Engineered Self-Organization Approaches to Adaptive Design

Jacob Beal

Conference on Through-Life Engineering Services

Nov 5-6th, 2012

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BBN Technologies

Work partially sponsored by DARPA; the views and conclusions contained in this document are those of the authors and not DARPA or the U.S. Government.

Design: Explicit → Implicit

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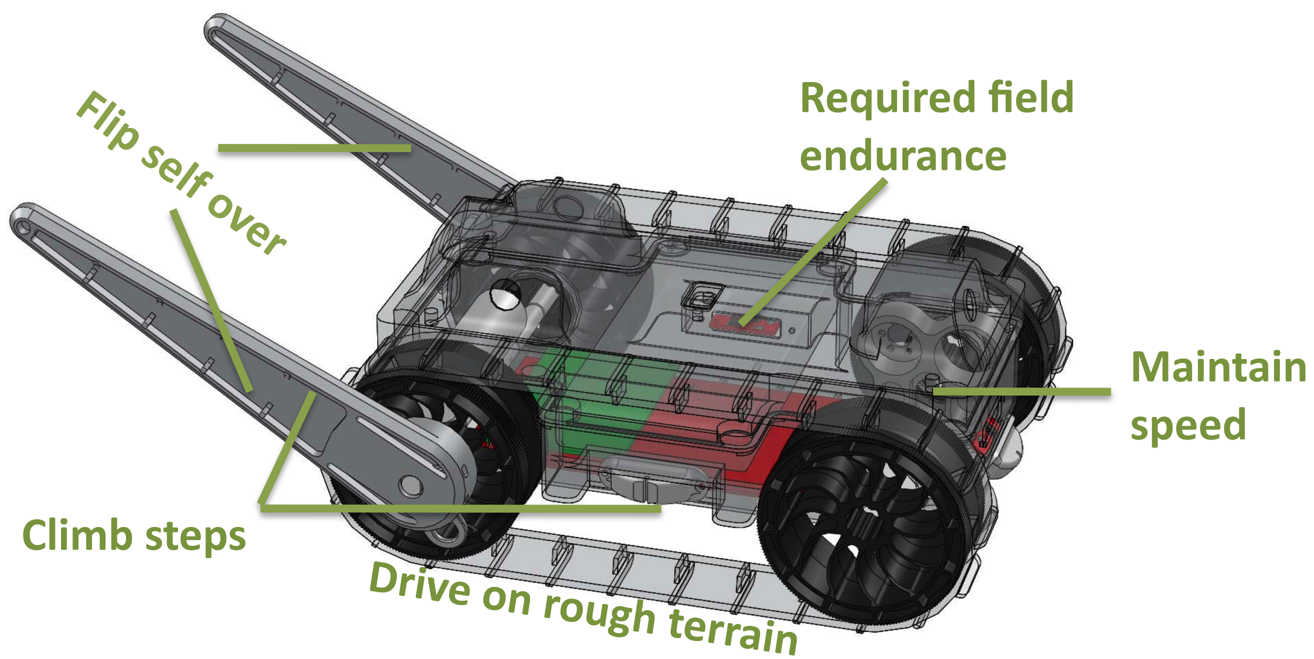
Design fragility from "compiled away" assumptions…



… can be mitigated by autonomous, ongoing integration

Maintenance as a side-effect of normal operation

Self-organization phenomena are useful building blocks!

Outline

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- Engineered Self-Organization
- Three techniques:
  - Networks as manifolds
  - Stochastic coordination
  - Functional blueprints
- Summary & Future outlook

Definitions:

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- **Self-Organization** is aggregate structure or behavior that arises from local interactions

"local-to-global" solutions

- **Engineered Self-Organization** is design that predictably leads to specified self-organization

Key: Equivalent Composition Models

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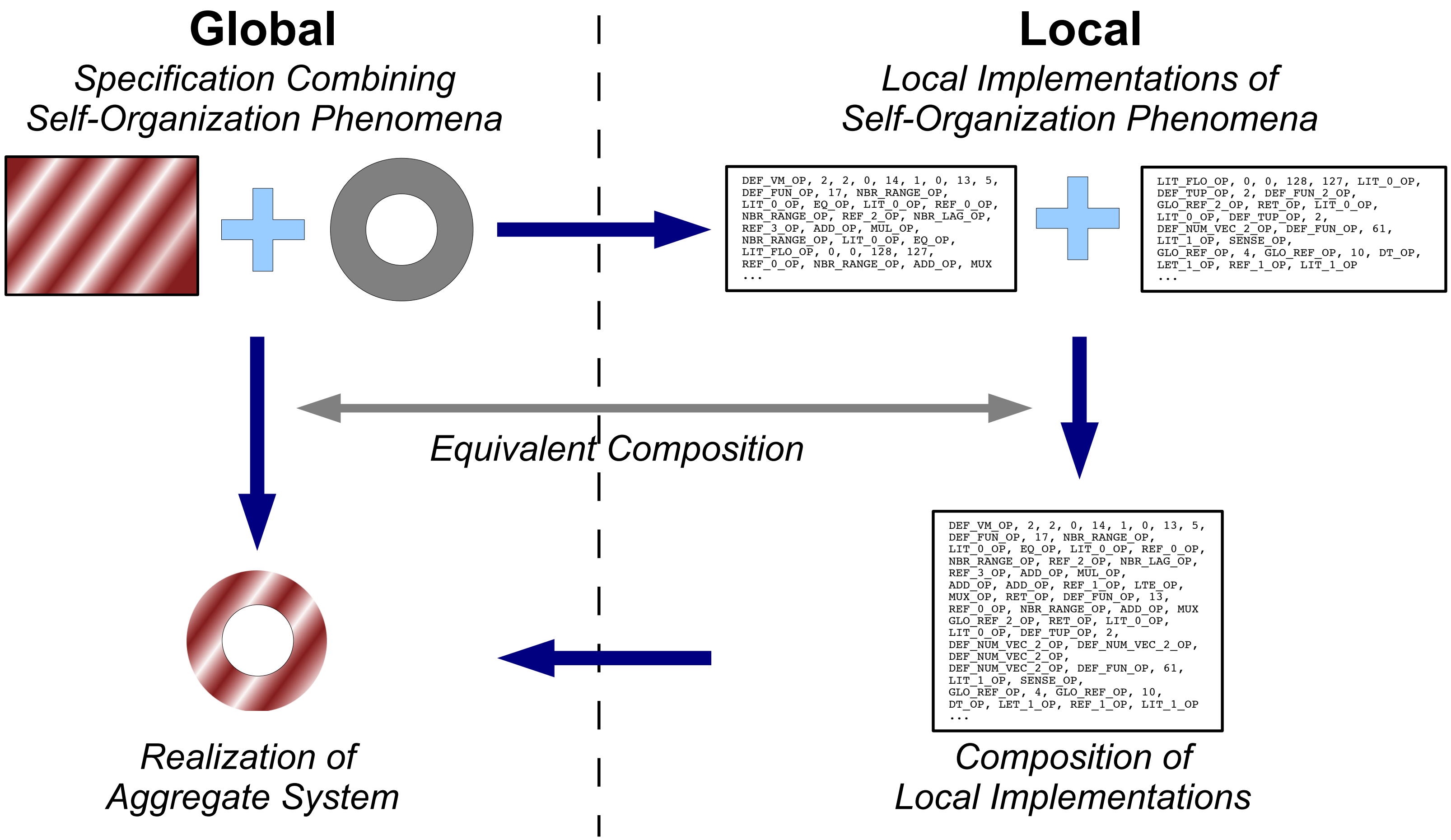

Value: only specify aggregate behavior, details autonomously set at runtime
Cost: initial design harder, extra overhead, NO SILVER BULLET

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Spatial Computers

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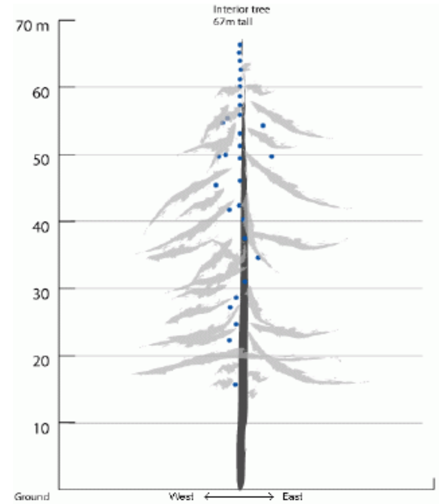
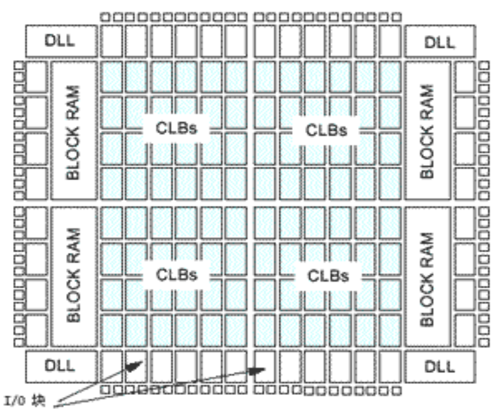
Robot Swarms

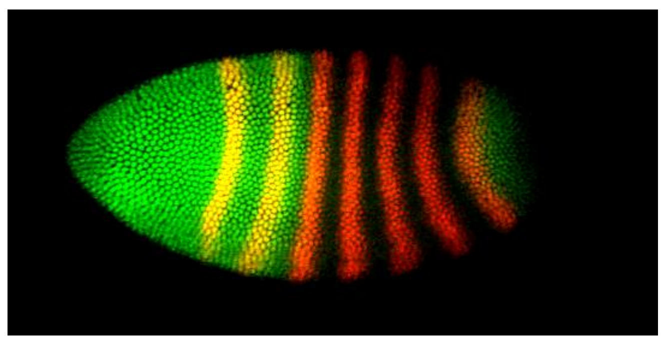
Biological Computing



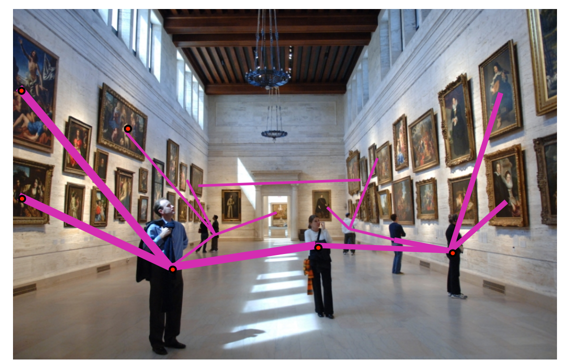
Sensor Networks



Reconfigurable Computing

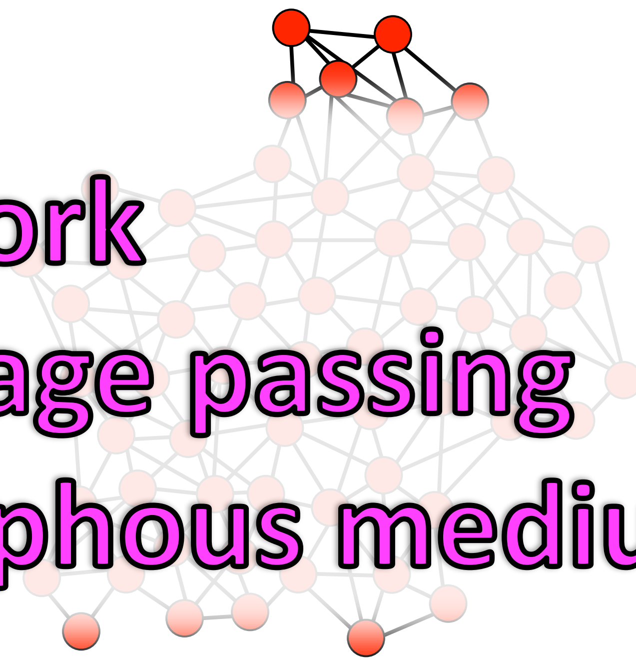


Cells during Morphogenesis



Pervasive Computing

Amorphous Medium



Global: network
Local: message passing
Link: amorphous medium

- Continuous space & time
- Infinite number of devices
- See neighbors' past state

Approximate with:
- Discrete network of devices
- Signals transmit state

Example: Mesh-Network Cell Phones

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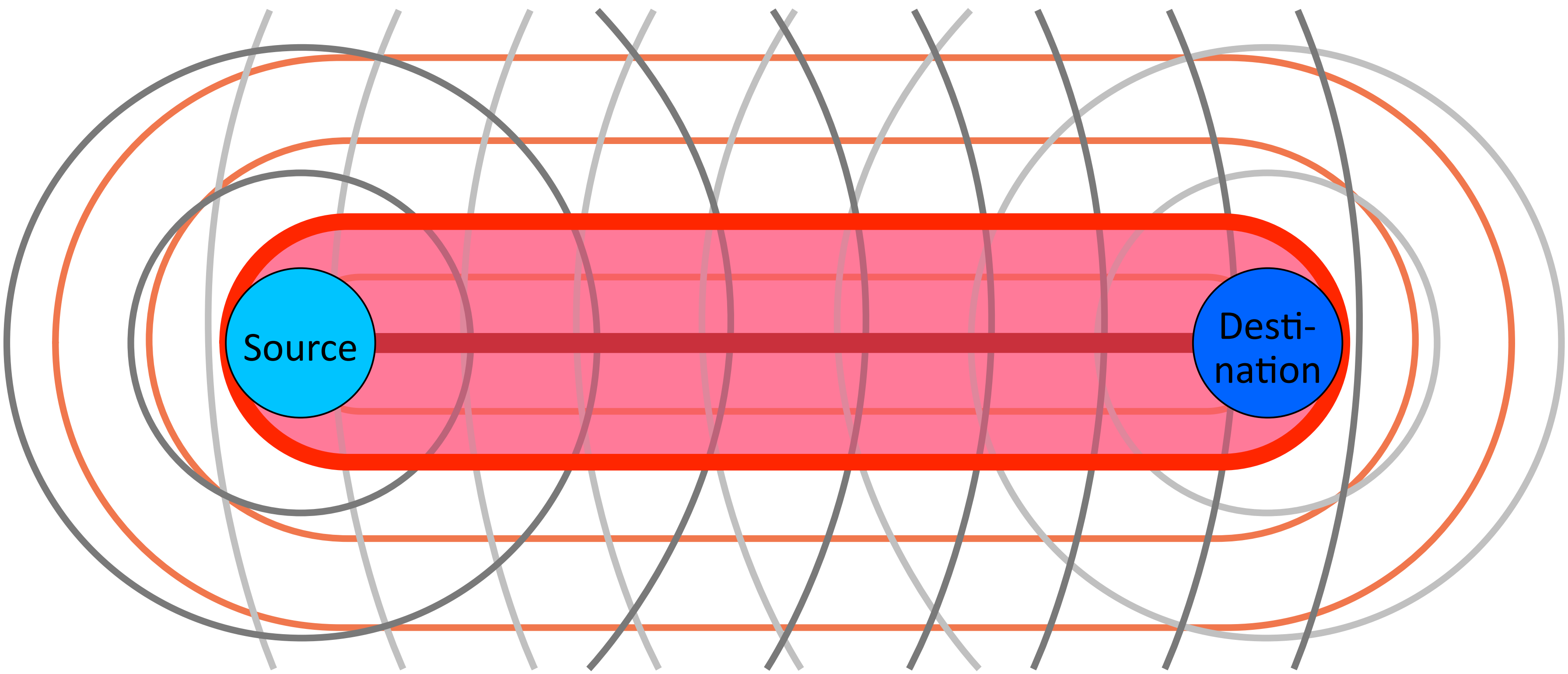
Geometric Program: Channel



(cf. Butera '02)

Computing with fields

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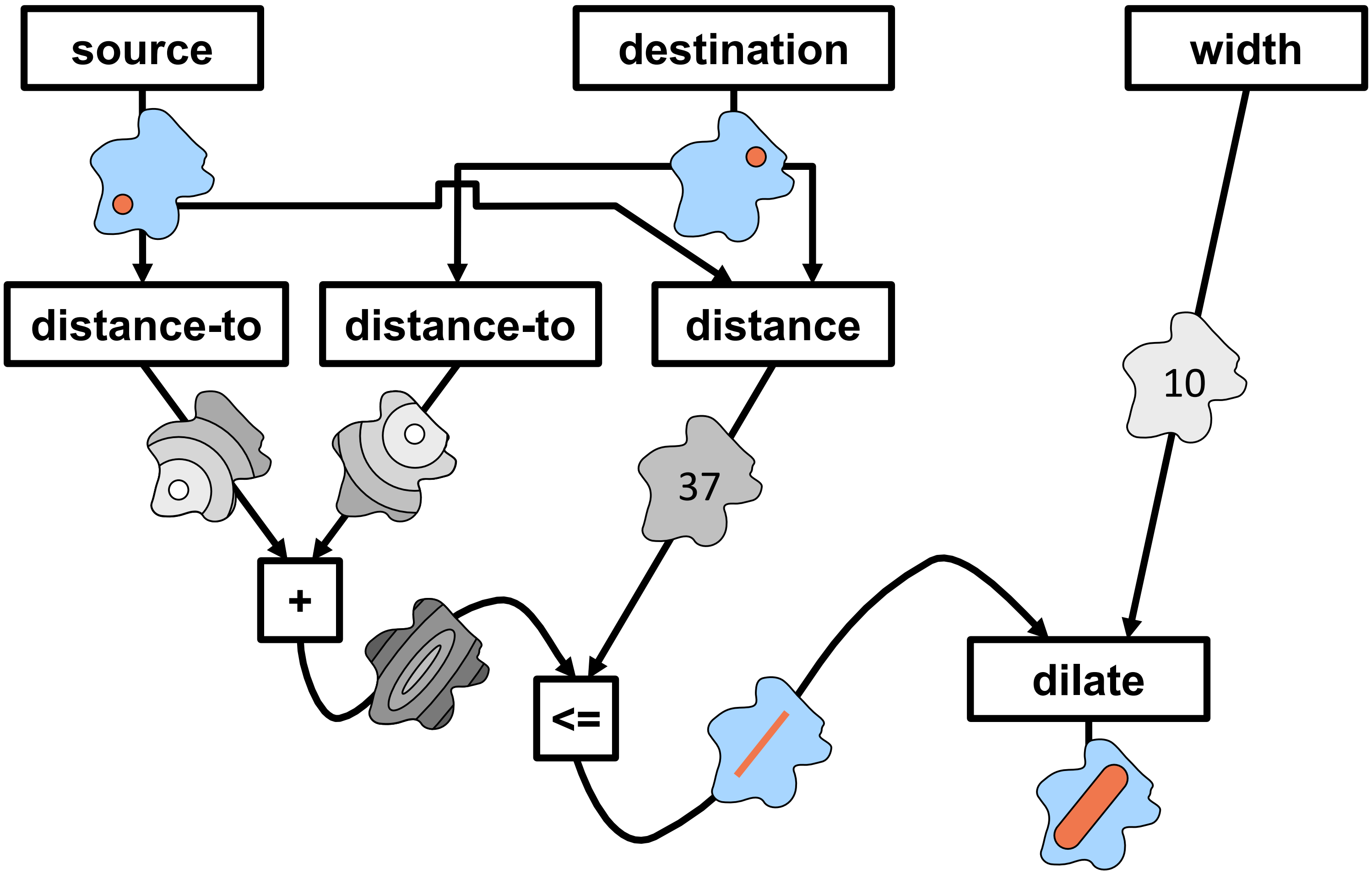
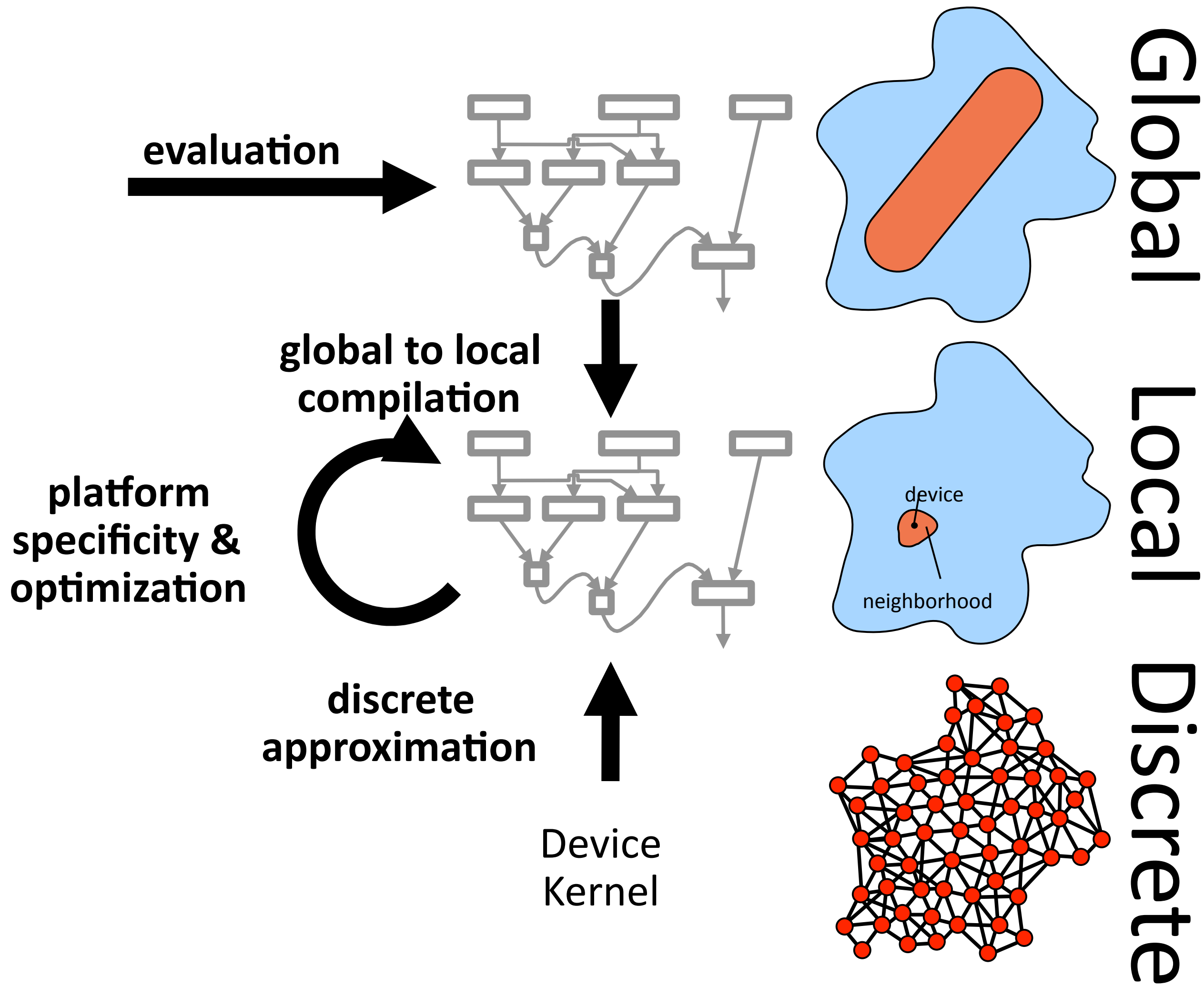


Proto

```
(def gradient (src) ...)
(def distance (src dst) ...)
(def dilate (src n)
  (<= (gradient src) n))
(def channel (src dst width)
  (let* ((d (distance src dst))
         (trail (<= (+ (gradient src)
                       (gradient dst))
                    d)))
    (dilate trail width)))
```



[Beal & Bachrach, IEEE Intel.Sys. '06]

Proto's Families of Primitives

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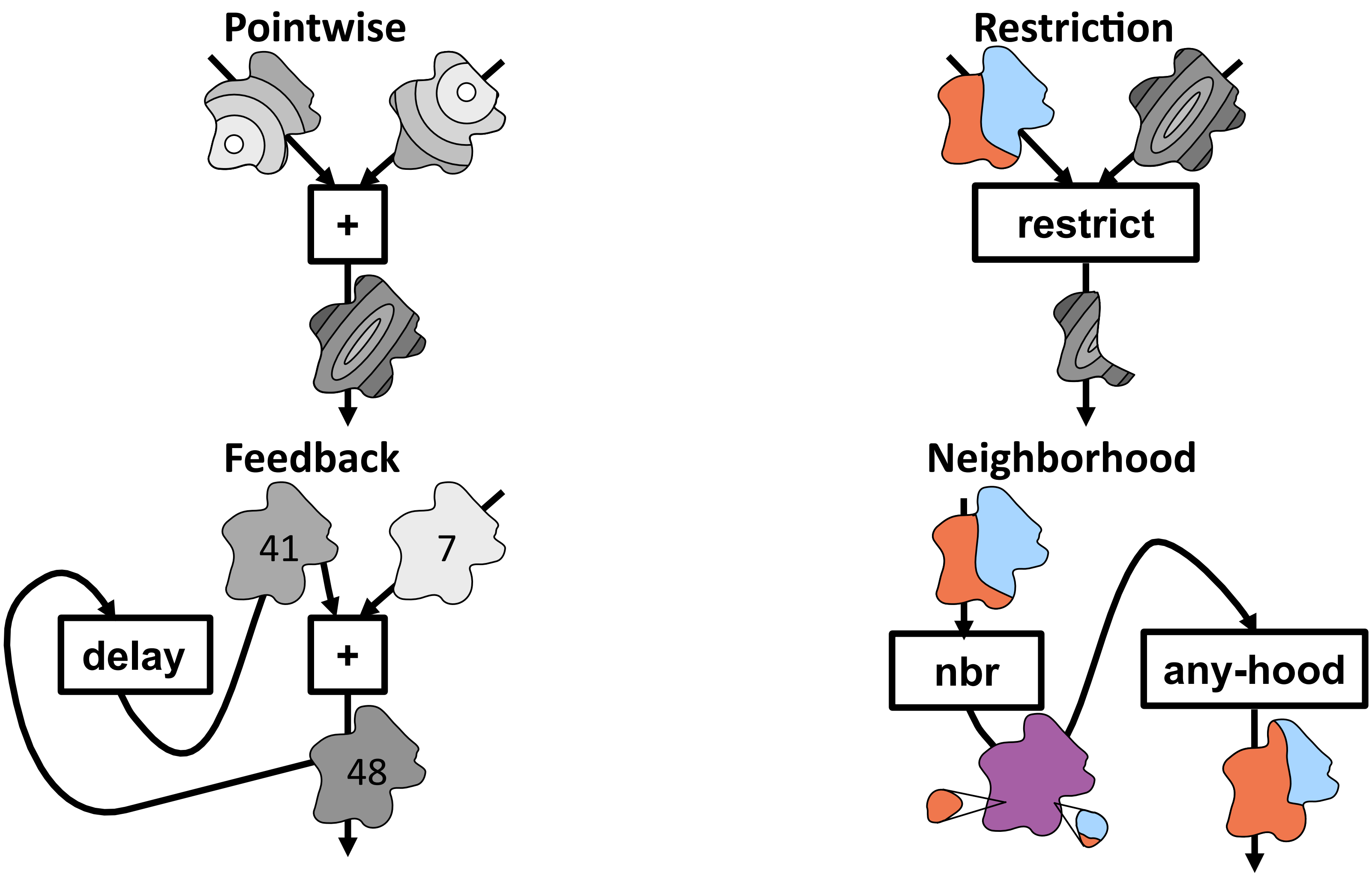

Formal semantics: [Beal, Usbeck & Benyo, Comp.J. 2012], [Viroli, Beal & Usbeck, Sci.Comp.Prog. 2012]

Example Applications

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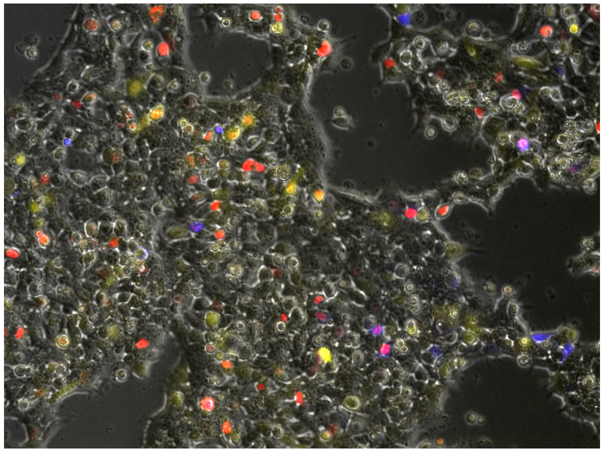
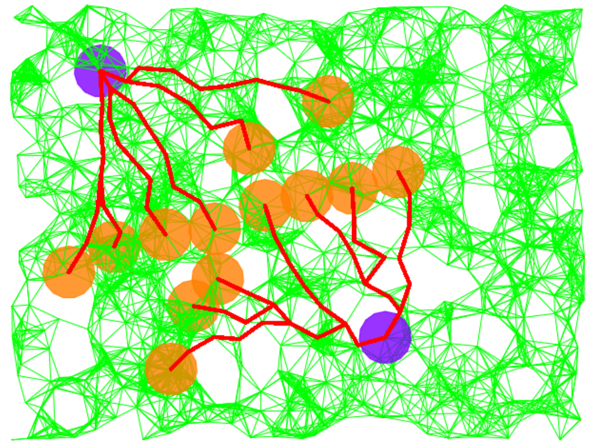
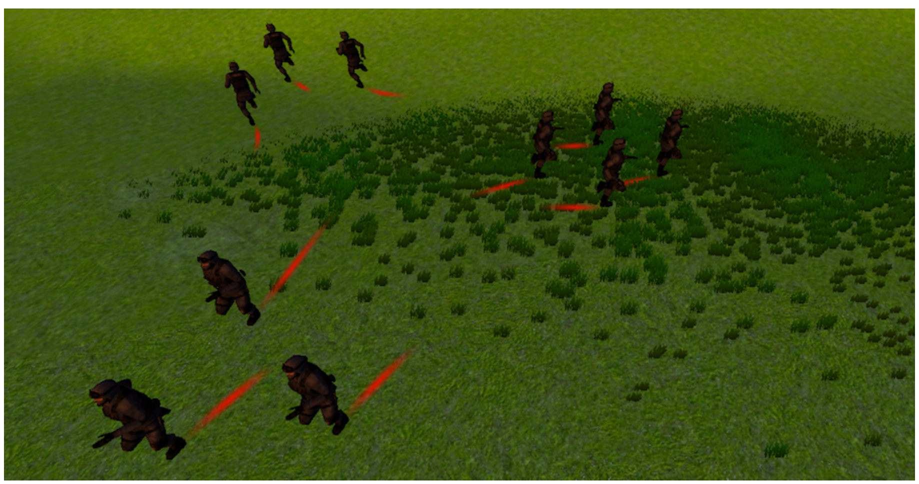


Synthetic Biology



Decentralized publish/subscribe



Agent-based tactical simulation

Swarm search and rescue

[Beal et. al., ACS Syn.Bio. 2012] [Usbeck & Beal, AGERE 2011]
[Beal, Usbeck & Krisler, SCW 2012] [Bachrach, Beal & McLurkin,NCA 2010]

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  - Networks as manifolds
  - **Stochastic coordination**
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Problem: Energy Demand Response

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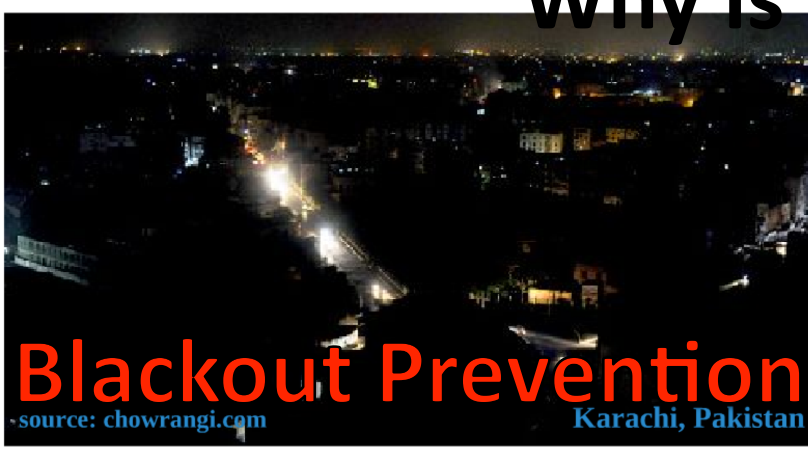
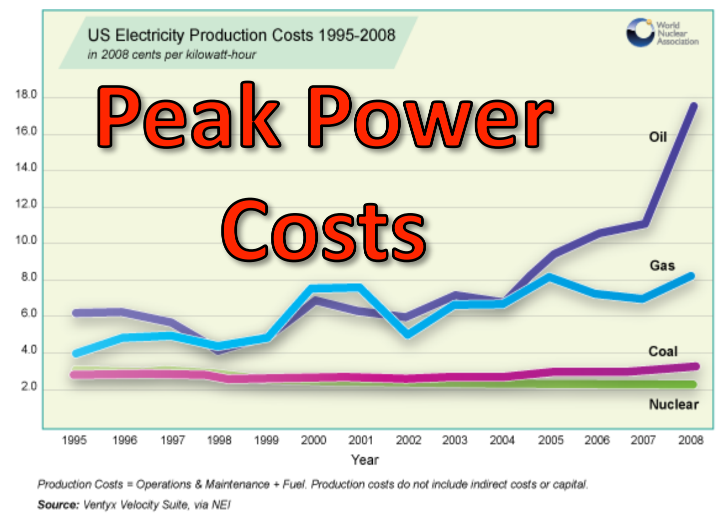
Why is DR important?





Inefficiency of Demand vs. Intention

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- Demand/supply mismatch is extremely costly
  - $ billions to utilities, local governments
- Consumers dramatically reduce demand when:
  - … aware of actual appliance energy use
  - … informed about neighbors' energy use
  - … aware of stress on power grid

*Coordination opportunity: peak-shaving & demand management by **automating volunteerism***

Challenges: privacy, scalability, deployability, consumer interface…

Capturing User Requirements

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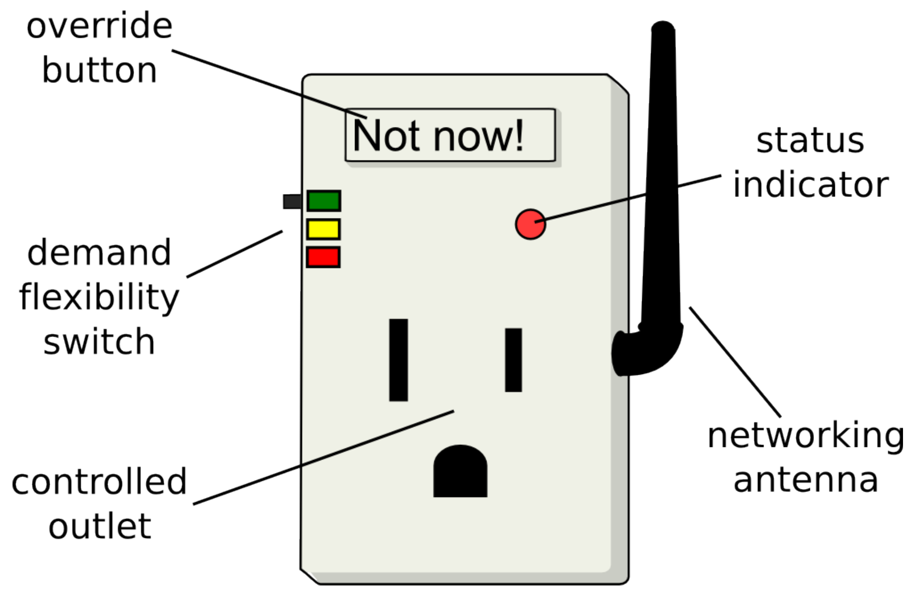
- **Anytime Flexible**
- **Peak Power**
- **Emergencies Only**
- Uncontrolled

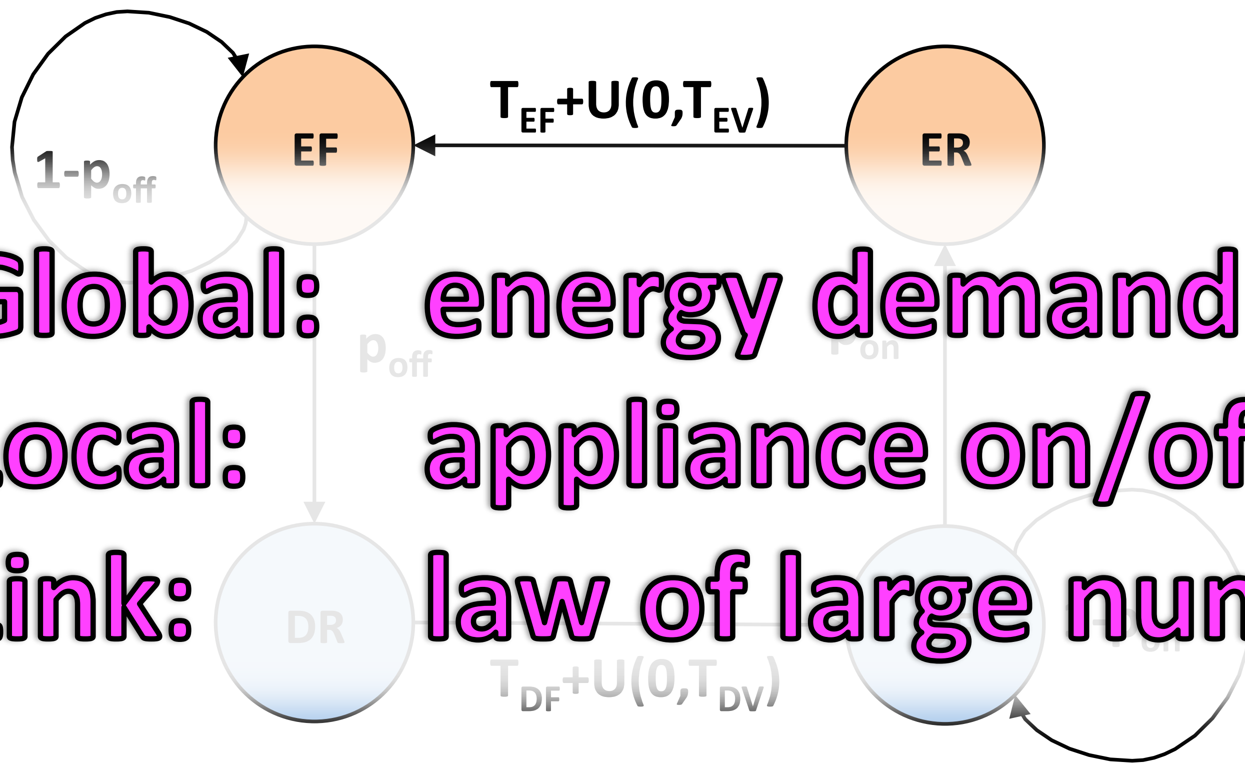


Qualitative Energy Flexibility

Smart plugs, new appliances, home automation, …

Servitization of electricity:
Input based → performance based (need-fulfillment)

ColorPower State Transitions



Global: energy demand

Local: appliance on/off

Link: law of large numbers

- (E)nabled vs. (D)isabled
- (R)efractory vs. (F)lexible

[Ranade & Beal, SASO 2010], [Beal, Berliner & Hunter, SASO 2012]

Formal Control Problem

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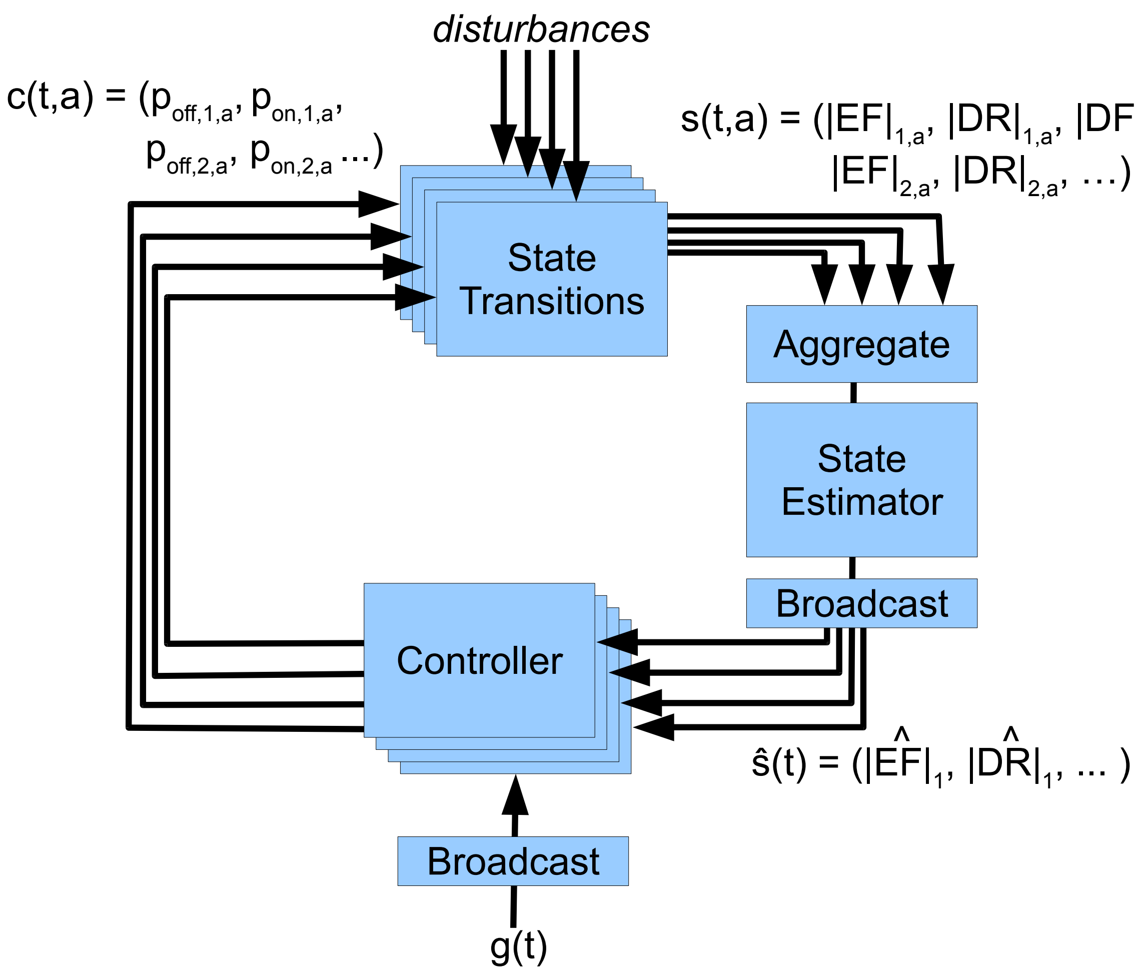

For each ColorPower client, set p_{on}, p_{off} for each device group, such that the total enabled power in s(t) tracks g(t)

ColorPower Algorithm: Intuition

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- Fairness assured by executing equivalent stochastic algorithm on all clients
- Intuition: spend flexibility with three “allocations”
  1. Goal tracking & hard priority constraints
  2. Soft priority
  3. Cycling (trading off fairness against future reserves)
- Any “unspent” flexibility is allowed to accumulate, improving future controllability

ColorPower Algorithm: Equations

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Boundary color b: $D_{b+1} \leq g(t) < D_b$

Allocation 1: Goal Tracking

Correction Goal:

$$C^g = \alpha \cdot (g(t) - \sum_i |\hat{EF_i}| + |\hat{ER_i}|)$$

Downward shift:

$$\Delta_i^{g-} = \begin{cases} 0 & \text{if } C^g \geq 0 \text{ or } i > b \\ |\hat{EF_i}| & \text{else if } \sum_{j \leq i} |\hat{EF_j}| \leq |C^g| \\ |C^g| - \sum_{j<i} |\hat{EF_j}| & \text{else if } \sum_{j<i} |\hat{EF_j}| < |C^g| \\ 0 & \text{otherwise} \end{cases}$$

Upward is converse

Allocation 2: Color Priority

$$|\hat{EF_i}|' = |\hat{EF_i}| - \Delta_i^{g-} \quad |\hat{DF_i}|' = |\hat{DF_i}| - \Delta_i^{g+}$$

Downward shift:

$$\Delta_i^{p-} = \begin{cases} 0 & \text{if } i \geq b \text{ or } \sum_{j \leq i} |\hat{EF_j}|' > |DF_b|' \\ |\hat{EF_i}|' & \text{else if } \sum_{j \leq i} |\hat{EF_j}|' \leq |DF_b|' \\ |DF_b|' - \sum_{j<i} |\hat{EF_j}|' & \text{else if } \sum_{j<i} |\hat{EF_j}|' < |DF_b|' \end{cases}$$

Upward is converse

Allocation 3: Cycling

$$|\hat{EF_b}|'' = |\hat{EF_b}| - \Delta_i^{g-} - \Delta_i^{p-}$$

and similar for other states

Reserve fraction f:

$$\frac{|EF_b|}{|ER_b|} \geq f \text{ and } \frac{|DF_b|}{|DR_b|} \geq f$$

$$r(t) = (D_b - g(t))/(g(t) - D_{b+1})$$

$$p_{on,ss} = \frac{1}{f \cdot T_D}$$

$$p_{off,ss} = \frac{1}{\frac{1}{r(t)}(f+1)T_D - T_E}$$

when enabled domainates, else converse

$$\Delta_b^{c-} = \Delta_b^{c+} = \min(p_{off,ss} \cdot |EF_b|'', p_{on,ss} \cdot |\hat{DF_b}|'')$$

Computing p_{on} and p_{off}

$$p_{off,i,a} = \frac{\Delta_i^{g-} + \Delta_i^{p-} + \Delta_i^{c-}}{|EF_i|}$$

$$p_{on,i,a} = \frac{\Delta_i^{g+} + \Delta_i^{p+} + \Delta_i^{c+}}{|DF_i|}$$

Simulation Studies

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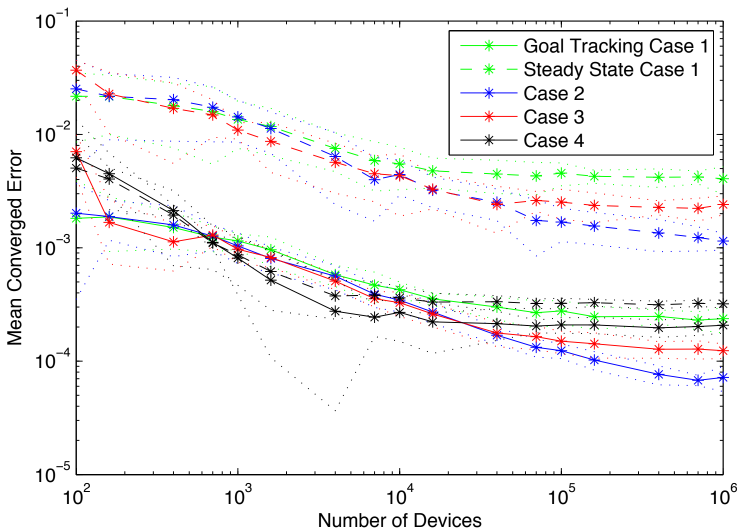
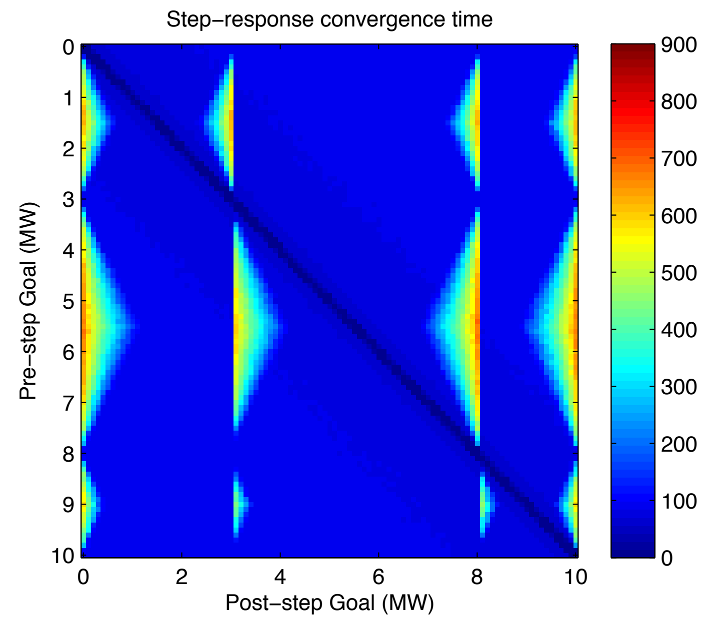
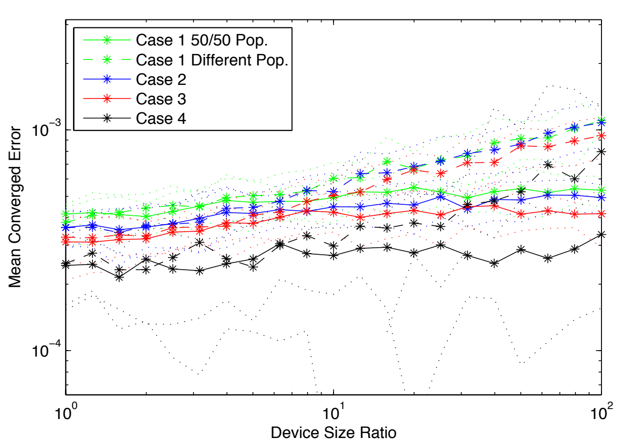
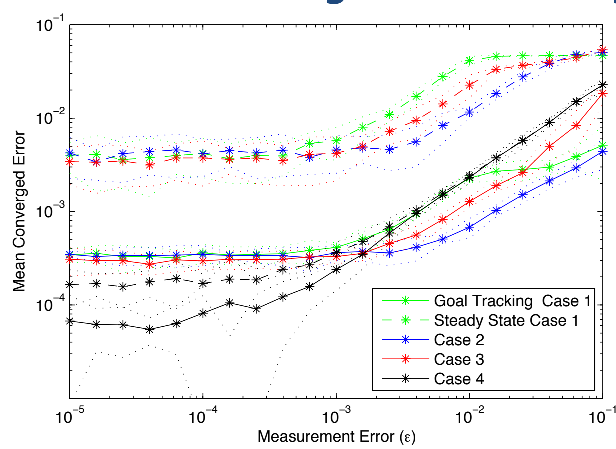


Scalable: More devices = better accuracy



Fast convergence matching predictions





Good tolerance of heterogeny and error

Current State: Transition to Pilots…

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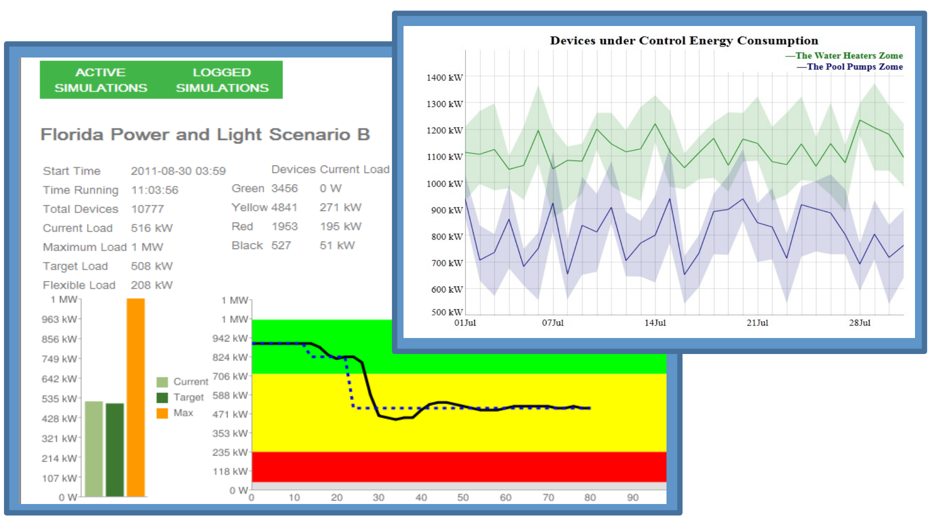
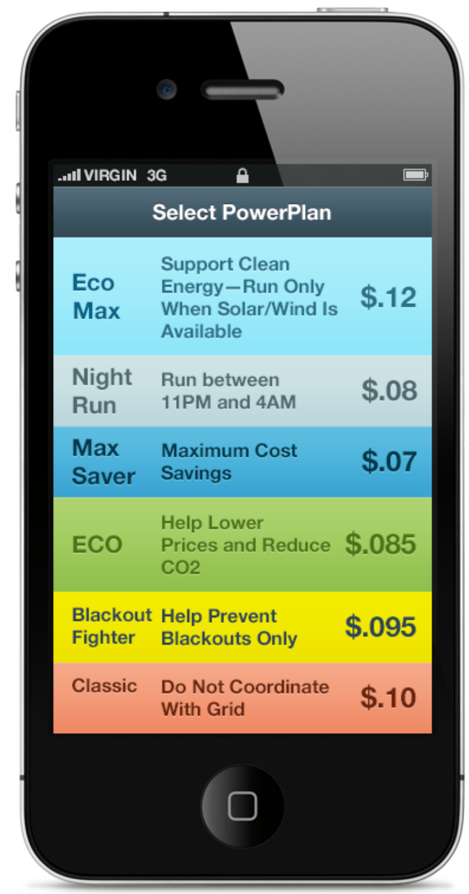
colorpower

- Partnership with energy industry startup
- Integration and product development
  - Market integration
  - Consumer HCI & incentives
  - Operations interface
  - PDD, reference designs
  - Service models

…





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MADV: Morphogenesis for Redesign

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Operation experts are not engineering experts…

... but have good ideas for new uses and upgrades

What if your robot can climb stairs…

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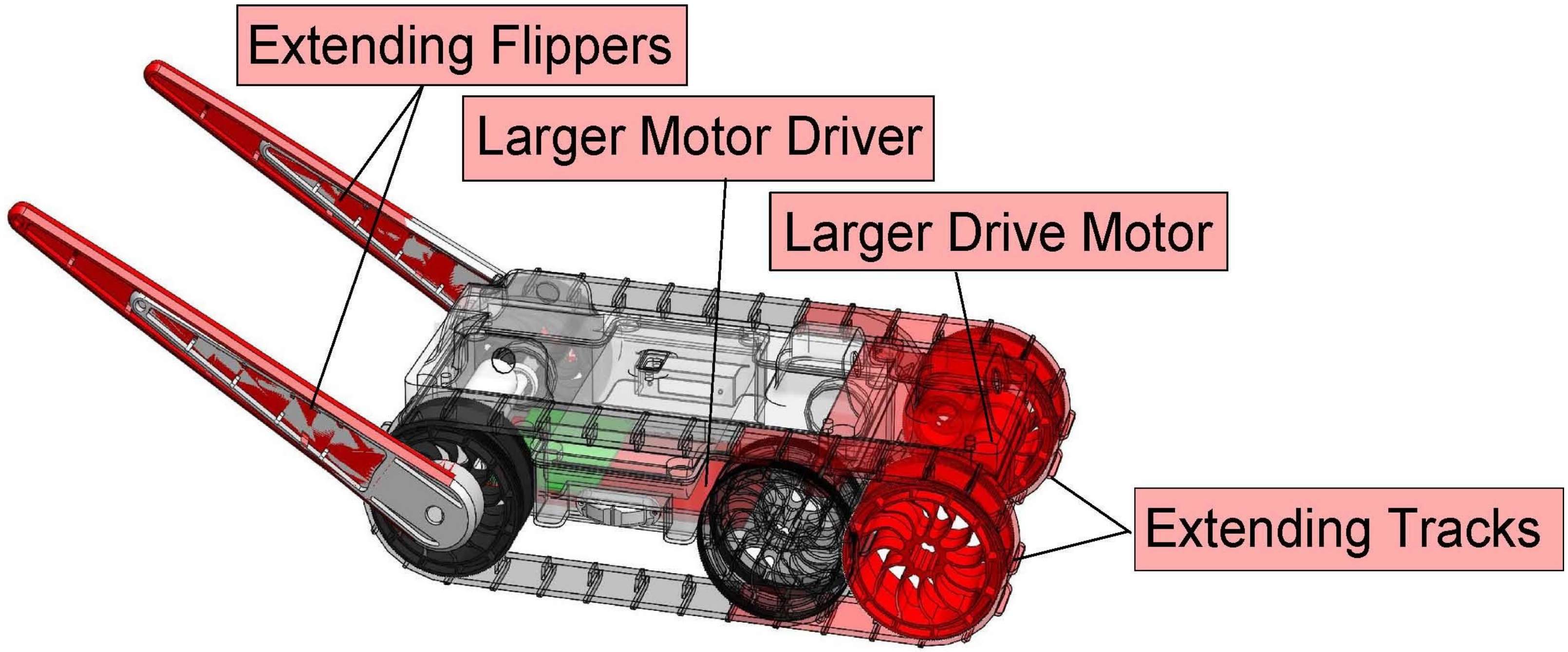
… but you want to check cars for IEDs?

Problem: Robot Redesign Complexity

Even "simple" robots require careful design of many interacting components…



… and small changes have large consequences.

A phylogeny of engineered systems?

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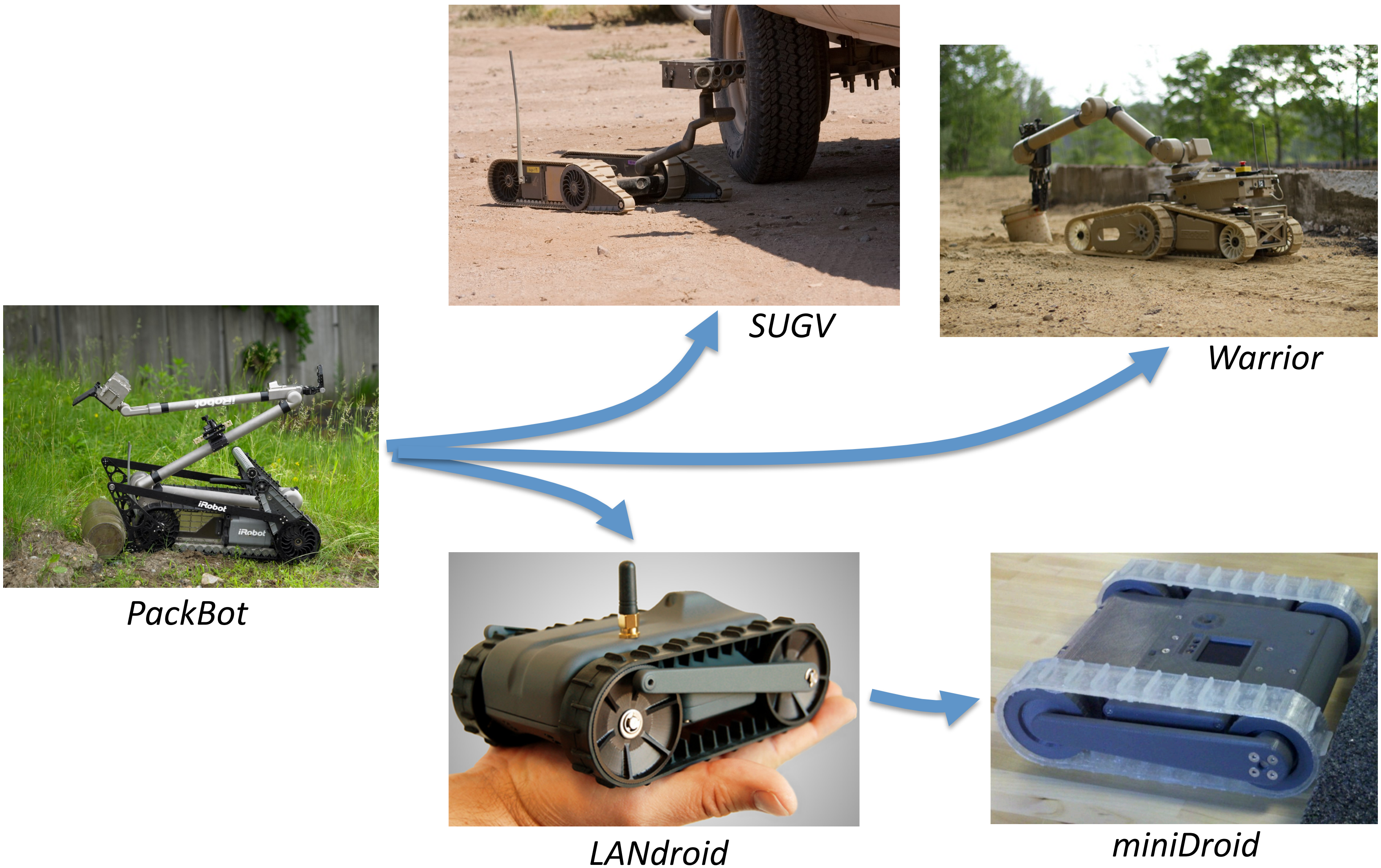

Functional Blueprints

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Functional blueprints requirements:

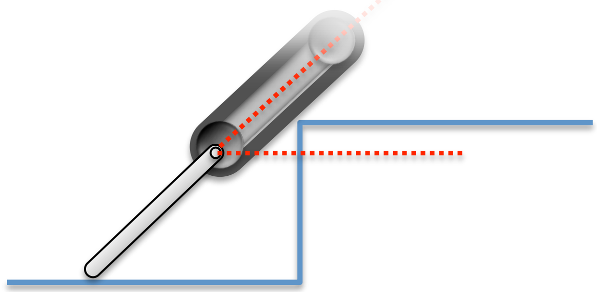
- Behavior that degrades gracefully
  - Stress must be between 0 and 1
- Incremental adjustment program
- Initial viable design

Global: design specification

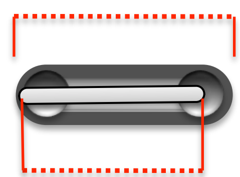
Local: parameter values

Link: functional blueprint

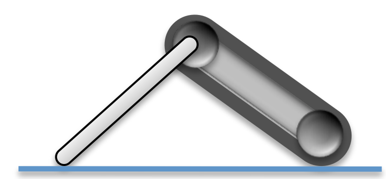
Examples



Step Climbing
(via ascent angle)

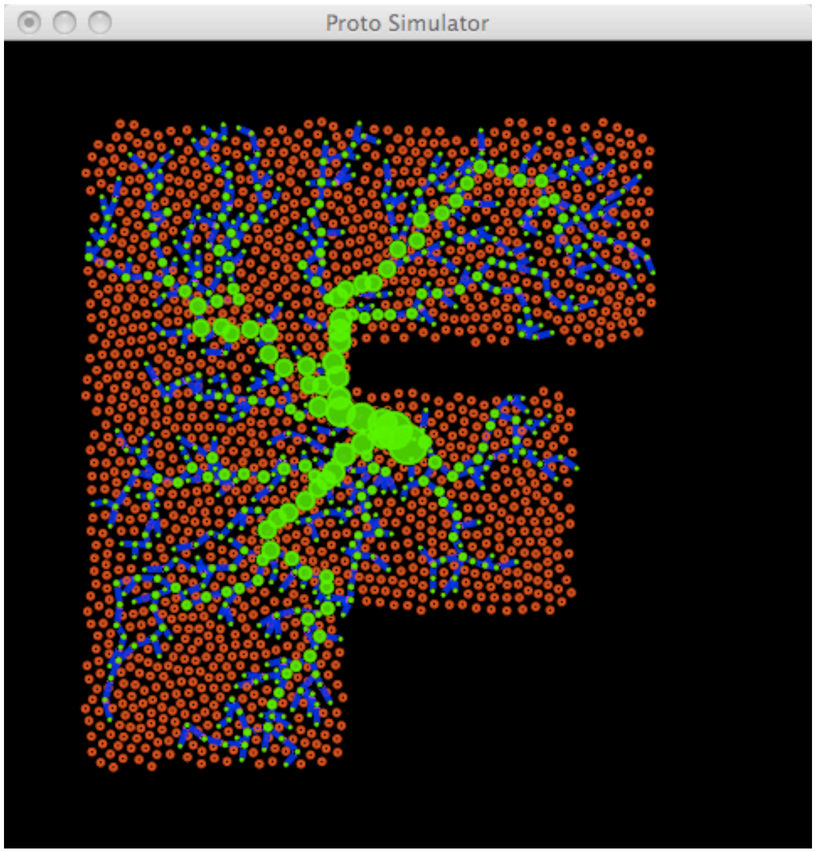


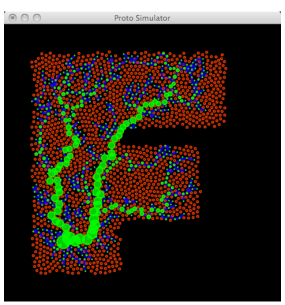
Flipper/Body Ratio

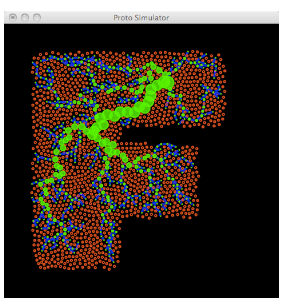


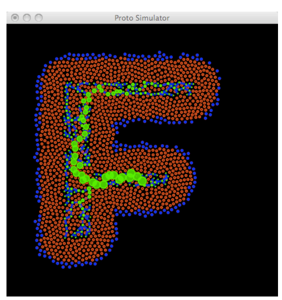
Self-Righting
(via torque/mass)

Preliminary Test: Cartoon Vascularization

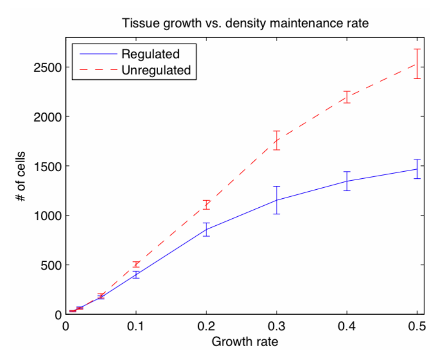


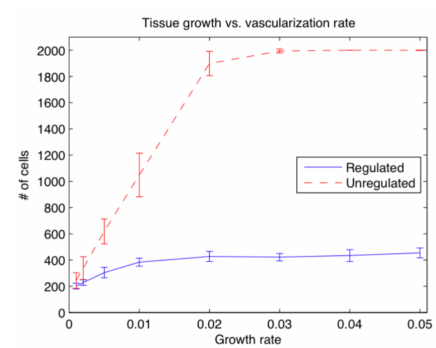






- Functional blueprint model of vascularization
  - Stress: oxygen, elastic stress
  - Adjustment: leaking, vessel grow/shrink
- Red cells are healthy, blue cells are oxygen-deficient
- Can model vascularization and density co-regulation





[Beal, Swarm Intel. 2010]

MADV Architecture

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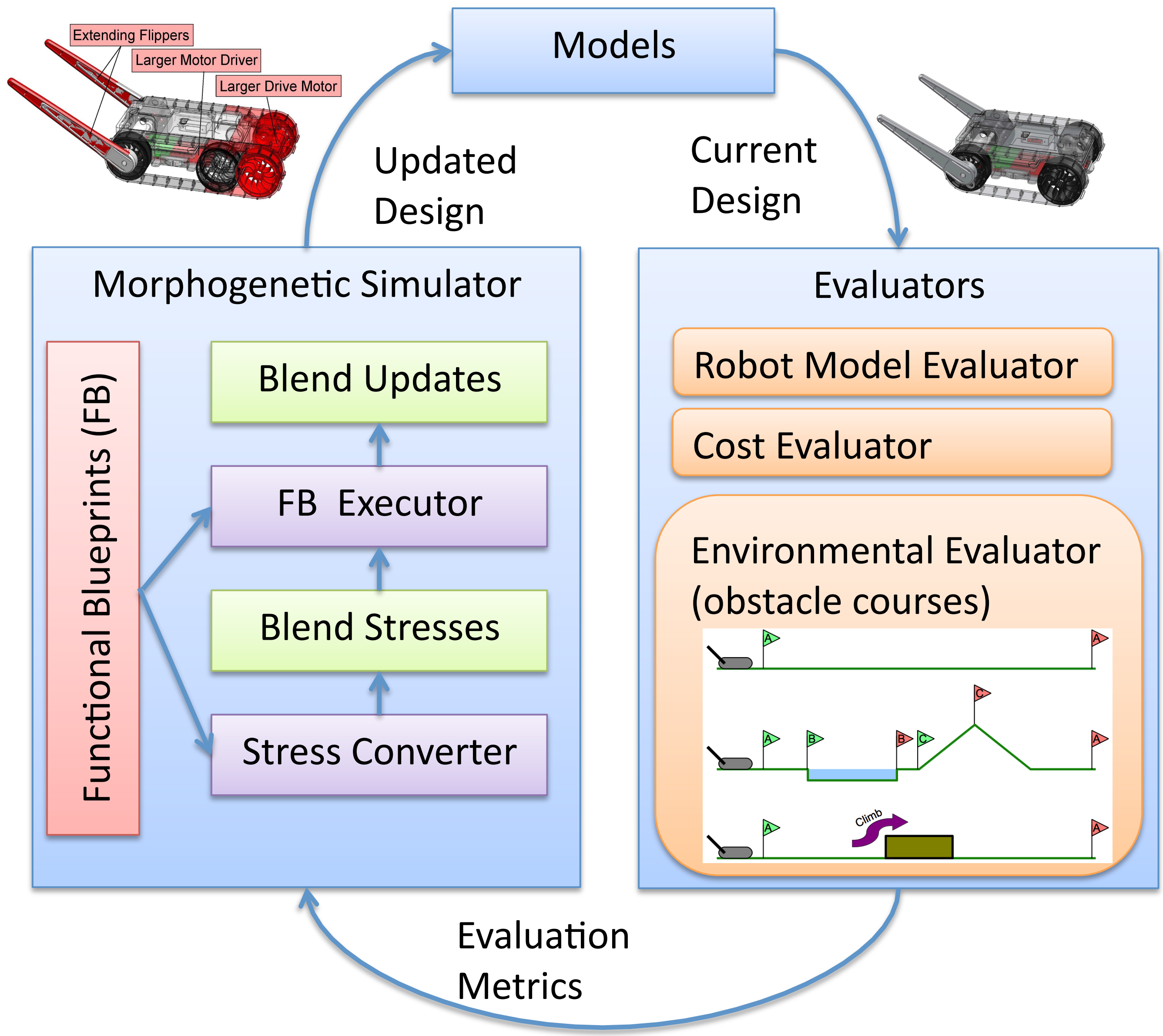

Incremental Changes Ensure Progress

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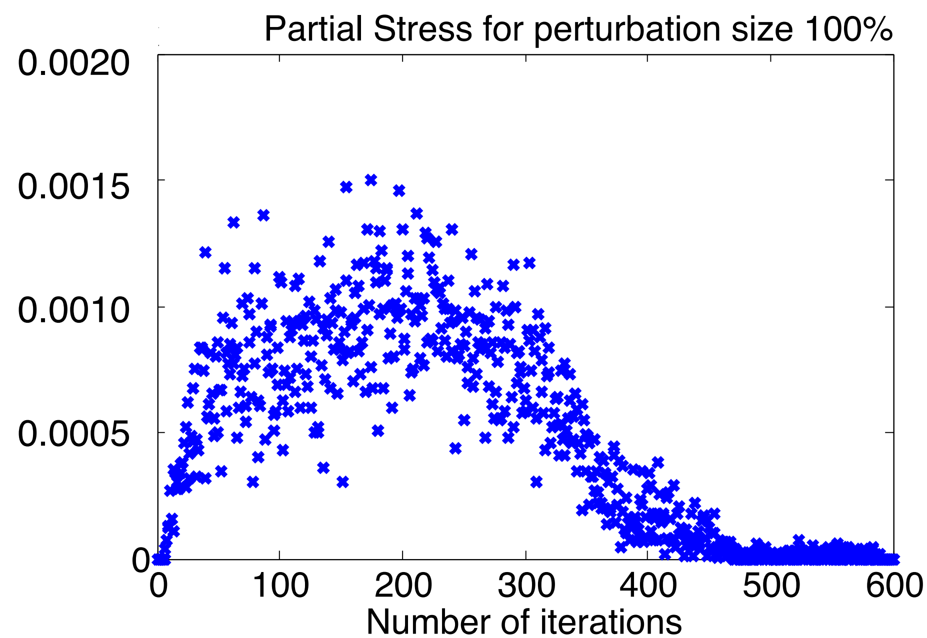
Incremental, *not* evolutionary!

- Always keep design viable
  - Stress-modulated incremental changes
- Stress disperses quickly through the network of functional blueprints

$$V = sign\left(\sum_i V_i\right) \cdot \max_i \left(V_i \frac{\sum_i V_i}{\sum_i |V_i|} \right)$$

Blending function



*No need for best design, just **some** working design*

[Adler et al., ICMC 2011]

Morphogenesis resolves design constraints

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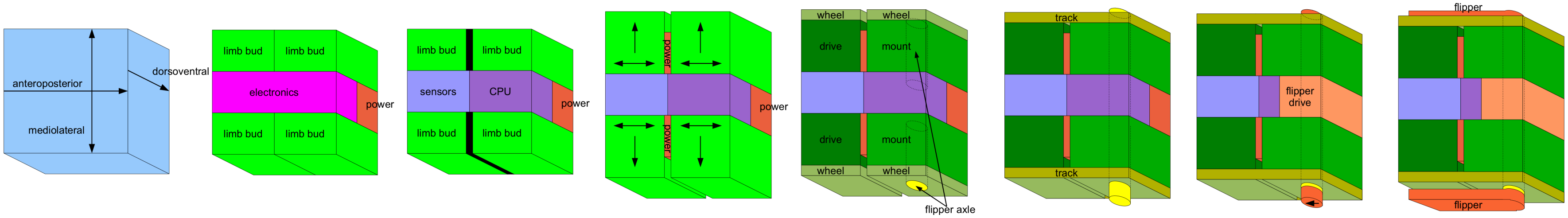
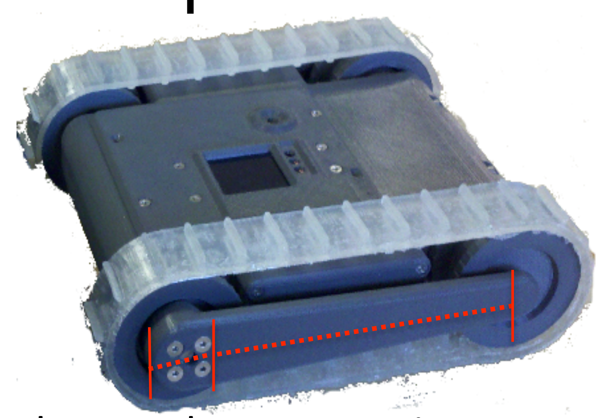
Manifold evolution based on biological development



Implicit parameters specified through geometric relationships developed between components

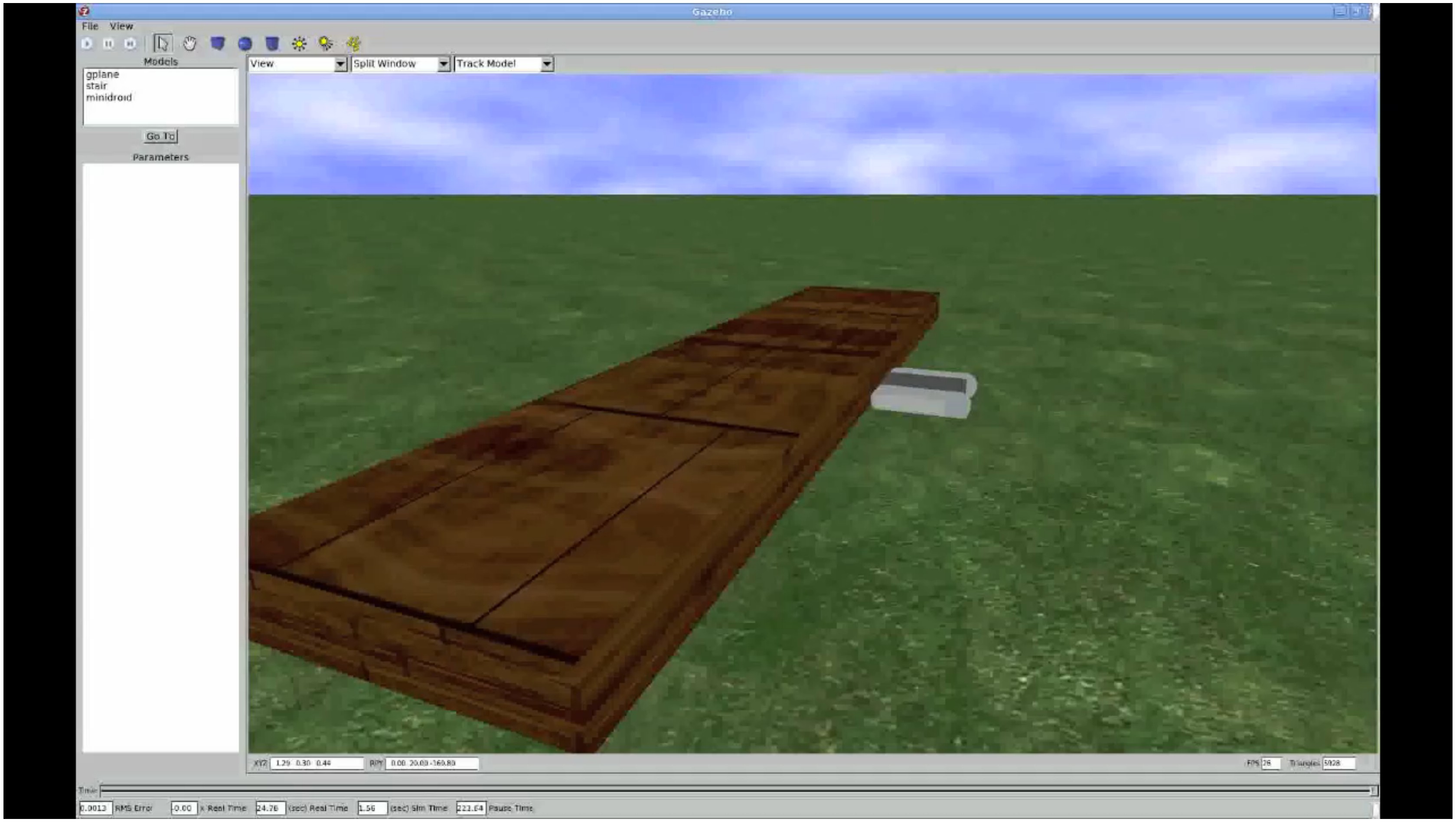
- Abstraction of components
- Reduced dimensionality
- Greater design flexibility



Flipper Length = Axle + Extension

[Beal et al., GECCO 2012]

Example: Climbing a larger step



7 interacting functional blueprints

And on toward complete blueprints…

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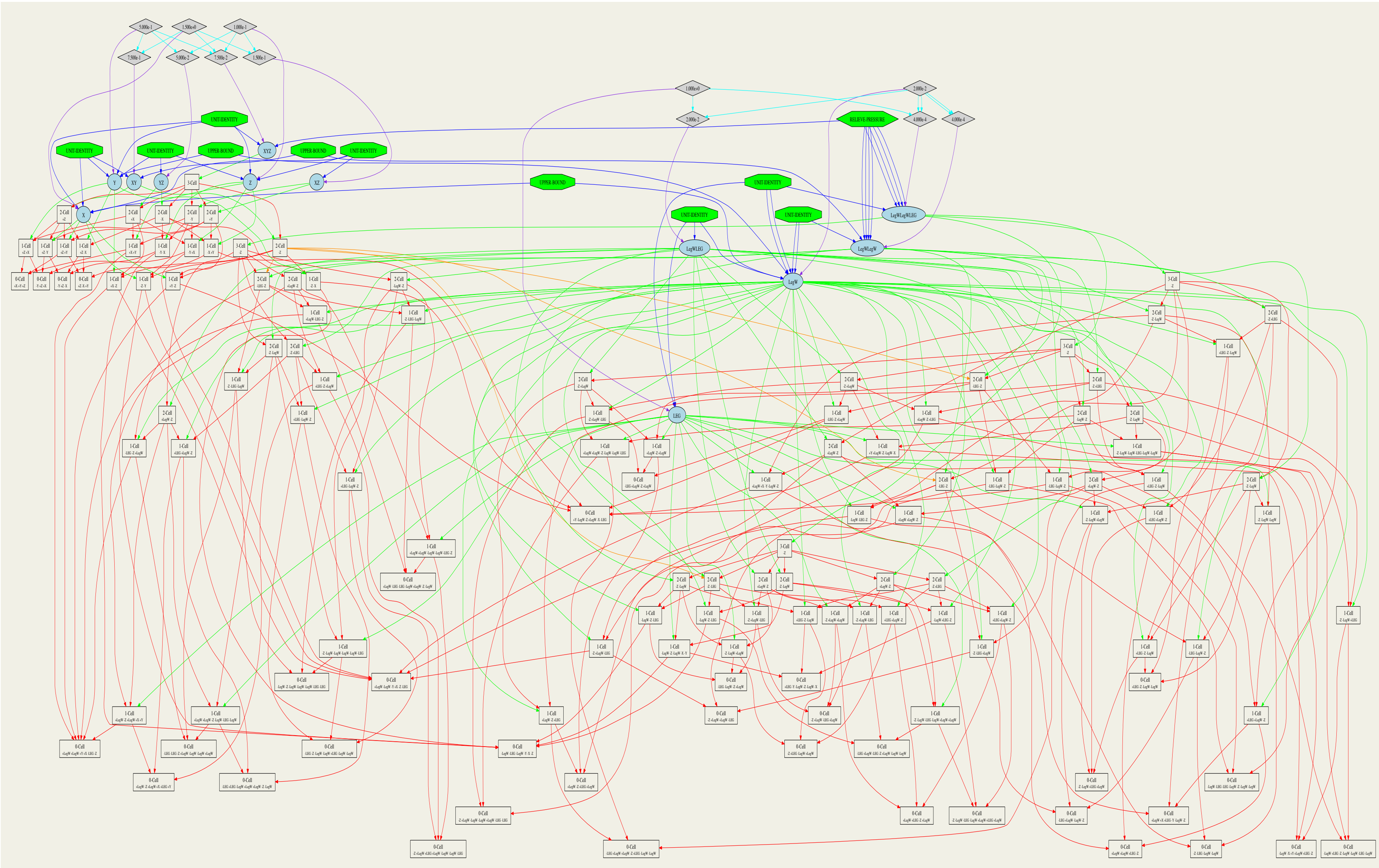

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  - Functional blueprints
- **Summary & Future outlook**

Summary

- Engineered self-organization helps with hard problems of design, scalability, and maintenance

Global:	**Communication Network**	**Aggregate Demand**	**Design specifications**
Local:	**Message passing**	**Appliance power consumption**	**Individual design parameters**
Model Enabling Composition:	**Amorphous medium**	**Law of Large Numbers**	**Functional blueprints**

- No silver bullet --- but many useful techniques

Three Strands of Development

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- Discovery / adaptation of new self-organization phenomena to provide global behaviors

  Example: functional blueprints

- Refinement of self-organization phenomena into engineering techniques suitable for routine use

  Example: spatial computing with Proto

- Application to real-world problems of systems design and maintenance

  Example: ColorPower stochastic control

Acknowledgements

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Aaron Adler
Brett Benyo
Jeff Berliner
Jeff Cleveland
Ryan Irwin
Susan Katz
Brian Krisler
Jessica Lowell
Gretchen Markiewicz
Hala Mostafa
Kyle Usbeck
Fusun Yaman

iRobot

Annan Mozeika
Benjamin Axelrod

colorpower

Vinayak Ranade
Kevin Hunter

DARPA

Interns: Katie McGuire, Taylor Campbell