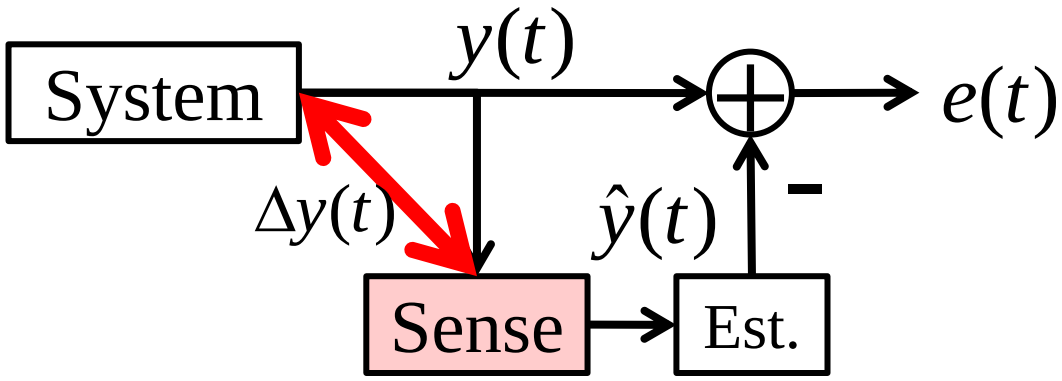
back-action

$\Delta y(t)$

$$E\left(\Delta y^2(t)\right) \geq kTt$$

$$E\left(e^2(t)\right) \geq \frac{kT}{t} + O(1)$$

error $e(t)$

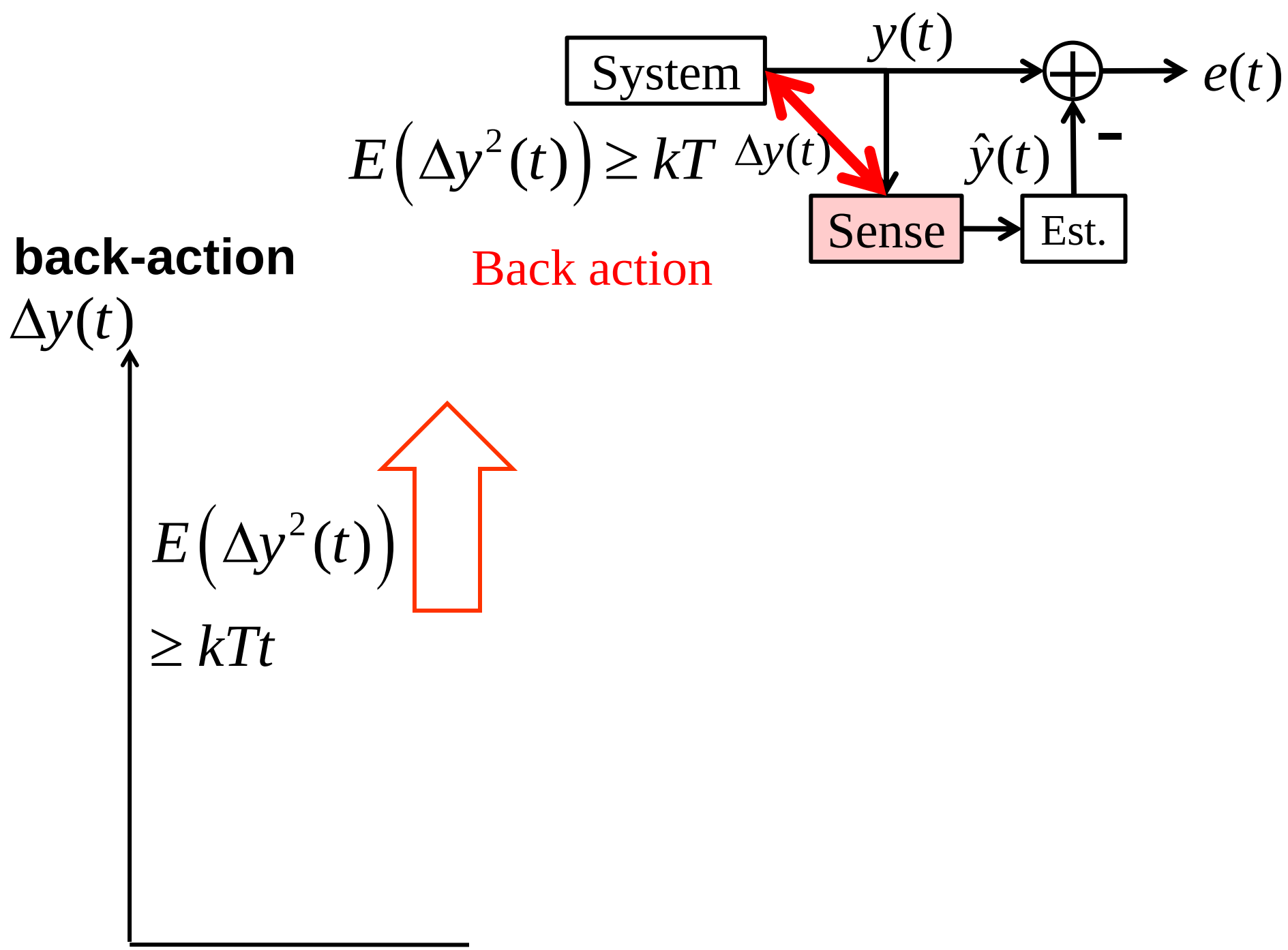


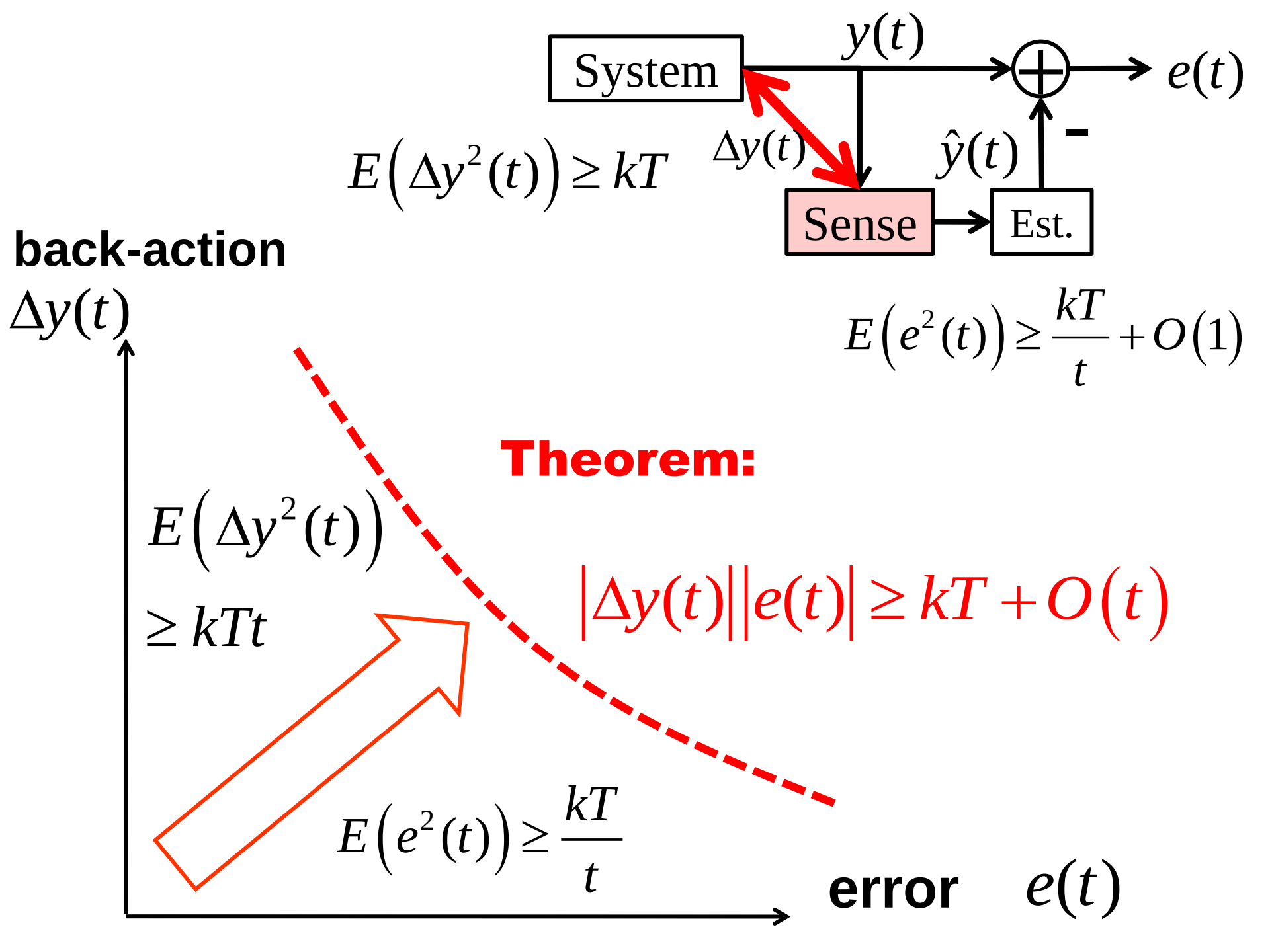
$$E\left(e^2(t)\right) \geq \frac{kT}{t} + O(1)$$

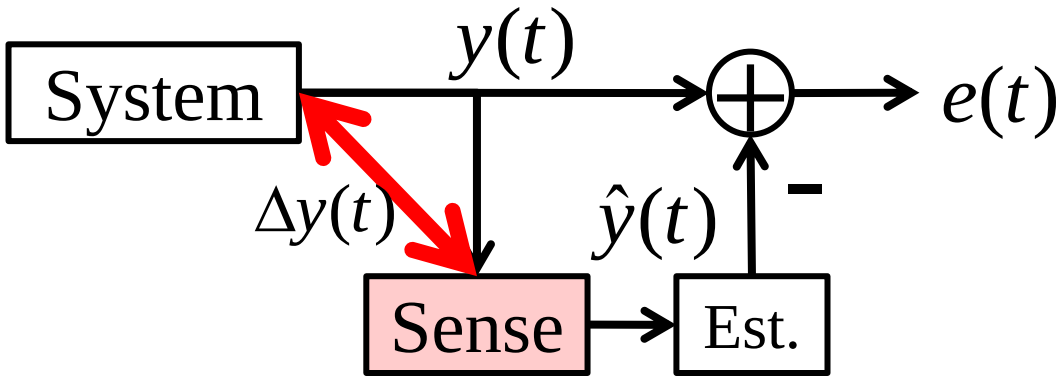
Sensor "noise"

$$E\left(e^2(t)\right) \geq \frac{kT}{t}$$

error $e(t)$


System
$y(t)$
$e(t)$
$E\left(\Delta y^2(t)\right) \geq kT$
$\Delta y(t)$
$\hat{y}(t)$
-
Sense
Est.
Back action
back-action
$\Delta y(t)$
$E\left(\Delta y^2(t)\right)$
$\geq kTt$


System
$y(t)$
$e(t)$
$\Delta y(t)$
$\hat{y}(t)$
-
Sense
Est.
$E\left(\Delta y^2(t)\right) \geq kT$
back-action
$\Delta y(t)$
$E\left(e^2(t)\right) \geq \frac{kT}{t} + O(1)$
Theorem:
$E\left(\Delta y^2(t)\right)$
$\geq kTt$
$|\Delta y(t)||e(t)| \geq kT + O(t)$
$E\left(e^2(t)\right) \geq \frac{kT}{t}$
error $e(t)$



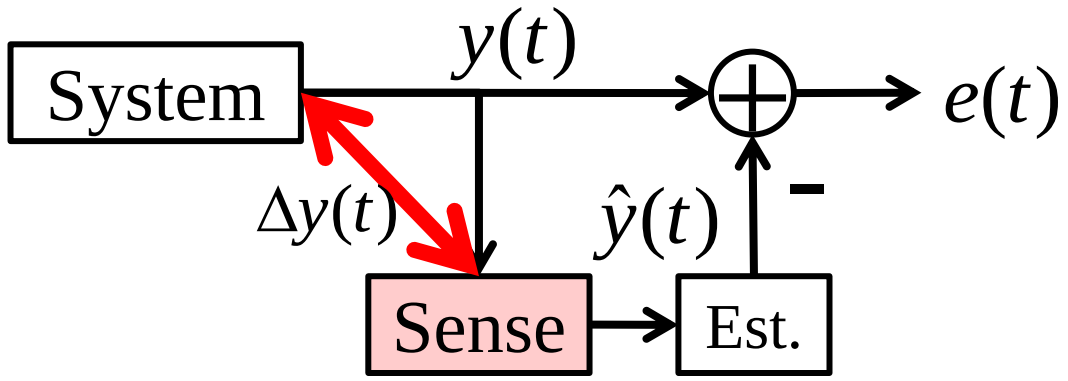
back-action

$\Delta y(t)$

$$|\Delta y(t)||e(t)| \geq kT + O(t)$$

Cold sensors
are better
and faster
(but not cheaper)

error $e(t)$



back-action

larger t
more data

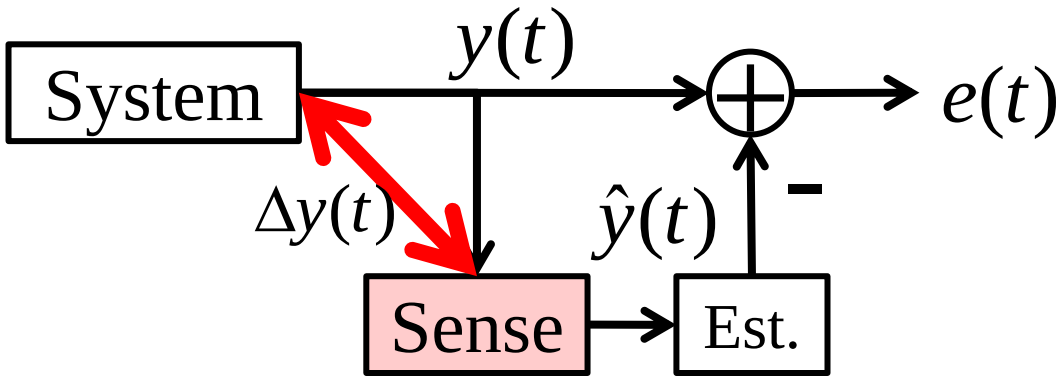
$$\left|\Delta y(t)\right|\left|e(t)\right| = kT$$

$$E\left(\Delta y^2(t)\right) \geq kTt$$

smaller t
less data

$$E\left(e^2(t)\right) \geq \frac{kT}{t}$$

error



back-action

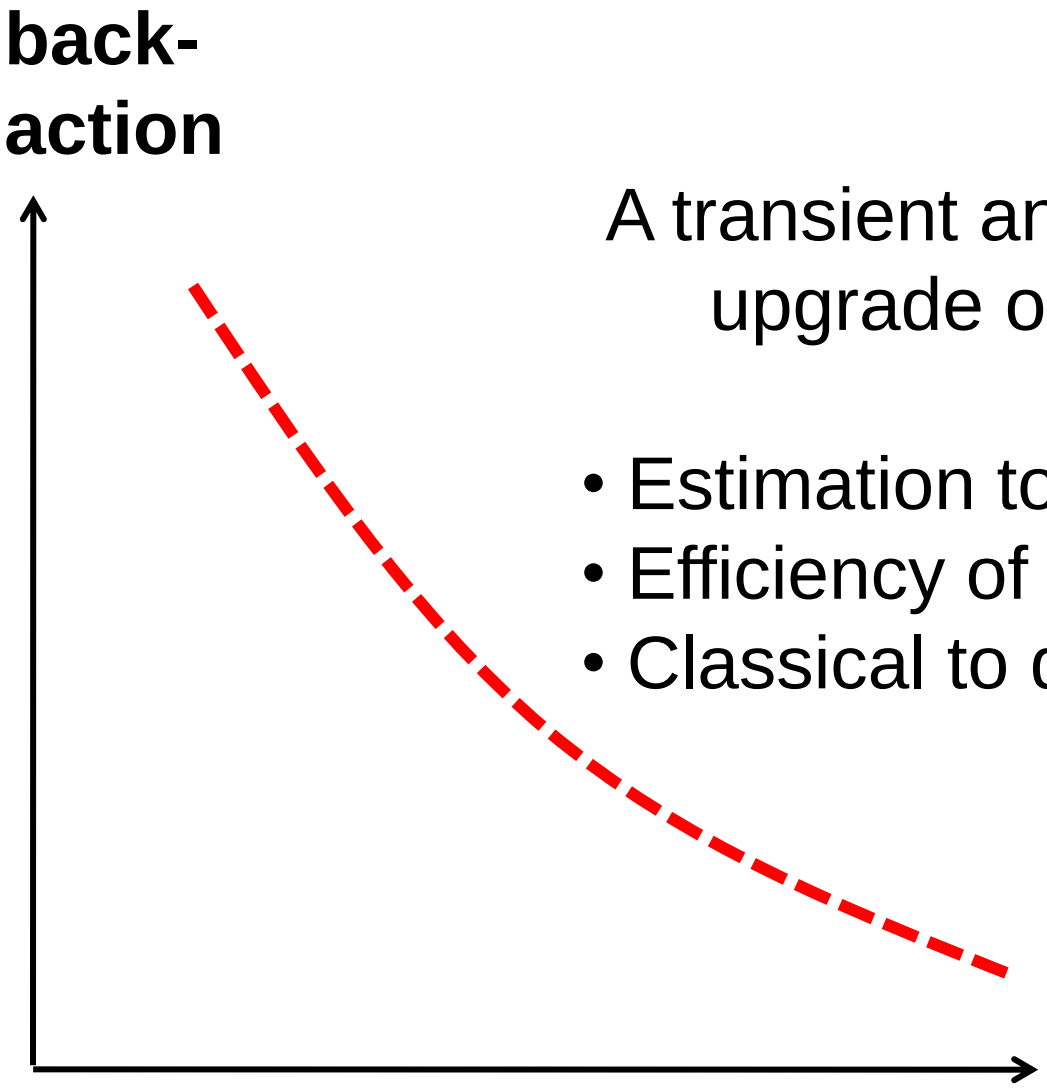
A transient and far-from-equilibrium upgrade of statistical mechanics

$E\left(\Delta y^2(t)\right) \geq kTt$

$|\Delta y(t)||e(t)| \geq kT + O(t)$

$E\left(e^2(t)\right) \geq \frac{kT}{t}$

error



A transient and far-from-equilibrium upgrade of statistical mechanics

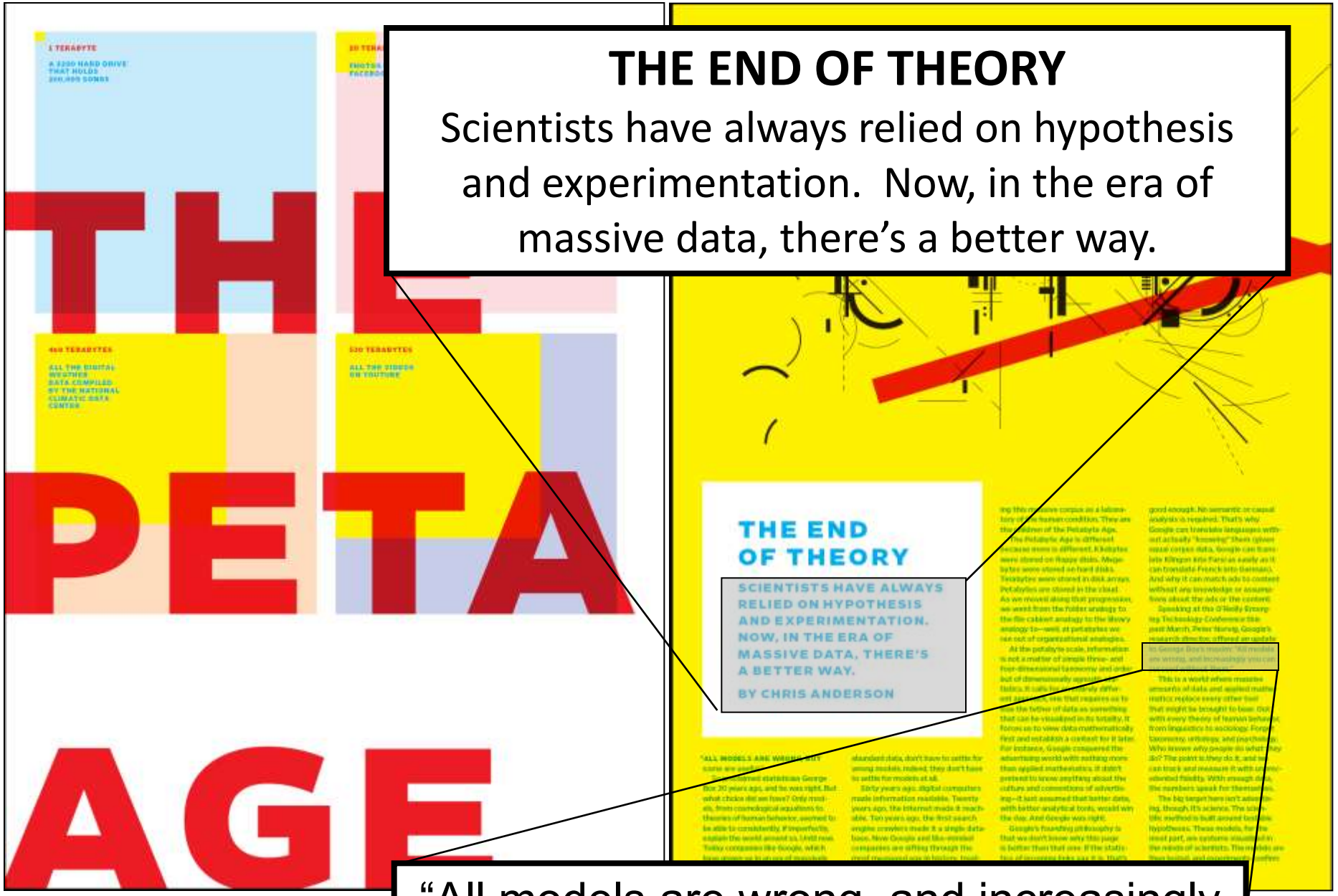
- Estimation to control
- Efficiency of devices, enzymes
- Classical to quantum

Some frivolities

and/or a rant

Save our children

There is a treatment.



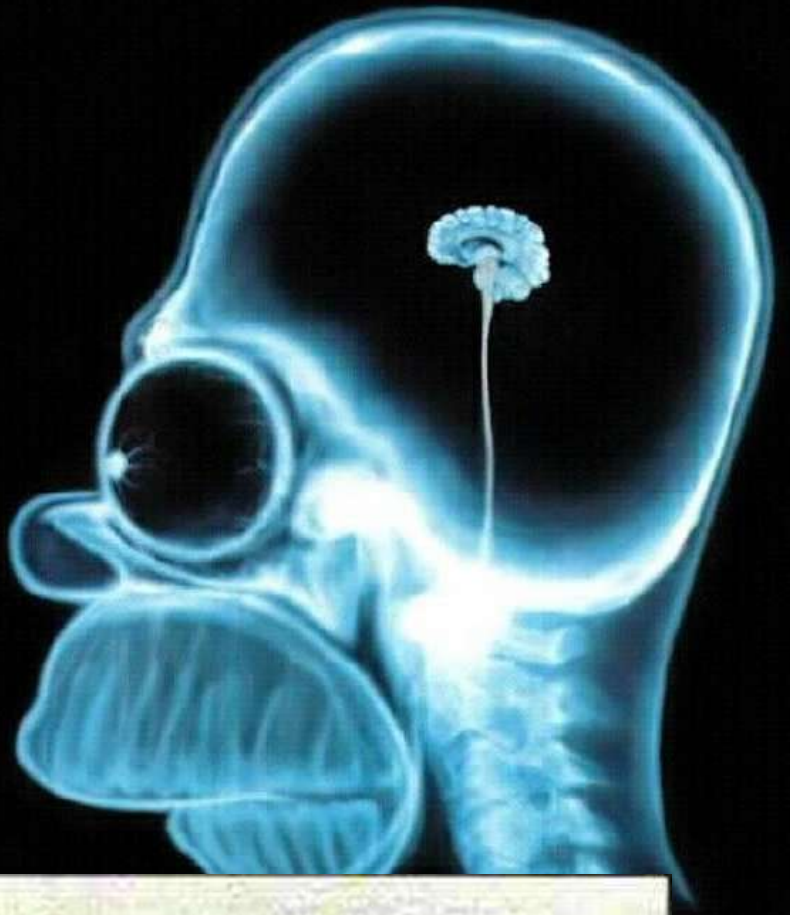
THE END OF THEORY

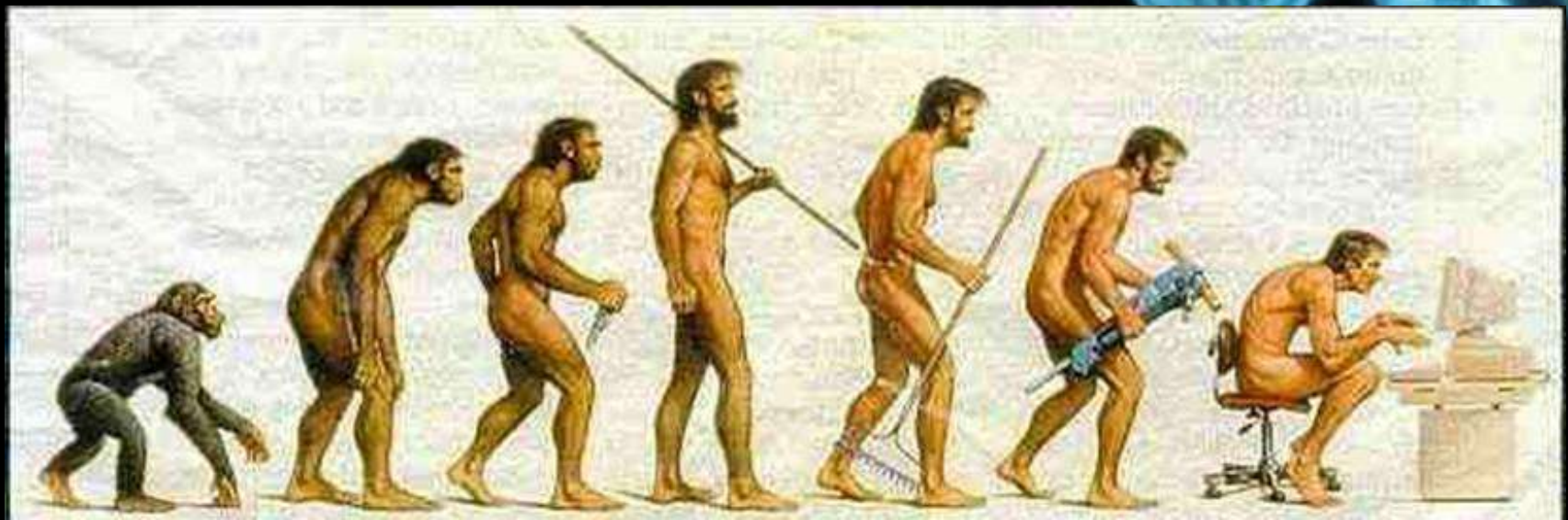
Scientists have always relied on hypothesis and experimentation. Now, in the era of massive data, there's a better way.

"All models are wrong, and increasingly you can succeed without them."

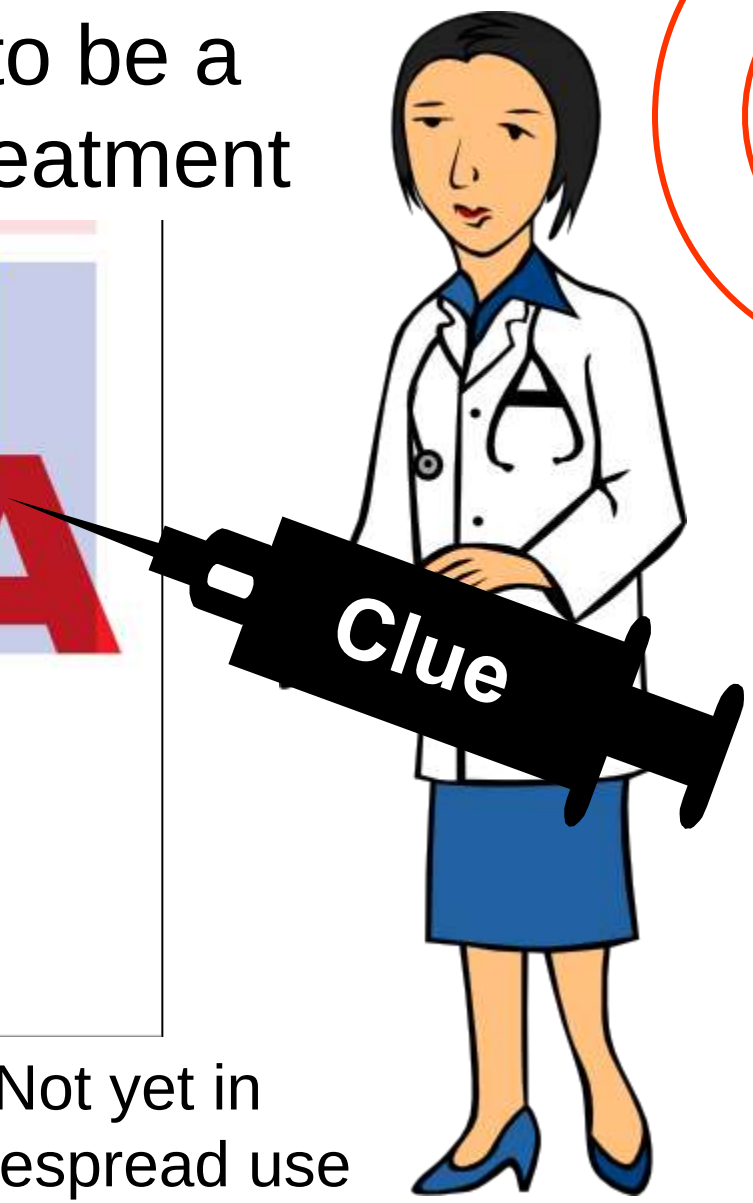
New words

- **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



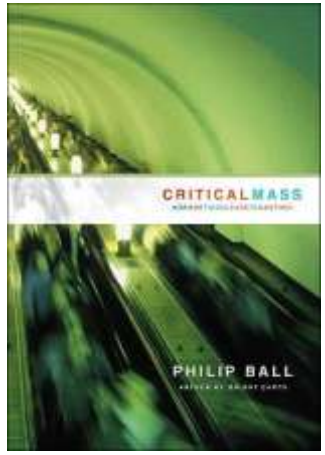


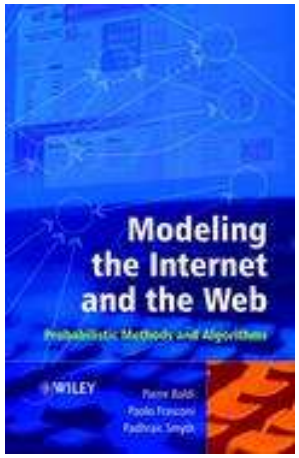
Fortunately there seems to be a treatment

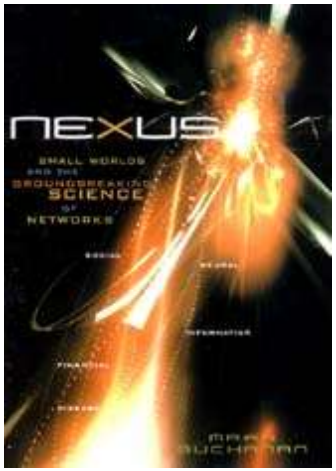


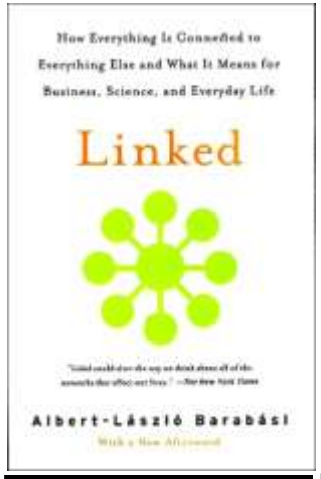
Peta-philia

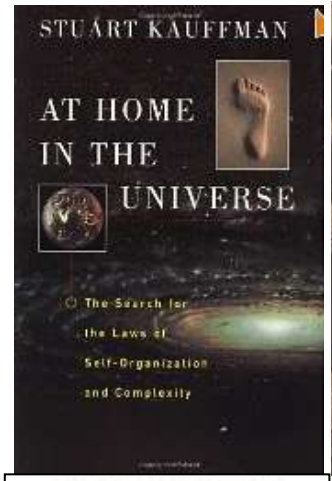
Not yet in widespread use

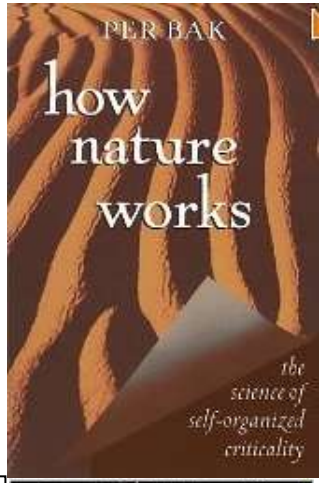

CRITICAL MASS
PHILIP BALL

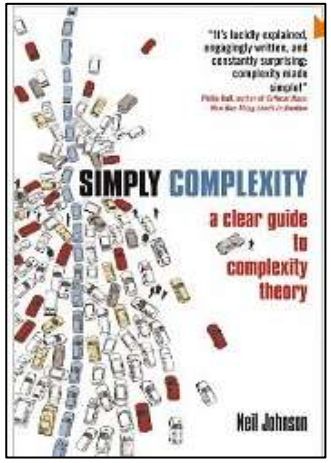

Modeling the Internet and the Web
Probabilistic Methods and Algorithms
WILEY

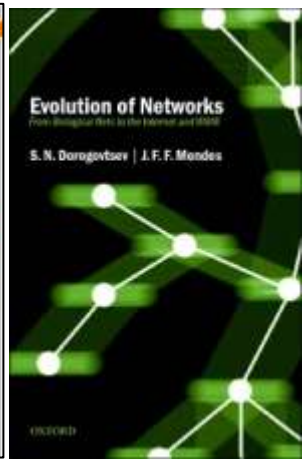

nexus
SCIENCE OF NETWORKS

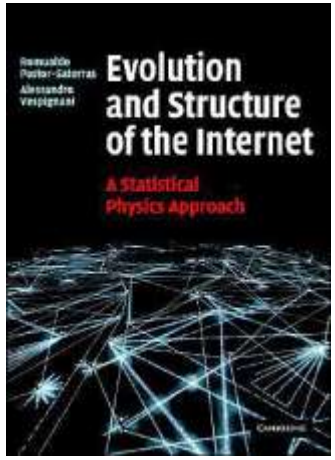

How Everything Is Connected to Everything Else and What It Means for Business, Science, and Everyday Life
Linked
Albert-László Barabási

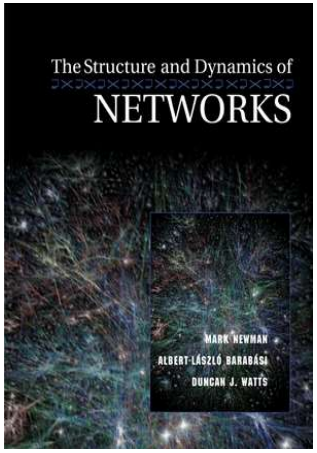

STUART KAUFFMAN
AT HOME IN THE UNIVERSE
The Search for the Laws of Self-Organization and Complexity

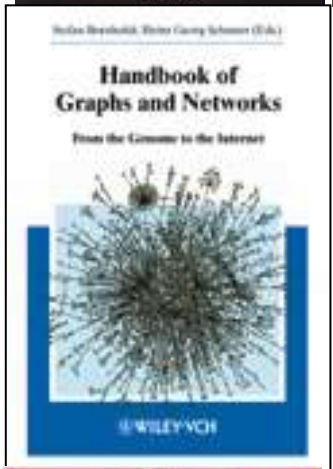

PER BAK
how nature works
the science of self-organized criticality


SIMPLY COMPLEXITY
a clear guide to complexity theory
Neil Johnson


Evolution of Networks
S. N. Dorogovtsev | J. F. F. Mendes


Evolution and Structure of the Internet
A Statistical Physics Approach


The Structure and Dynamics of NETWORKS
MARK NEWMAN
ALBERT-LÁSZLÓ BARABÁSI
DUNCAN J. WATTS


Handbook of Graphs and Networks
From the Genome to the Internet
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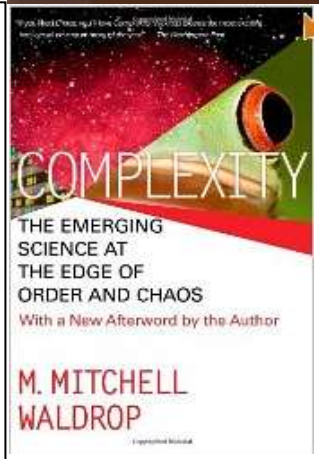
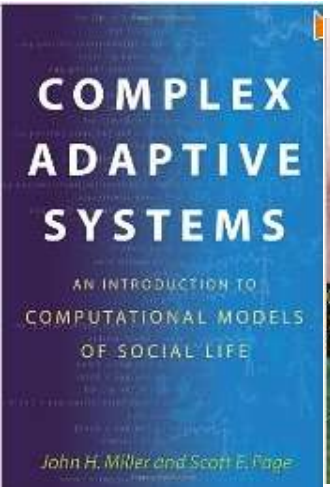
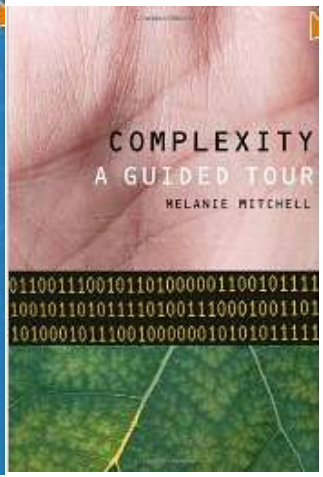
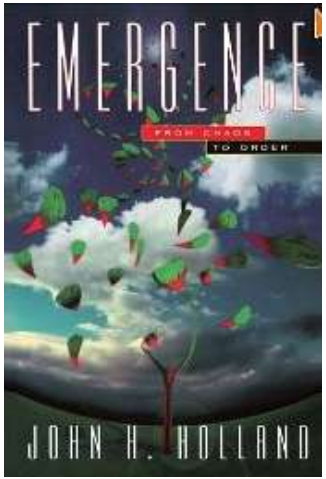
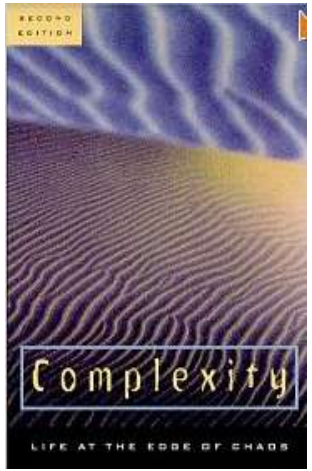
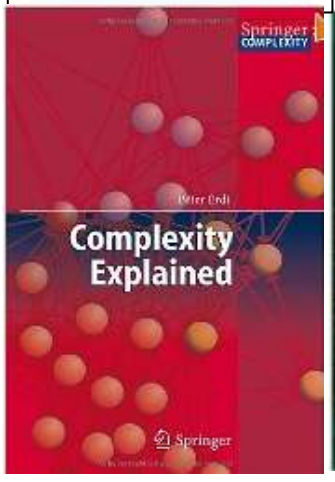

COMPLEXITY
THE EMERGING SCIENCE AT THE EDGE OF ORDER AND CHAOS
With a New Afterword by the Author
M. MITCHELL WALDROP

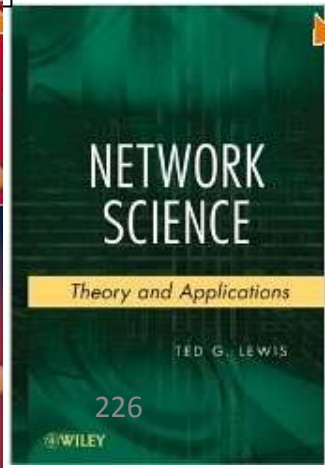

COMPLEX ADAPTIVE SYSTEMS
AN INTRODUCTION TO COMPUTATIONAL MODELS OF SOCIAL LIFE
John H. Miller and Scott E. Page


COMPLEXITY
A GUIDED TOUR
MELANIE MITCHELL


EMERGENCE
FROM CHAOS TO ORDER
JOHN H. HOLLAND


SECOND EDITION
Complexity
LIFE AT THE EDGE OF CHAOS


Springer COMPLEXITY
Complexity Explained
Springer


NETWORK SCIENCE
Theory and Applications
TED G. LEWIS
WILEY

Complex systems?

Even small amounts can create bewildering complexity

Fragile

- Scale
- Dynamics
- Nonlinearity
- Nonequlibrium
- Open
- Feedback
- Adaptation
- Intractability
- Emergence
- …

Complex systems?

Robust

- Scale
- Dynamics
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Fragile

- Scale
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Complex systems?

Robust complexity

- Scale
- Dynamics
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- Emergence
- …

- Resources
- Controlled
- Organized
- Structured
- Extreme
- Architected
- …

Architecture

Robust complexity

- Scale
- Dynamics
- Nonlinearity
- Nonequlibrium
- 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
- Nonequlibrium
- Open
- Feedback
- Adaptation
- Intractability
- Emergence
- …

Convey the basics?

- Is there any way to tell some aspects of layered architecture
- that is broadly accessible