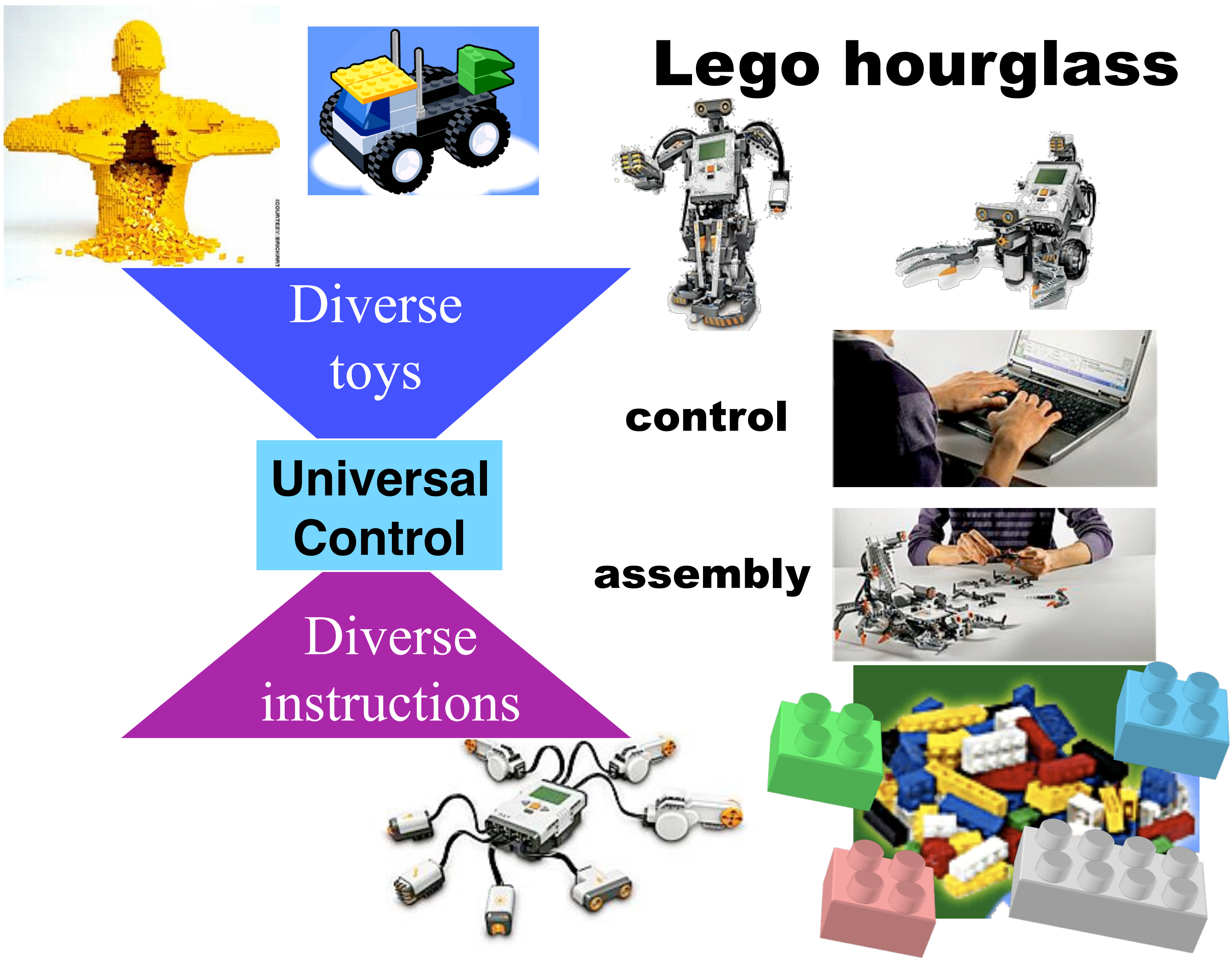


Lego hourglass
Diverse toys
Universal Control
Diverse instructions
control
assembly

Robust yet fragile

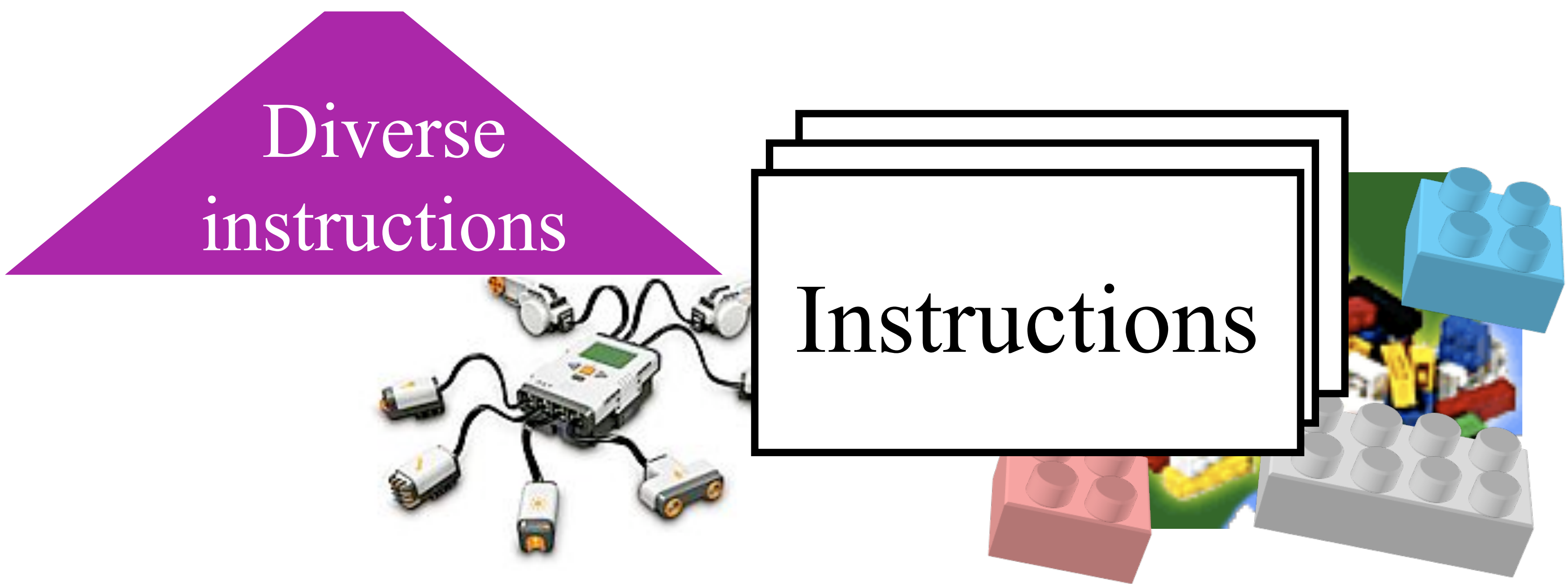
Extremes of

- Robust yet fragile
- Simplicity and complexity
- Constrained and flexible
- Frozen and evolvable
- Digital and analog
- Diverse and conserved

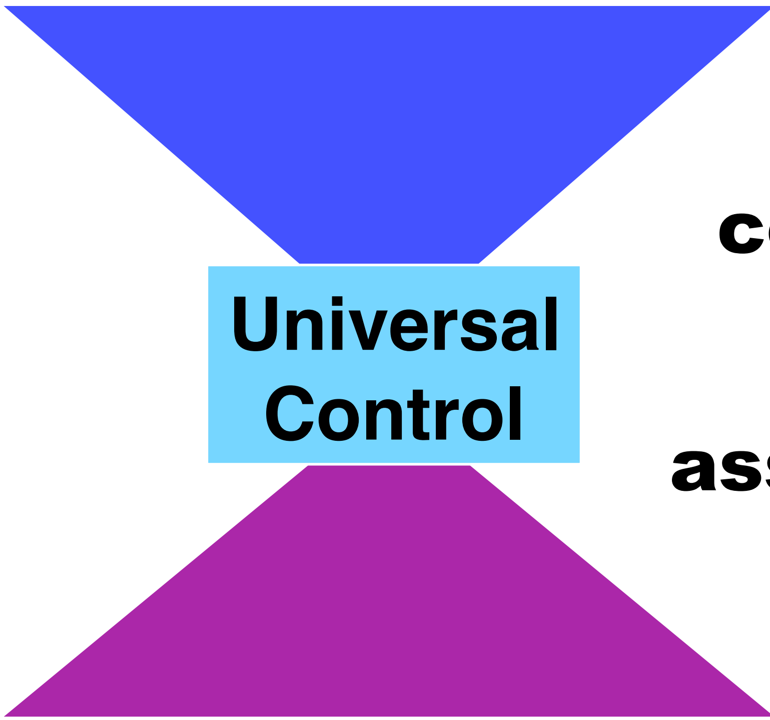
Lego hourglass

Diverse toys

Lego hourglass



Lego hourglass



control

assembly

Lego *system* requirements

	Alternative designs?			
Performance				
Trauma				
Allowed connections				
Reuse				
Evolvable parts				
Evolvable systems				
Labor cost				
Parts cost				

Lego hourglass

Huge variety

Standardized mechanisms
Highly conserved

control

assembly

Huge variety

Lego

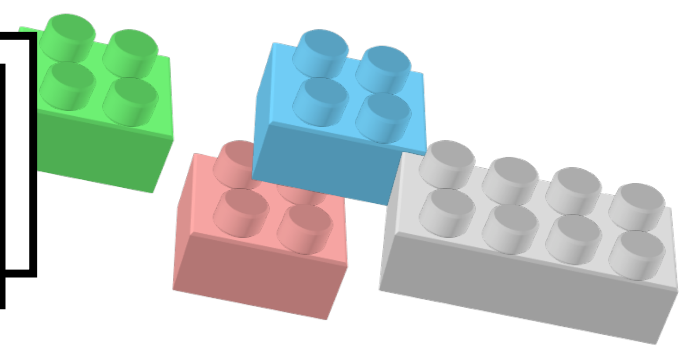
Huge variety

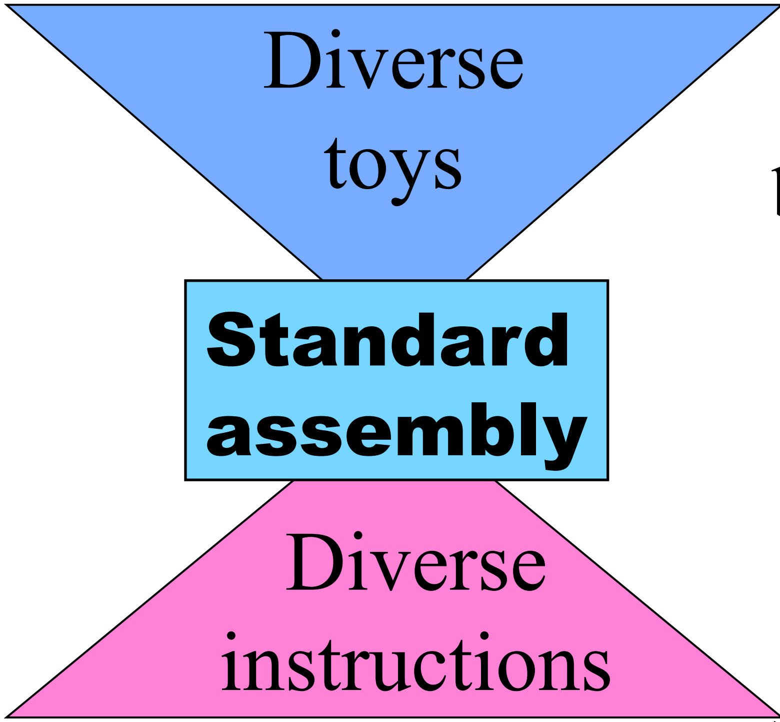
Limited environmental uncertainty needs minimal control

Standard assembly

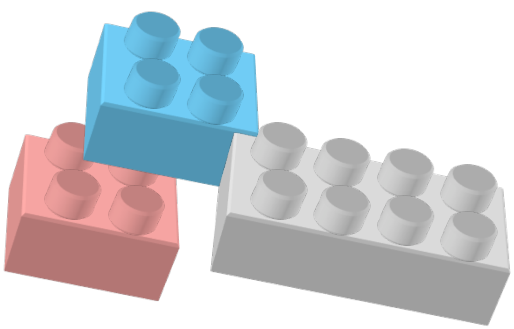
Huge variety

Instructions

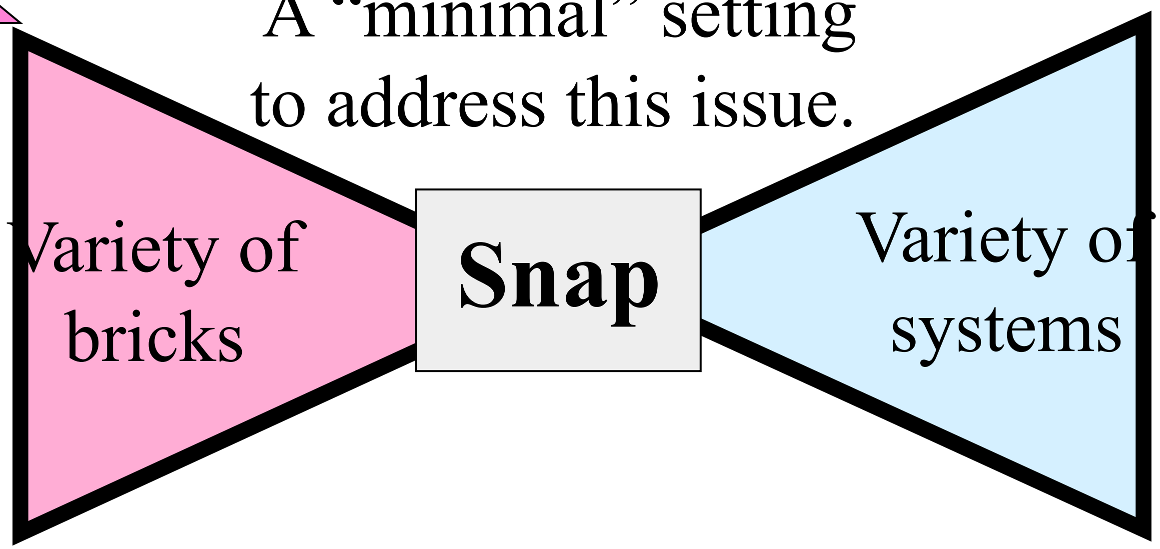




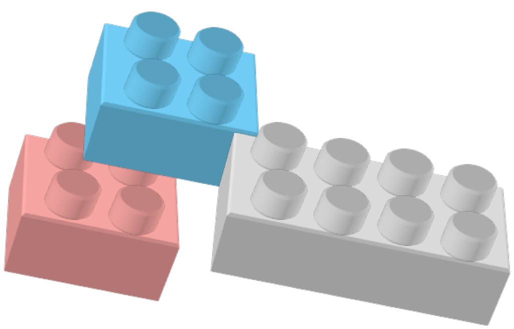
Question: what is the difference between hourglass and bowtie here?

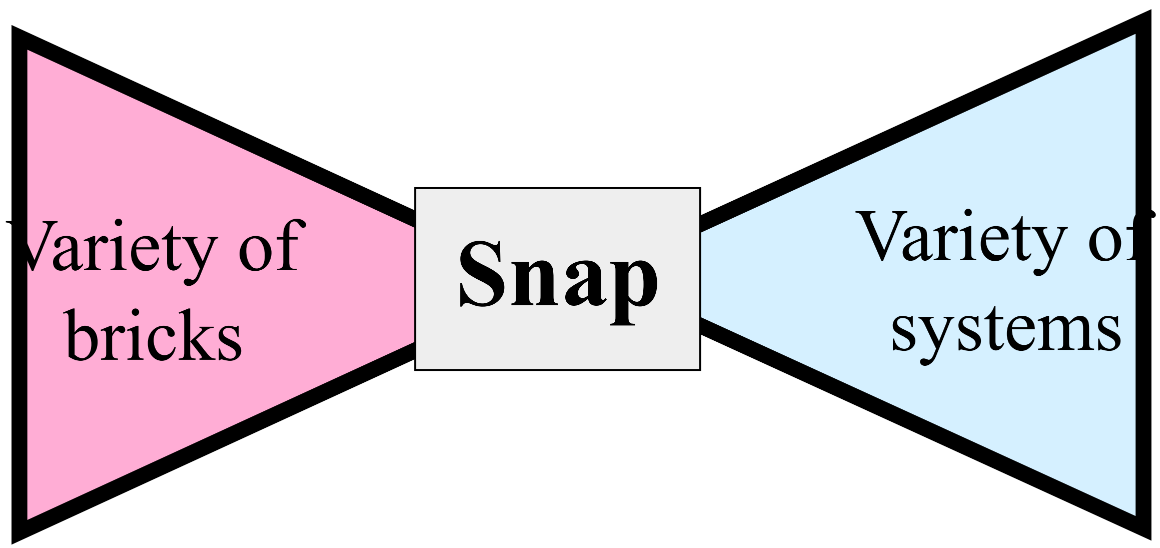


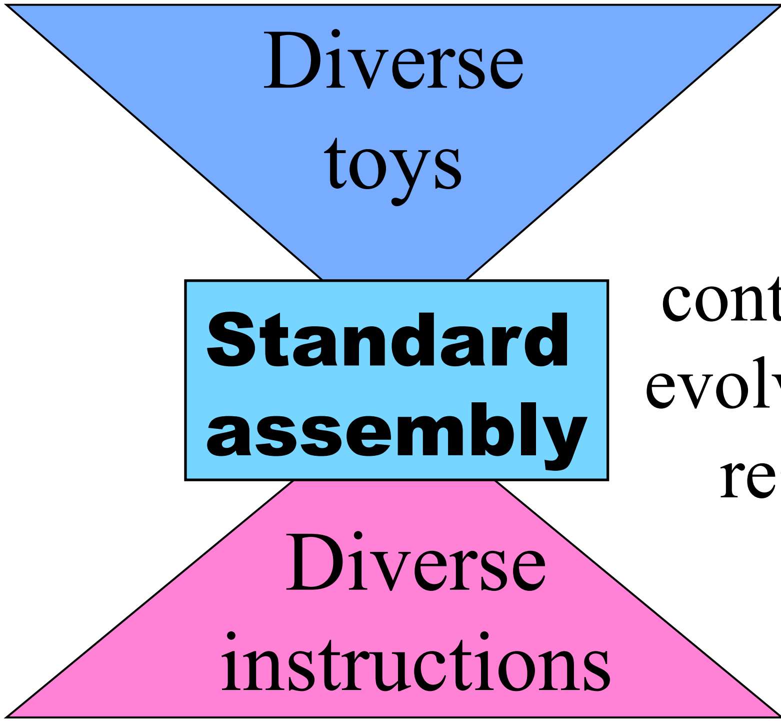
A "minimal" setting to address this issue.



The snap is a static interface specification.

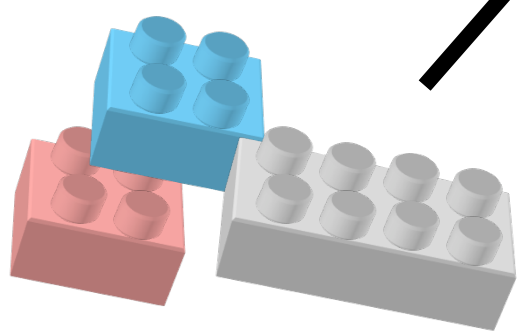


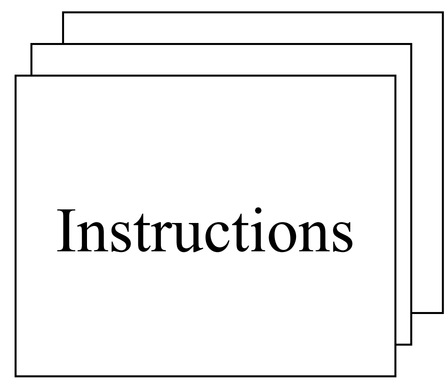


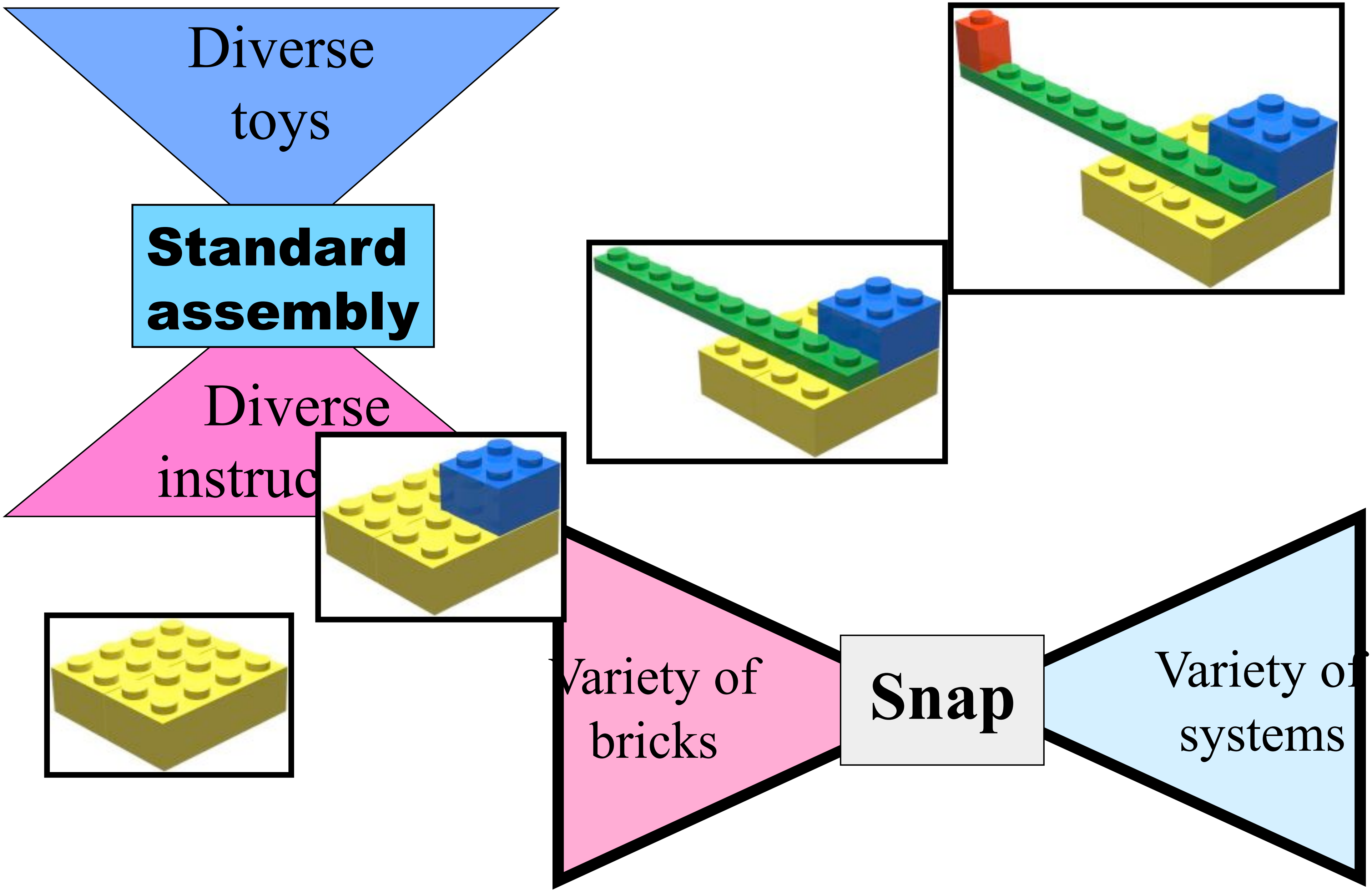


Assembly is a control process that evolves in time, and respects the snap, but adds to it.

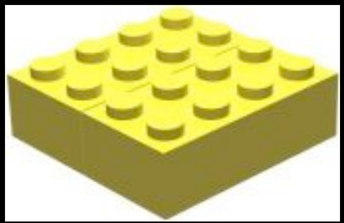
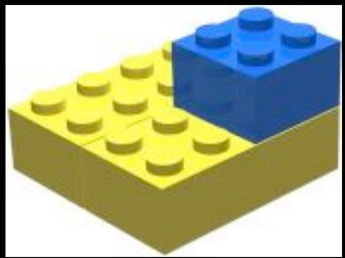
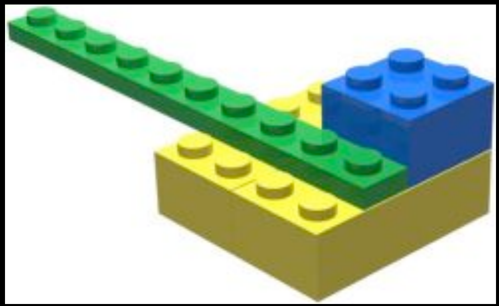
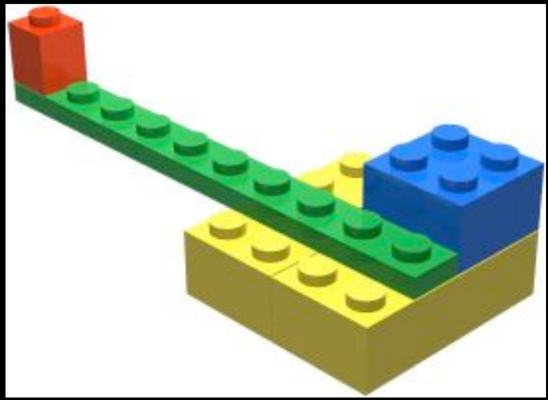
It inputs instructions and components and outputs assembled systems.

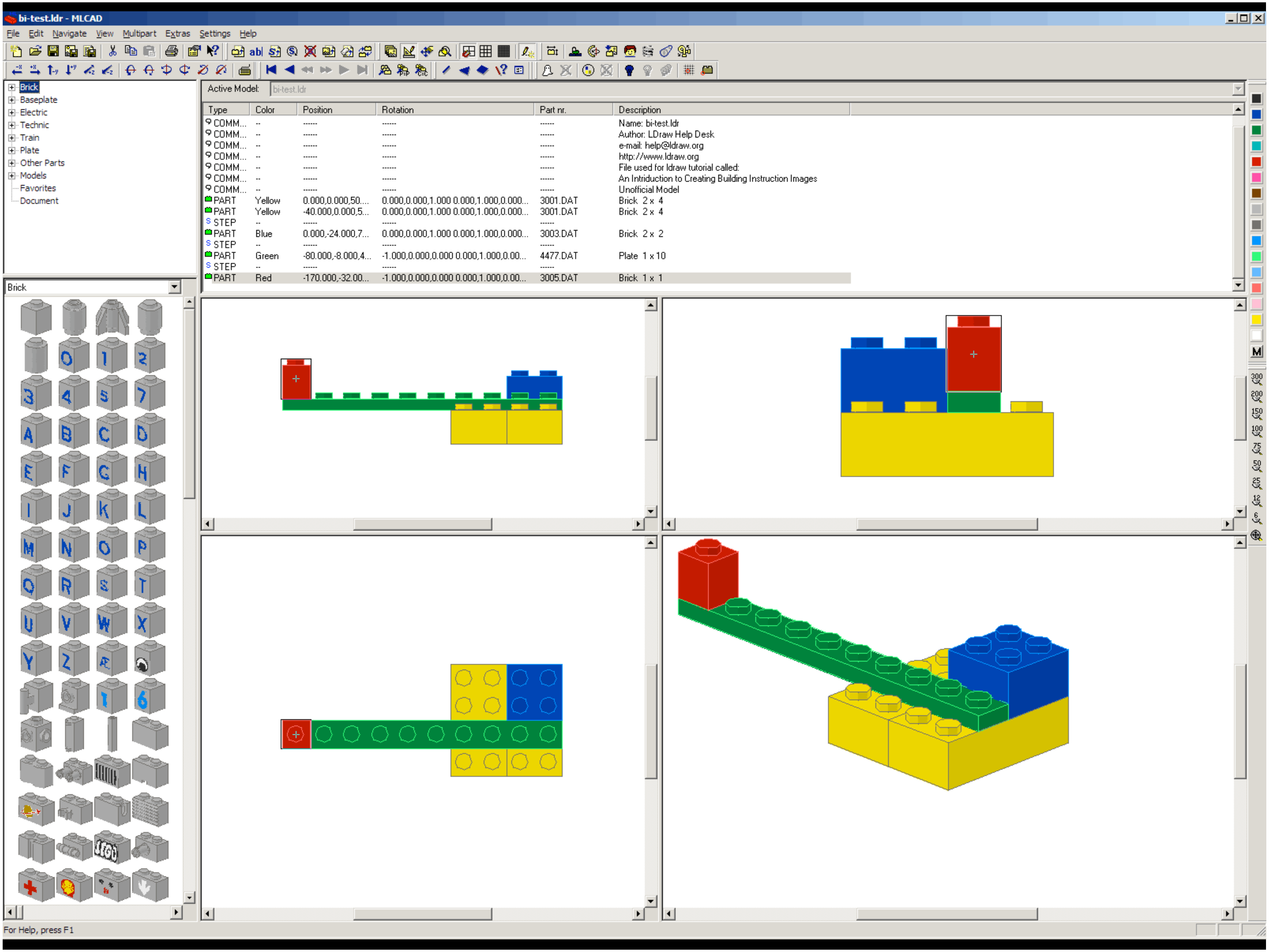


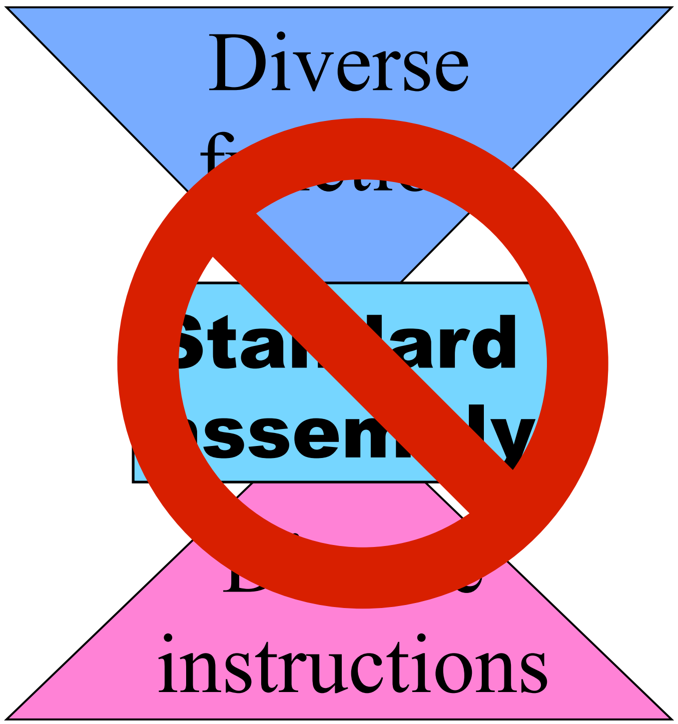




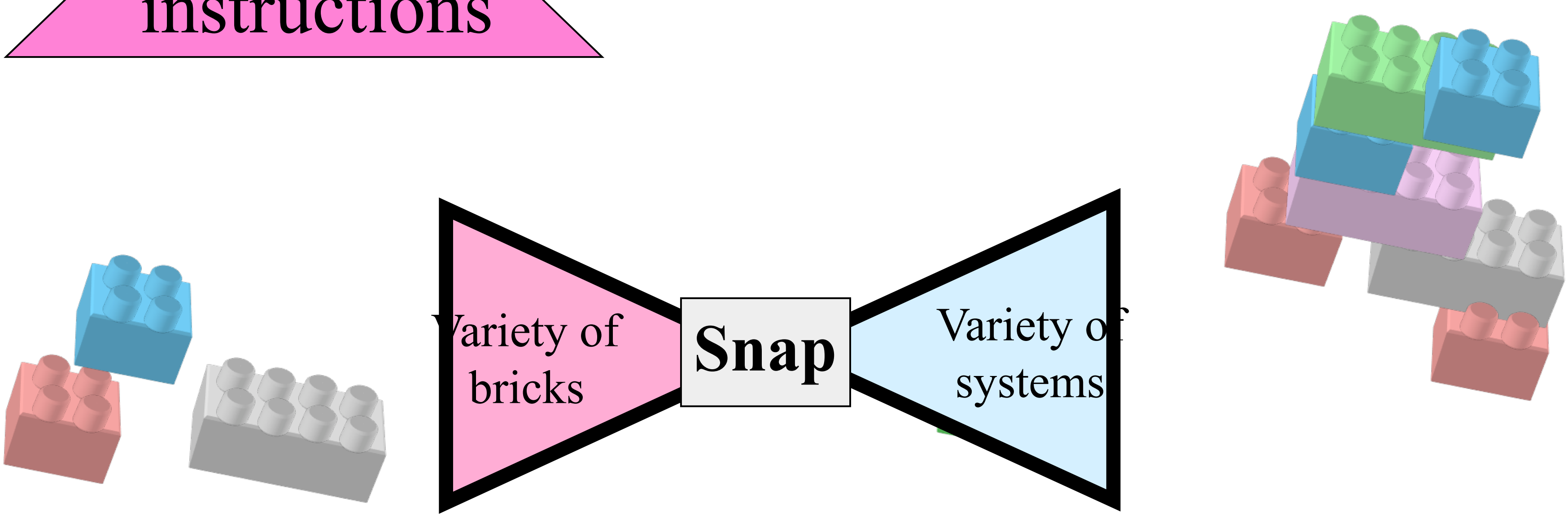
Diverse toys
Standard assembly
Diverse
instruc
Variety of bricks
Snap
Variety of systems

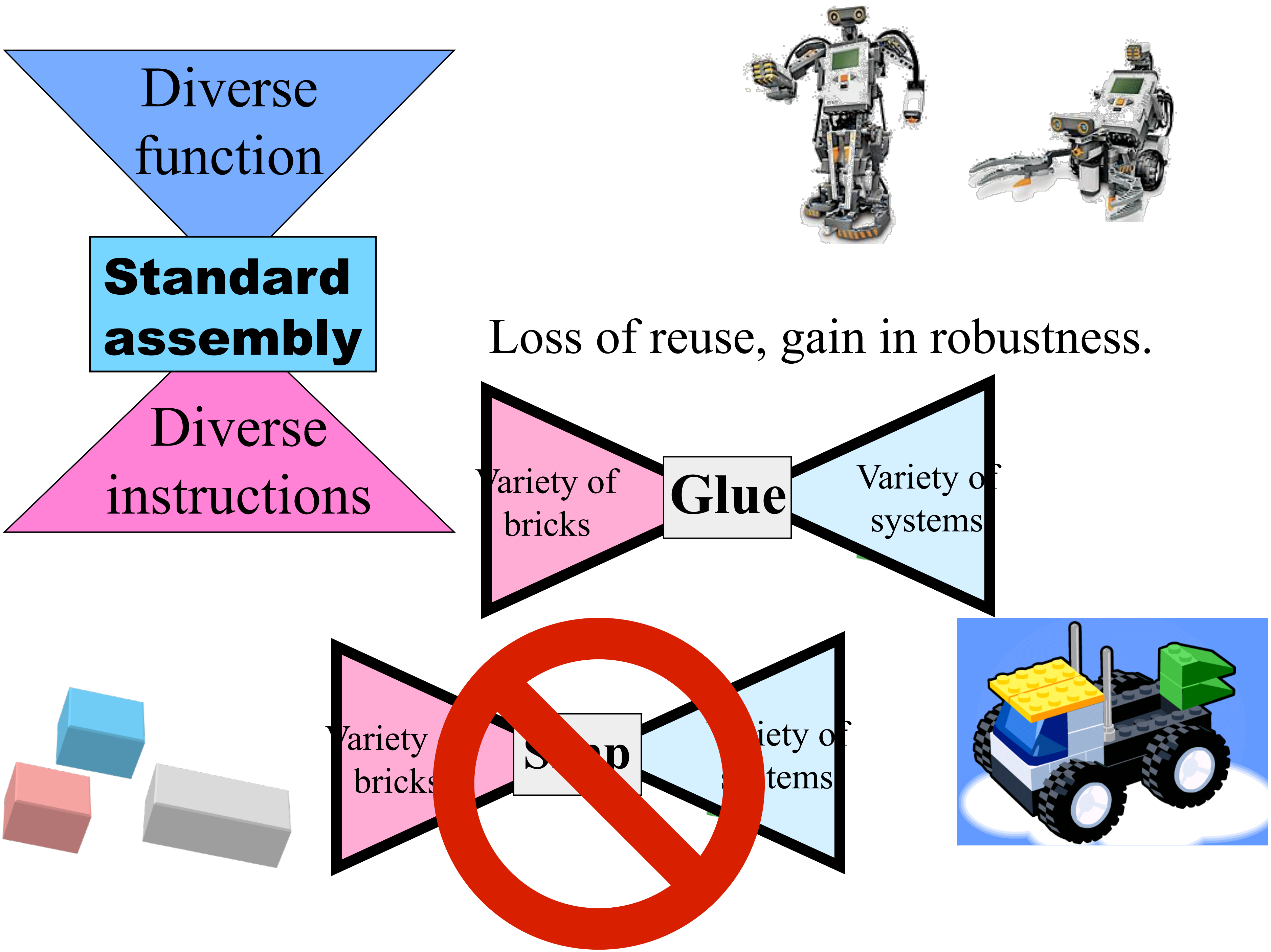





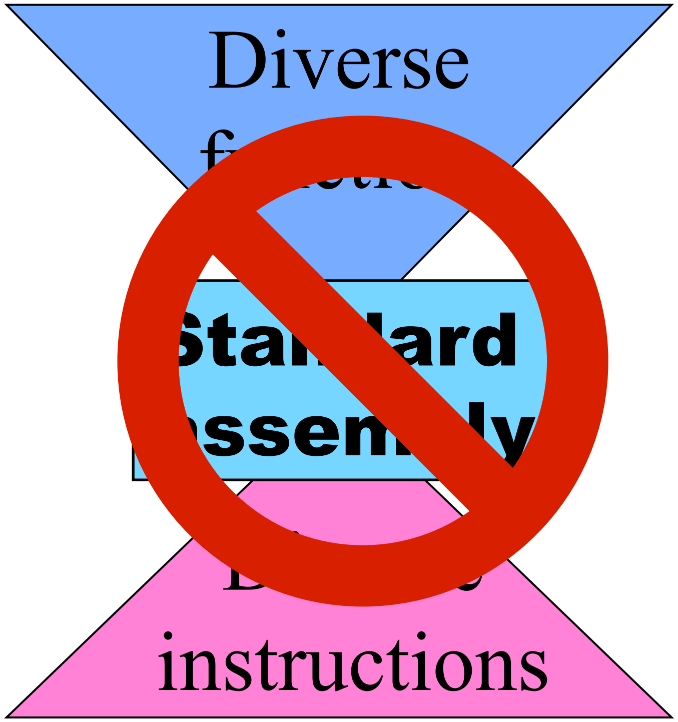

bi-test.ldr - MLCAD
File Edit Navigate View Multipart Extras Settings Help
Brick
Baseplate
Electric
Technic
Train
Plate
Other Parts
Models
Favorites
Document
Active Model: bi-test.ldr
Type Color Position Rotation Part nr. Description
COMM... Name: bi-test.ldr
COMM... Author: LDraw Help Desk
COMM... e-mail: help@ldraw.org
COMM... http://www.ldraw.org
COMM... File used for ldraw tutorial called:
COMM... An Intriduction to Creating Building Instruction Images
COMM... Unofficial Model
PART Yellow 0.000,0.000,50.... 0.000,0.000,1.000 0.000,1.000,0.000... 3001.DAT Brick 2 x 4
PART Yellow -40.000,0.000,5... 0.000,0.000,1.000 0.000,1.000,0.000... 3001.DAT Brick 2 x 4
STEP
PART Blue 0.000,-24.000,7... 0.000,0.000,1.000 0.000,1.000,0.000... 3003.DAT Brick 2 x 2
STEP
PART Green -80.000,-8.000,4... -1.000,0.000,0.000 0.000,1.000,0.00... 4477.DAT Plate 1 x 10
STEP
PART Red -170.000,-32.00... -1.000,0.000,0.000 0.000,1.000,0.00... 3005.DAT Brick 1 x 1
Brick
For Help, press F1

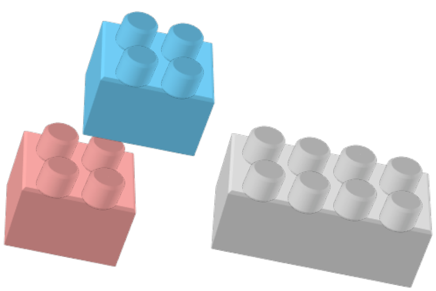
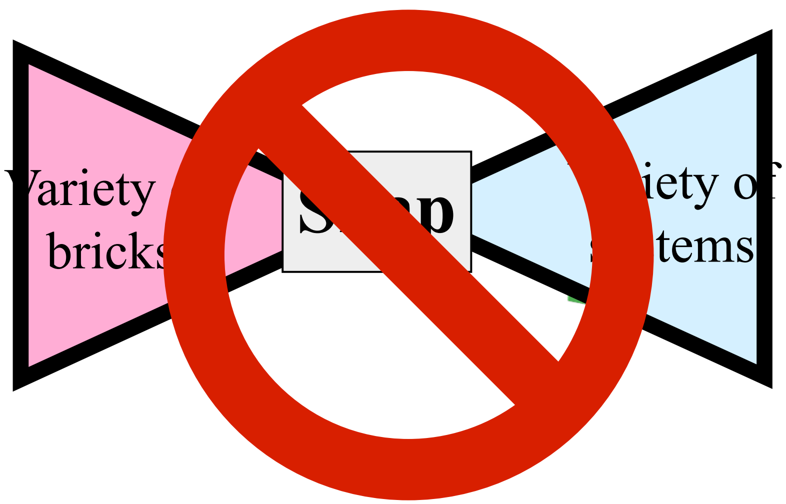


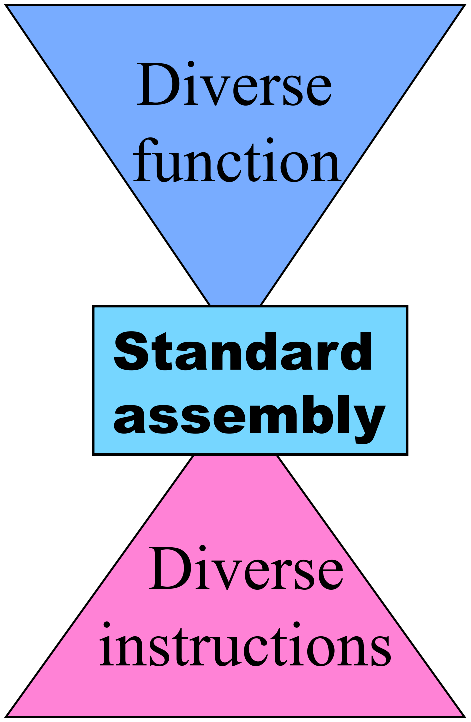
Random, uncontrolled, snap connection of Lego parts yields “nonfunctional” toys.




Diverse function
Standard assembly
Diverse instructions
Loss of reuse, gain in robustness.
Variety of bricks
Glue
Variety of systems
bricks

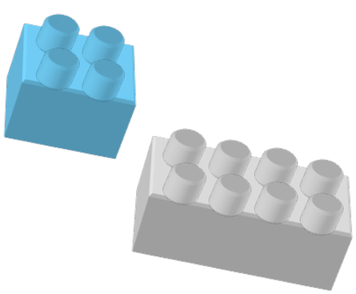

Diverse
instructions

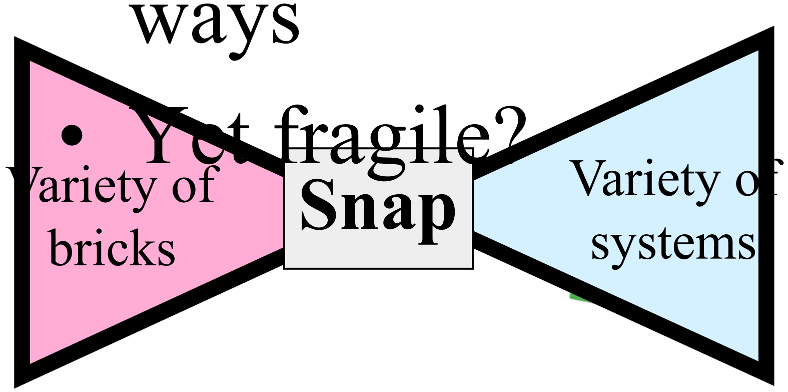


bricks

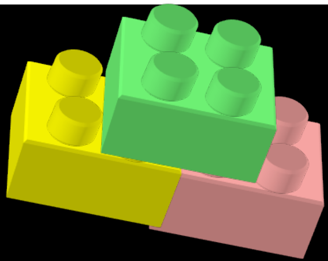


Robustness/ Evolvability

- A huge variety of new and different toys can be built
- From a huge variety of different components
- Both toys and components can be rearranged and added in new ways
- Yet fragile?

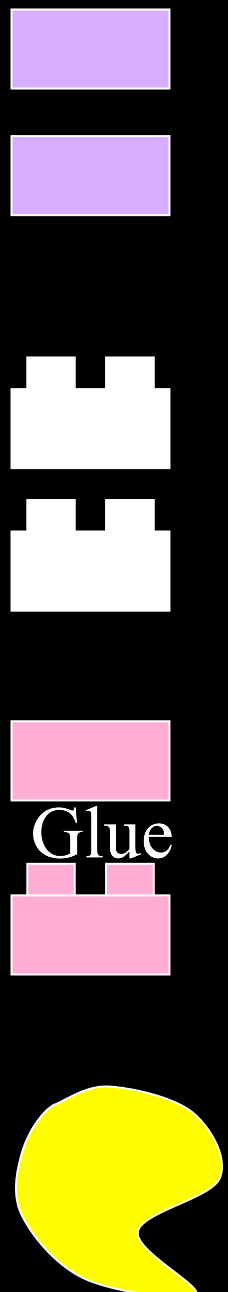




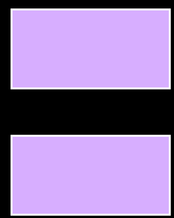


Yet fragile

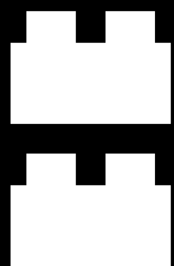
- Add or remove a tiny, indistinguishable amount of material from either side of a key interface.
- → ***Complete failure.***
- Other parts of the bricks may be nicked or cut with minimal impact
- This robust, yet fragile (RYF) feature of protocols is a candidate for a universal law
- What robustness/fragility properties do alternative protocols have?



Consider some alternative interfaces and their tradeoffs…

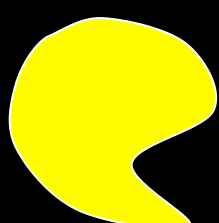


No interface. Simple blocks.



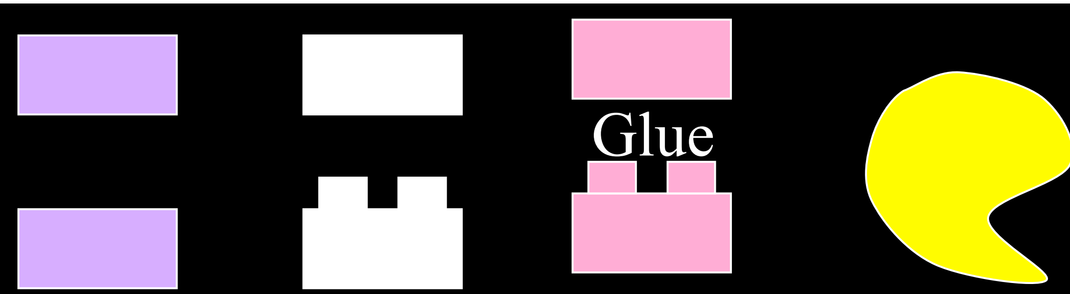
Standard interface. (Wild type.)

Add glue to hold the parts together.



Injection mold the whole toy from scratch.

↑ better
↓ worse

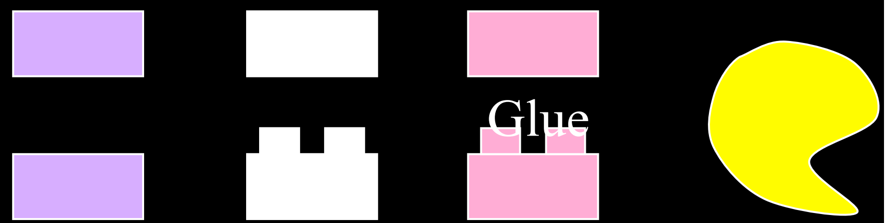


	Smooth	WT	Glue	Mold
Performance	↓	---	---	↑↑
Trauma	↓↓	---	↑	↑↑
Allowed connections	↑↑	---	---	↓↓
Reuse	---	---	↓↓	↓↓
Evolvable parts	↓	---	---	↓
Evolvable systems	↓↓	---	---	↓
Labor cost	↓	---	↓	↓↓
Parts cost	↑	---	↓	↑

- Lego is "optimally robust" (Pareto) not "optimal."
- Similar to complex engineering systems and biology.

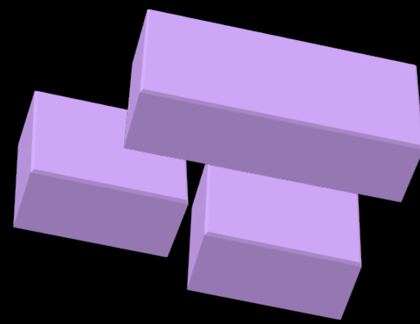
↑ **better**

↓ **worse**

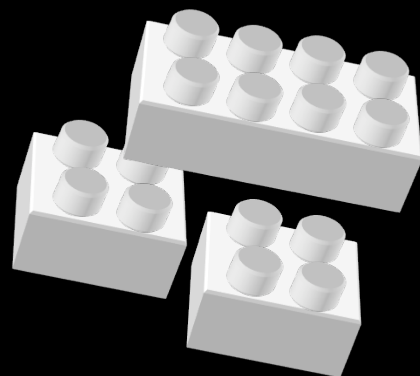


	Smooth	WT	Glue	Mold
Performance	↓	---	---	↑↑
Trauma	↓↓	---	↑	↑↑
Allowed connections	↑↑	---	---	↓↓
Reuse	---	---	↓↓	↓↓
Evolvable parts	↓	---	---	↓
Evolvable systems	↓↓	---	---	↓
Labor cost	↓	---	↓	↓↓
Parts cost	↑	---	↓	↑

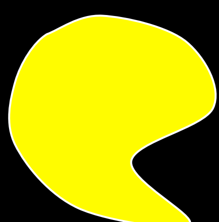
Fragility: Perturbing the snap connector?



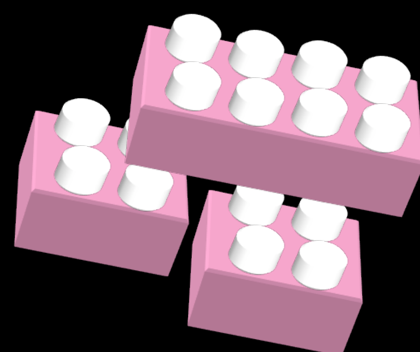
Smooth is robust



WT is ***very*** fragile

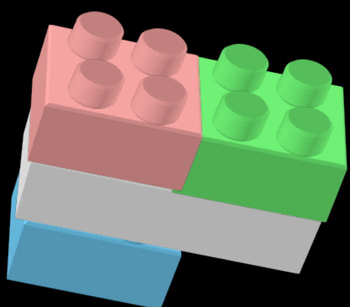


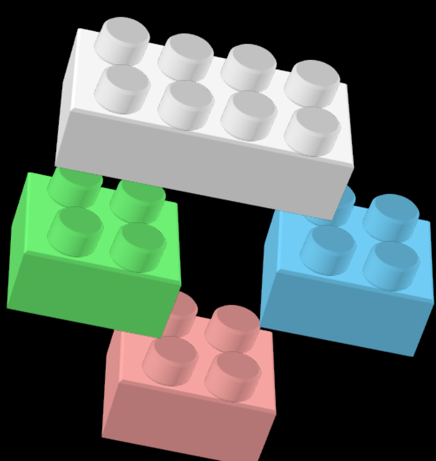
No connections, no fragility



Glued is less fragile

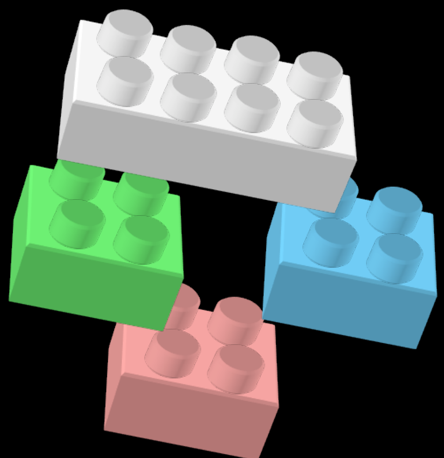
Robust or fine-tuned?

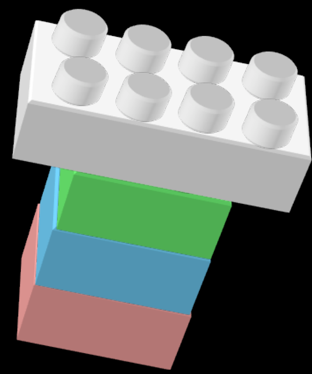


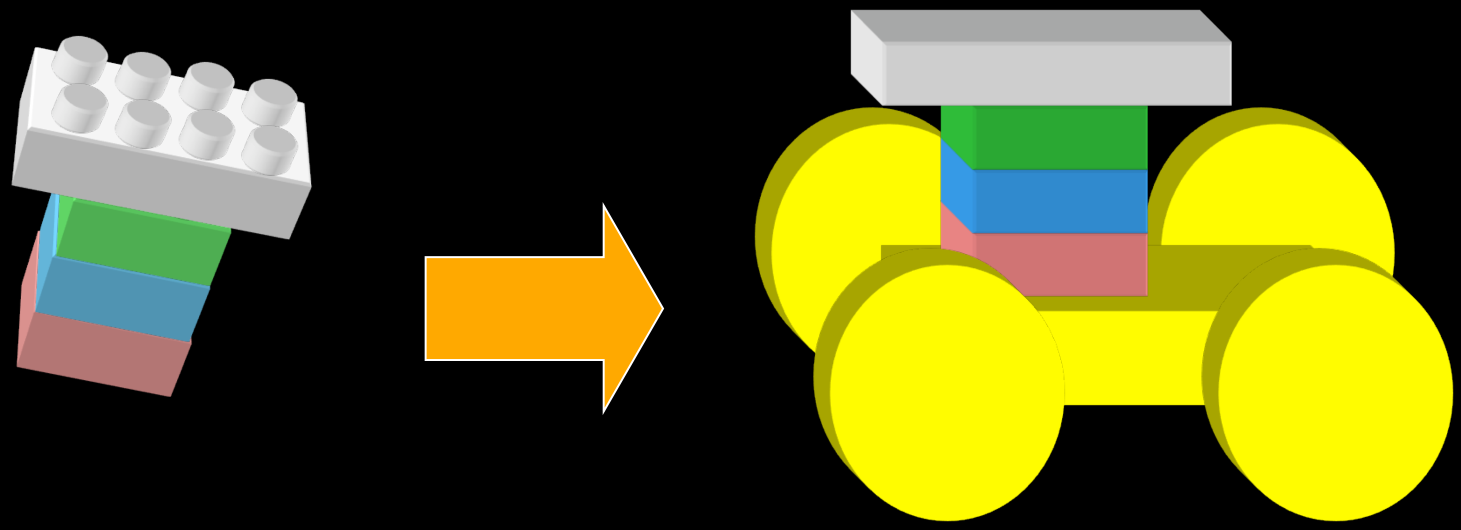


- Set of all possible interconnections is a (combinatorial) huge set.
- Set of interesting toys is also large, but an infinitesimally small subset. Very special and finely tuned.
- Similarly, among the potential toy ***systems*** using the same basic plastic material, Lego is highly structured and finely tuned.
- At the component level, the stud-and-tube coupling is very finely machined.
- Robust yet fragile (RYF) is universal

The evolution of complexity



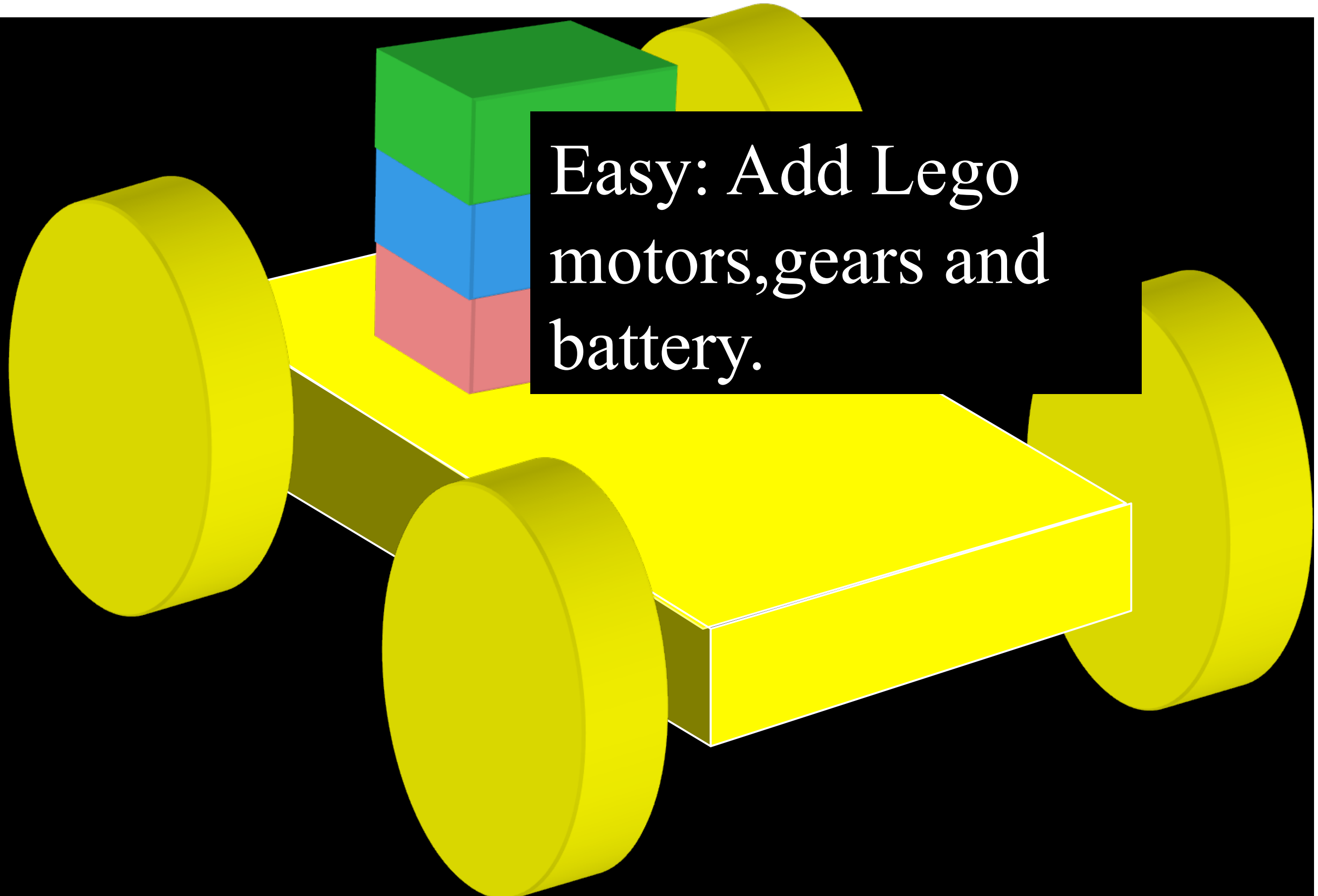




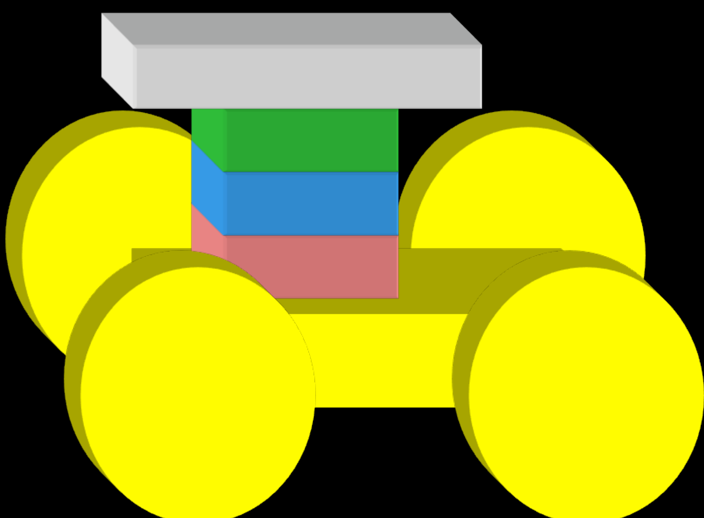
Suppose you want to put a structure on wheels?

Easy: Find Lego parts with wheels.

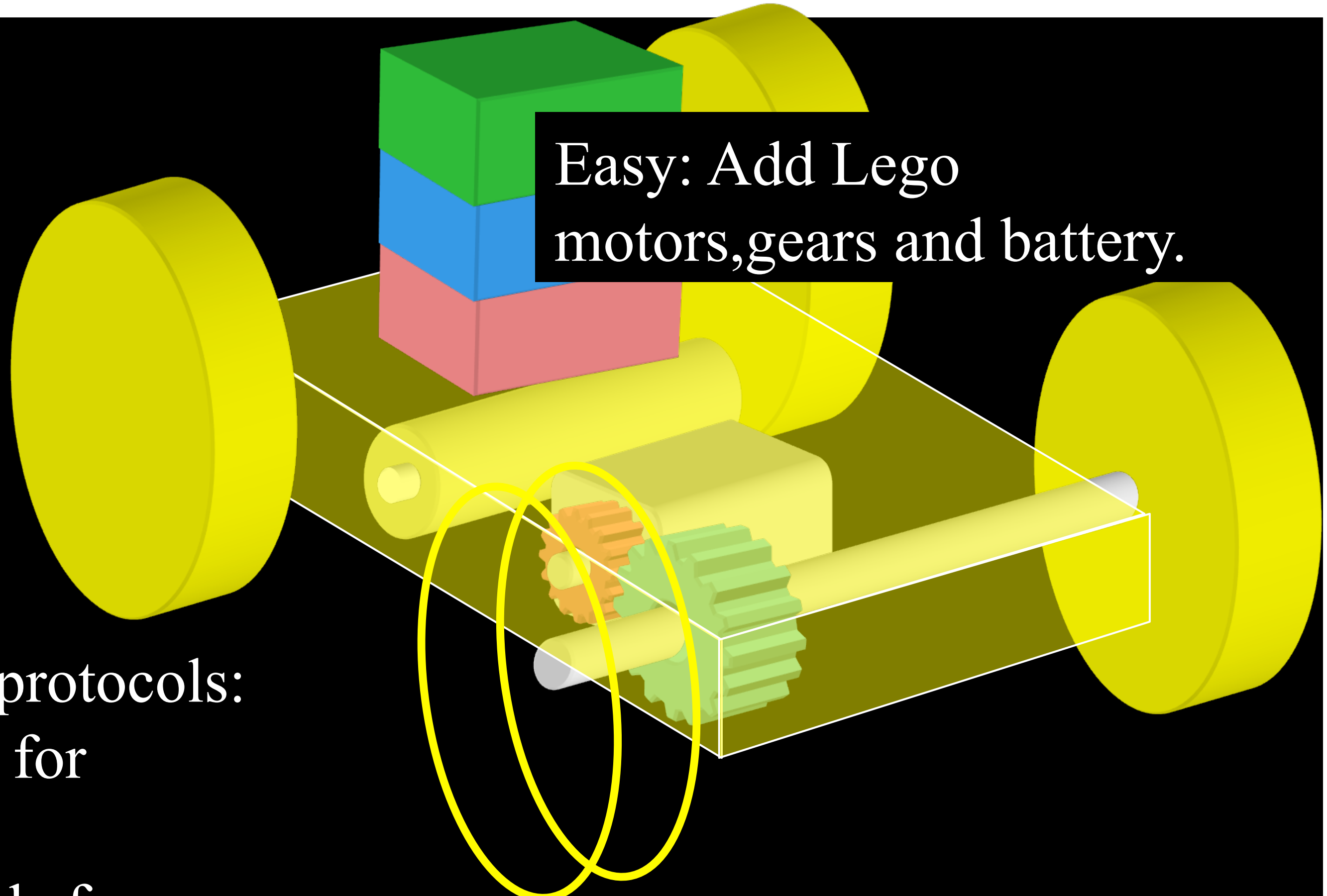
Suppose you want to motorize a vehicle with wheels?



Easy: Add Lego motors,gears and battery.



Suppose you want to motorize a vehicle with wheels?

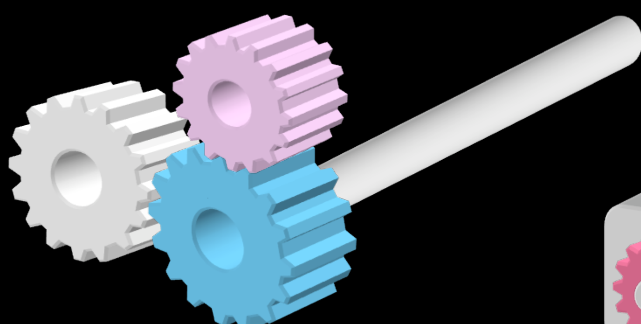


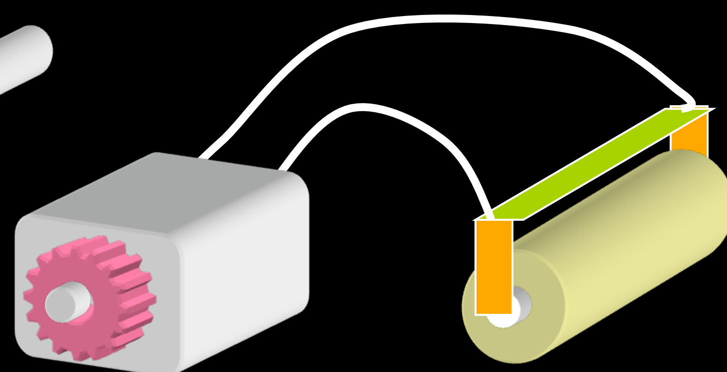
Easy: Add Lego motors,gears and battery.

This adds additional protocols:

• Electrical protocols for batteries and motors.

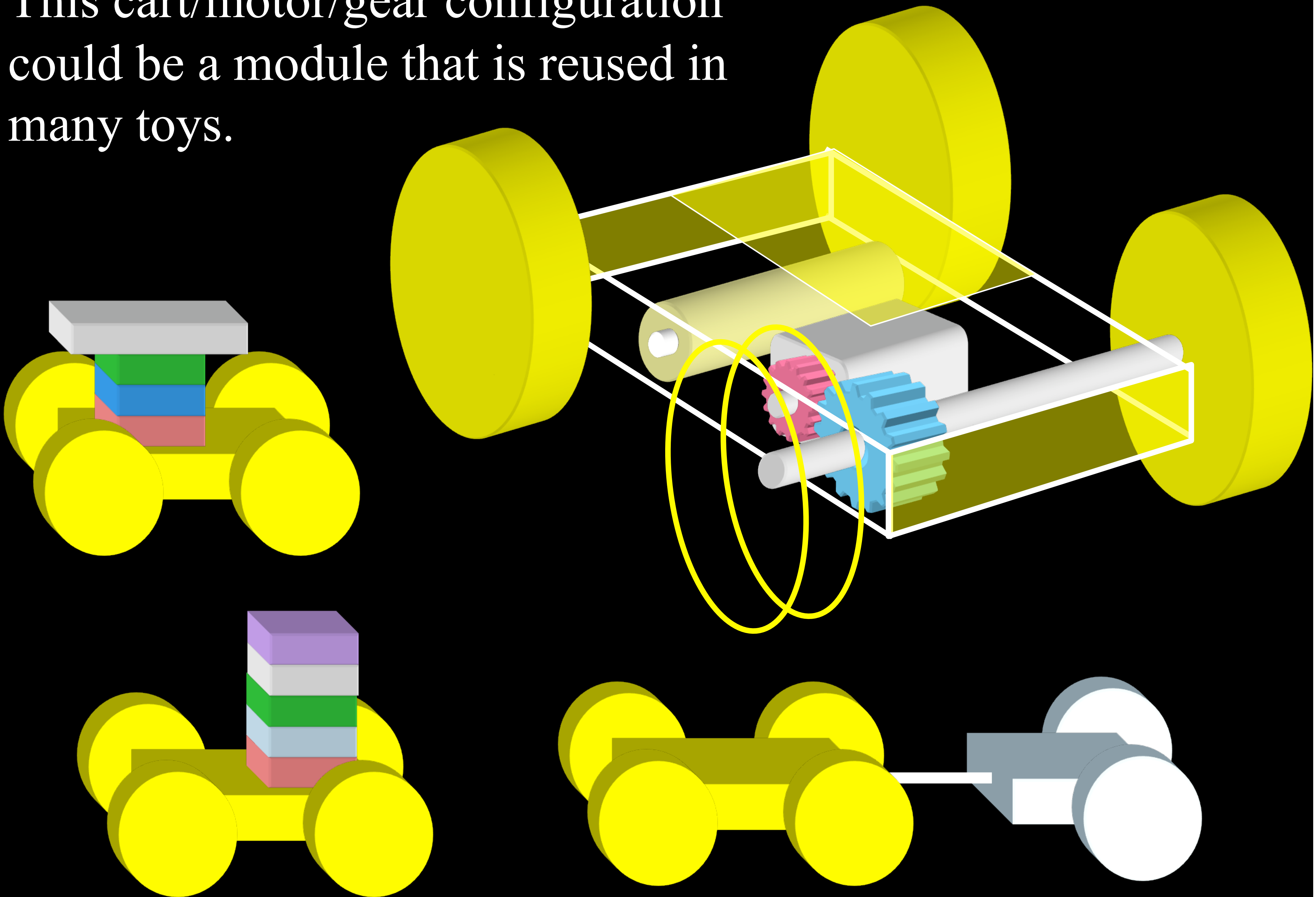
• Mechanical protocols for gears and axles.



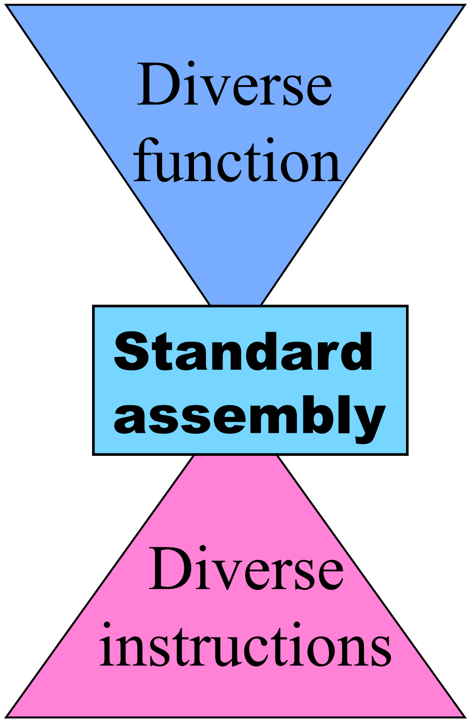


Additional protocols and modules.

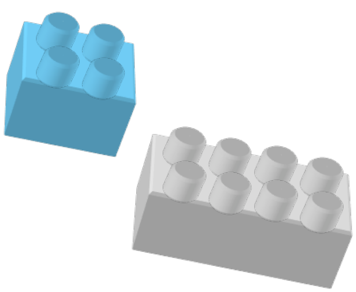
This cart/motor/gear configuration could be a module that is reused in many toys.

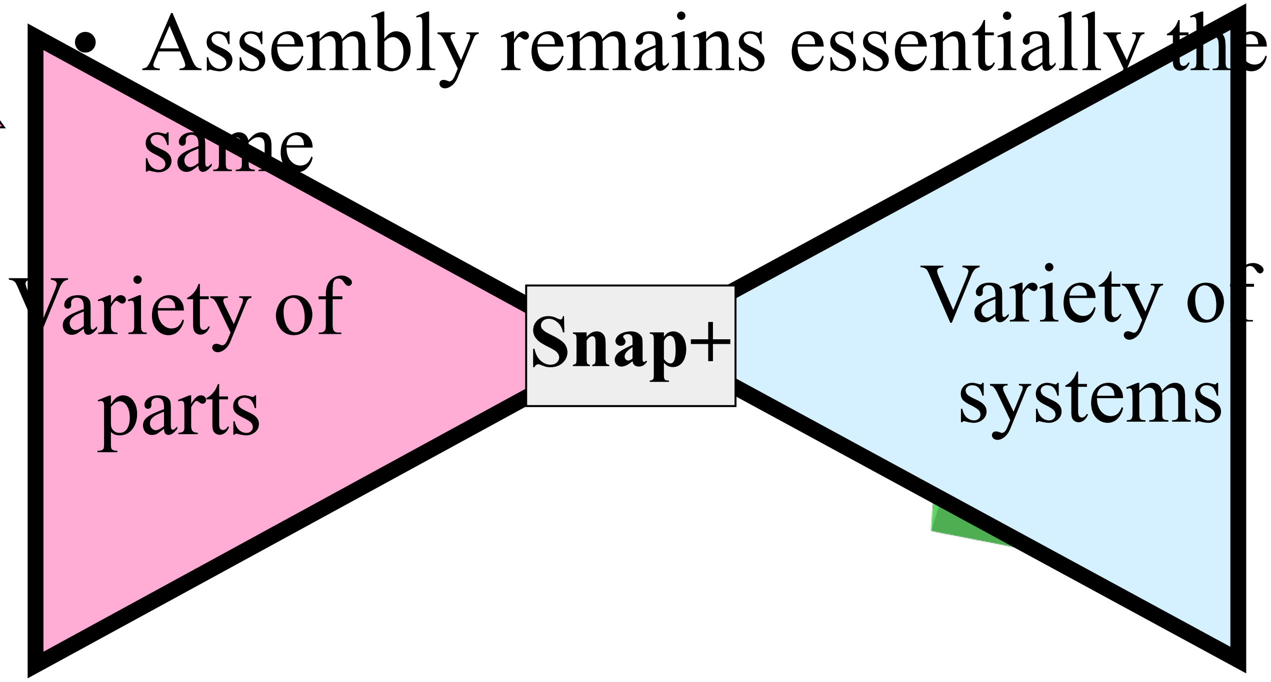


Evolvability

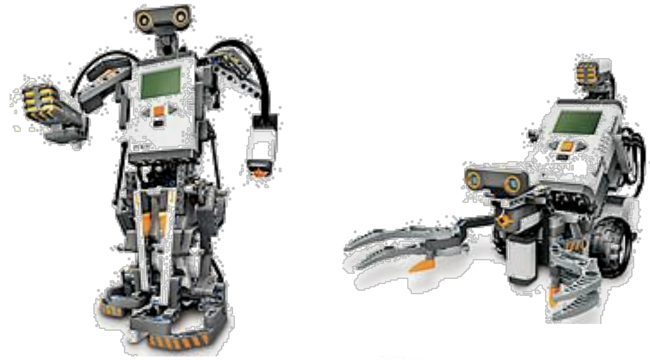


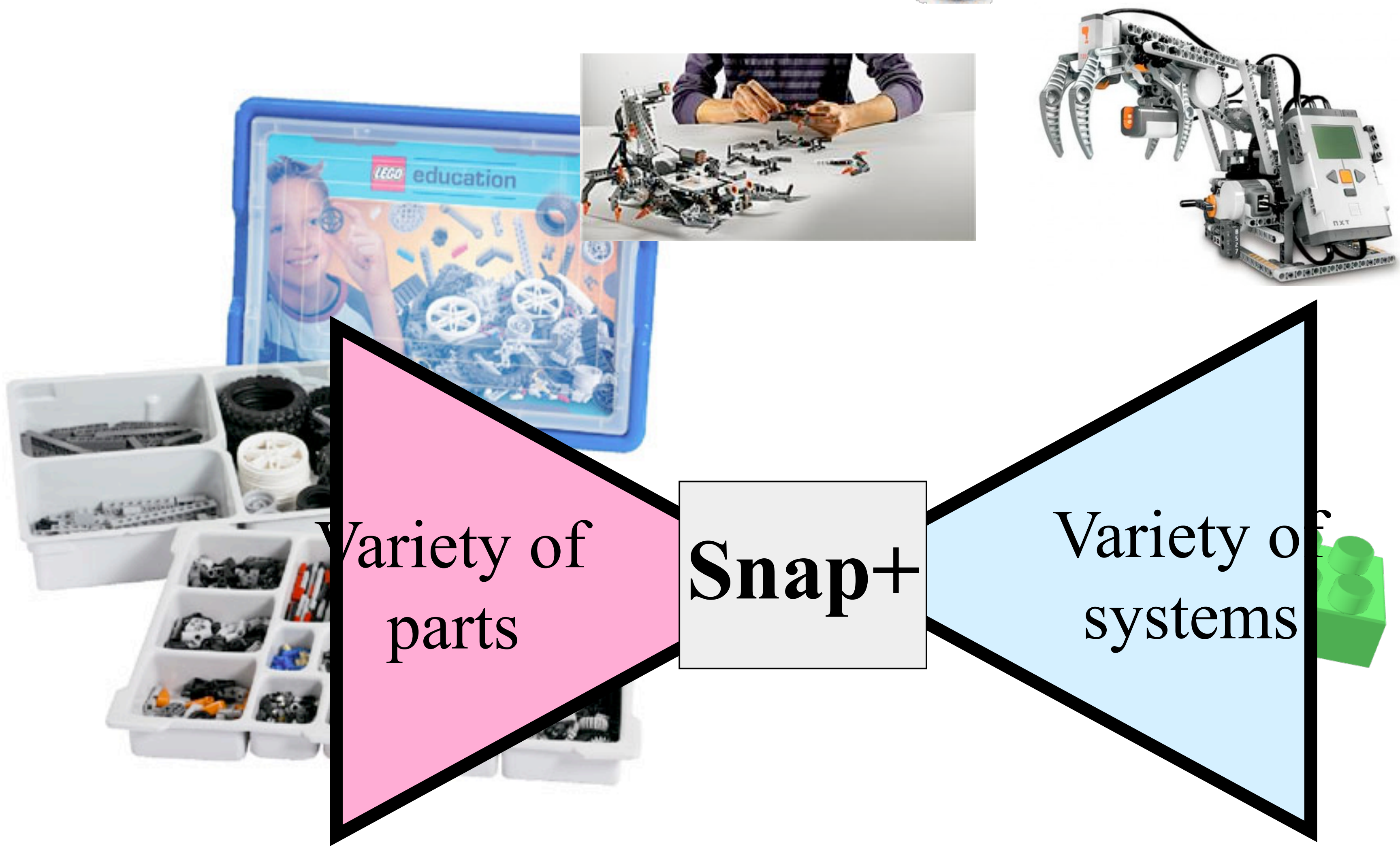
- The snap/brick can be augmented with additional parts and interfaces
- Assembly remains essentially the same





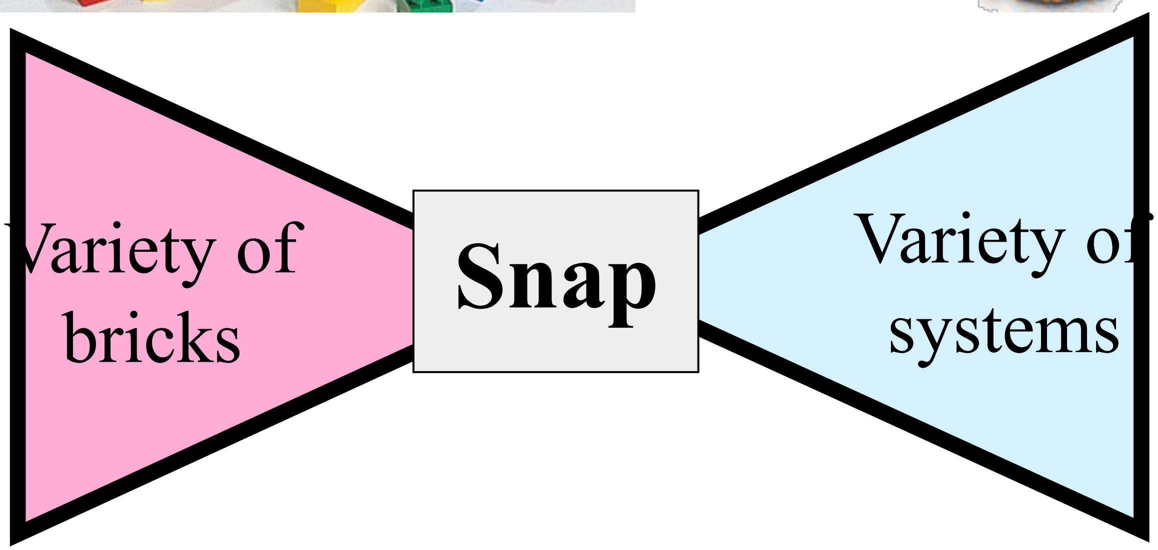
Complex toys can be created, and require additional layers of control.

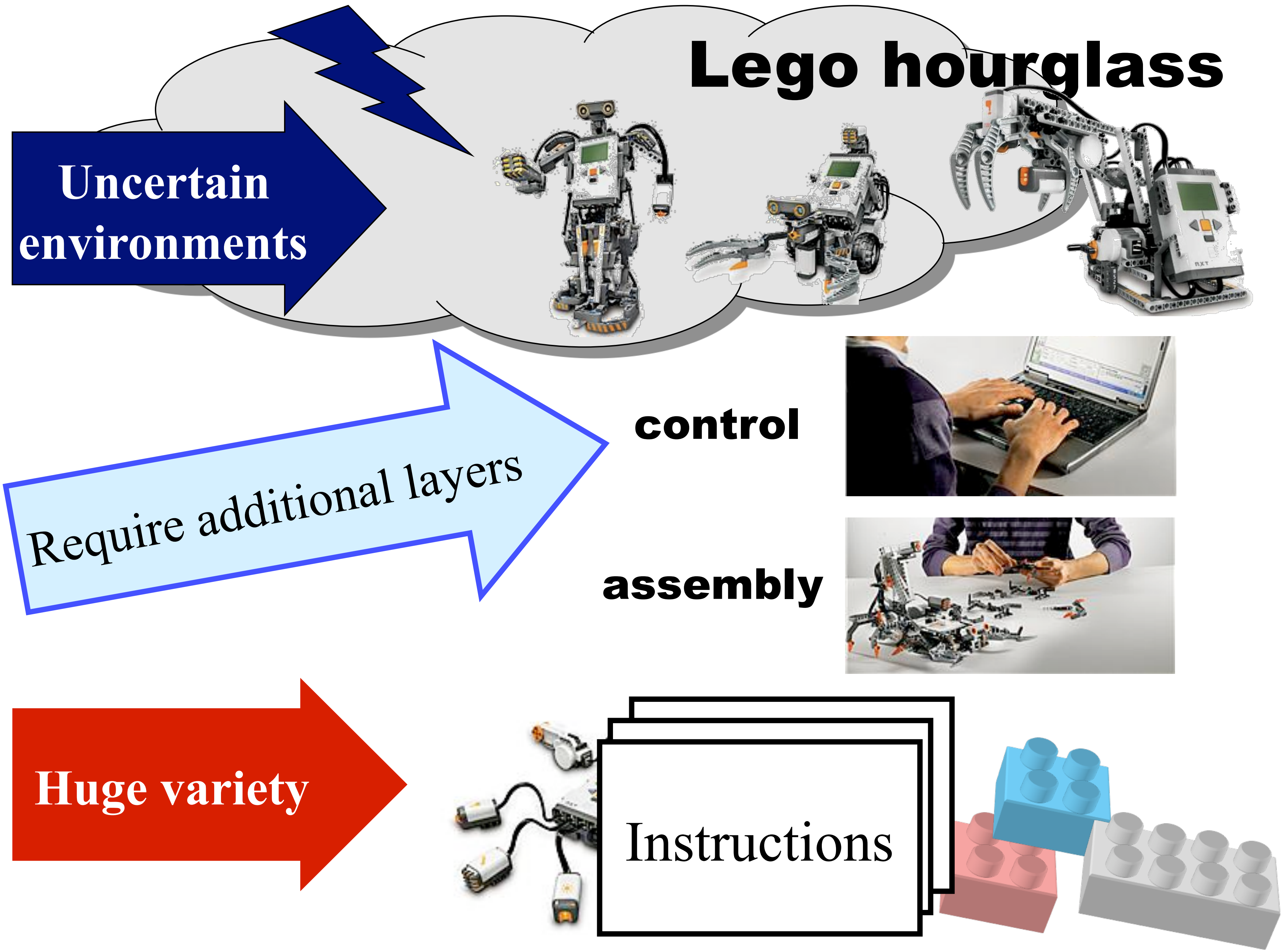




Random

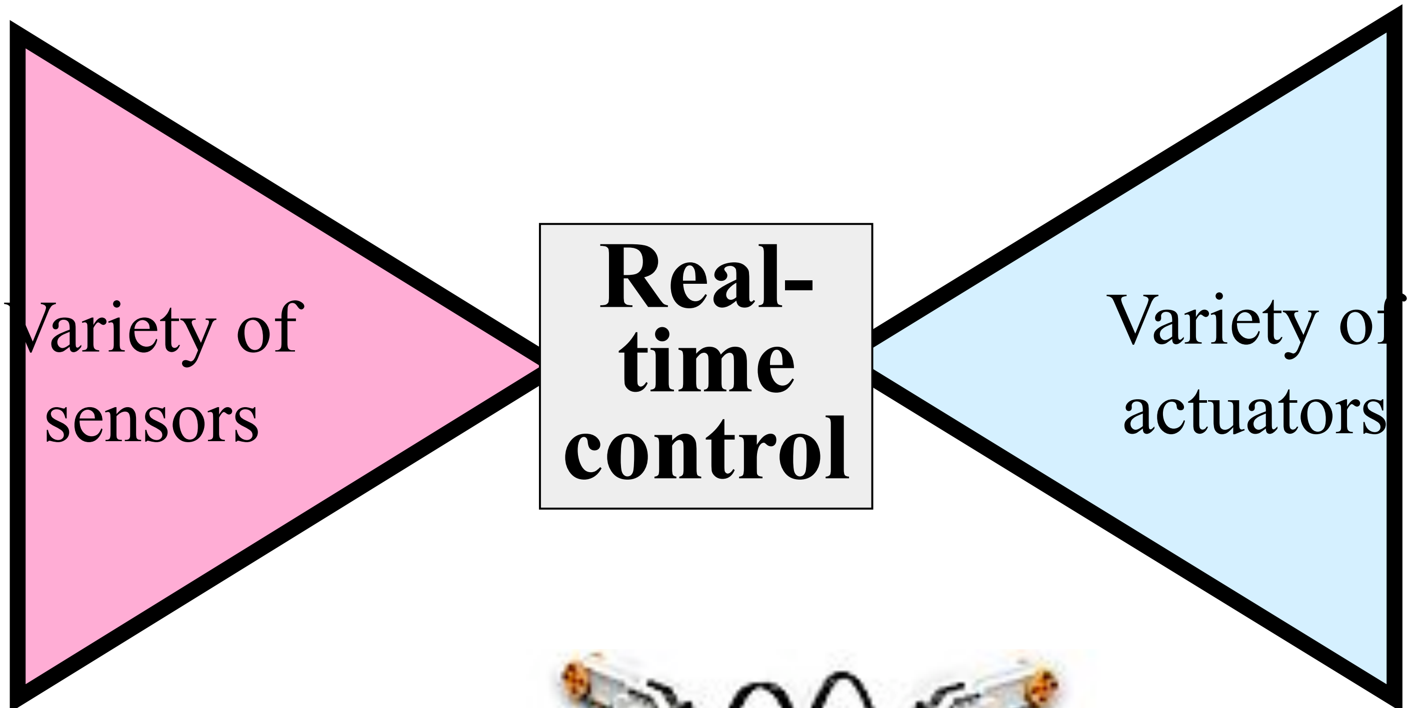
Not random



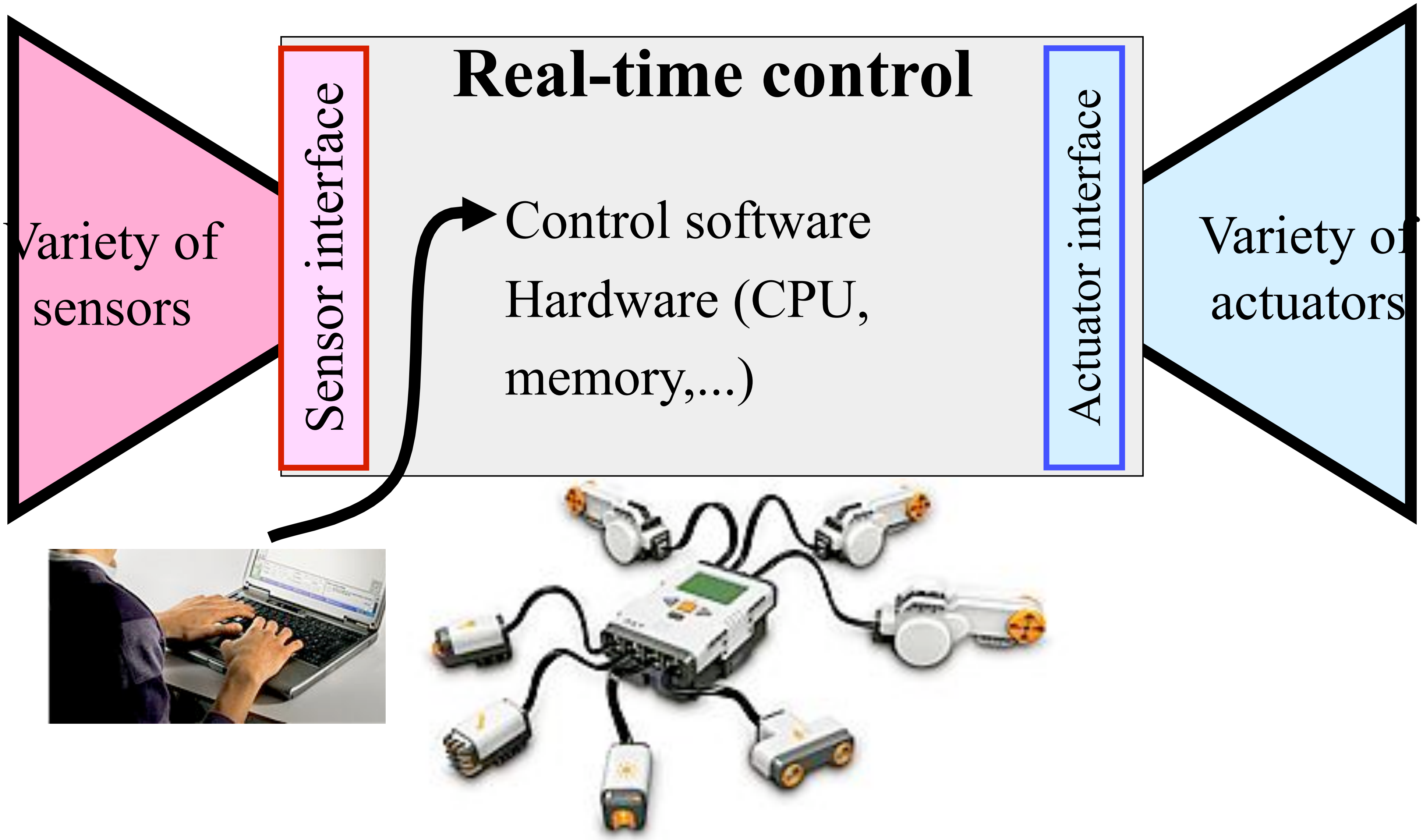


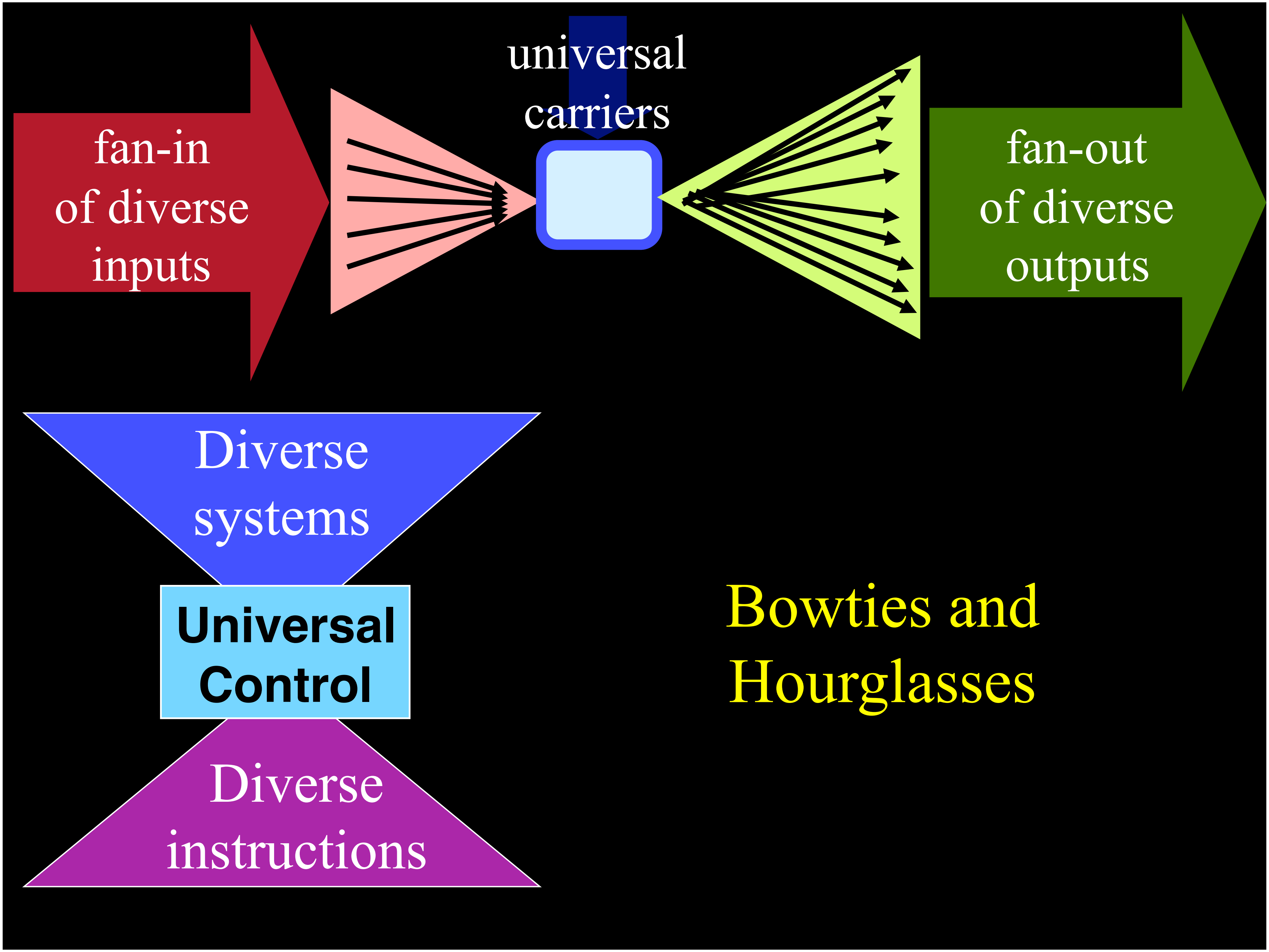
Lego hourglass
Uncertain environments
Require additional layers
control
assembly
Huge variety
Instructions

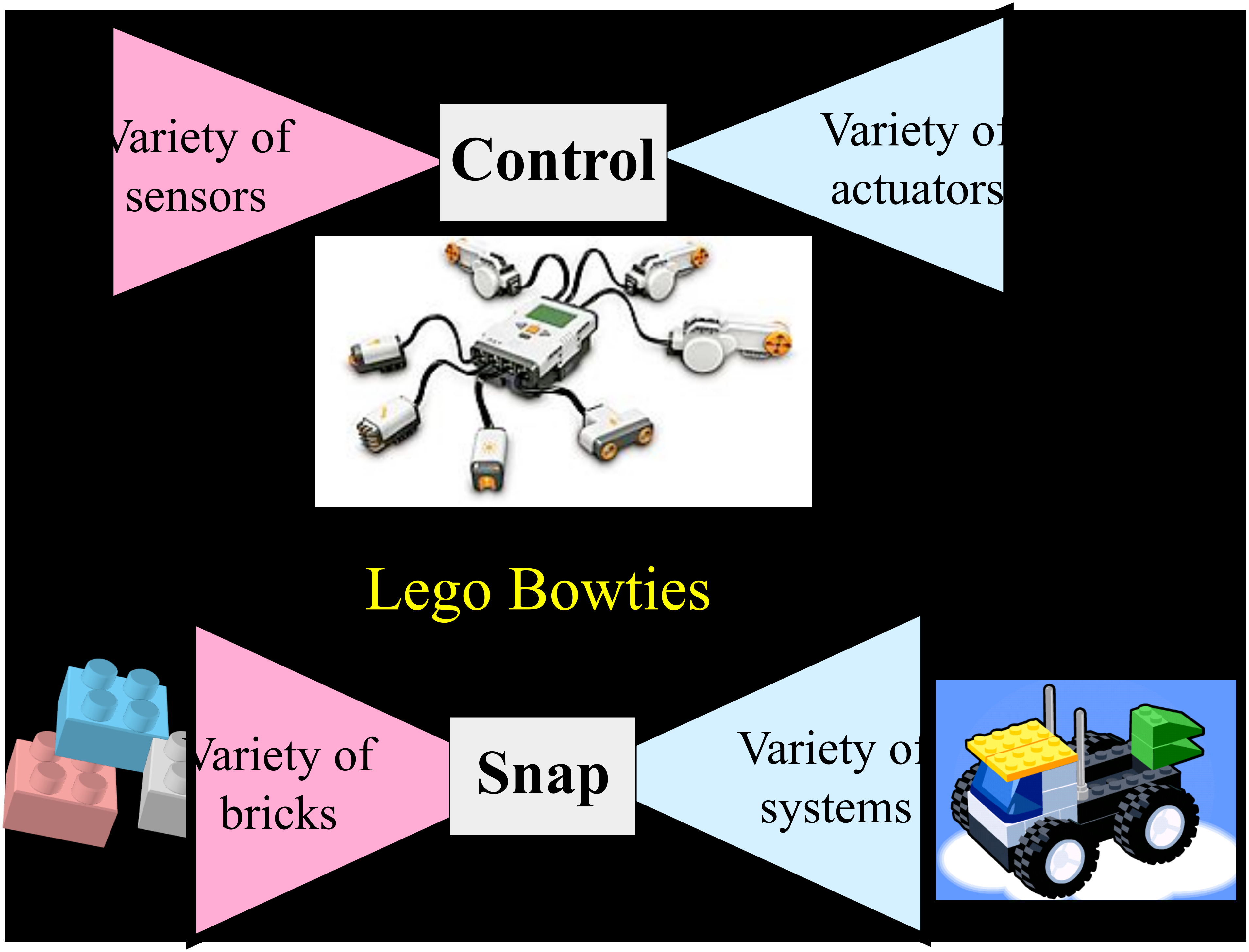
NXT controller



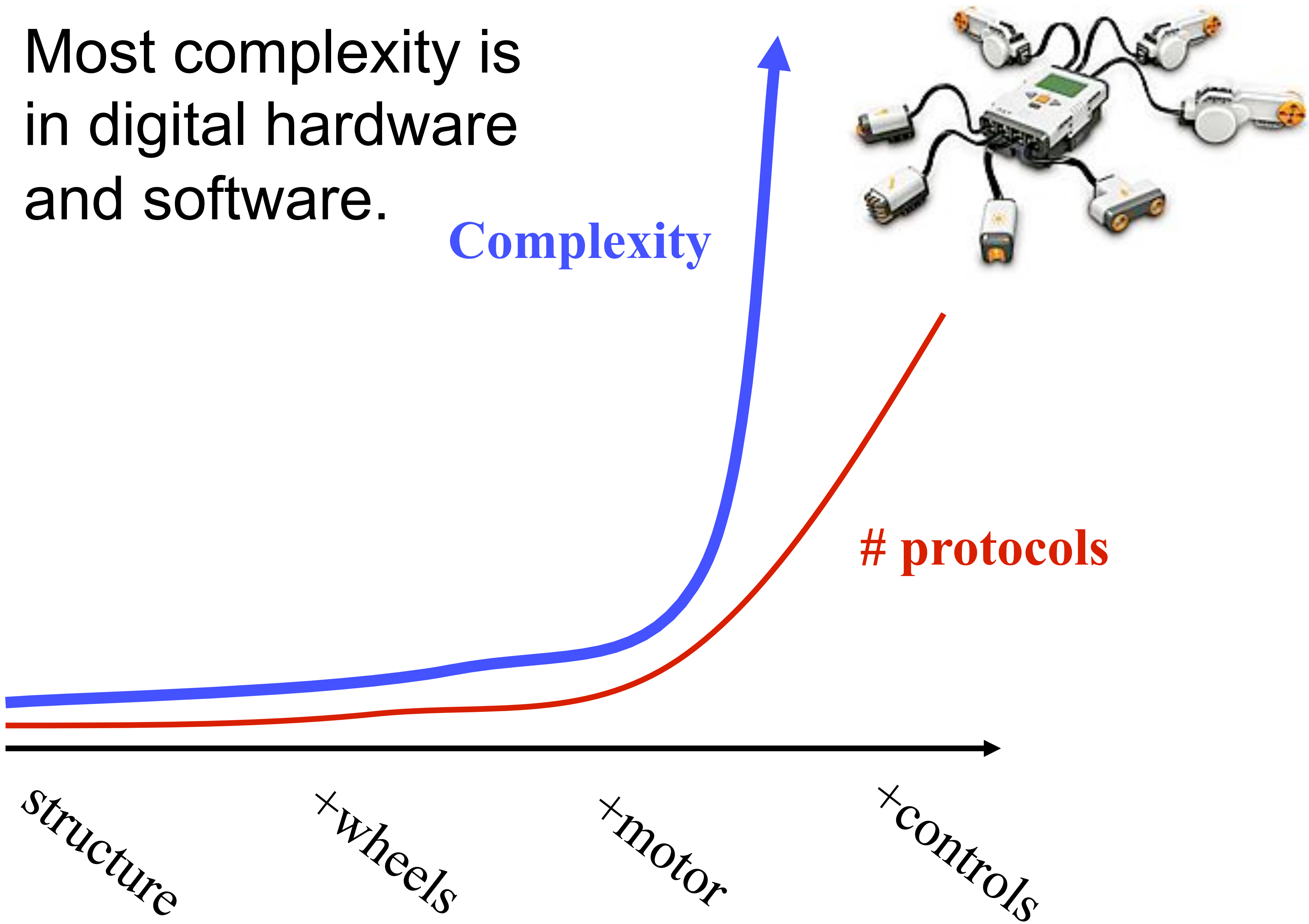
NXT controller

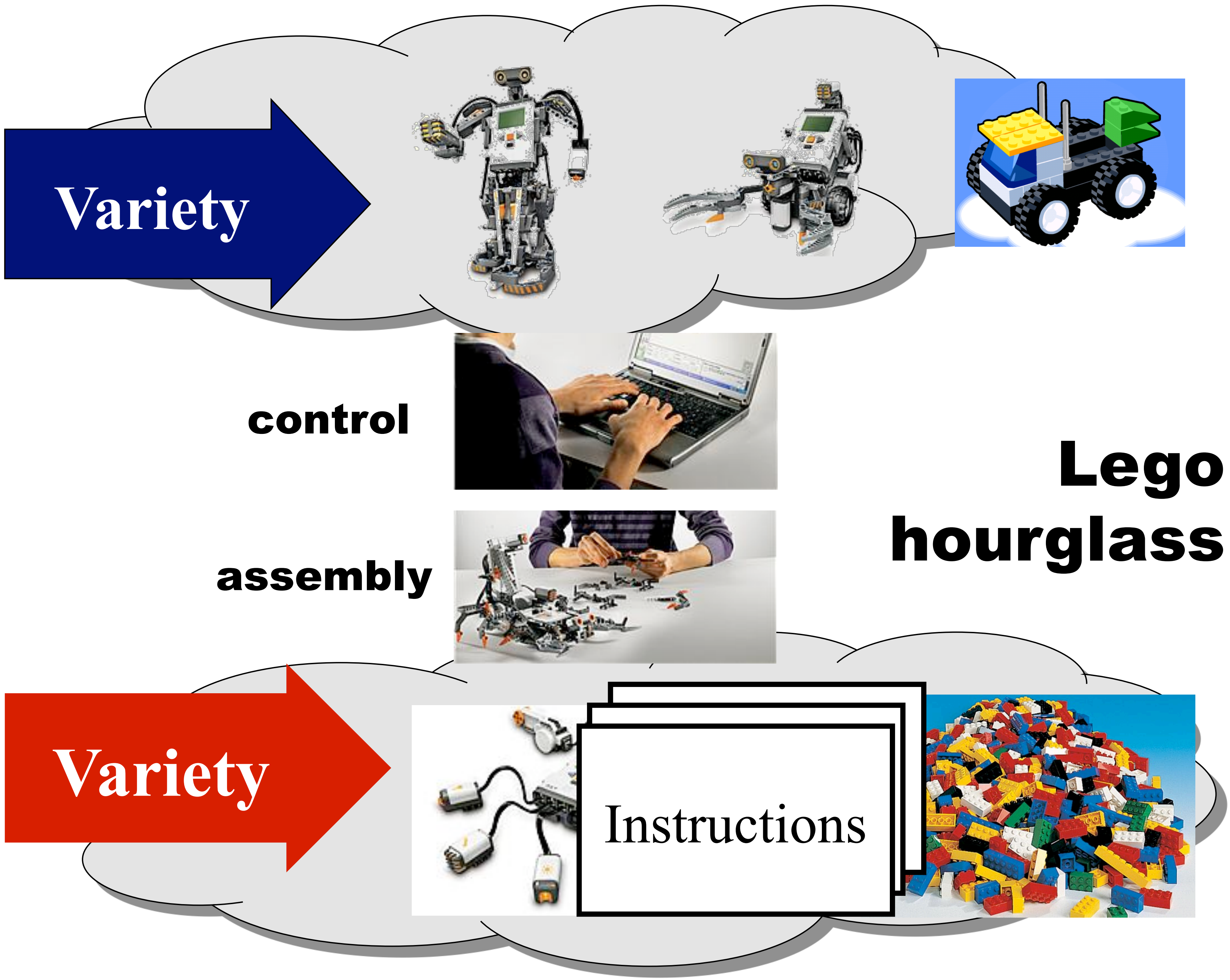



universal carriers
fan-in of diverse inputs
fan-out of diverse outputs
Diverse systems
Universal Control
Diverse instructions
Bowties and Hourglasses


ariety of
sensors
Control
Variety o
actuators
Lego Bowties
ariety of
bricks
Snap
Variety o
systems

Most complexity is in digital hardware and software.



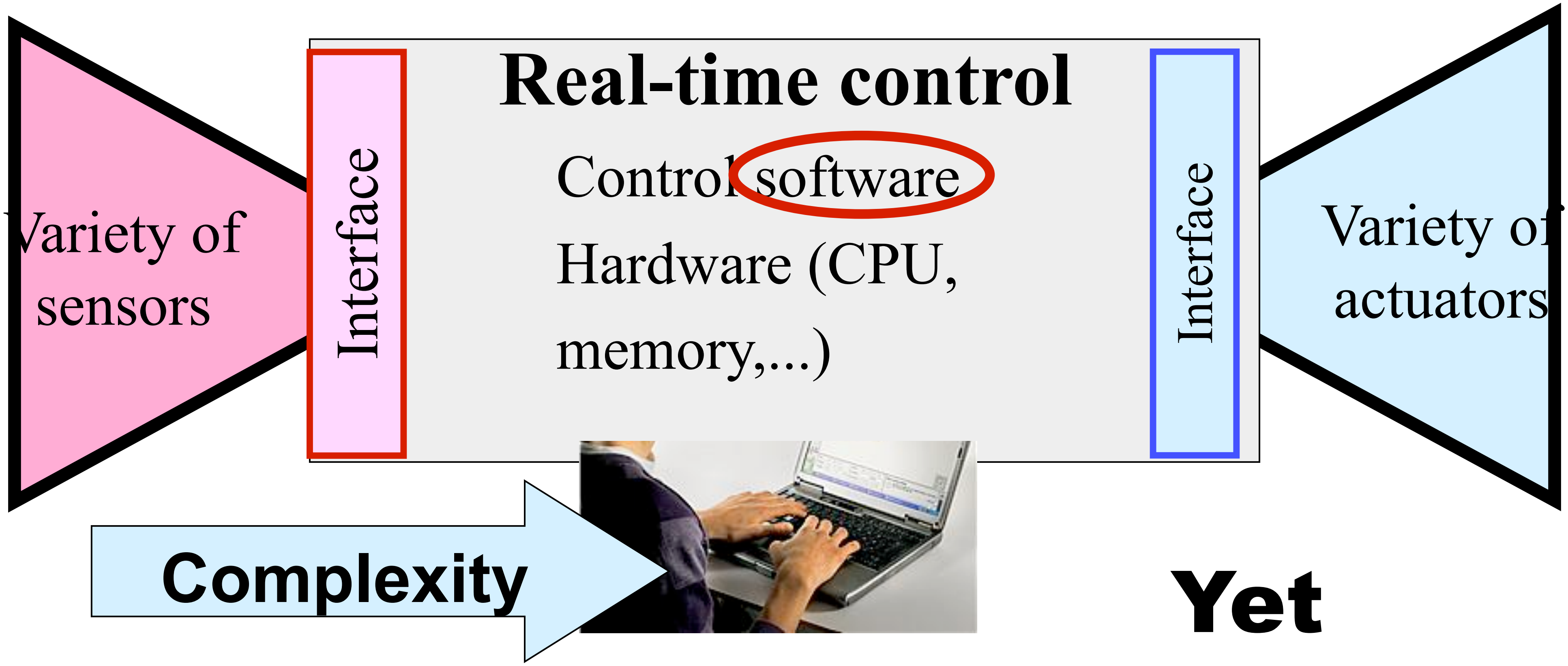

Variety
control
assembly
Lego
hourglass
Variety
Instructions

Variety

Robust

Yet fragile?

Variety


Real-time control
Control software
Hardware (CPU, memory,...)
Variety of sensors
Interface
Interface
Variety of actuators
Complexity

Yet fragile?

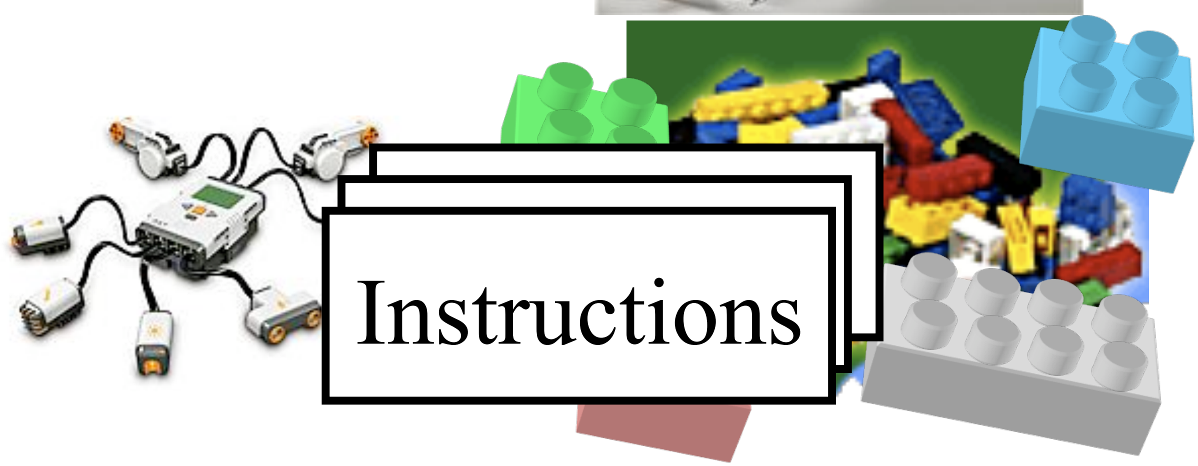
Lego hourglass

For a single toy

Complexity →

control

assembly



Analog behavior

Kinematics

Dynamics

control

Digital description

Control

Assembly

Instructions

Toy *system*

Lego hourglass

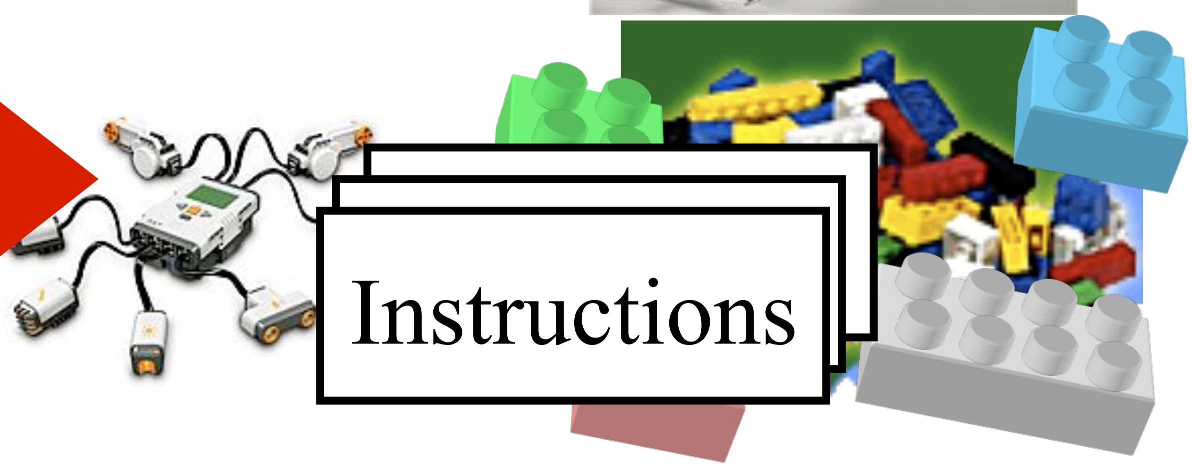
Huge variety of toys

Standardized mechanisms
Highly conserved

control

assembly

Huge variety of instructions



Instructions

Lego hourglass

Huge variety of toys

Standardized mechanisms
Highly conserv

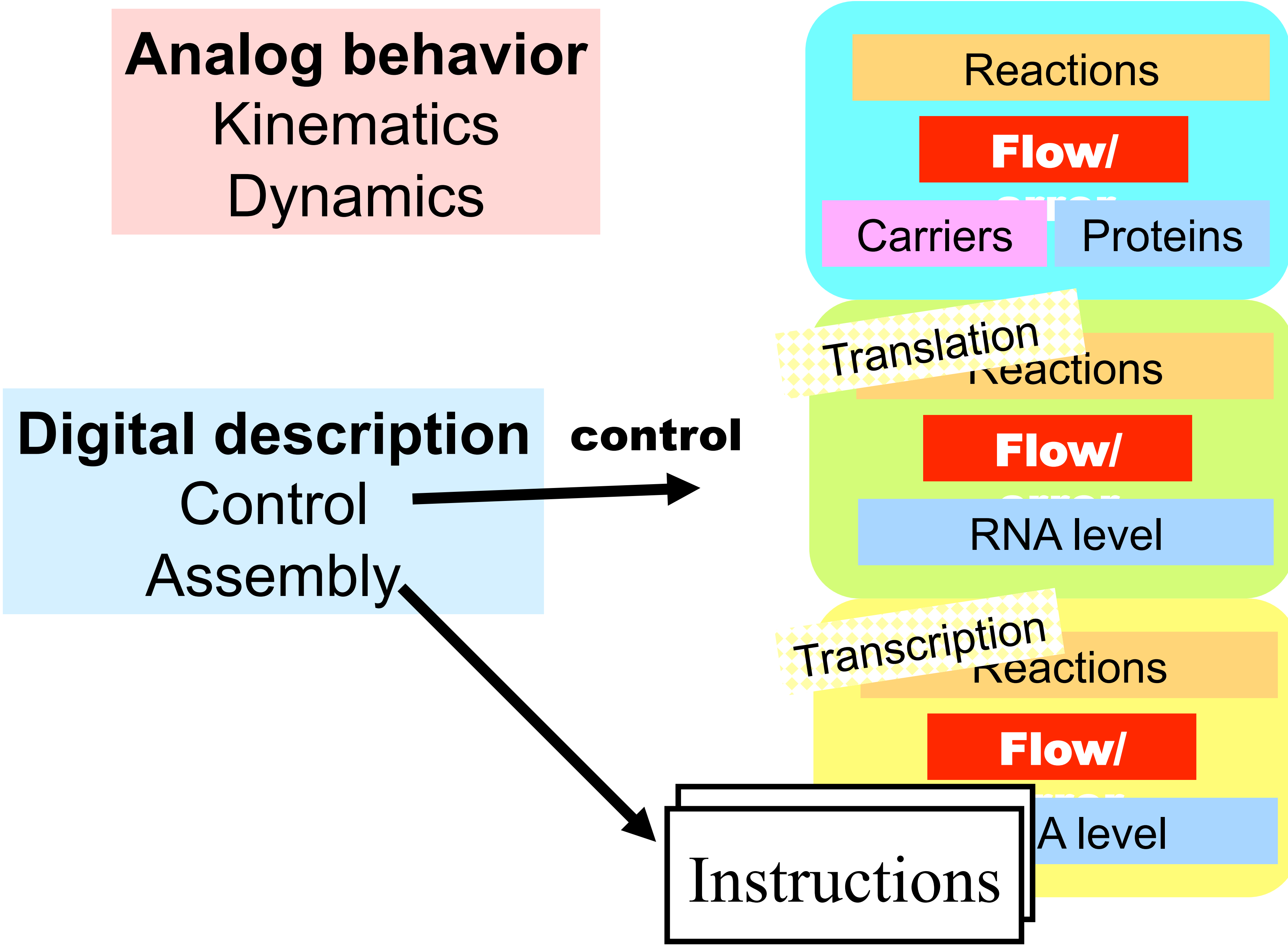
control

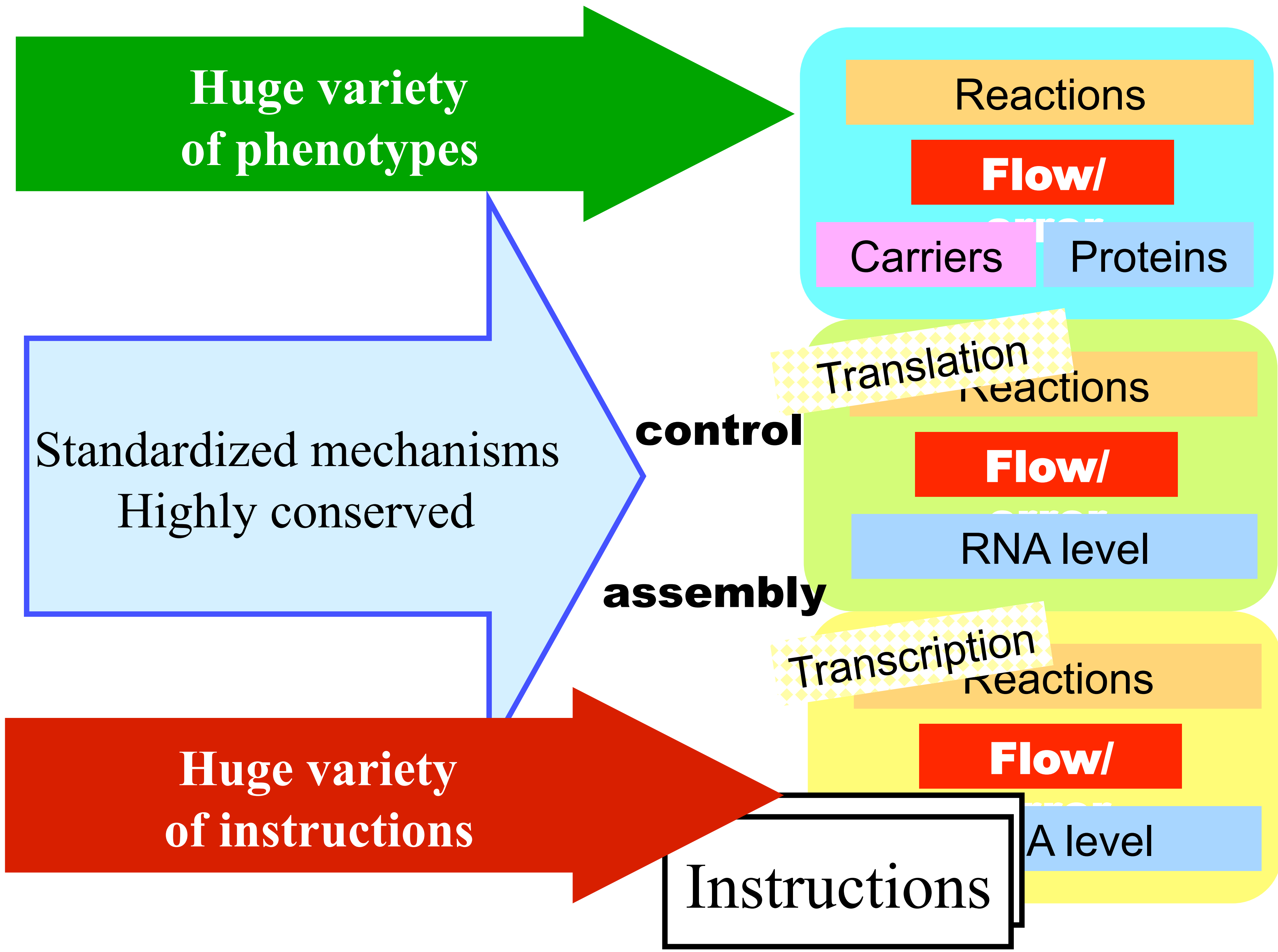
sembly

Large (<< huge)
Variety of parts

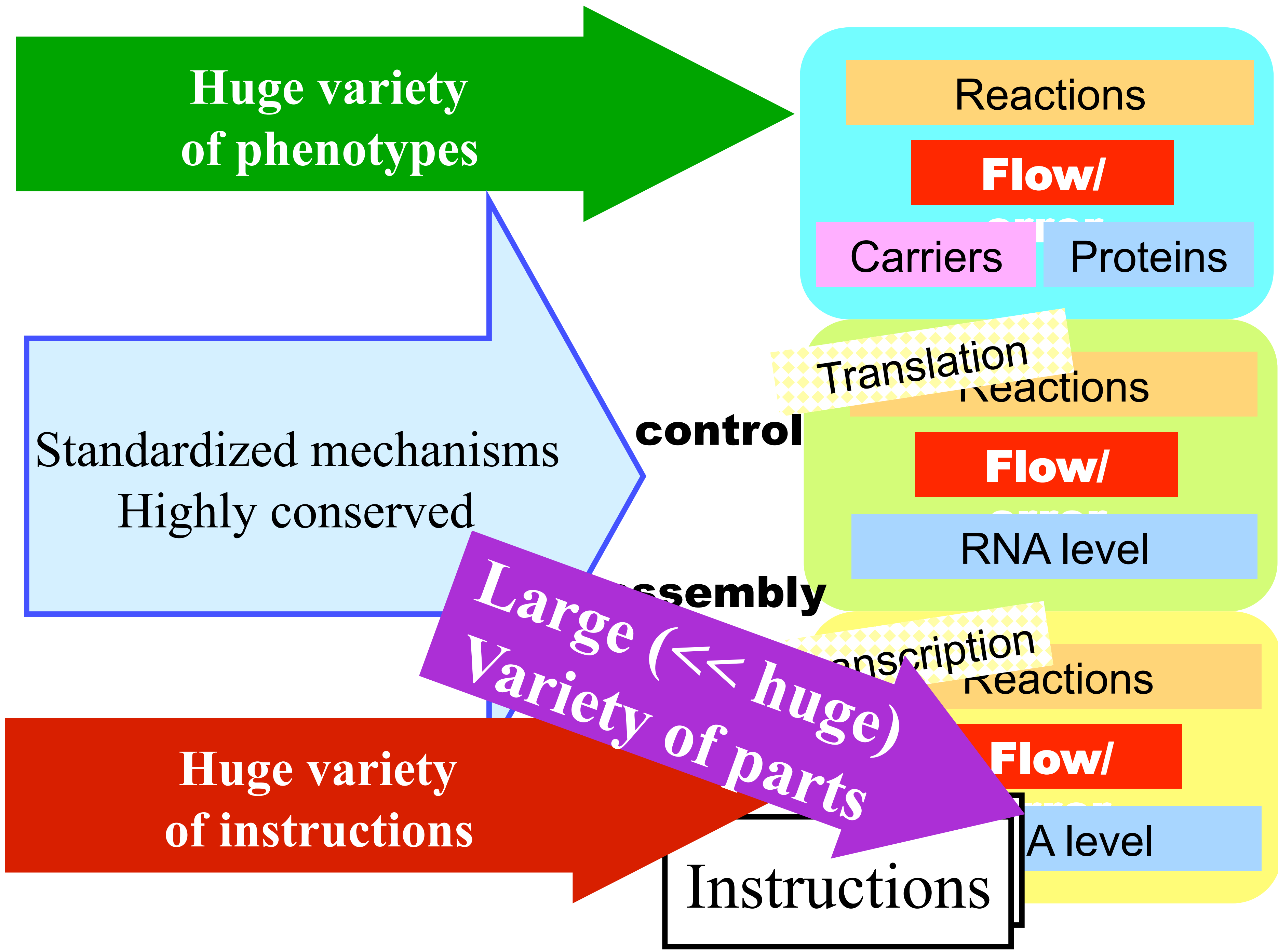
Huge variety of instructions

Instructions


Analog behavior
Kinematics
Dynamics
Digital description
Control
Assembly
control
Reactions
Flow/
Carriers
Proteins
Translation
Reactions
Flow/
RNA level
Transcription
Reactions
Flow/
A level
Instructions



Huge variety of phenotypes
Reactions
Flow/
Carriers
Proteins
Standardized mechanisms
Highly conserved
Translation
Reactions
control
Flow/
RNA level
assembly
Transcription
Reactions
Flow/
A level
Huge variety of instructions
Instructions

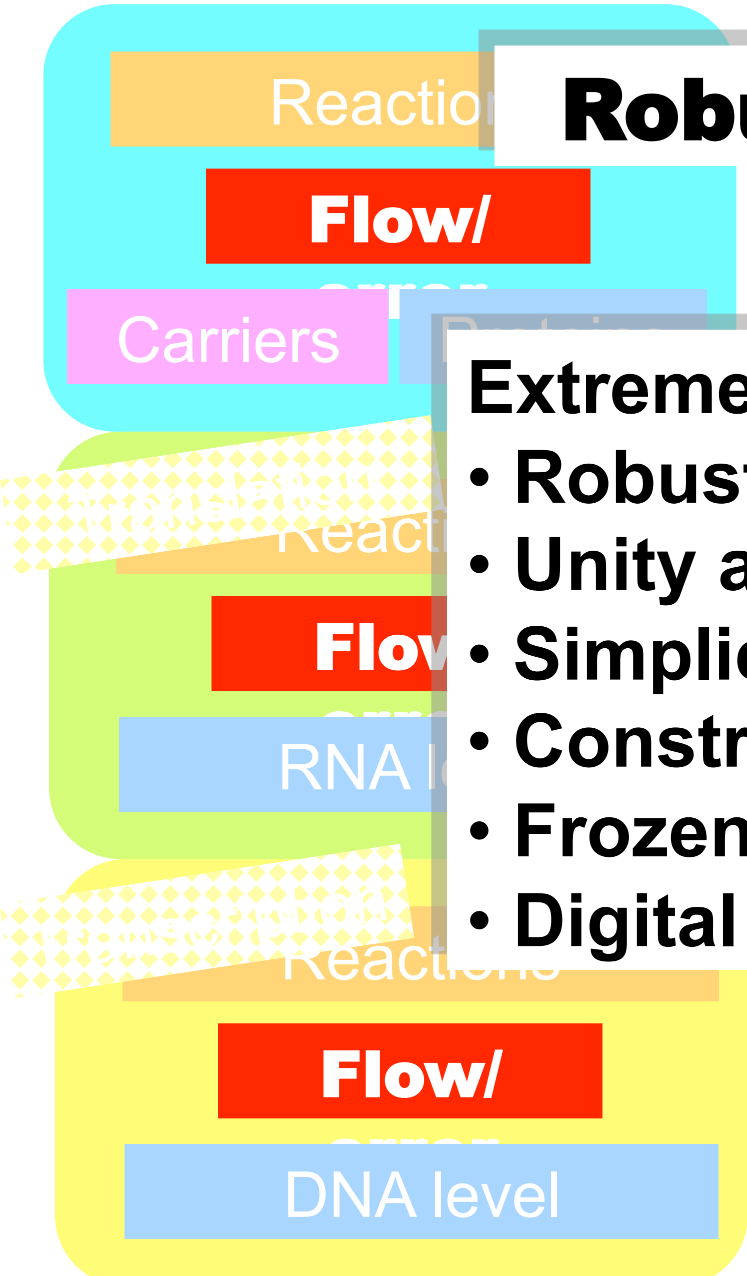


Huge variety of phenotypes
Reactions
Flow/
Carriers
Proteins
Translation
Reactions
control
Flow/
RNA level
Standardized mechanisms
Highly conserved
Large (<< huge) Variety of parts
Reactions
Flow/
Huge variety of instructions
Instructions

Robust yet fragile

Extremes of

- Robust yet fragile
- Unity and diversity
- Simplicity and complexity
- Constrained and flexible
- Frozen and evolvable
- Digital and analog



Lessons from Lego:

- ***Hourglass*** organization of control
- Infinitely ***diverse*** toys from moderately diverse parts
- ***Conserved*** control mechanisms
- ***Bowties*** within layers

- ***Complexity*** in individual toys is overwhelmingly in the conserved control parts
- This complexity is largely hidden in ordinary operation
- Greater internal complexity means more ***robust yet fragile*** external behavior

Diverse

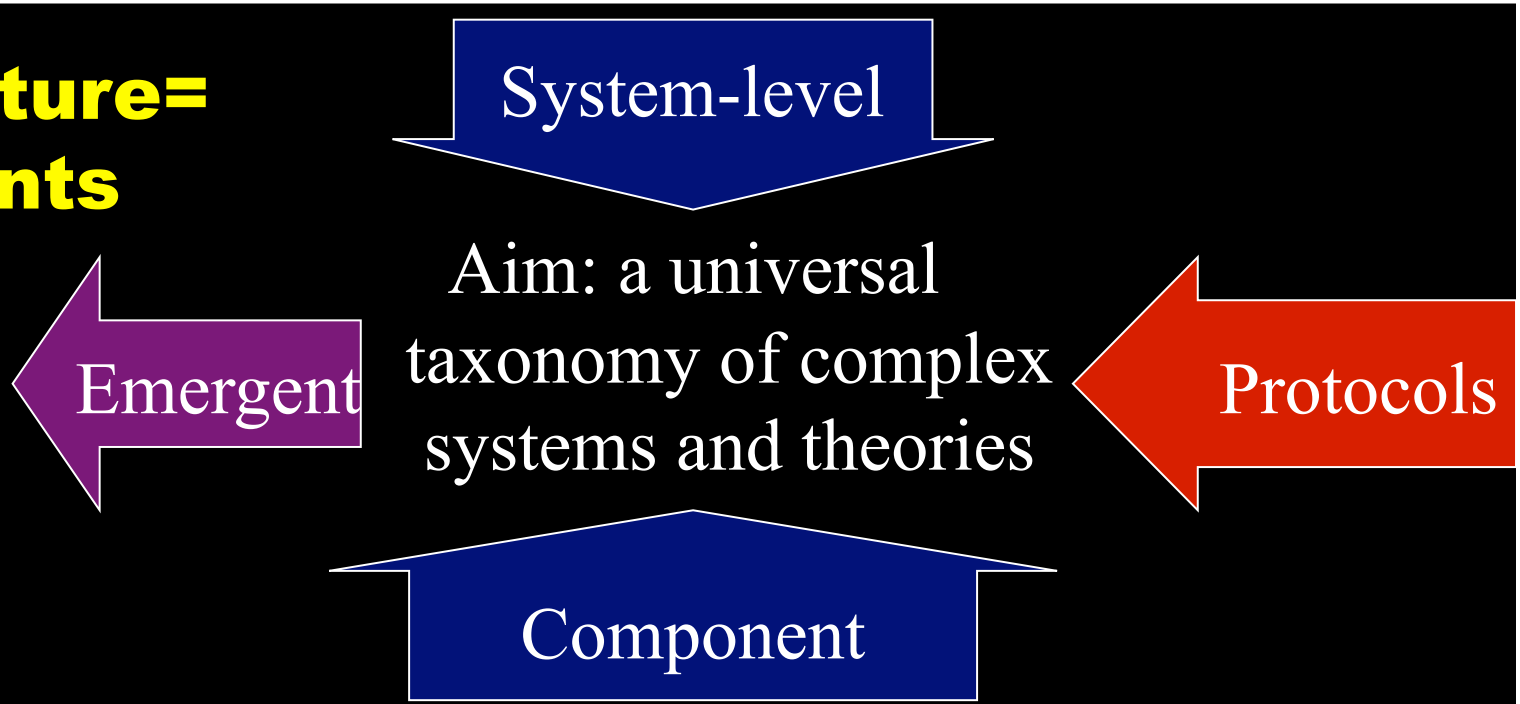
control

Conserved

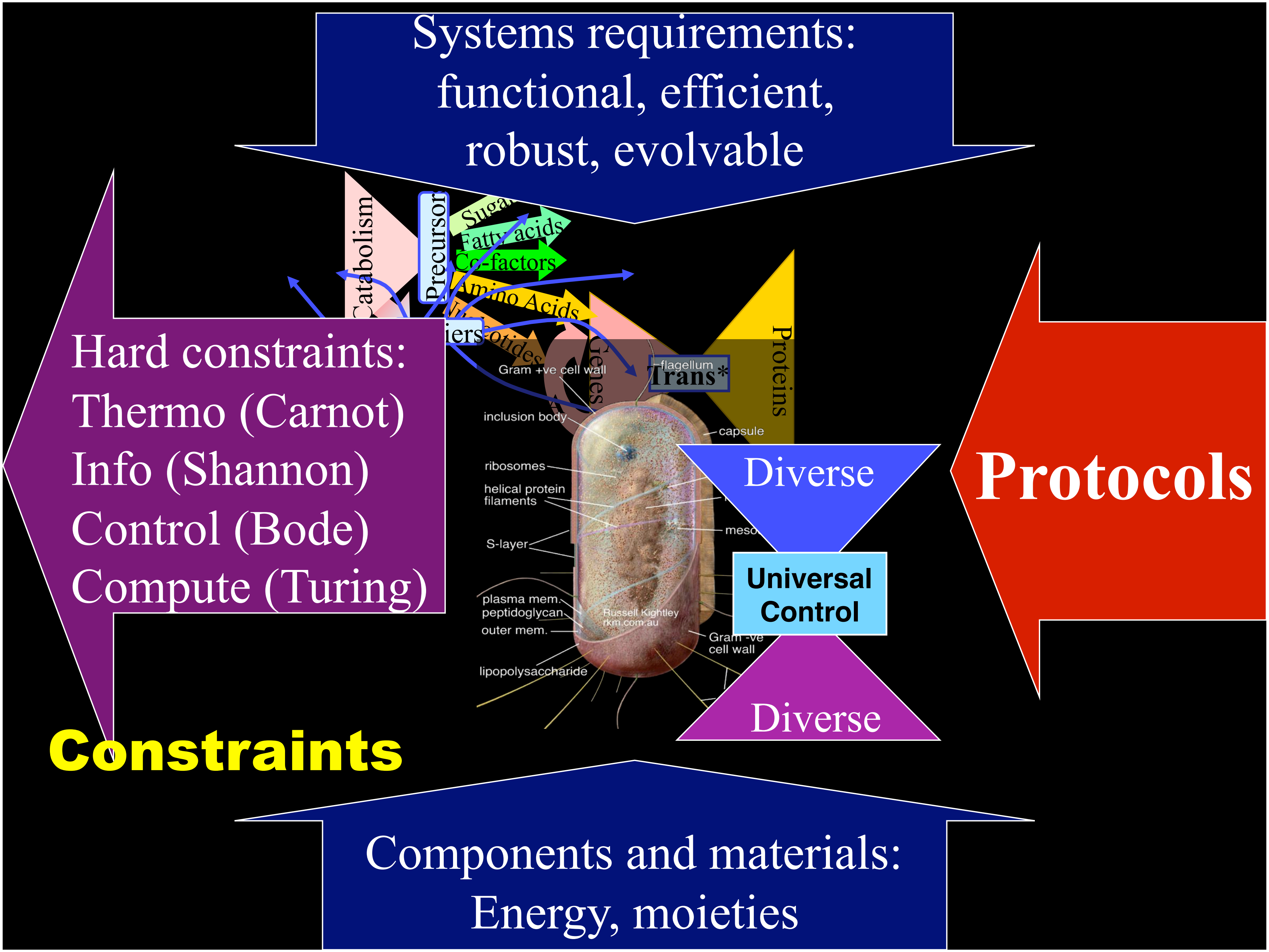
assembly

Diverse

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
Protocols
Diverse
Universal Control
Diverse
Components and materials:
Energy, moieties
Catabolism
Precursor
Fatty acids
Co-factors
Amino Acids
Genes
Trans*
Proteins
flagellum
Gram +ve cell wall
inclusion body
capsule
ribosomes
helical protein filaments
S-layer
plasma mem.
peptidoglycan
outer mem.
lipopolysaccharide
Russell Kightley
rkm.com.au
Gram -ve cell wall

Essential ideas

- Listening to engineers and physicians

- Robust yet fragile (RYF)
- "Constraints that deconstrain" (G&K)

- Network architecture
- Layering
- Control and dynamics (C&D)
- Hourglasses and Bowties
- Unity and diversity