Complex Adaptive Systems – Conceptualizing the Problem

Matthew Koehler
James Holdener

Mike Norman
Rob Pitsko
Glenda Turner

It usually takes me three weeks to prepare a good impromptu speech.

~ Mark Twain

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Agenda

- **Complex (adaptive) systems engineering?**
  - Conceptualizing the problem…
- **A potential path through the morass?**

- **This is an informal luncheon keynote to discuss some of the problems associated with the engineering of complex systems**

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Complicated or Complex?

- **Is the system in question complicated or complex?**
  - Heterogeneity, adaptation/learning, many interconnections…?

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Kayak traffic by: http://www.i-am-bored.com/bored_link.cfm?link_id=97089
Vehicle traffic by: http://h30499.www3.hp.com/t5/HP-Security-Products-Blog/Traffic-jam-Big-data-and-security-analytics/ba-p/6295539#.U9kISFb_zj8

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Complicated or Complex?

Physics!

- **Is the system in question complicated or complex?**
  - Heterogeneity, adaptation/learning, many interconnections…?

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Complicated or Complex?

Now put it together and add a human…

- **Is the system in question complicated or complex?**
  - Heterogeneity, adaptation/learning, many interconnections…?

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Complicated or Complex?

Now add a human…

…and increase the throughput…

- **Is the system in question complicated or complex?**
  - Heterogeneity, adaptation/learning, many interconnections…?

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Vehicle traffic by: http://h30499.www3.hp.com/t5/HP-Security-Products-Blog/Traffic-jam-Big-data-and-security-analytics/ba-p/6295539#.U9kISFb_zj8

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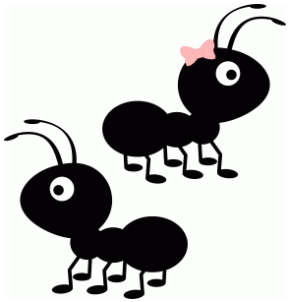
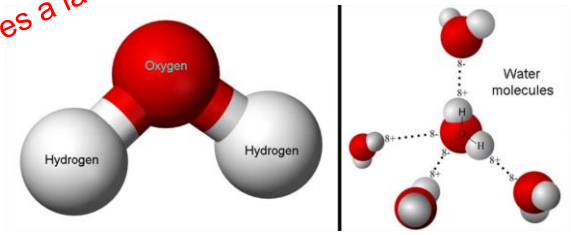
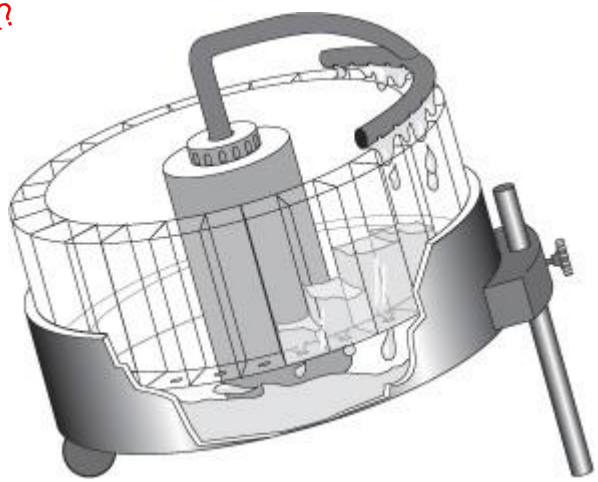
Complicated or Complex?



But does a lack of humans mean you're off the hook?





- **Is the system in question complicated or complex?**
  - Heterogeneity, adaptation/learning, many interconnections…?

Chaotic water wheel by: https://sites.google.com/site/margynelson/chaotic-waterwheel.jpg
Water molecule by: http://astrobob.areavoices.com/files/2013/04/Water-molecule-panel-1024x409.jpg
Ants from: http://img.free-gazo.com/img/wp-content/uploads/1974/08/be5997358b415a26dbc89d0918723d51.gif
Brown rice from: https://encrypted-tbn3.gstatic.com/images?q=tbn:ANd9GcQQvFg68xu2XzOdRlvYFPteTRhNen3FryGosI08B4lrR5fRycdRSg

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Complicated or Complex…

- **No agreed upon definition of complexity, but there are recurring themes…**
  - Many parts
  - Interconnectivity
  - Heterogeneity (broadly speaking)
  - Macroscopic structures or “emergent” phenomena
  - Potential for adaptation or learning

- **So, not always an easy question to answer but VERY IMPORTANT**
  - Complicated systems are different than complex systems
  - Decision making, design, and engineering tools are much better defined within a complicated environment

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So what?

- **Engineering vs. Complex (Adaptive) Systems…**
  - One definition of engineering: “the action of working artfully to bring something about”
  - Complex systems: heterogeneity, adaptation, *emergence*, …
- **Hmmmm:**
  - Engineering: do something specific
  - Complex systems: do something else

There is a tension between engineering (where one designs and creates a system with *a priori* known performance characteristics) and complexity (where the system has emergent properties that, by definition, are not known *a priori*)

Godzilla and friend from: http://www.geekedoutnation.com/wp-content/uploads/2014/02/Godzilla-and-Gabara.jpg

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So…quit?

- **Unfortunately, we can't quit…**
- **As a nation (and even as a species) we face many socio-technical problems that require intervention**
  - Development
  - Security
  - Economic stability
  - Climate change
  - Social resilience
  - Etc.
- **Can't really get around it any more…**
- **So, we've spent time trying to figure out how to do this in a principled, defensible way**

http://www.readyforwildfire.org/docs/files/Image/ready.jpg

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A potential way to approach the problem…

- **Now we'll spend a few minutes discussing how we approach these problems…**

Problem solvers from: http://www.nevilleclarke.com/article/59.jpg

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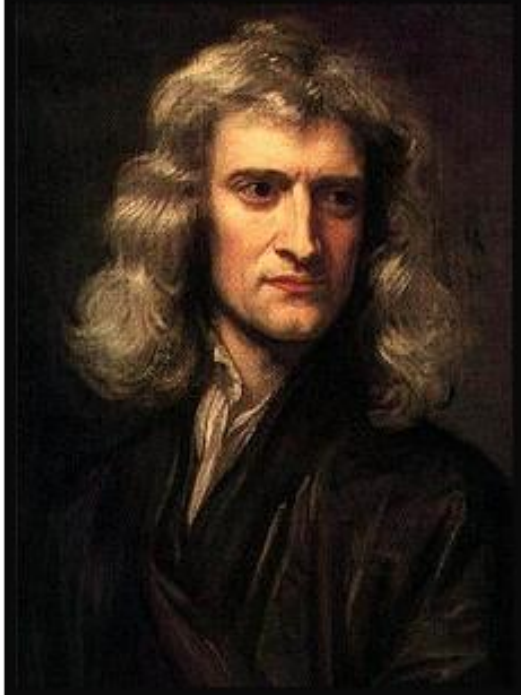

If I have seen further than others, it is by standing upon the shoulders of giants.

(Isaac Newton)

izquotes.com

- **There is a great deal of solid science that underlies complex systems, build on it!**

Turtles by: http://www.awazieikechi.com/standing-shoulders-internet/
Newton by: http://izquotes.com/quote/135288

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Learn to love the theory (and not just data)…

- **Don't forget about all the theory that is out there, it will help you "draw the box." It is painful but worth it…**
- **And help with "out of sample" questions…**

Leaping sheep by: http://4.bp.blogspot.com/-VkxtRH1tzi4/T_luWpQWp-I/AAAAAAAACmk/YAeVmOzD8Mk/s1600/gravity-just-a-theory.jpg
Theory cat by: http://science.howstuffworks.com/science-vs-myth/everyday-myths/string-theory.htm

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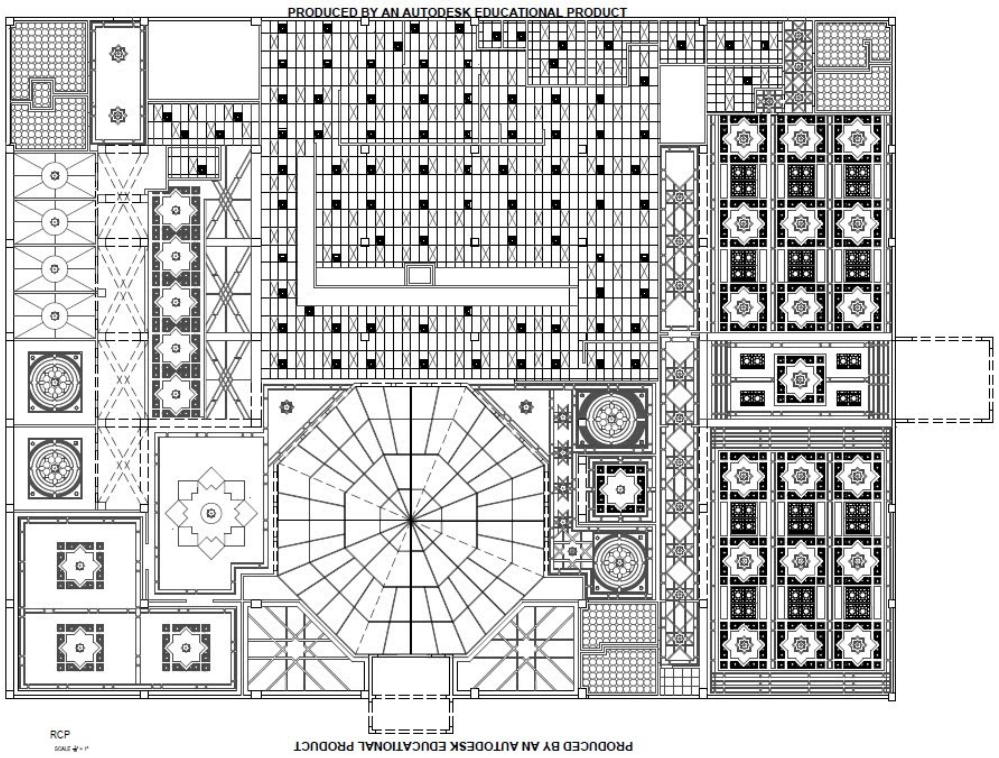
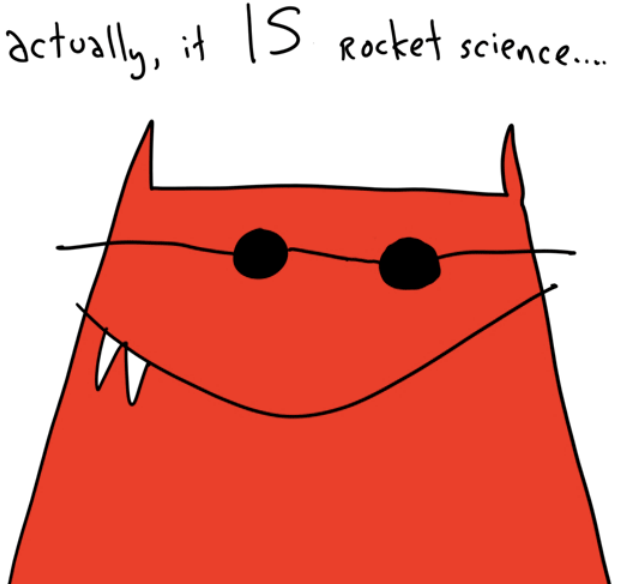
The details matter but (almost) no one cares…





- **You need to get it right, have things documented and defensible, but don't lead with that, tell a high-level story that focuses on the actionable results your Sponsor cares about….**

Building by: http://id4756id4755.blogspot.com/2011/03/final-rcp-drawing.html
Detail monster by: http://gapingvoid.com/office-art/

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Have more than one hammer…

- **I love a good agent-based model as much as the next person but it isn't always the only answer…**

Scared screw by: http://www.warentin.com/cont/cartoon-pictures-of-nail-polish-rk-rs-lxwfjpr
Lots of tools by: http://j-walkblog.com/index.php?/weblog/posts/lots_of_tools/

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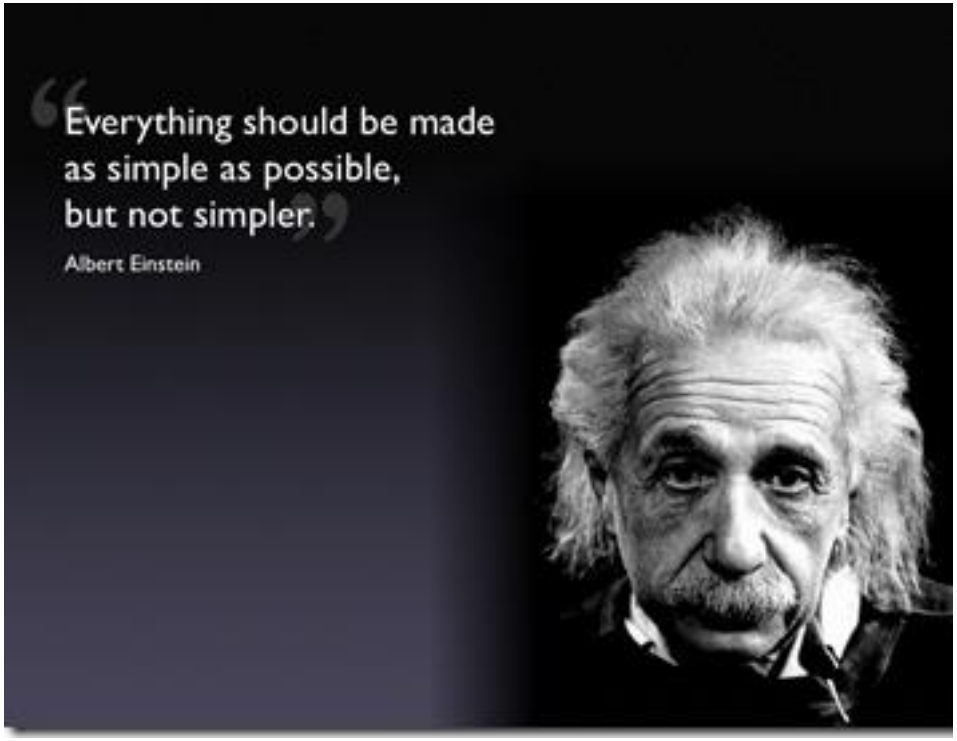
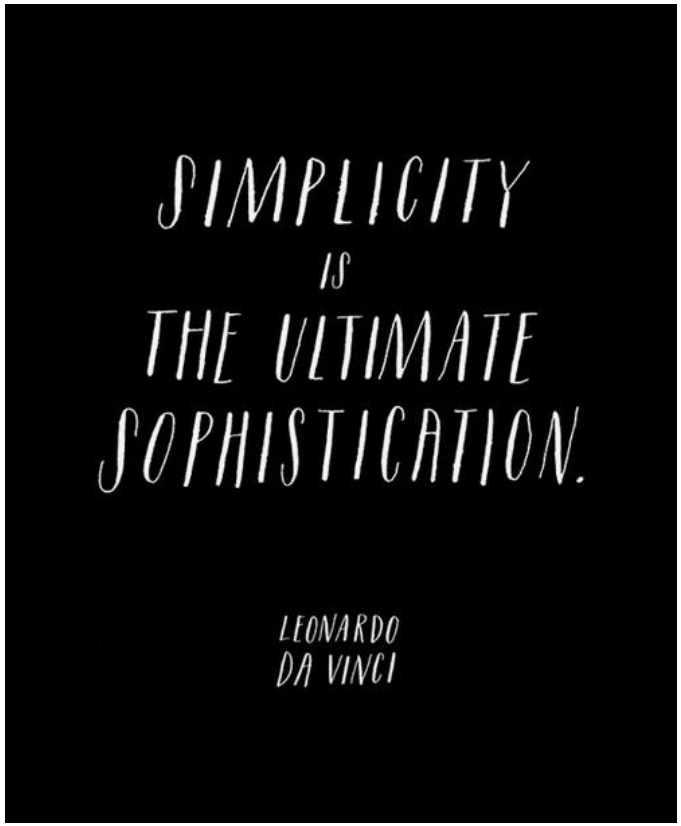
Start simply, then stop





- **It is unbelievably easy to make these sorts of analyses unintelligibly complicated. Don't!**

Da Vinci quote by: http://25.media.tumblr.com/tumblr_mdoi7vO7lg1qag8b8o1_500.jpg
Einstein quote by: http://ptpower.com/keep-it-simple/

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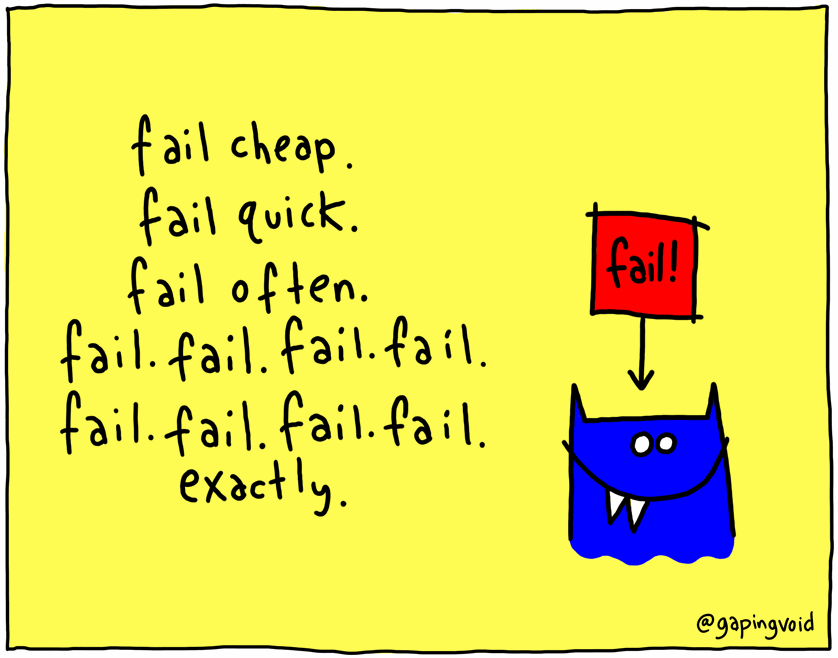
Fail Early and Often…Complex Systems work best with iterative development



Always make new mistakes

~Esther Dyson

- **Prototype your analyses quickly and iterate with your Sponsor. These analyses will likely be unusual for your Sponsor so they need to be exposed to them over and over again…**

Crashing arrows by: http://thumbs.dreamstime.com/z/failure-metaphor-business-concept-separated-white-34688002.jpg
Failure monster by: http://gapingvoid.com/wp-content/uploads/2012/07/fail-often-p-2405.gif
Tina Fey quote from: http://www.sometimesalwaysneverblog.com/2013/10/trusting-your-gut-kate-hampton.html

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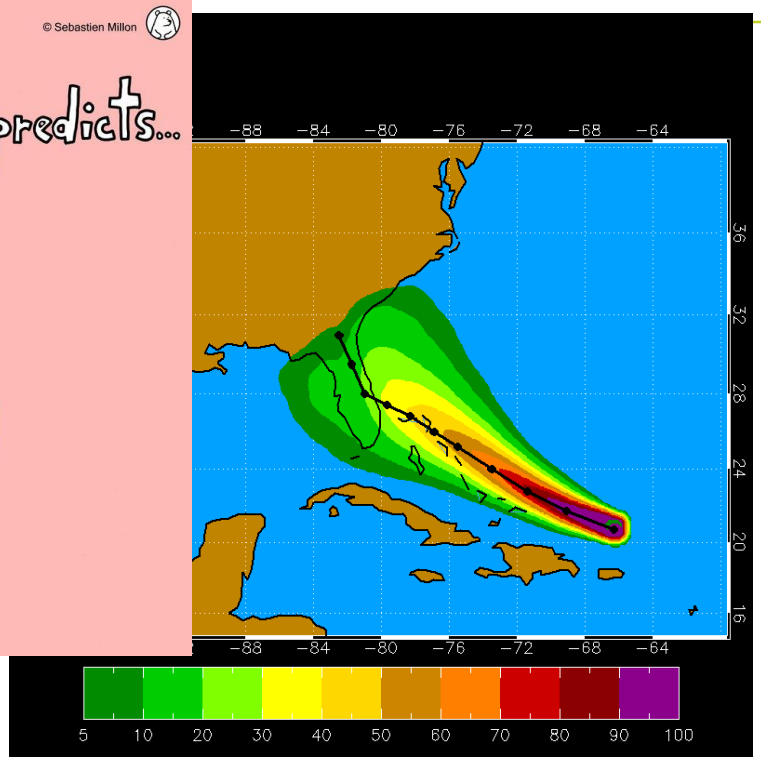
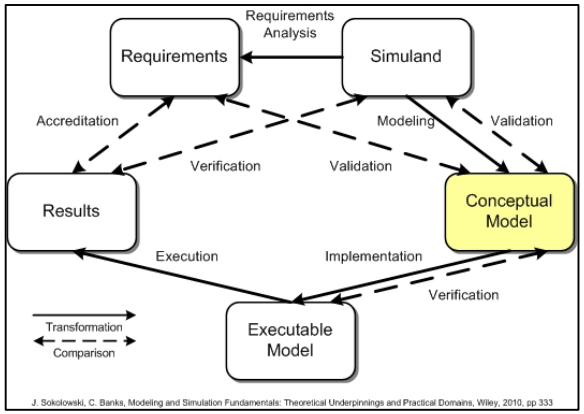
Despite the science and toolkit, prediction is very difficult for complex systems





"*Prediction is hard, especially about the future.*"

~ Niels Bohr

- **Prediction: it's really really hard in these contexts…**
- **Better to think about these systems like weather forecasting: although we cannot produce point prediction we can make meaningful statements about likely future events that can inform decision-making**

Wind speed uncertainty by: http://rammb.cira.colostate.edu/research/tropical_cyclones/tc_wind_prob/figure_2_left.PNG
Prediction cat by: http://sebreg.deviantart.com/art/Prediction-Cat-153596008
VV&A diagram by: http://en.wikipedia.org/wiki/User:Riksands#mediaviewer/File:VV%26A_Comparisons.jpg

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Models…

- **"No substantial part of the universe is so simple that it can be grasped and controlled without abstraction. Abstraction consists in replacing the part of the universe under consideration by a model of similar but simpler structure."**
- **Society is messy, heterogeneous, path dependent, etc.**
- **Humans are just as bad…learn, boundedly rational, change, die, etc.**
- **To understand future states of society (i.e., a complex system), in all but the most trivial cases, it will be most efficient to simulate it**

- **So, to paraphrase Box: models are not just useful, they are critical**

Rosenblueth and Wiener, (1945) Philosophy of Science, vol. 12, no. 4, pp. 316-321.
Buss, et al., (1991) Complex Systems vol. 5, pp. 525-539.
Axtell, (2000) Brookings Institution working paper.

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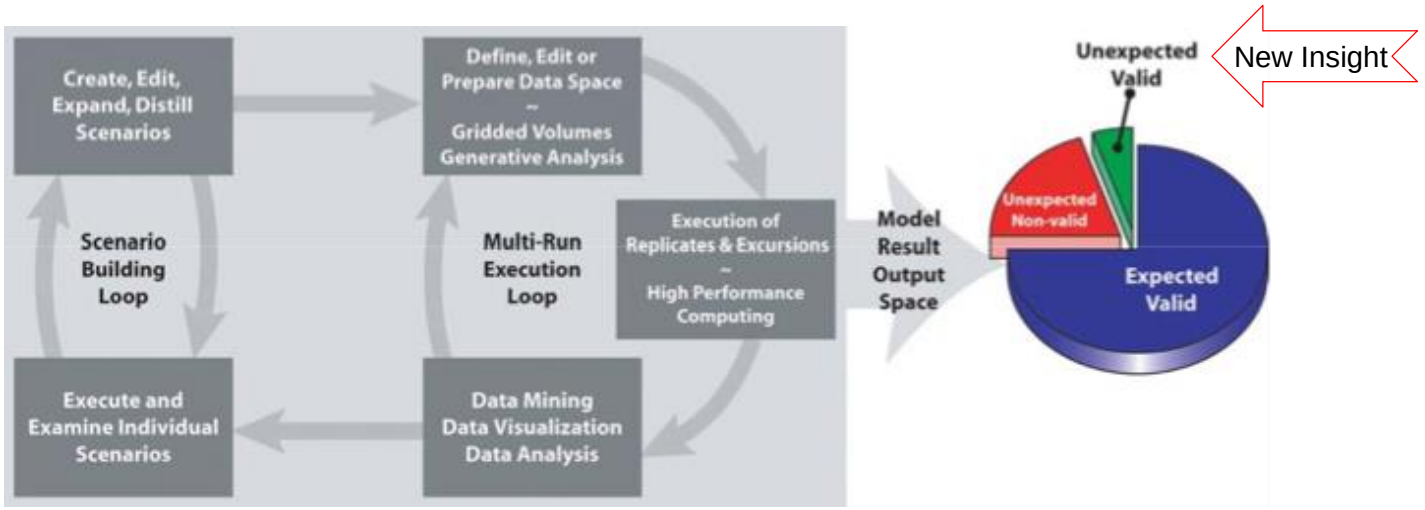
The Logic of it all…

- Each run of the model/simulation is a deduction or "sufficiency theorem"
- collect a bunch of runs for inductive inference
- to solve abductive questions…



- And breaking your model is NOT a bad thing (despite the horror)!
- So, this is all about models…

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Okay, now what…?

- **Models are useful, simulations are too…**
- **But how useful?**

Up to this point we have discussed the theory of complex systems and how to deal with them in a rigorous manner. To have an impact they must not only be rigorous, but fit within a decision support framework. This requires relating these analyses to the real world.

- **One must be able to make meaningful statements about how well the model/simulation relates to the world**
  - If we are going to gain scientific credibility we need to be able to stand on each other's shoulders
  - Need be able to explain what we did, how we did it, and how it relates to the real world so we can replicate and extend
- **Often this is referred to as Verification, Validation and Accreditation (VV&A)…largely grew out of the DoD (a mixed blessing)**
  - Verification: Did you build the model correctly?
  - Validation: Did you build the correct model?
  - Accreditation: Should be model be trusted for a particular purpose?

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How do you verify these things?

- **Verification is painful but the components that go into it are important for you and all the folks that will come behind you**
- **Starts with a detailed *formulation* — a narrative that explains in detail what the model is and how it will work**
  - This is how non-coders can look under the hood of your model
- **As you develop your code you map it back to the formulation**
  - This part really hurts…
- **Likely more effective than trying to just share your code for replication and extension (also: replication is something we should be embracing!)**

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How do you validate these things?

- **What are you modeling? Is there an analogous or referent system in the real world?**
- **What data are available?**
- **How will the model be used? What sort of conclusion do you want/need to be able to draw from information derived from the model/simulation? Will others be using the model (folks that were not involved in its creation)?**

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Putting a few things together…

- **Docking (Axtell et al. 1995): are two models equivalent?**
  - Identity—results of the two models are indistinguishable
  - Distributional—results of the two models are statistically indistinguishable
  - Relational—results of the two models show that similar changes in inputs cause similar relational changes in outputs
- **Levels of Empirical Validity (Axtell 2005):**
  - Level 0—Micro-level qualitative correspondence
  - Level 1—Macro-level qualitative correspondence
  - Level 2—Macro-level quantitative correspondence
  - Level 3—Micro-level quantitative correspondence

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Moving to the “real world”

- **Traditionally docking was model-to-model**
- **Can be thought of as model-to-referent (e.g. Burton 2004)**
  - “Referent” can be the real world, here you are calibrating your model
- **Model/Simulation use**
  - Thought experiments
  - Basic experimentation with generating mechanism
  - Understanding likely dynamics (coarse forecasting)
- **How “productized” is it/will it be, where are you in the lifecycle?**
  - What to do? How to do it? Putting it together? Fielding?

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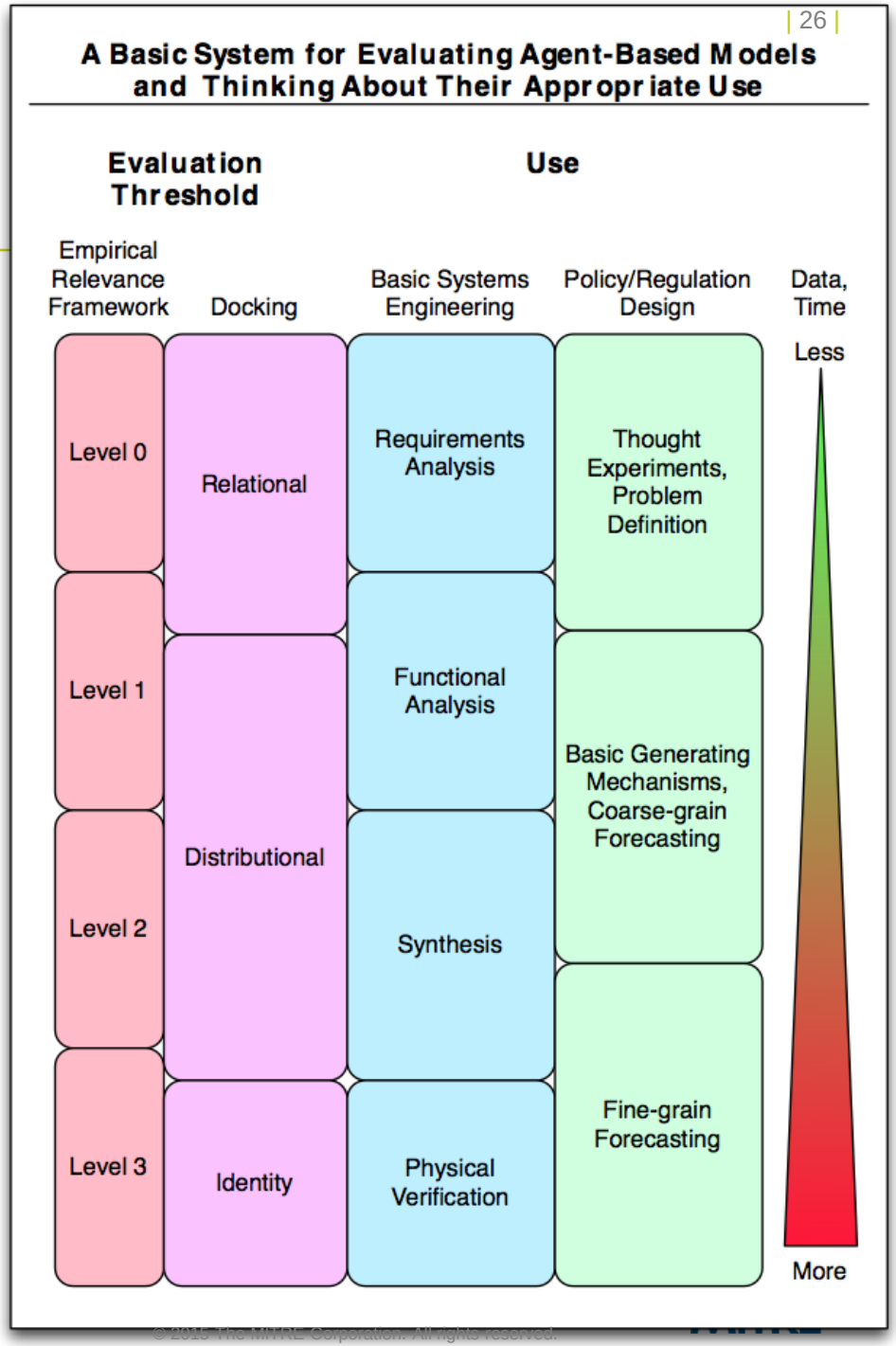
Putting it all together…

- **Looks nice!**
- **How well does this work in the real world?**
  - Reasonably well…
  - We've used this framework for:
    - Model-to-model docking
    - Model-to-data docking
    - Model-to-HITL experiment docking



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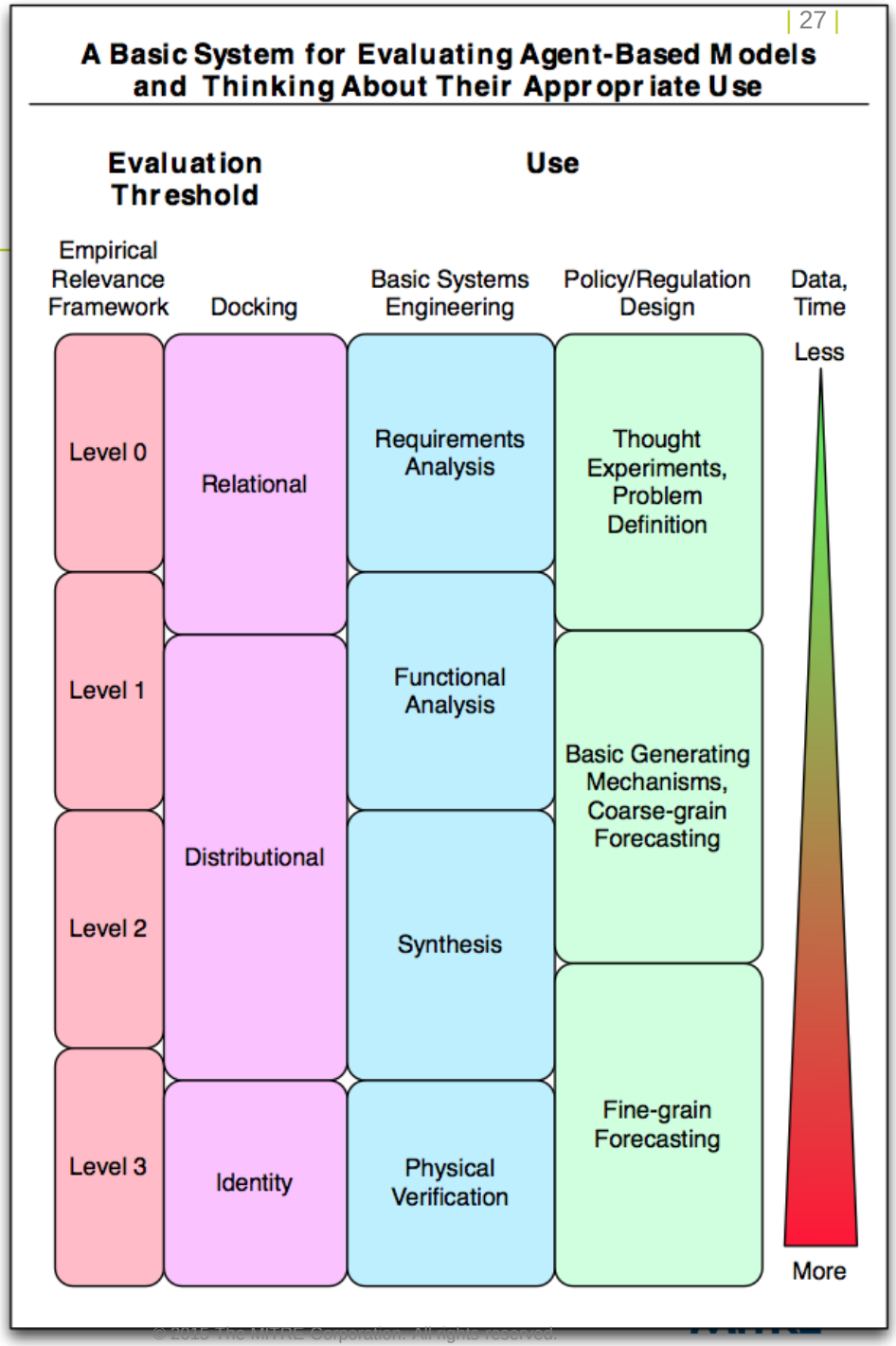
Putting it all together…

- **Based upon data and theory your overall model may be at different levels on this chart**
  - Physical components may be Level 3, while
  - Social components may only be Level 0
- **That's fine, but don't "overdrive" your results; if the most abstract feature of your system is Level 0, then no fine-grained forecasting!**



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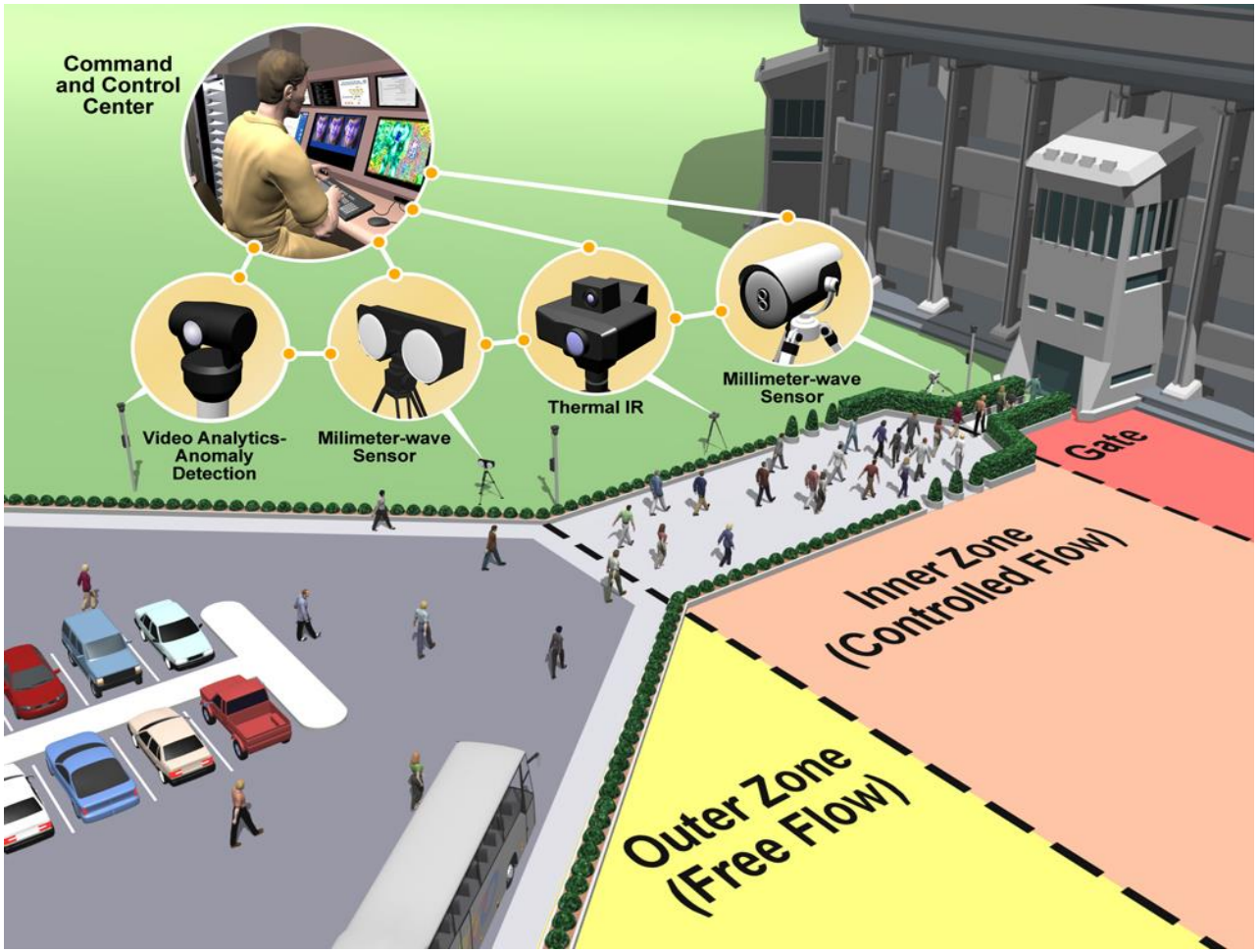
For example: Operational Concept



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Approach

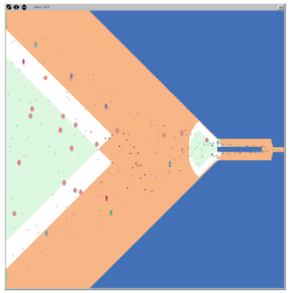
Detailed Sensor Model

Representative Geometry

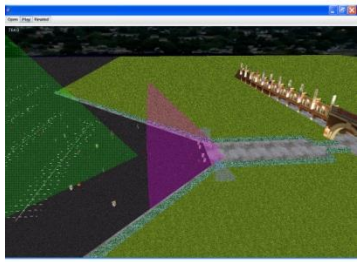
Representative Behaviors

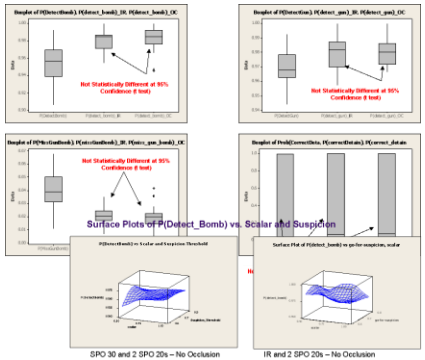
Building Blocks

Rapid NetLogo Prototype



Higher-Fidelity Repast Model





Variable	Mean	StDev	Minimum	Maximum	Range
P(DetectBomb)	0.95456	0.02272	0.90625	0.9927	0.08645
P(detect_bomb)_OC	0.98128	0.01383	0.94531	1	0.05469
P(detect_bomb)_IR	0.98071	0.0107	0.95425	1	0.04575
P(DetectGun)	0.96767	0.01331	0.94406	0.99265	0.04859
P(detect_gun)_OC	0.98028	0.00873	0.96644	1	0.03356
P(detect_gun)_IR	0.979	0.01251	0.94937	1	0.05063
P(MissGunBomb)	0.04013	0.01332	0.01049	0.06803	0.05754
P(miss_gun_bomb)_OC	0.01925	0.00808	0.00375	0.04151	0.03776
P(missGunBomb)_IR	0.02037	0.00775	0.00669	0.03537	0.02868
Prob(CorrectDetain)	0.3525	0.4663	0.0095	1	0.9905
P(correct_detain)_OC	0.4023	0.4503	0.0148	1	0.9852
P(correctDetain)_IR	0.4019	0.4499	0.0149	1	0.9851

Optimization

Data Analysis

Human in the Loop Validation!

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Looking ahead

- **We, as a community, are the experts, the current consumers are not, we have to hold our own feet to the fire and perform complexity science in a rigorous, defensible way…**

- **We need to work together to develop these ideas and articulate best practices**

Hot feet from: http://i.istockimg.com/file_thumbview_approve/30718328/5/stock-illustration-30718328-feet-to-the-fire.jpg

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Questions?

- "***Prediction is very difficult, especially about the future***"
  - Niels Bohr
- "***Imagine how hard physics would be if electrons could think***"
  - Murray Gell-Mann
- "***Plain question and plain answer make the shortest road out of most perplexities***"
  - Mark Twain

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