Complexity:
From Concepts to Applications

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"Roadmap"

- Complexity – What is it?
  - Edmonds: *"What is Copmlexity? – The philosophy of complexity per se with application to some examples in evolution"*
  - What is meant by "complexity."
  - Can we identify properties that make something complex?
- Complexity – Coping Strategies
  - Xiao: "*Off-loading, Prevention and Preparation: Planning Behaviours in Complex Systems Management"*
  - How do humans cope with complexity?
  - What are complexity reduction strategies?
- Complexity – Applications
  - Pawlak: *"A Framework for the Evaluation of Air Traffic Control Complexity"*
  - How can we use the concept of complexity?
  - What issues arise in trying to measure it?

Structure of Presentation

- For each question:
  - ~ 10 min. summary of paper
  - ~ 10 min. discussion

Complexity

What is it?

What is Complexity?

- Edmonds paper:
  - Arising from philosophy PhD on complexity.
  - Focuses on application of complexity to evolution.
- Complexity as a “Paradigm”
  - Is “Complexity” just a label for difficult systems?
    - i.e. ones that are difficult to handle using reductionist / Newtonian analysis techniques?
  - Suggests this approach loses richness of the concept:
    - Seems intuitive that a system can be more complex than another, but lose basis for comparison on this view.

What can Complexity refer to?

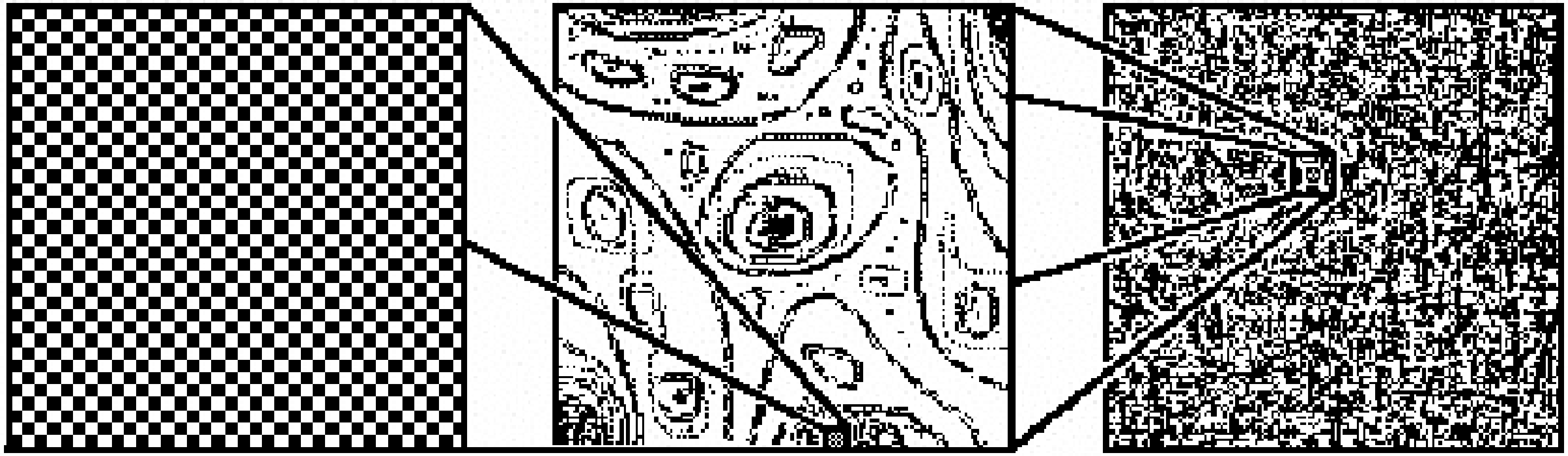
- Revolves around 2 questions:
  - Is complexity an intrinsic "property" of a system?
    - Definable and measurable in the same way as "mass"
  - Does complexity only make sense relative to a given observer?
    - "System complexity" and "Observer complexity"
    - Complexity as a relation between systems, but not intrinsic property of either?
- Edmunds restricts subsequent discussion to "finitely presented languages"
  - Implies complexity dependent on language of representation chosen.

Potential Complexity Concepts

- Size / Count
  - Indicator of general difficulty in dealing with the system.
  - Perhaps only represents potential for complex system?
    - E.g. micro-processor vs. chest of nails
- Ignorance
  - Complexity as lack of knowledge
    - E.g. "The brain is too complex",
    - E.g. "The internal state of the electron is complex because we are ignorant of it"
- Minimum Description Size (MDS)
  - Emerges from computer science
  - Kolmogorov complexity
    - Minimum possible length of a description in a language
    - Implies:
      - highly ordered expressions are simple,
      - random expressions are maximally complex

Potential Complexity Concepts

- Variety
  - Necessary for complexity, but not sufficient?
- Order and Disorder
  - Complexity as mid-point between order and disorder
    - Right-most diagram interpreted as having no rules:
      - But what if it is so complex, but we just don't recognize it?
    - What if one diagram is embedded in another?



Source: Edmonds, 1999

Edmonds' Proposed Definition of Complexity

- *That property of a language expression which makes it difficult to formulate its overall behavior, even when given almost complete information about its atomic components and their* ***inter-relations***

Questions for Discussion

- What are your definitions of Complexity?
- Are there any properties of a system that are “sufficient” to describe its complexity?
- What properties are “necessary” to capture complexity?

Complexity

Coping Strategies

Complexity, Mental Models and Coping Strategies

- Problem solving in complex dynamic environments needs two models:
  - Model of Task Demand:
    - How task environment imposes on operator.
  - Model of Performance:
    - How operator responds to demand.
    - Related to Miwa's talk last week on cognitive models of humans.
- Central challenge in building models is to characterize the strategies used by operators and the consequent cognitive load on them.

Studying Complex Decision Making

- Most studies focus on *incidents*, and study "EPR" cycle:
  - ***E**vent → Mental **P**rocess → **R**esponse (EPR)*
- Consequences:
  - Expertise studied tends to be only response to problematic situations
    - Misses prevention techniques
  - Load associated with coordinating efforts beyond EPR cycle missed
  - Experiments confined to single EPR do not reveal strategies for workload management.
- Models need to consider
  - Coordination of actions,
  - Human's role in anticipation and preparation.
  - Preparation, maintenance, and management of response plans.
- *Identified **planning** as a key coping strategy in complex environments.*

Planning

- Planning has two functional roles:
  - Off-loading deliberation
    - Cognitive resources can be limited at time of action.
  - Coordination
    - Interaction with other operators requires planning.
- Most research focuses on algorithmic part of planning
  - E.g. ordering of actions of humans
- *But planning also plays key role in coping with cognitive load in complex environments.*

Phenomenology of Non-Event Driven Processes

- Unprepared crises vs. Anticipatable crisis situations
  - Unprepared crisis may require "on-site inspiration"
  - Deliberation precedes most anticipatable crisis situations
- Deliberation:
  - Limits the range of possibilities being considered
  - Allows for preparation of response plans
    - Mental resources
  - Prompts positioning of required materials
    - Physical resources
- Under such circumstances problem solving is non-event driven
  - Cognitive processes are activated not by problematic situation, but by anticipation of need for deliberation and coordination.

Examples of Non-event Driven Planning Phenomena

- Off-loading Strategy
  - Reduce workload during busy times by doing steps in advance
    - E.g. drawing up syringes before starting phase of anesthesia.
    - E.g. preparing for future cases during current one.
- Preventative Strategy
  - Identify potential concerns as guide to preventing troublesome situations from happening.
    - "Superior pilot is one who will *avoid* situations in which he/she has to exercise his/her superior skills."

Examples of Non-event Driven Planning Phenomena (2)

- Resource Preparation Strategy
  - Adapt physical configuration of workspace for each patient
  - Prepare necessary physical resources for expected contingencies
    - E.g. checking blood supplies at the blood bank
- Response Preparation Strategy
  - Plan for, and deliberate about consequences of an action
  - Two processes involved?

    1) Rehearsal for responses to things going bad

    2) Checking of availability of emergency responses
      - E.g. surveying "Bail out" protocols
  - Strategy is to prepare responses to variety of possibilities ahead of time
    - Complicated decisions not occurring in "real-time"

Examples of Non-event Driven Planning Phenomena (3)

- Action Maintenance Strategy
  - Strategy to help keep track of actions taken
    - E.g. Hand on switches
    - E.g. Manual charting
  - Local control rules used for simplifying actions
    - E.g. Action occurs once blood pressure reaches certain value, rather than continual assessment of its value.
- Evidence from other Domains
  - Similar strategies observed in aircraft control

Planning Theory of Human Behaviour: A New Framework

- Human problem solvers actively engage in
  - Anticipation
  - Deliberation
  - Coordination
- Mental simulation and rehearsals provide a basis for preparing mental and physical resources for identifying and responding to potential problems.
  - Simplifies operator demands in complex environments.

Questions for Discussion

- What do you think of the strategies identified?
- What are some other domains where such strategies might be found? How general are the strategies?
- What examples of other "complexity reduction" strategies were you able to identify?

Complexity

Applications and Measurement

Why Should We be Interested in Complexity?

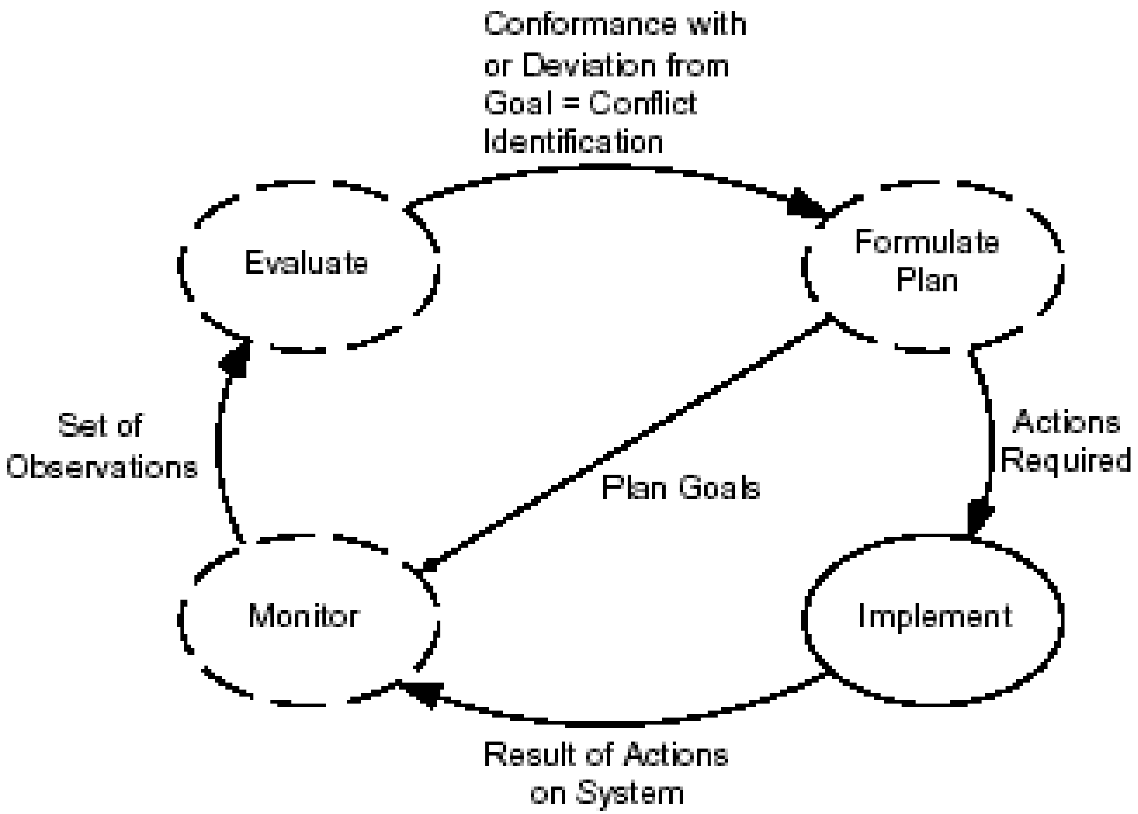
- Safety
  - Need to understand impact of changes in complex systems on operators.
- Example: Introducing “Free Flight” in Air Traffic Control
  - Present Situation
    - Controllers have responsibility for ensuring separation between aircraft
    - Aircraft are generally flying along structured routes.
  - “Free Flight” Scenario
    - Aircraft given responsibility for self-separation
    - Aircraft select and fly any route.
    - Controllers intervene as necessary to resolve conflicts.
  - Problem
    - How to define when situations are too complex for controller to intervene?

Complexity of Air Traffic Control: Required Task Processes

- Controllers primary task → maintain separation
  - Conflict detection and resolution
- 4 Main Processes:
  - Planning
    - Determine actions to resolve each traffic conflict
    - Need to evaluate impact of actions on total system – cascading effect
  - Implementation
    - Putting into action the plan
    - May require planned coordination – not necessarily only a physical task.
  - Monitoring
    - Ensure conformance of situation to plans
  - Evaluation
    - Ensure plan is successfully resolving all conflicts

Complexity of Air Traffic Control: Required Task Processes (2)

- Complexity arises from cognitive demands of each of the processes:
  - Each process is occurring for different aircraft at different times.
  - Each process can initiate other processes



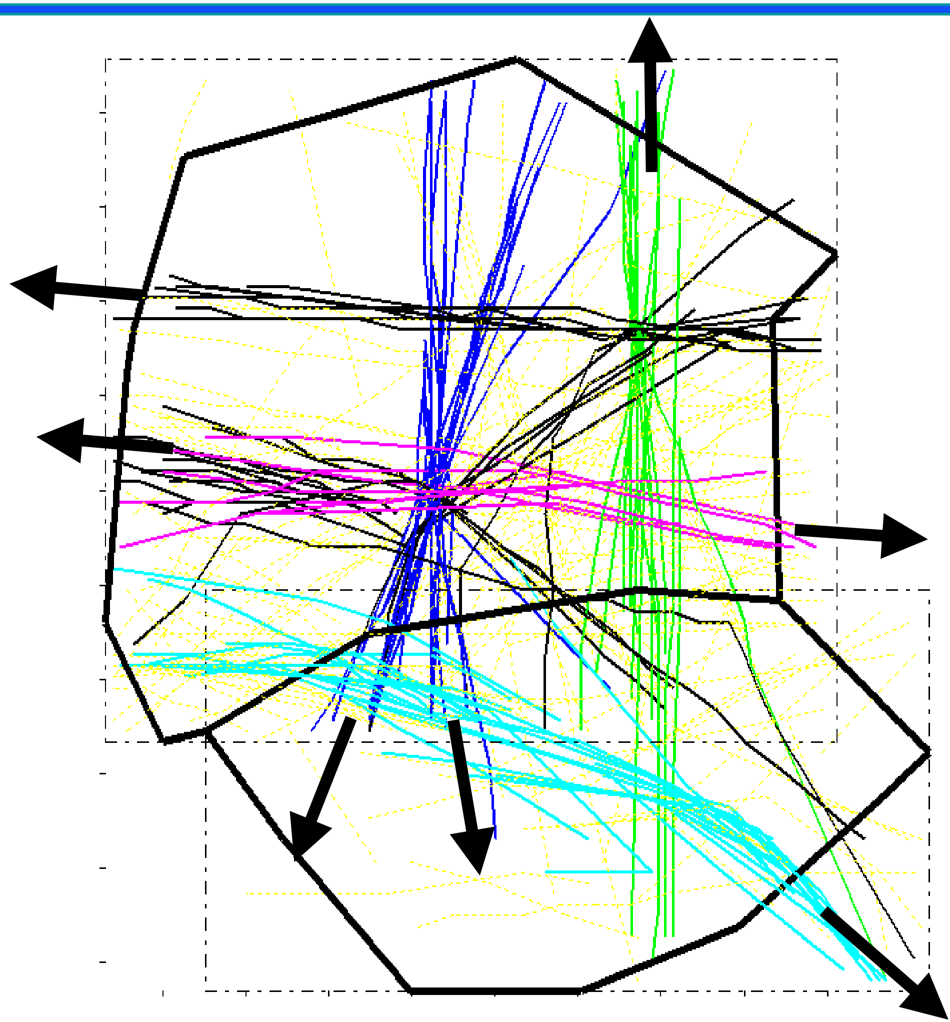
Source: Pawlak, 1996

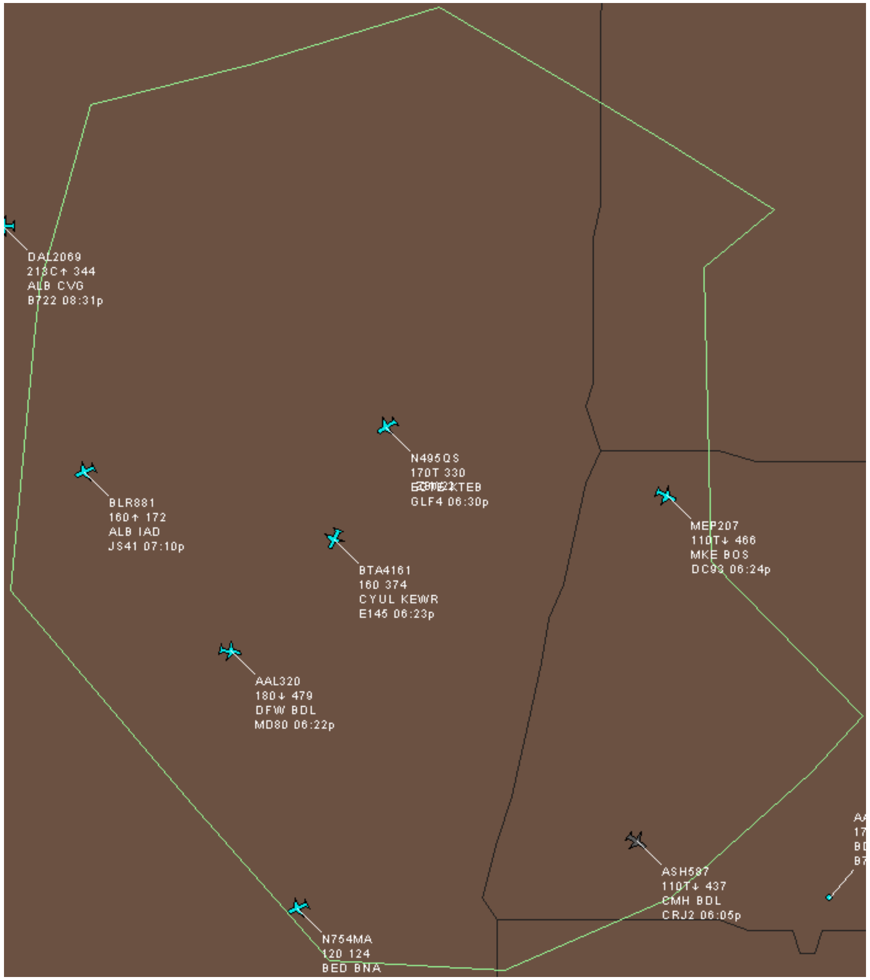
Complexity Reduction Strategies in Present ATC System

- Existing organization of traffic flows provides "Complexity Reduction" mechanisms:
  - Finite and relatively small set of routes reduces number of potential conflict locations.
  - Aircraft on same route can be separated by altitude or time
    - Easily monitored and controlled (E.g. through speed restrictions)
  - Multiple aircraft on same route create "Streams"
    - Allows focus on intersection of streams
      - Simplifies identification of potential conflicts
    - Eliminates having to analyze every aircraft pair for conflicts

"Aircraft Flows" Used as Complexity Reduction Mechanism

ZBW, Albany Low Altitude Sector (110 – FL230), October 19, 2001





Physical Workload "Measures of Complexity"?

- Measurable external actions:
  - E.g. Amount of time on specific tasks
  - E.g. Number of data entries
  - E.g. Time in communications
- Shortcomings of Physical measures
  - Some simple procedures require lengthy or multiple instructions
  - Repetitive data entries necessary, but not necessarily complex
  - Single instructions – eg. Turning aircraft onto base – actually very complex activities

Measuring Complexity Through Properties of ATC System

- Traffic and Airspace Measures
  - E.g. Numeric counts of number of aircraft in sector
  - E.g. Number of arrivals / departures
  - E.g. Number of aircraft in transition etc…
- But, need to capture effects of:
  - Experience
    - Repetition as simplification strategy
  - Structure
    - Limiting problem space, limits complexity.

Remainder of Paper…

- Discusses experiment assessing controller reaction to “Free Flight” scenarios
- Suggests development of formal metric as weighted sum of complexity factors

$$Complexity = \sum_i W_i f_i(\vec{x})$$

where x is the state representing the traffic situation, W_i is a weighting factor, and each f_i is a function capturing a complexity factor.

Questions for Discussion

- How does the definition of complexity affect how would go about measuring it?
- Is it realistic to assess complexity as a single number?
- Are there other domains where complexity measures are used / required?
- Is there a useful distinction between complexity and workload?