CSYS 300 – COMPLEX SYSTEMS FUNDAMENTALS, METHODS & APPLICATIONS

Modeling Systems of Interacting Specialists

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Modeling Systems of Interacting Specialists

Outline of Presentation

- Brief Biographical Note
- Where this Section Fits in the Structure of the Complex Systems Course
- Model motivation
- Basic parts and processes
  - Internal dynamics
  - Interaction processes
- Illustrative applications
- Question & Answer Session
Brief Biographical Note on Walt Beyeler

- **Education:**
  - BSEE from UNM

- **SNL Work Experience**
  - **1990s:** Subsurface flow and transport modeling for GCD, WIPP; Decision analysis for directing characterization
  - **2001-current:** infrastructure modeling and analysis, including
    - Applying complex systems ideas to infrastructures, especially financial systems
    - Using decision support to steer characterization
## CSYS 300 – COMPLEX SYSTEMS FUNDAMENTALS, METHODS & APPLICATIONS

*Modeling Systems of Interacting Specialists*

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*Note: These approaches represent a simplified set of complex systems concepts chosen for the CSYS500 systems lectures. Please see the initial two lectures for additional detail and expanded references.*
Modeling Approach

- Consider the diverse problems we confront involving systems composed of adapting interacting components (infrastructures, ecosystems, producers of goods and services...)
- Find the most basic features and processes that are common to all systems, and that dictate their ability to function as individuals and as viable parts of an interacting system
- Build and understand a formal model that captures these features and processes
- Approach the motivating problems through this common formal structure
- Entities that manage resource for their own benefit, and that interact to acquire resources they need.
- Closure: all resources come from somewhere, and that source has its own requirements
- Basic questions:
  - How does the system react to disruptions (loss of resources, producing entities, interconnection)?
  - How do remediations change these reactions?
  - Are there general insights that derive from specific system studies?
Essential Processes

- Resource consumption and production by entities
- Resource exchange among entities
- Change in entities’ state as they respond to resource availability
- Change in entity size or capacity
- Change in connection patterns among entities
- Change in the kinds of entities in the system

• Only some of these might be relevant for a particular problem. Time constants generally increase from top to bottom, so that slow processes can be considered “frozen”.
• The framework allows us to include all of these processes, and to set time constants so that the dynamics interact
Basic Elements

Entity

- Health
- Consumption
- Produced Resource
- Money
- Consumed Resource
- Production

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Causal Loop Diagram

• The major reinforcing loop around the outside creates the drive for growth
  – More consumption makes you healthier, leading to more production, more money (energy), more inputs, and more production.

• Growth is automatically regulated by flows through the market.
  – When input can’t be obtained health and production slides.
  – When output can’t be sold inputs can’t be acquired.
Internal Processes
Causal Loop Diagram

Entity States and Processes

- **Health**: Health decays unless it's sustained by consumption. Health enables production. Production can create resources. Production slows when output accumulates. Having more output decreases price.

- **Output Resource Level**: Sales deplete resources. Decreasing price increases sales.

- **Input Resource Level**: Purchases restore resources. Having more input fosters consumption. Consumption drains resources. Consumption increases health.

- **Input Price**: Increasing price increases purchases. Purchases consume money. Having more money increases price.

- **Output Price**: Sales provide money. Sales deplete resources.

- **Money Level**: Purchases consume money. Having more money increases price.

- **Consumption Rate**: Extra consumption can combat health declines. Having more input fosters consumption.

- **Production Rate**: Production can drain health. Production creates resources. Having more output decreases price.

- **Consumption**: Consumption increases health. Consumption drains resources. Extra consumption can combat health declines.

- **Production**: Production can create resources. Production eats up resources. Consumption increases health.

- **Input**: Input drains resources. Input restores resources. Input increases consumption.

- **Output**: Output decreases resources. Output provides money. Purchases consume money.

- **Money**: Money provides money. Money increases price. Having more money increases price.

- **Selling Rate from Market**: Selling rate to market.

- **Buying Rate from Market**: Buying rate from market.

Having more input fosters consumption. Consumption increases health. Production can create resources. Production eats up resources. Consumption increases health.
Effect of Health on Potential Production Rate

\[ p_{hi}^* \left( \frac{h}{h_0} \right) = \frac{p_{sat}^*}{1 + (p_{sat}^* - 1) \left( \frac{h(t)}{h_0} \right)^{-ep}} \]

- **ep = 1**
- **ep = 2**
- **ep = 10**
Stability Analysis for an Island Entity

\[ p_r - h^* = \frac{p_{sat} - 1}{1 + p_{sat} \eta_T} h^{*1-e_p} ; \quad p_r \equiv p_{sat} \frac{p_0}{c_0} \frac{1 + \eta_T}{1 + p_{sat} \eta_T} \]
Exchange Processes
Causal Loop Diagram

• The major reinforcing loop around the outside creates the drive for growth
  – More consumption makes you healthier, leading to more production, more money (energy), more inputs, and more production.

• Growth is automatically regulated by flows through the market.
  – When input can’t be obtained health and production slides.
  – When output can’t be sold inputs can’t be acquired.
Money Level

Input Resource Level

Resource Abundance

Resource Abundance Signal

Short Term Adjustment

Money Abundance Signal

Typical Money Level

Buying Rate from Market

Averaging recent values defines the typical resource abundance [29]

Averaging recent values defines the typical money level [26]

Resource abundance is gauged by the maintenance level [28]

Changes in abundance cue changes in prices [27]

Scarc resources and plentiful money cause prices to increase [24]

Reference price is a long-term average of bids [23]

Bid price results from adjusting a reference price [22]

Reference Price

Input Price

Typical Resource Abundance

Money Abundance

Averaging recent values defines the typical money level [26]

Averaging recent values defines the typical money level [25]

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Typical Money Level

Reference price is a long-term average of bids [23]
Entities may be connected to a market as a buyer, seller, or both. Entities may be connected to any number of markets. A specific market deals in a specific resource, and in a specific kind of transaction. It uses specific rules for matching prospective buyers and sellers. The general process of interacting through markets does not depend on these details, which are described later.

Entities make transactions by sending proposals to the markets they are connected to. They can do this at any time. Entities use their inventory of resources and money to decide whether and what to propose.

Markets may place limits on proposal (such as minimum size) and will reject non-compliant proposals. Proposals define the terms under which the entity will buy or sell the resource. Any resulting transaction will be at least as favorable to the entity as their proposal.

Markets collect proposals from prospective buyers and sellers, and try to pair them off according to some rule.

When a match is made, the buyer and seller are notified of the terms of the deal and are called on to settle on those terms. If they default (for example because they don’t have enough money or resource) the other party is notified and the deal is canceled.

Settlement details depend on the kind of transaction that’s handled by the market. The market can skim some fraction of the money or resource or both.
Two basic kinds of transactions can be arranged through markets: spot transactions and contract transactions. The only current kind of contract implemented entails exchange of a set amount of resource at a set price for a specified number of periods. Contracts with different periods and durations can be defined in the model, but each kind of contract trades in its own market.

Entities use their inventory of resources and money to establish a price for the resource. In the current implementation they maintain bids in all markets at that price – they will end up trading more (or only) in the market that tends to give them the best deal.

Proposals are simply defined by an amount and price. In contract markets, the amount is the amount per contracted exchange. Because the contract period and duration are fixed in a given market these aspects are not negotiated.

Markets use a continuous double auction to match bids and offers. Only the price is considered, and the transaction occurs for the smaller of the bid and offer amounts. Residual bids or offers can be automatically reposted (if they meet any minimum amount criterion).

For spot markets settlement results in an immediate transfer of resource and money between the seller and buyer.

For contract markets settlement creates a new contract link between the seller and the buyer. This contract tries to make periodic transfers of money and resource at the scheduled contract periods.
We can define three general patterns of interconnection between entities. These patterns can be thought of as creating increasingly close coordination between the production process and consumption process. Our initial implementation will be limited to the “loosest” pattern involving spot exchanges of lumps of stuff. This is a good pattern for many resources but a poor pattern for some services (such as labor or electric power) in which the resource is consumed as it is produced. We can reduce inventory times to minimize artificial latency in these cases.

In some exchanges (labor provision, electric power delivery) production and consumption are two views of the same process. Any production that is not used instantaneously is discarded: the Output Resource Level becomes an unusable accounting of surplus capacity.

Contracted exchanges of resources directly couple inventories of specific entities. They include inventory buffering but avoid search costs/delays.

One-off spot transactions are buffered by inventories and by market search processes. Coupling is both lagged and noisy.
## Latency of Different Coupling Mechanisms

<table>
<thead>
<tr>
<th>Consumption Rate Directly Coupled to Production</th>
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<tr>
<td>Consumption Rate Coupled through Direct Exchange of Stored Resource – Inventories Buffer Production Changes</td>
</tr>
<tr>
<td>Consumption Rate Coupled through Repeated Negotiated Exchange of Stored Resource – Inventories and Search Process Buffer Production Changes</td>
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<table>
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<tr>
<th>Rate</th>
<th>Production Rate</th>
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<tbody>
<tr>
<td>time</td>
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Exploring Simple Patterns of Interaction

Complete Interdependency

Some equilibrium results can be derived; Sensitivity to exchange process can be studied...

Using four resources minimally allows for input substitution and output specialization

Six distinct input/output patterns are possible

What happens when one type is especially productive?
Competitive Exclusion
Robustness/Efficiency Tradeoff

![Graph showing the relationship between relative production rate and relative health. The graph illustrates the tradeoff between efficiency and stability, where less efficient systems are more stable and more efficient systems are less stable. The area under the curve reflects robustness cost.](image-url)
Robustness/Efficiency Configuration
Robustness/Efficiency Tradeoff

Scatterplot of Average X-Producer ep vs. Y Abundance

- Y Abundance
- Average ep for X Producers in the Final Population

- Random Disruption
  - No
  - Yes
Robustness/Efficiency Tradeoff

Scatterplot of epXBar vs HbarX

- Scatter plot with data points representing different regimes.
- Axes labels and values provided for clarity.
- Legend showing nRegime 0 (black circles) and nRegime 1 (red squares).

Graph showing the relationship between epXBar and HbarX.
Robustness/Efficiency Tradeoff

Scatterplot of $\text{epXBar}$ vs $\text{newXMakers}$
3) How are decisions evaluated?

A) See how a possible sequence of actions plays out in many possible worlds

B) Rate each possible history according to some criteria

C) Repeat for many possible decisions

D) Find the *initial* decision that performs best:
   - Depends on how criteria, worlds are weighted

Note that this is the same process as recommended by RAND in their long-term decision-making methods.
4) How is a possible history evaluated?

World model may have components, which makes it easier to generate alternatives. Three are shown here: physics/economics, strategic behavior of US, and strategic behavior of all other actors.

Possible World

Other Strategies

Possible World

Decisions

Use Strategies

Decisions initiate production of systems at specified times

Strategic behavior is influenced by physics/economics

Production processes are influenced by physics/economics

Strategic behavior is influenced by capabilities

Interaction outcomes depend on how capabilities are used in context

Interaction outcomes change physics, economics, strategies, and capabilities

Capability Mix

Interaction Outcome

Physics/Economics: Properties Processes

time
State – Resource (including Entity) levels and relationships. Visibility varies across entities, and state information is mediated by a Sensing object.

Kinds of Control Actions

<table>
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<tr>
<th>Concrete Description</th>
<th>Abstract Description</th>
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<tr>
<td>Instantiate a new process</td>
<td></td>
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<tr>
<td>Connect to/Disconnect from a Market</td>
<td>Add/Delete a relationship between an Entity and a Market</td>
</tr>
<tr>
<td>Instantiate Entities</td>
<td>Trigger a specific kind of production process</td>
</tr>
<tr>
<td>Adjust parameters on processes</td>
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</tr>
<tr>
<td>Join/Leave a compound Entity</td>
<td>Add/Delete a relationship</td>
</tr>
<tr>
<td>Set defense policy</td>
<td>Change boundary rules</td>
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Control Actions are undertaken by a specific Entity. They may fail or succeed probabilistically.
Formulations of Decision-making
Formulations of Decision-making (cont.)
Formulations of Decision-making
Process Patterns
Process Patterns (cont.)

Producing Process
- includes making new Entities

Transporting Process
- includes theft and (with loss) destruction

Capacity-producing Process
Simple Structure of an Economy
Production Chain Dynamics
Summary

- Many interesting systems are composed of specialized users and producers of resources
- The essential processes that operate in such systems can be modeled using a few simple elements, which can be configured and interpreted to study particular problems
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Modeling Systems of Interacting Specialists

QUESTIONS & ANSWERS

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