Overview

• What are wicked problems?
• What is systems thinking?
• What are the key features of complex systems?
• What are the common analytical approaches for studying complex systems?
• What do these offer that is different from current public health and epidemiology approaches?
• How should we intervene on environmental health problems?
“A Wicked* Problem”

- No clear problem definition
- Multi-causal, multi-scalar, inter-dependencies
  - An input spreads out, bounces around, echoes throughout system
- Many possible responses and many possible endpoints
- Responses don’t solve, have trade-offs
- Can be unstable (problem itself is moving target)
- Exists over long temporal scales, have to wait a long time to figure out what works
- Multiple stakeholders
- Usually socially complex
- Straddles organizational and disciplinary boundaries
- Has a history of policy failure

* Very difficult to resolve, Rittel & Webber 1973


Past Responses to Environmental Health Problems

- Compartmentalized, pollutant-specific
- Generally one hazard type at a time
  - Chemical, biologic, physical, ergonomic, safety, psychosocial
- Generally one exposure agent at a time
- Generally one medium at a time (e.g., air, water)
- Focus on symptoms, not causes
- Did not incorporate complexity, e.g., person, community
- Risk-based
  - Many assumptions, usually with incomplete data
- What can systems thinking teach us about new approaches?
Why Are We Teaching You About Systems Thinking?

• Public health problems are getting more difficult to solve, they are more commonly wicked

• Council on Education for Public Health (CePH)
  – Five core disciplines: biostatistics, epidemiology, environmental health sciences, health services administration, and social and behavioral sciences

• Association of Schools of Public Health (ASPH)
  – 5 CePH core disciplines, plus 6 interdisciplinary / cross-cutting competencies:
    – Communication & informatics, diversity & culture, leadership, professionalism, program planning and systems thinking

Systems Thinking Defined

• Barry Richmond 1987: “The art and science of making reliable inferences about behavior by developing an increasingly deep understanding of underlying structure.”

• Holistic approach to evaluating an issue; conceptual orientation

• Focuses on way a system’s constituent parts are inter-related (complexity), work and change over time (dynamics), and are related to functioning whole
  – Change is a common theme; from chaos theory; butterfly effect and tipping point; makes long-term prediction difficult
  – System behavior results from reinforcing & balancing feedbacks

• Traditional approaches to analysis break problems down into separate, smaller elements (reductionism = linear, atomistic, mechanistic)
Origins of Systems Thinking

Largely developed in 20th century with many contributors

- Ludwig von Bertalanffy: biologist – General System Theory
- Ross Ashby, psychiatrist; Gregory Bateson, anthropologist:
  - Cybernetics: the origins of system theory; scientific study of communication and control of regulatory feedback (aka automatic control systems, including biologic and engineered)
- Jay Forrester, computer engineer:
  - Systems dynamics: an approach to understanding nonlinear behavior of complex systems using stocks, flows, feedback loops, time delays
- Murray Gell-Mann and Kenneth Arrow (Santa Fe Institute): defined complex adaptive systems
- Russell Ackoff, management thinker: operations research
- Peter Senge, management thinker:
  - Learning organization theory: systems approach to understanding organizations that facilitate learning by members and continuous transformation
- Joshua Epstein, economist:
  - Agent-based models: create visual representations of complex systems; define interactions between agents with simple rules and emergence and self-organization are observed


Early Jay Forrester model: The World Model for The Club of Rome (with Donella Meadows)

- Was asked: how are major global problems – poverty and hunger, environmental destruction, resource depletion, urban deterioration, unemployment – related and how might they be solved?
- Forrester’s model showed that growth was the problem, population & economic
- Economic growth: the very thing that politicians are trying to promote

“If present growth trends in world population, industrialization, pollution, food production, and resource depletion continue unchanged, the limits to growth on this planet will be reached sometime within the next one hundred years.”
What is a Complex System?

1. “One whose properties are not fully explained by an understanding of its component parts” (Gallagher R, Appenzeller T. Beyond reductionism. Science 1999)
2. The system’s components and feedback loops cause its behavior (Meadows 2008; Mitchell 2009)
3. The interactions produce an emergent effect that is different from the effects of the individual elements
4. Effect persists over time, adapts to changing circumstances (e.g., tobacco company reduces prices in response to increased taxes)
5. The interesting and important part of a system is its emergent behavior, so cannot decompose it

Characteristics of a System

1. A system is composed of parts (elements)
2. All the parts of a system are related (interconnected), through feedback loops
3. These elements and connections are the system’s structure; structure determines behavior
4. Behavior emerges from its key feedback loops over time
5. Meadows: a system’s behavior is its “function” (nonhuman system) or “purpose” (human system)
6. Purpose and function are deduced from behavior, not from rhetoric or stated goals
   - What is the purpose of the U.S. food, community socioeconomic, and built environment systems?
Traditional analysis focuses on the individual pieces of what is being studied.
- Isolates smaller and smaller parts of what is under study

Systems thinking focuses on how the things under study interact with other constituents of the system.
- Expands view to consider larger and larger numbers of interactions as an issue is under study

You are losing the forest for the trees. You are losing the forest for the xylem and the phloem

Adapted from P. Woessner

Emergence

- “Arising of novel and coherent structures, patterns, & properties during process of self-organization* in complex systems.”
  - *Social sciences refer to as spontaneous order; chaos theory as “predictability in sea of chaotic unpredictability”
  - Occurs in many physical, chemical, biological, robotic, cognitive, and social systems
  - Examples: ecosystems, Internet, crystallization, groupthink, herd behavior

- Common properties of emergent phenomena:
  - Radical novelty: not previously observed in the complex system under observation; neither predictable nor deducible
  - Coherence: appear as integrated wholes that tend to maintain identity over time; the separate lower-level components form a higher-level unity
  - Macro level: emergents are behaviors usually at the macro level
  - Dynamical: arise as system evolves over time
  - Ostensive: emergents are recognized by showing themselves

## Systems Thinking

### Examples of Emergence

- Group of starlings + starling desire to avoid collision + starling desire to stay close to neighbors → complex behavior of flying flock
- Wind + humidity + evaporation + Coriolis effect → hurricane
- Sand + wind + small obstructions → sand dunes
- Biomolecule + biomolecule + biomolecule + biomolecule + biomolecule → life, or love, or artistic creativity
- People + places + culture → city, self-organized into neighborhoods

[www.evolutionofcomputing.org; www.pbs.org/wgbh/nova](http://www.evolutionofcomputing.org; www.pbs.org/wgbh/nova)

### Mindsets and Models

- We try to understand world: we make observations and then inferences
- We assemble ideas into mental models
- Everything we think we know about the world is a model
- Our models have a strong congruence with the world (otherwise we change them)
- This provides us with confidence that we understand the world
- Models never fully represent real world

"Thinking consists of two activities: constructing mental models and then simulating them in order to draw conclusions and make decisions." – Barry Richmond (U.S. systems scientist)

"All models are wrong, but some are useful." – George Box (Professor of Statistics)
**Systems Thinking**

**The Iceberg Model**

*Four levels of thinking*

- **Events**
  - What just happened?
  - I caught a cold.
- **Patterns/trends**
  - What trends have there been over time?
  - I’ve been catching more colds when sleeping less.
- **Systemic structure**
  - What has influenced the patterns? **Why?**
  - What are the relationships among the parts? **How?**
  - I have more stress at school, not eating well, & difficulty accessing healthy food near home or school.
- **Mental models**
  - What assumptions, beliefs, and values do I hold about the system? What beliefs keep the system in place?
  - Education and career are the most important piece of identity, healthy food is too expensive, rest is for the unmotivated.

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**Event Oriented Thinking**

Thinks in straight lines

```
A → C → D
B
```

In event oriented thinking everything can be explained by causal chains of events. From this perspective the **root causes** are the events starting the chains of cause and effect, such as A and B.

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**Systems Thinking**

Thinks in loop structure

```
A → B → C → D → E
```

In systems thinking a system’s behavior emerges from the structure of its feedback loops. **Root causes** are not individual nodes. They are the forces emerging from particular feedback loops.

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Albert Einstein: “The problems we have created in the world today will not be solved by the level of thinking that created them.”

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Systems Thinking

Is it a System? Or a Bunch of Stuff?

- Can you identify individual parts?
- Do the parts affect each other?
- Do the parts together produce an effect that is different from the effect of each part on its own?
- Does the effect persist in a variety of circumstances?

1. **Elements**
   - Typically most obvious part of dynamic system
   - Changing elements often has little effect on system behavior

2. **Interconnections**
   - Often involve the flow of information
   - Changing connections usually changes system behavior

3. **Function or purpose**
   - Often least obvious part of a dynamic system
   - Determined by observing a system’s behavior
   - System behavior reveals itself as a series of events over time

Adapted from P. Woessner and J. Beltowska

How do Complex Systems Behave?

- Uncertainty
- Unpredictability
- Delays and lags
- Non-linear
- Stocks and flows characteristics
- Inter-connected, tightly coupled, adaptive & evolving
- A trade-off between optimality and resilience (to optimize performance generally remove redundance)
- Tipping points – unknown until breached
- Feedbacks, oscillating, self-organizing, counterintuitive (cause & effect distant in space & time)
- Have multiple possible equilibrium states – some may be hostile to human needs and purposes
- Emergent properties – the appearance of new features that were not predictable at the start

Three common methods for studying complex systems (Luke 2012)

1. **System dynamics**: uses informal and formal models with computer simulation to uncover and understand endogenous sources of complex system behavior [stock, flow, feedback loops]

2. **Network analysis**: measurement and analysis of relationships and flows among actors (e.g., people, organizations, other information processing entities)

3. **Agent-based modeling**: uses computer simulations to examine how elements of a system (agents) behave as a function of their interactions with each other and their environment

### The Basics of Systems Dynamic Modeling

![Systems Dynamic Model Diagram]

- We are limited in our ability to form and reform mental models
- Systems modeling allows us to move from “what” to “what if”
- These also allow us to make our thinking visible to others
- Basic building blocks: **stocks, flows, and loops**

Adapted from P. Woessner
Systems Thinking

Stocks, Flows, Dynamic Equilibrium

• A stock is the foundation of any system and the elements that can be seen, felt, counted, or measurable
  – Do not have to be physical
  – Stock is present memory of history of changing flows
    • Sum inflows > sum outflows, stock level rises
    • Sum outflows > sum inflows, stock level falls
    • Sum outflows = sum inflows, stock level in dynamic equilibrium

• Stocks act as delays, buffers or shock absorbers in system

• Stocks allow inflows & outflows to be de-coupled & independent

From D. Meadows

Feedback Loops

• Formed when changes in a stock affect the flows into or out of the same stock

• A closed chain of causal connections from a stock, through a set of decisions / rules / physical laws / actions that are dependent on the level of the stock, and back again through a flow to change the stock

• Balancing feedback loops
  – Equilibrating or goal-seeking structures in systems
  – Sources of stability and sources of resistance to change

• Reinforcing feedback loops
  – Self-enhancing, leading to exponential growth or to runaway collapses over time

• Information delivered by a feedback loop can affect only future behavior; it cannot deliver a signal fast enough to correct behavior that drove the current feedback

• A stock-maintaining balancing feedback loop must have its goal set appropriately to compensate for inflows and outflows to stock

• Systems with similar feedback structures produce similar dynamic behaviors

From D. Meadows
Room temperature regulated by a thermostat and furnace

A one-stock system with two competing balancing loops

There can be shifting dominance and also delays of feedback loops. When one loop dominates the other it has a stronger influence on system behavior.

**Shifting Dominance, Delays, Oscillations**

- Complex behaviors of systems often arise as the relative strengths of feedback loops shift, causing first one loop and then another to dominate behavior
- A delay in a balancing feedback loop makes a system likely to oscillate
- Changing the length of a delay may make a large change in the behavior of a system

From D. Meadows
Constraints on Systems

- In physical, exponentially growing systems, there must be at least one reinforcing loop driving the growth and at least one balancing loop constraining the growth.
- Because no system can grow forever in a finite environment.
- Nonrenewable resources are stock-limited.
- Renewable resources are flow-limited.

From D. Meadows
Source of System Surprises

• Relationships in systems can be nonlinear
• There are no separate systems. The world is a continuum. Where the boundaries are drawn changes system behavior.
• At any given time, the most limiting input is the most important
• Physical entities with multiple inputs and outputs have many layers of limits
• There always will be limits to growth
• Exponentially growing quantities reach limits surprisingly rapidly
• When there are long delays in feedback loops, foresight is essential
• The bounded rationality of each actor in a system may not lead to decisions that further the welfare of the system as a whole

From D. Meadows

Summary of Systems Thinking

Non-systems thinking
“Inductive”

Today’s solutions = tomorrow’s problems

Systems thinking
“Deductive”

www.atkisson.com
Systems Thinking

Systems Approaches to Wicked Problems

• Move from events and symptoms to deep understanding and root causes
• Think non-linearly; think in loops
• Consider cumulative effects of multiple stressors
• Evaluate a range of alternatives
• Analyze upstream & downstream life-cycle implications
• Involve a broad range of stakeholders
• Use interdisciplinary scientific approaches
• Include all key determinants (e.g., biologic, ecologic, epidemiologic, social, cultural, economic, and political)
• Incorporate long time horizons
• Be willing to consider previously unprecedented interventions

Systems Analysis Guidelines

• All models are simplifications of the real world
  — You decide how much detail to include
• There are no right answers
  — Mapping out a system allows you to see potential actions
  — As you become more proficient, you recognize consequences of different interventions
• Cause and effect will not be closely related in time a space
  — Don’t look for leverage points near the symptoms of the problem
• Good results depend on bringing in many perspectives
  — Make your system model more informed
• Use your intuition when working with archetypes
  — Is probably good enough as a starting point
• Look for multiple levels operating simultaneously

Adapted from P. Woessner and J. Beltowska
Places to Intervene in a Complex System  
(Meadows 1999, 2008)

1. Power to transcend paradigms  
2. Paradigm that system arises out of  
3. Goals of the system  
4. Power to add, change, evolve, or self-organize system structure  
5. Rules of the system  
6. Structure of information flow  
7. Gain around driving positive feedback loops  
8. Strength of negative feedback loops  
9. Length of delays  
10. Structure of material stocks & flows  
11. Size of buffers & other stabilizing stocks  
12. Constants, parameters, numbers

- Look for **leverage points**  
- Places within a complex system where a small shift in one thing can produce big changes in everything  
- Leverage points: “points of power”  
- Often we know what these are intuitively, but push in wrong direction – counterintuitive  
- **Example:** politicians push growth to solve world’s problems, but growth may be causing them \( \rightarrow \) poverty, hunger, environmental degradation  
- **Example:** Forrester’s urban dynamics study – reduce subsidized housing \( \rightarrow \) improve employment, welfare costs

In descending order of effectiveness and difficulty

<table>
<thead>
<tr>
<th>Intervene point</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transcend</td>
<td>There are no paradigms and mindsets; extreme flexibility</td>
</tr>
<tr>
<td>Paradigm/mindset</td>
<td>Economic &amp; population growth are not good; no private land owners</td>
</tr>
<tr>
<td>Goals</td>
<td>Corporation: from ↑ stockholder wealth ( \rightarrow ) ↑ public good</td>
</tr>
<tr>
<td>System structure; self-organizing</td>
<td>System changes itself; result of biologic, social, cultural, technological evolution; biological and cultural diversity represent self-organization</td>
</tr>
<tr>
<td>Rules</td>
<td>JHSPH faculty promoted based on solving real-world problems; U.S. President can serve 30 years</td>
</tr>
<tr>
<td>Structure information</td>
<td>TRI, emissions reporting, real-time feedback on energy use, specify on tax returns what your taxes can be used for</td>
</tr>
<tr>
<td>[+ ] feedback (↓)</td>
<td>Slowing population growth, slowing economic growth (interest rates)</td>
</tr>
<tr>
<td>[- ] feedback (↑)</td>
<td>FOIA for government secrecy, whistle blower protection, pollution taxes, strengthen democracy</td>
</tr>
<tr>
<td>Delays</td>
<td>Reduce time to new technologies</td>
</tr>
<tr>
<td>Physical structure</td>
<td>Rebuild cities and transportation networks</td>
</tr>
<tr>
<td>Buffers</td>
<td>Invest in engineering to increase size of water reservoirs</td>
</tr>
<tr>
<td>Numbers</td>
<td>Cap campaign spending; ambient air quality standards</td>
</tr>
</tbody>
</table>

*The higher on the list, the more the system will resist the change.*
In 1950s and 1960s, urban decay and the problems it caused were America's biggest problem. There were urban riots in Los Angeles, Newark, Detroit, DC; MLK was assassinated; increasing crime; racial tensions; white flight; business flight; vicious cycle. Jay Forrester of MIT, who ends up sharing an office with past mayor of Boston, John F. Collins, visiting faculty at MIT, gets involved in 1968.

**Systems Analysis as a Tool for Urban Planning**

**JAY W. FORRESTER, FELLOW, IEEE**

*IEEE TRANSACTIONS ON SYSTEMS SCIENCE AND CYBERNETICS, VOL. 98C-6, NO. 4, OCTOBER 1970*

"The results suggest that most of today's popular urban policies lie between neutral and detrimental in their effectiveness. Quite different policies are suggested when one comes to an understanding of why urban areas evolve as they do."

UA = underemployed arrivals

Sustainability in Vietnam

Atkinson adapted from: 

Four archetype stories
1. Limits to growth
2. Fixes that fail
3. Tragedy of the commons
4. Shifting the burden

= delay
Some Early Thinking: Relevance to Public Health


- The health of a population is a complex adaptive system
- Many public health problems (e.g., obesity) have been resistant to understanding causes and developing interventions using past approaches
- Complexity theory has had many early successes applied to public health and should be used more


- Factors can exist at many levels, from molecular to behavioral, social, environmental, and policy
- Factors can influence one another and be influenced by health, with dynamic feedbacks and changes over time
- Advocate a shift to complex systems dynamic approaches that incorporate these complexities

Recent calls for increasing use in studies of obesity


Obesity is a complex adaptive system with individuality (many actors at many levels), heterogeneity (diverse actors), interdependence (connections, feedbacks, non-linearity), emergence (unpredictable phenomena), and tipping (small changes lead to big effects)
How Do We Know What Interventions Work in Public Health? (Rutter Lancet 2017)

Traditional approach to public health intervention evaluation
- Descendants of methods used to evaluate clinical interventions
  - Linear models of cause & effect
  - Require randomization, comparison groups, control
  - One factor at a time, control others
  - Often aimed at individuals and not in circumstances in which they live

Complex system approach to evaluation
- Conceptualizes poor health and health inequalities as outcomes of a multitude of interdependent elements within a connected whole.
- Allows a wider set of approaches, and emergence, feedback, adaptation
- Cannot generally be resolved with single interventions
- Complex, multiple, upstream, population-level actions and outcomes
- Question is not whether an intervention works to fix a problem, it is if and how it contributes to reshaping a system in favorable ways, at multiple levels and over long time periods.
Skills for wicked problems

- Systems thinking
  - 14 habits (Waters Foundation)
- How to involve and work with stakeholders
- Novel data sources
  - Electronic, mobile, remote sensing, commercial, from citizens, digital world around us
- Big data streams
- Data integration
- Computational models and skills
- Science translation to policy, careful decision-making
- Science communication
  - Numbers numb, stories sell
- Continuous monitoring, evaluation, and integration


- 117 publications included in review; see figure below
- Growing appreciation for ‘multiple levels’ and systems of influence; public health not yet taken advantage of full systems science toolbox
- Applications for tobacco, alcohol, obesity, social determinants (SDH)
- Regarding systems modeling, found models not to be accountable, process that produced fully described
- Regarding use of systems approaches to identify best practices for policy interventions, authors similarly believed more rigor, transparency, and scrutiny were needed

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References (others cited on individual slides)