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Adaptive Complexity Revealed



With challenges for modeling and the V&V and UQ of those models

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U.S. DEPARTMENT OF ENERGY

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Goal of this Talk

- Lay out fundamental elements and dynamics of adaptive systems
- Illuminate modeling and V&V and UQ challenges with them

The Natural Selection Algorithm

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1. New Candidates	Sexual Recombination and Mutation	Random Walk from Prior Successful Candidates
2. Test Candidates	Do they survive to reproduce? How many offspring do they have?	Those better adapted to current conditions will, on average, have more offspring
3. Repeat with New/Surviving Population		

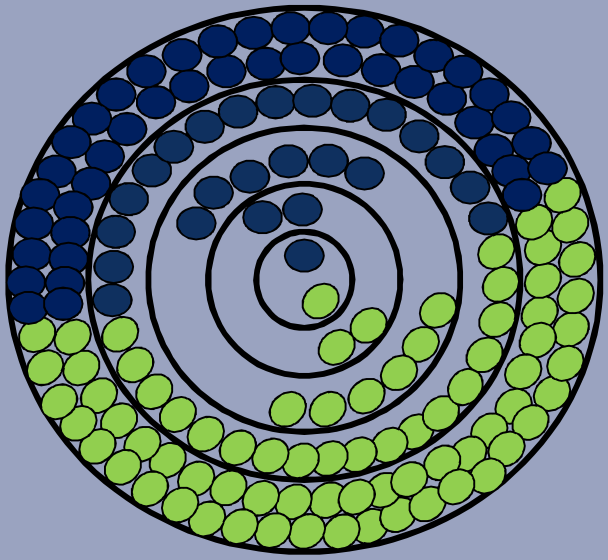
Starting Point

- Stable, homogeneous environment
- Asexual reproduction
- Individuals are born mature and fertile, and stay fertile
- Unlimited resources
- No predation, no food chain
- No illness or accidental death
- Extremely abstract and unrealistic

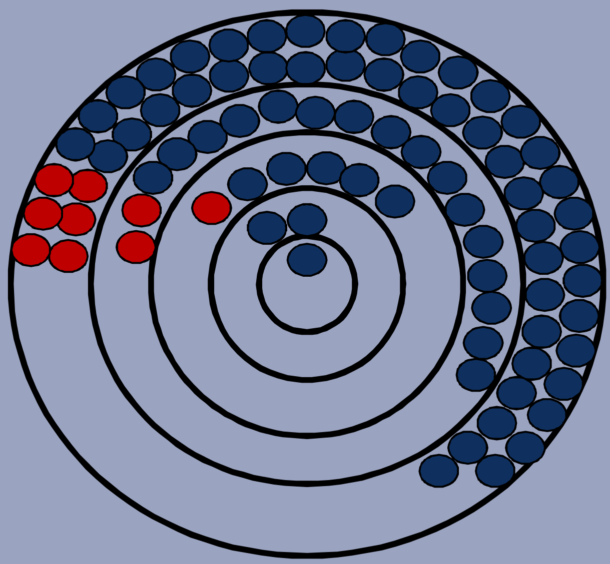
Unbounded Growth

- Green population is immortal.
- Blue population lives to the birth of their great grandchildren

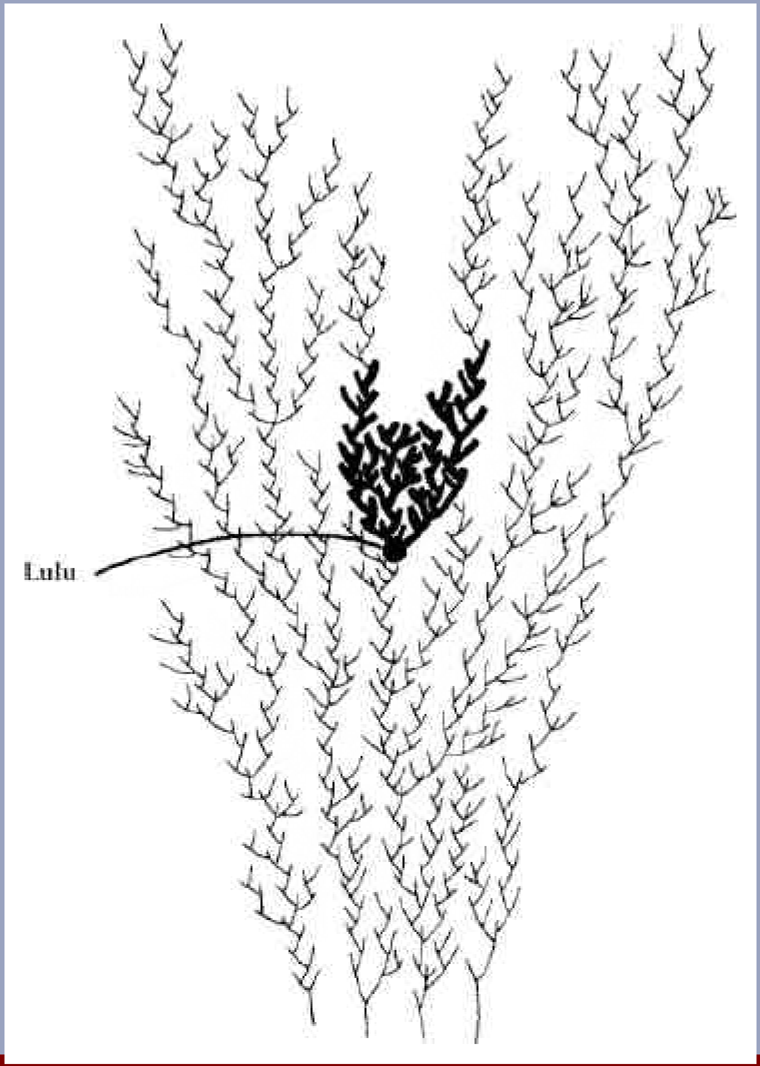
Populations are a simple function of fecundity and longevity. While green is growing faster than blue, they are not competing and are both unbounded.

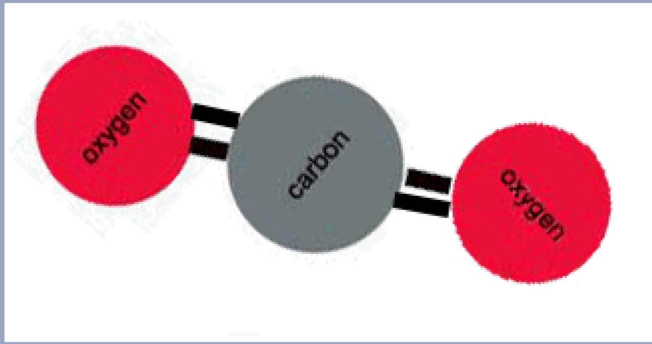


Adding Copying Errors



Types in Adaptive Complexity Are Not Platonic Essences

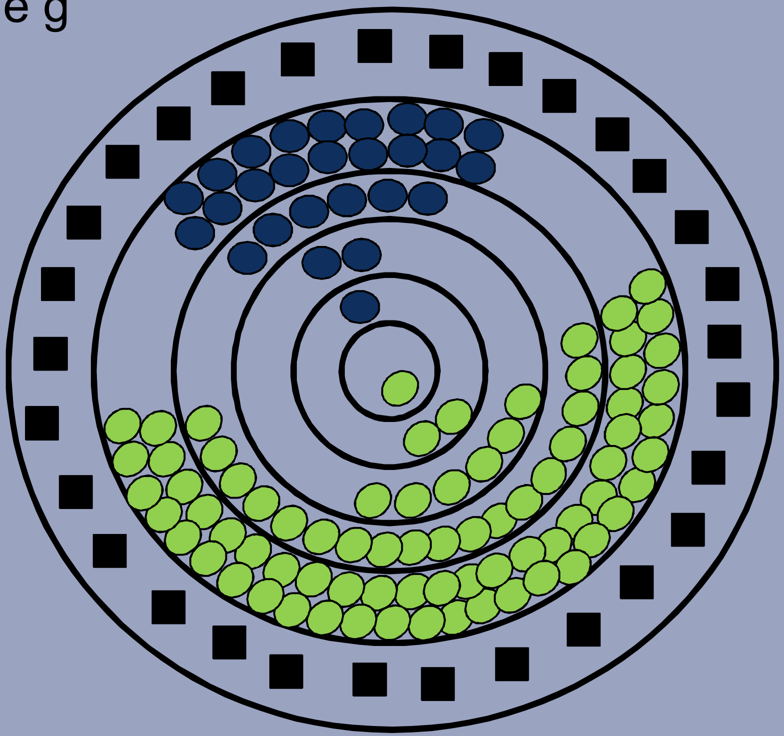




- Most species definitions have arbitrary components
- Because natural selection works by tinkering, individuals within a type can differ greatly
- More generally, the natural selection process rarely produces discrete types, but rather continuous variation.

Adding Scarce Resources

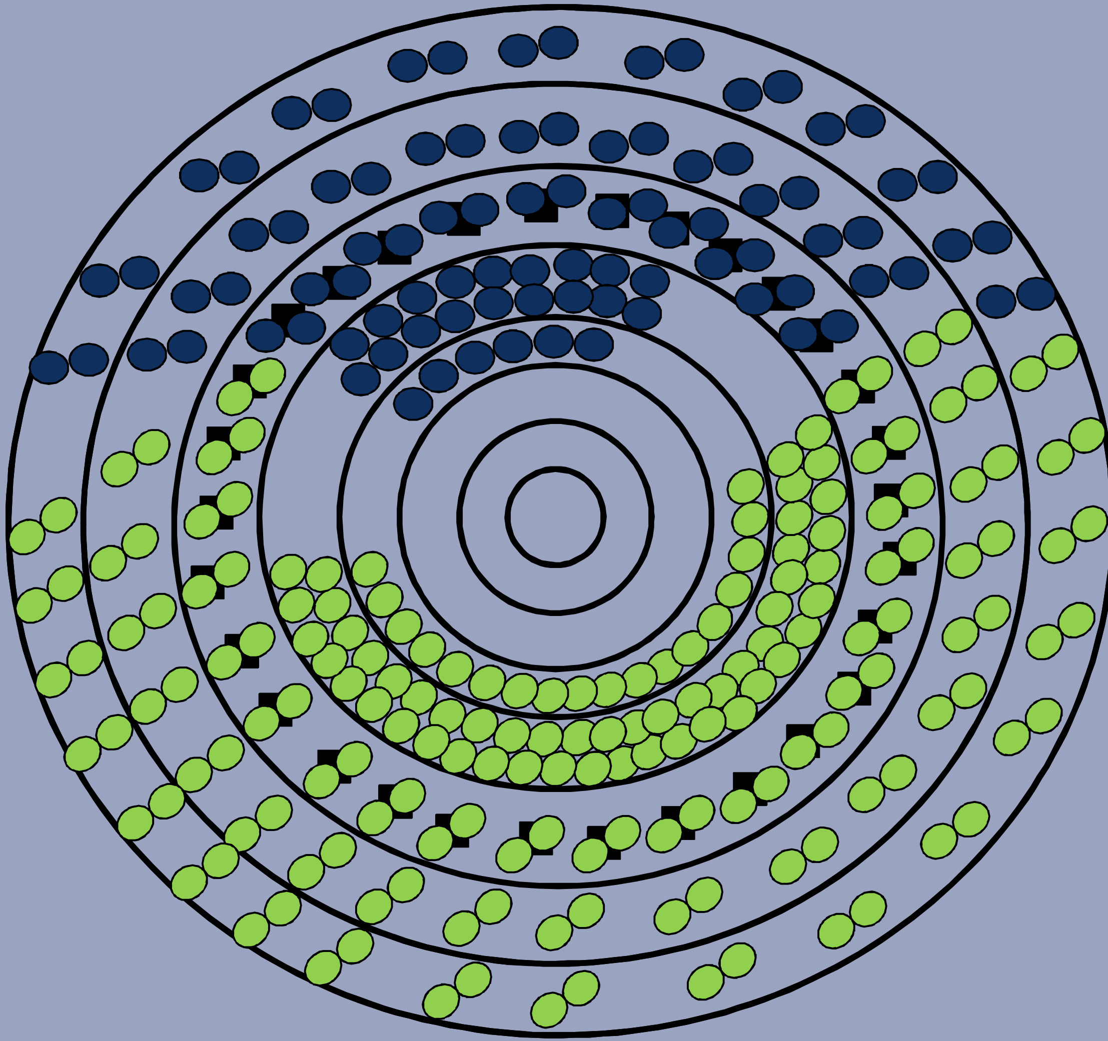
Assume the g-3 generation dies just before the g generation is produced.



The scarce resource might be food, but it could also be other things. Let's imagine it's nesting sites.

Assume an individual that acquires a resource will reproduce at its fecundity rate; otherwise it will not reproduce that generation.

Adding Scarce Resources

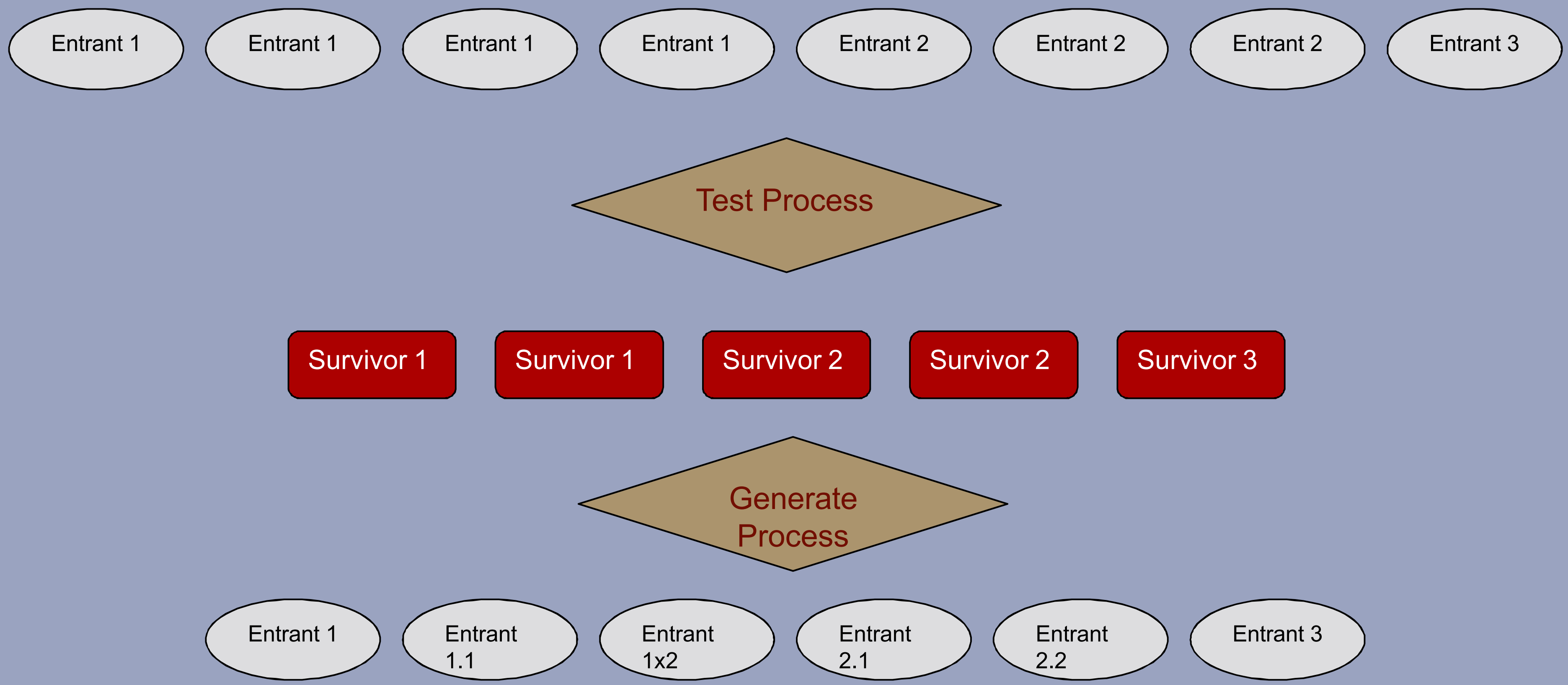


Assume the blue population consistently gets slightly more than its fair share of resources.

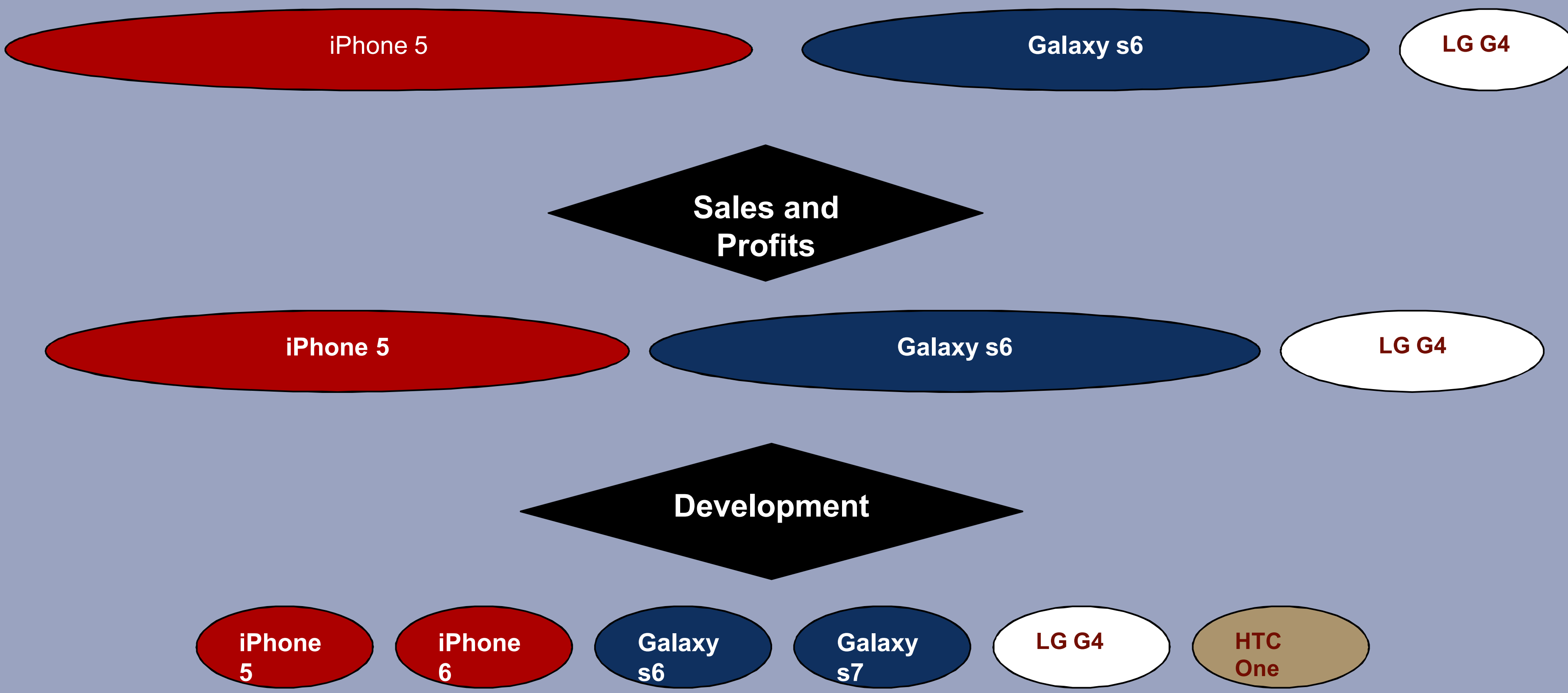
In this example, blue expands from 25% of the population in g5 to 38% by g8.

This slight advantage trumps start date, fecundity, and longevity. So long as neither population can produce more offspring per resource (and green cannot shift to another resource), green will go extinct.

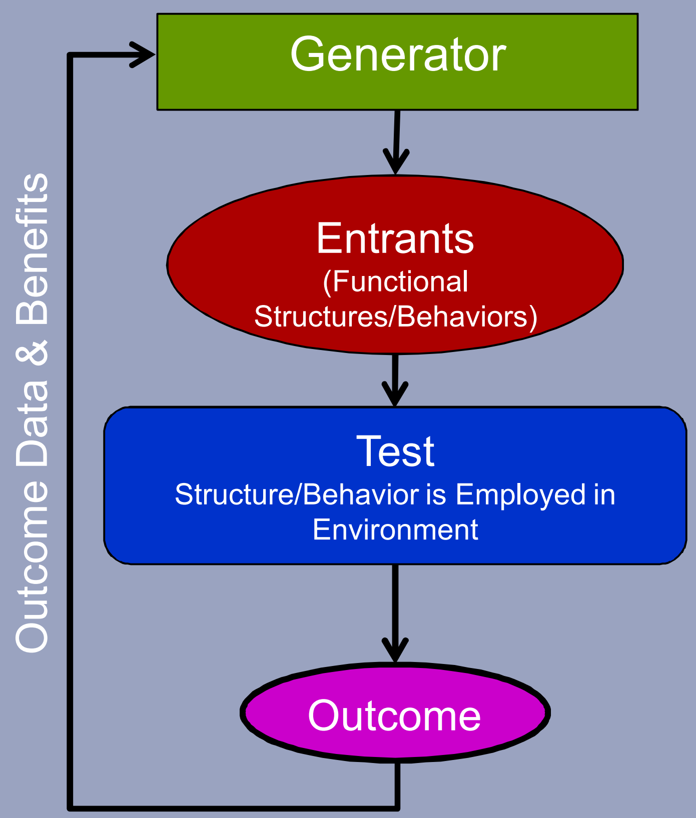
Generate and Test Process



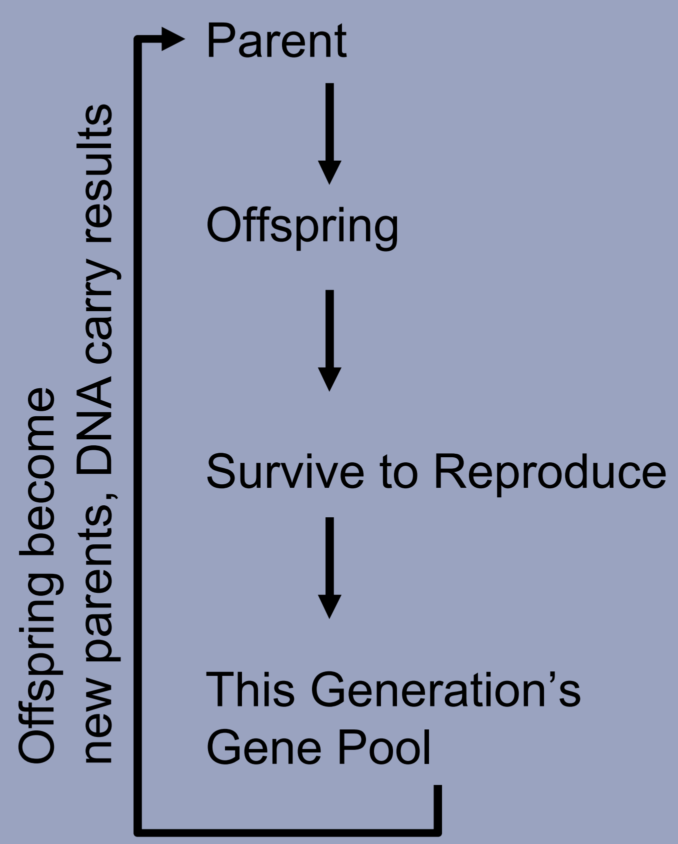
Commerce Example



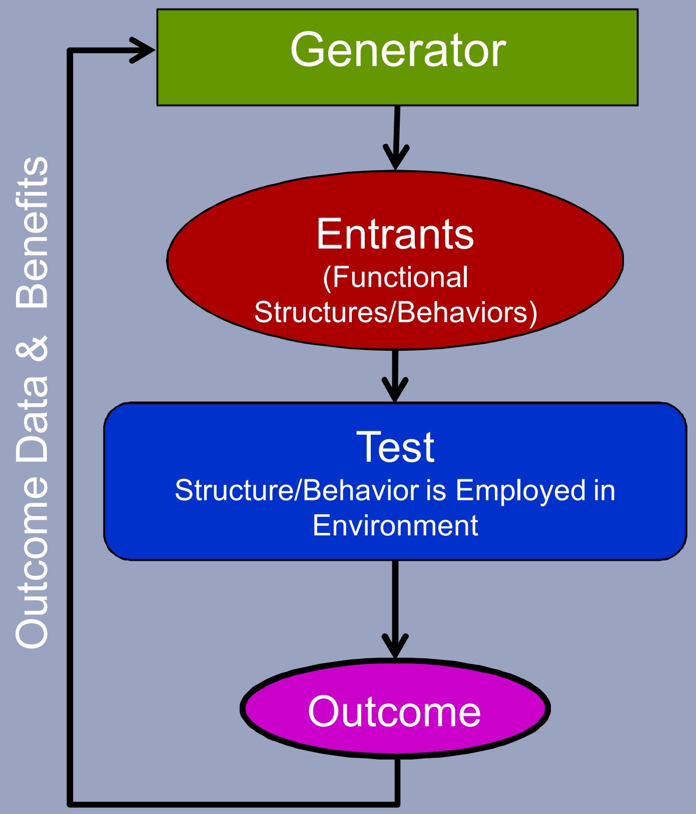
Generate and Test



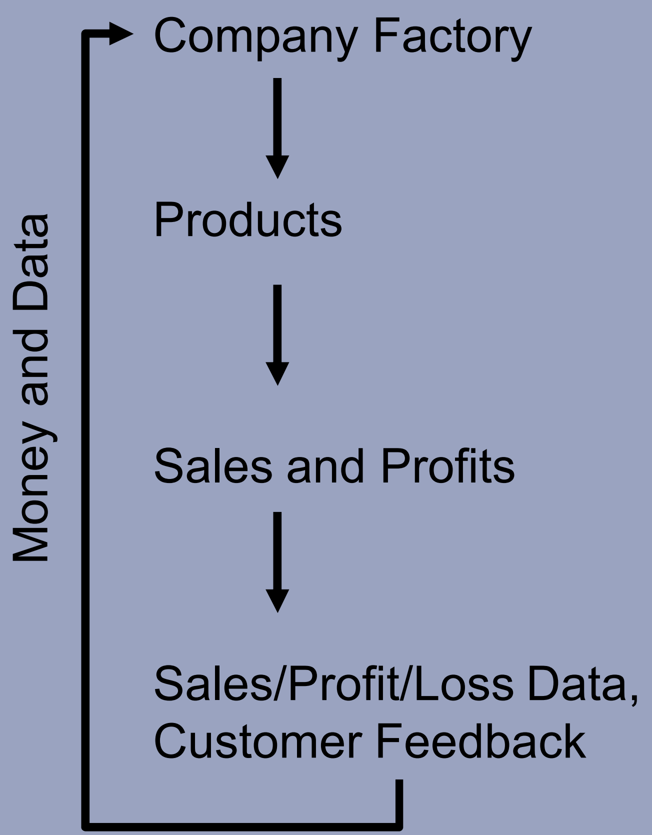
Organism-Level Natural Selection



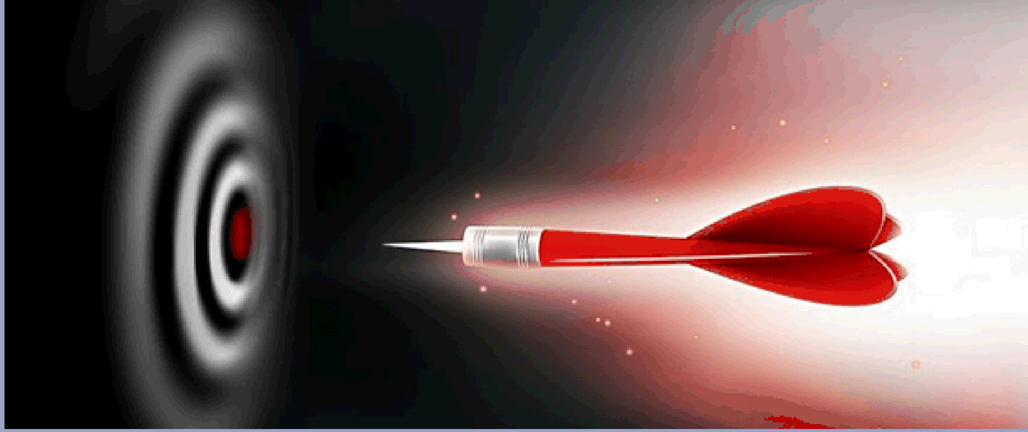
G&T: Commerce



Commercial Manufacturing



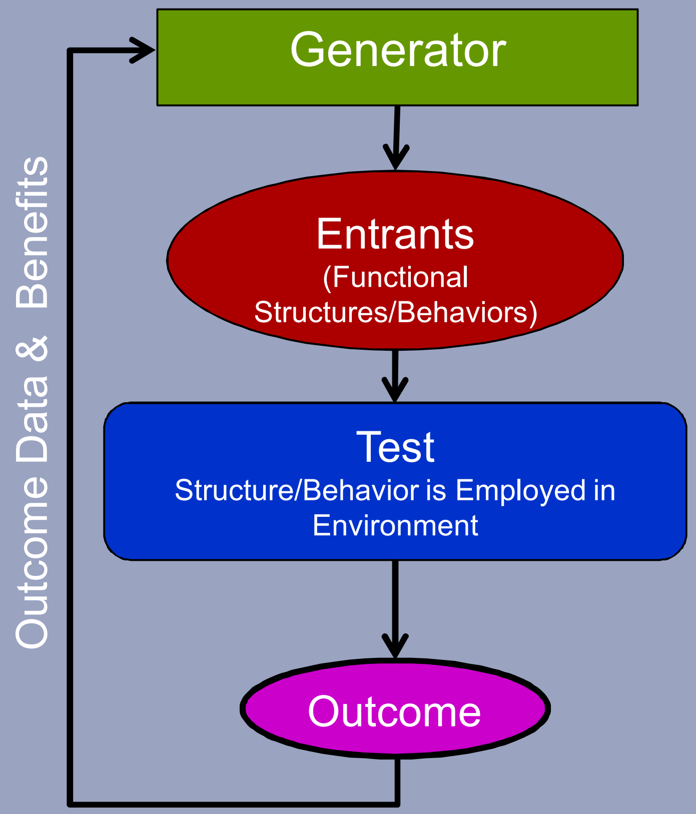
Functionality is Born



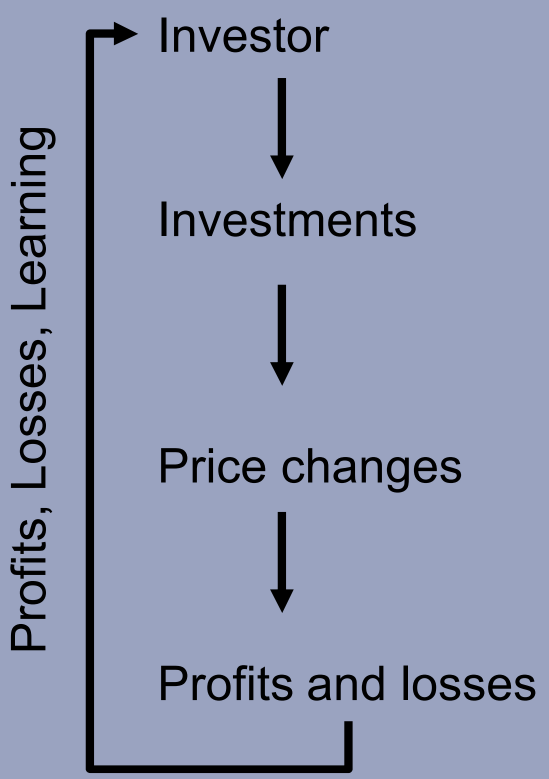
Generate-and-test feedback loops create and sustain functionality

- These systems are/appear goal directed in that they use flexible means to achieve an end
  - Functionality--means and ends, purposes--is not produced outside adaptive complexity
  - There are hierarchies of ends and means in adaptive systems
  - All but the ultimate (survive to reproduce) ends can change
    - e.g., when we added resource scarcity
- Generate and test cycle benefits include:
  - Novelty/Innovation/Creativity
  - Adaptedness (over time)
  - A life of their own: these systems work and ‘strive’ and adapt without an outside push
    - But also cancer
- Implications for modeling: optimization, etc.

G&T: Investment

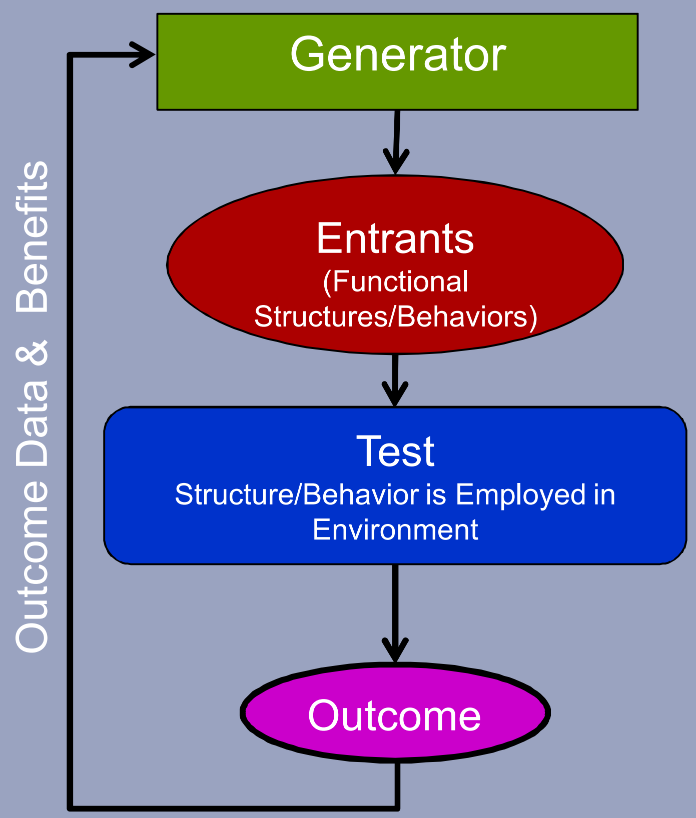


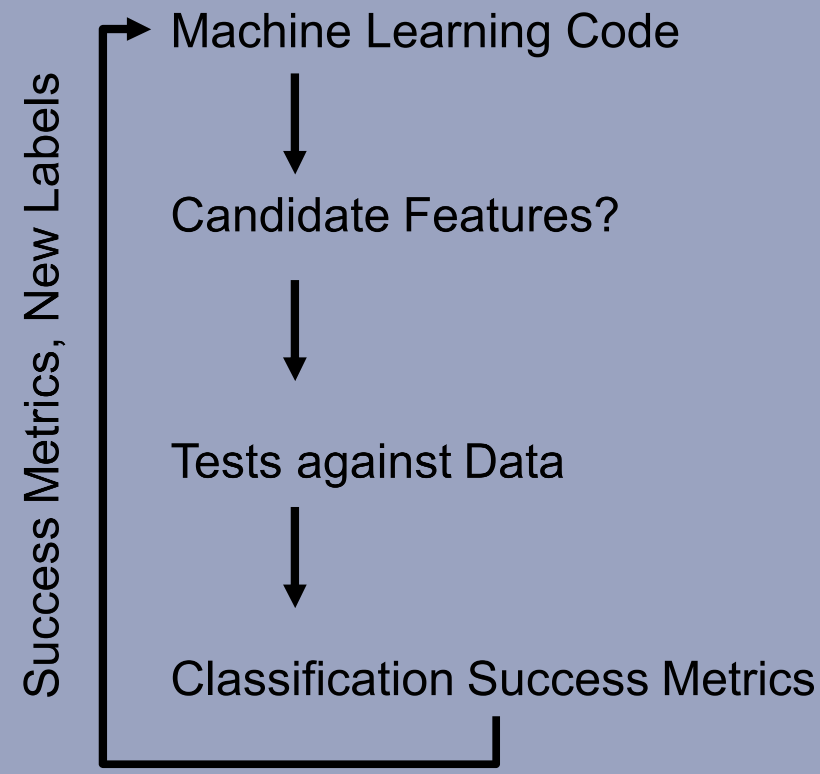
Investment



G&T: Cyber Algorithms

Machine learning classification of incoming network traffic as malware or goodware

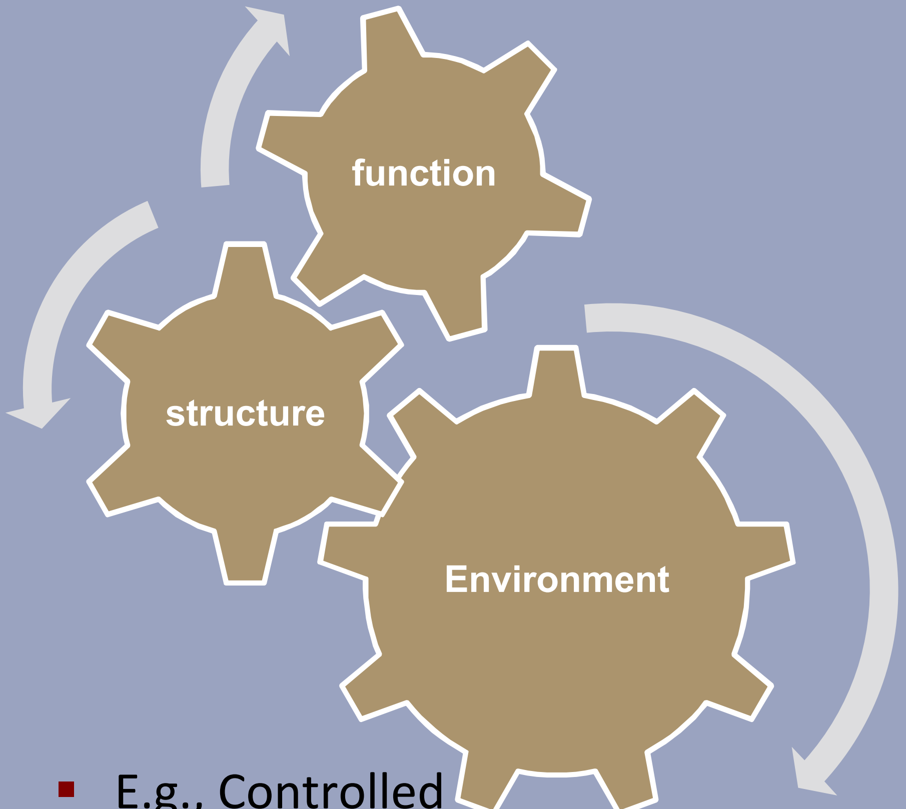




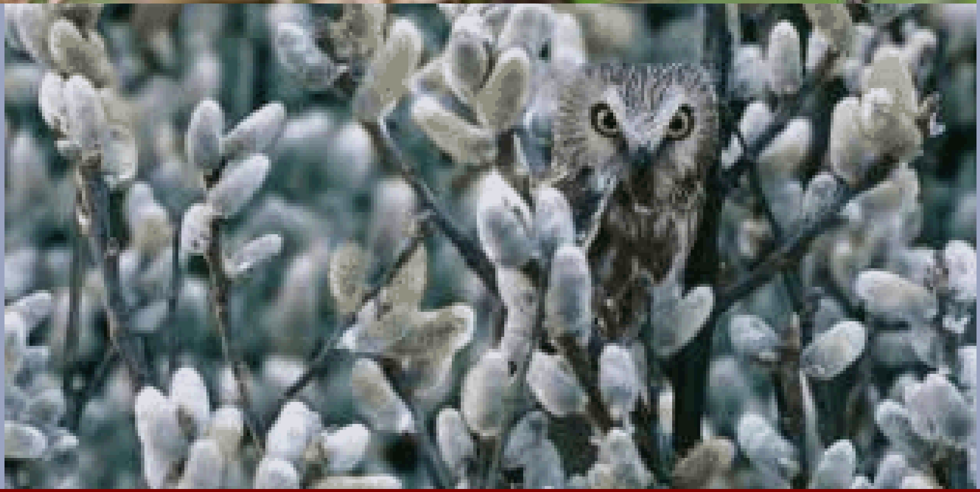
Adding a Variable Environment

- Over time and space
- Variation in the environment, including the biological environment, is what drives and preserves diversity and robustness/resilience.

Mutual Adaptedness of structure, function and environment (past-present)



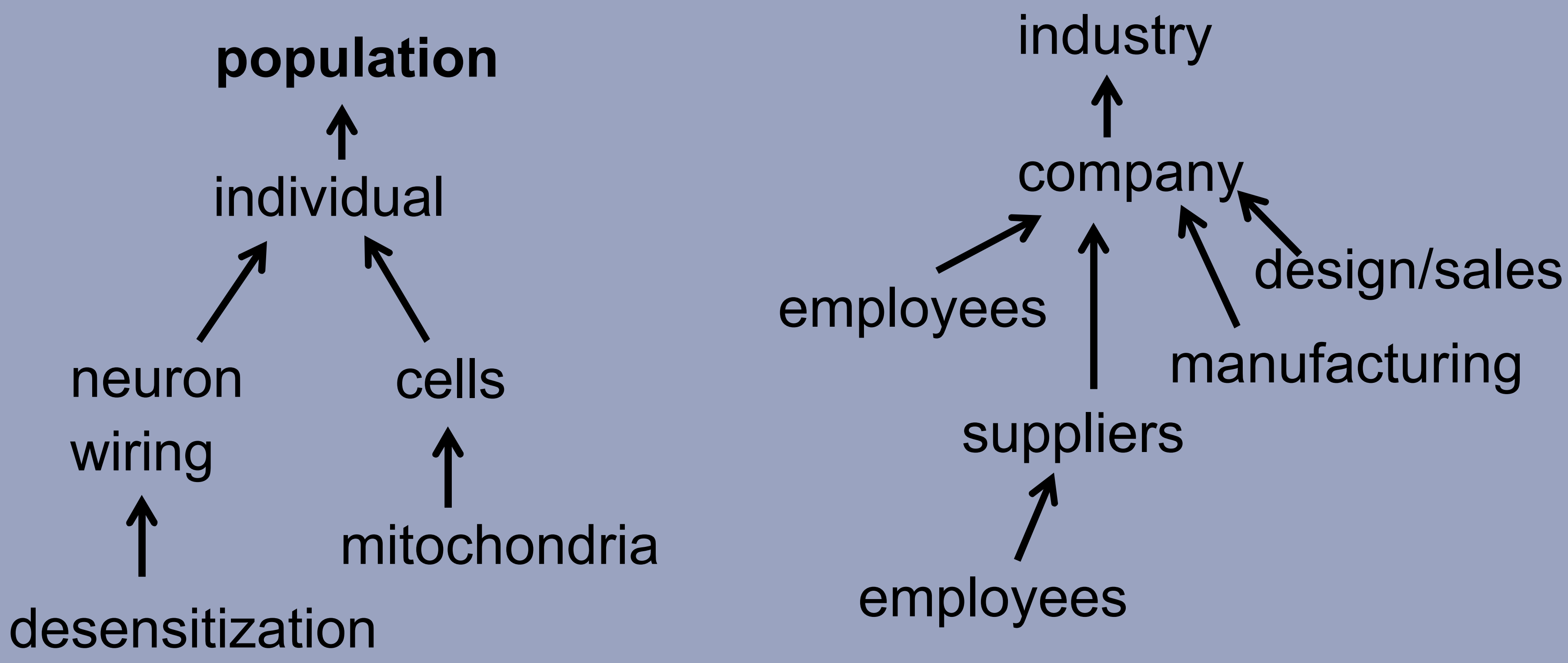
- E.g., Controlled variables reveal function



Latent Information and Functionality

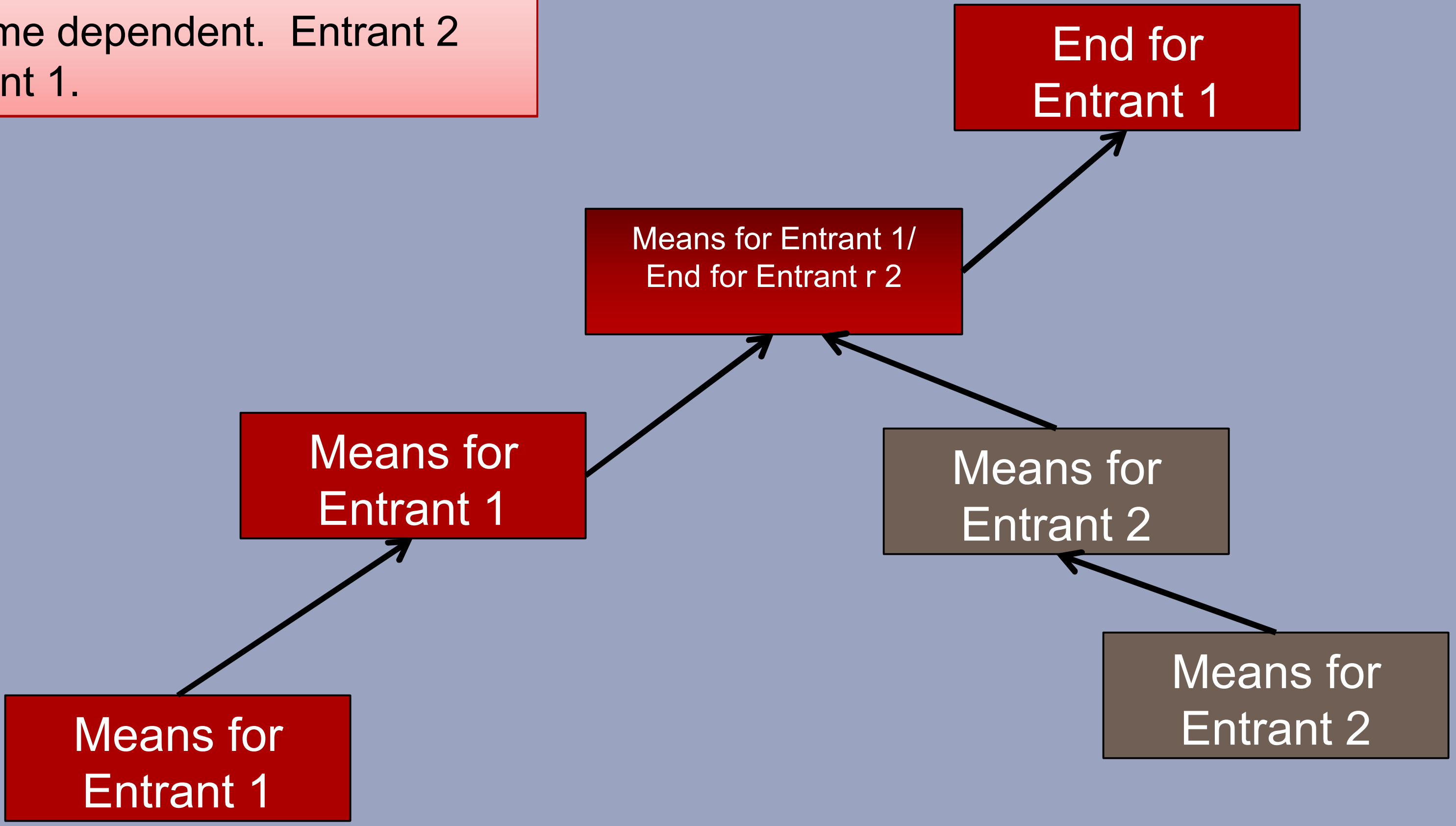
- Adaptedness is only evident when it is needed
- I carry all the genetic material for a female, but my female traits aren't exposed in my body, and thus not acted on by selection while inside of me
- (But they popped back up in my daughter's body and lifespan)
- Homeostasis often works by mysterious means, and hides out-of-bounds behaviors

Hierarchies of Generate-and-Test

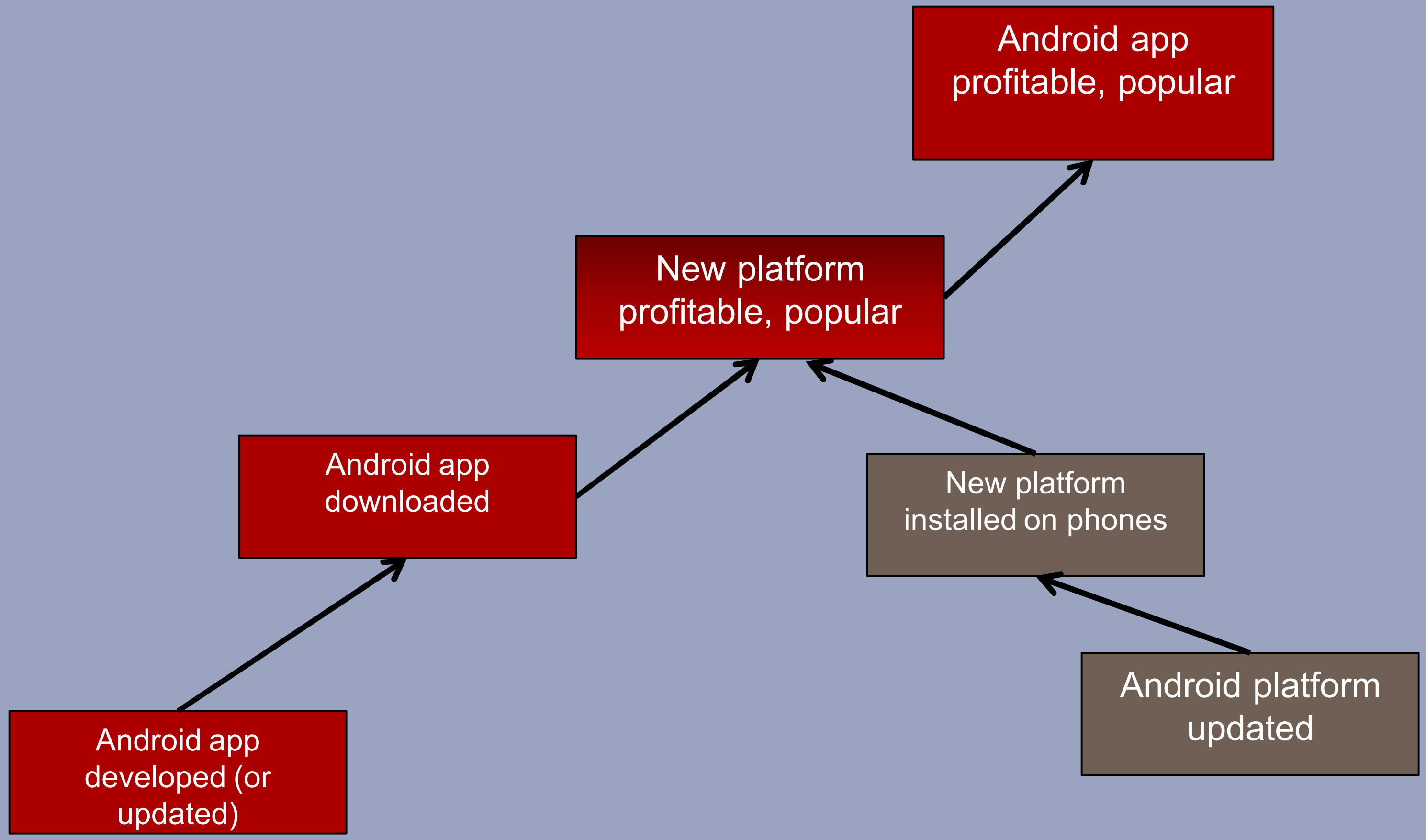


Enslavement

Entrant 1 Needs Entrant 2 to survive and has thus become dependent. Entrant 2 can trust Entrant 1.



Android App Example



Models

Anything that 'computes' and is used to support a decision

Nothing is less real than realism. Details are confusing. It is only by selection, by elimination, by emphasis, that we get at the real meaning of things. --Georgia O'Keeffe

Minimalist Models ⟷ **Representational Models**

- Linear classifier
- Clustering algorithm
- F=MA (as a complete model)

- Meshed physics simulation
- Agent-based model
- System dynamics model
- Emulation

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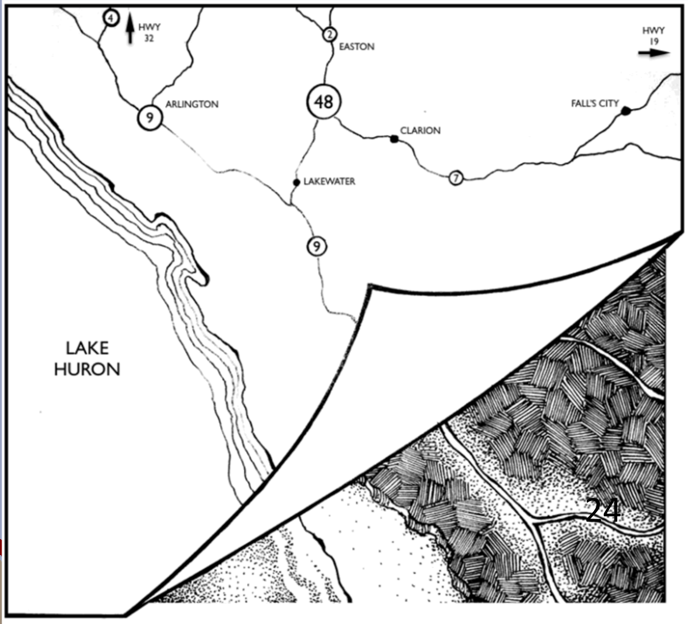
Challenges: What to Leave Out?

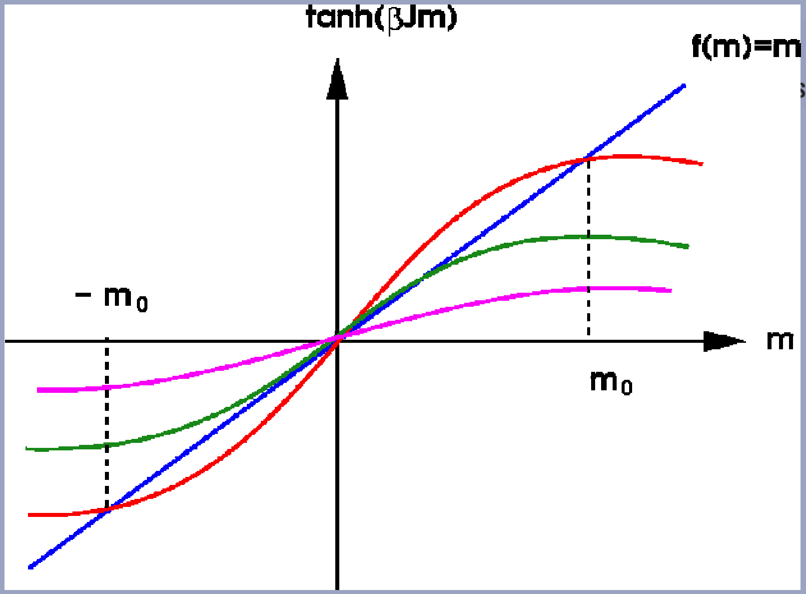
- This is a problem in all modeling, but compounded in adaptive systems:
  - Most types are heterogeneous (the boxes in the cyber model)
  - There are vast stores of latent information
  - There are vast stores of local information (each G&T cycle has its own)
  - There are important ‘distant’ connections
  - Threshold effects are common, so small changes often have outsized effects, and vice versa.
- Thus Butterfly Effects
- How can we improve validation establishing that nothing important for the use case was left out of the model?



Challenges: Capture Critical Functionality

- Model homeostatic mechanisms or ‘assume’ them?
- Economic and social models focus on goals and functions
  - e.g., most stock market models don’t model the actual trading system
  - Would you model teaching or parenting with physiologically accurate humans?
  - But when there is a complex engineered system, modelers often focus on representing it accurately, assuming the functionality is adequately captured
- What’s missed?:
  - Power line owners are in business for profit—not to keep the grid up
  - Where is the malware purveyor’s objective in the cyber model?
  - Where is the role of embarrassment or fear of punishment?
- How do we validate that a model pursues a goal, or robustly (but inconsistently) performs a function like its real-world counterpart?

‘Mean Field’ Approaches are Risky



- In non-adaptive models, it is frequently a good assumption that messy behavior is approximately random, or randomly distributed
- In adaptive models, slight tendencies can be critical (e.g., scarce resources example)
- Latent information is adaptedness—lying in wait for a triggering event. The change implemented is ‘designed’ to sustain functionality in the environment presumed to be signaled by the triggering event
- Nonetheless, ‘mean field’ approaches can be effective in adaptive complexity (e.g., Chicago school economic models)
- How do we know when we can safely assume a mean-field distribution?

Basic Approaches

- Relatively fixed, detailed, descriptive model (e.g., system dynamics or agent-based)
- Radically generalizable heuristics (e.g., fight or flight, utility theory/satisficing, supply & demand)
- Emulate generate and test
  - Machine learning, etc.
- Multiple models at multiple scales, and/or with divergent methods. Can you get similar answers? Or ask the right question to the right model, feed that answer into the other, etc.?
- More effort to determine limits within which models are valid
- Ask different questions

Hope: Advantages for the Modeler

- Adaptedness:
  - Structure, function, and the environment are highly correlated.
  - There is good reason to think the past can predict the future
- Heterogeneity is limited by common functionality.
- Homeostasis,’ or dynamic stability, can often be assumed

- Goals can often be known, or inferred confidently
- Goal/function-driven models, where appropriate, can often allow one to eliminate massive amounts of physical detail
- Goal/function-drive models can capture critical simplifying constraints (e.g., enslavement of apps by Android)