The Theory of Systems: An Information Oriented Approach

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Why?

• We **recognise** systems in our experience: we are surrounded by them:
  
  • physical (mechanical, electrical, electronic, software, etc)
  
  • cosmological
  
  • chemical
  
  • biological
  
  • social (ethnic, organisational, governmental, etc)

• General belief that a system is “**more than the sum of its parts**”

• But **what is a system?** What makes the difference and how do systems work? Are there any general principles? What can we learn about building systems?

• We want to present a **synthesis** based on known scientific principles
Dramatis Personae

• This synthesis is based on the work of, amongst others:
  
• Sir Isaac Newton

• Sir Benjamin Thompson/Count Rumford

• Ludwig Boltzmann

• Charles Darwin

• Alan Turing

• Richard Feynman

• and others …
Definition

• A **system** is a collection of **components** which are more **strongly** bound to each other than they are to their environment (**identity** property)

• A **component** may be anything, including another **system** (**hierarchy** property)

• **BUT** note that many of these words (e.g. “component”, “bound”, “environment”) are not precisely defined, so further explanation is needed
Why can Systems Exist?

- Ultimately, systems can exist because:
  - there are **stable, long lived components** with which to build them (e.g. protons, nuclei, atoms)
  - there are **forces** which can **bind** components together (e.g. strong, weak, electromagnetic, gravitation)
  - BUT what are the equivalents of force in a biological or social system?
Locality

• The essence of a system is that it is local and its rules are local … as are scientific laws

• Every system has a boundary, which separates what is “in the system” from what is “outside the system”

• Every system has an “environment”, which is just another name for “everything outside the system”

• So we can draw a diagram to show a system and its boundary
Schematic of a System

- Boundary
- Environment = everything outside system

Components and local rules
What is the Environment?

• The “environment” is everything else in the Universe and it has an effect on any system:
  
  • E.g. all systems exchange heat with their surroundings and are subject to gravitational forces
  
  • When the environmental effects are small, systems tend towards equilibrium
  
• Every system also affects its environment and leaves its “footprint” on it
Binding vs. Containment

• How does a system maintain its identity?

• It must have:
  
  • internal binding forces which are stronger than those exerted by the environment, OR
  
  • a physical envelope which contains components and separates them from the environment

• or both
Inputs and Outputs

- Energy
- Matter
- Information

Components

Energy
Matter
Information
Systems Principle # 1

- Outputs from a system must balance inputs
  - In Physics, this is known as the conservation of mass/energy
  - Systems move and change, but you cannot build a perpetual motion machine!
  - Sometimes also known as the First Law of Thermodynamics
How Systems Change

• In small scale systems, change is **deterministic** and **reversible** (e.g. collisions between particles)

• Given the **state** of the system **at a given time**, we can calculate a **subsequent** state or an **earlier** state using **equations of motion**

• By “state”, we mean a complete specification of the **momentum** (energy & direction) of each component (e.g. particle) in the system

• This state is known as **information**; momentum is conserved, therefore information is conserved (usually)
Large Scale Systems

- By **large scale**, we mean systems with **many components** and, especially, **many similar components** (e.g. molecules of gas)

- The equations of motion for a large system **cannot be solved**, so motion appears random

- The effect of **many interactions** between components (e.g. collisions between gas molecules) is to **share energy** between the components, leading to an equilibrium **state** (e.g. energy profile) with many indistinguishable “**microstates**”

- We characterise this by **statistical measures**, e.g. **temperature** and **pressure**
Ideal Gas as a System

- Pressure
- Temperature
- Volume

$PV = NkT$  \ (Ideal Gas Law)
Systems Principle # 2

- In large scale systems, change is irreversible
- Systems are fragile!
- This occurs because all microstates are equally likely but only a few are simple and “useful”
- In Physics, this is known as the Second Law of Thermodynamics
Irreversibility!
Lack of Information

• It’s impossible to have **full knowledge** of the state of a large scale system: calculation/measurement could take longer than the age of the universe

• We **perceive** this as “disorder”

• The Second Law of Thermodynamics is a consequence of this lack of information, usually called **entropy**, which always increases

• $S = k \log W$ (W = number of micro states)
Systems Encode Information

- All large scale systems have *information encoded within them*:
  - at the **low level** (e.g. direction of motion, magnetisation, nuclear spin, etc.)
  - at larger scale, a **record of irreversible change**
- This is what makes geology, archaeology, forensic science and memory devices possible
Maxwell’s Sorting Demon

• Maxwell suggested that the supposedly irreversible changes to a gas could be reversed by the action of a “sorting demon”

• the demon would manipulate a “trap door” separating two chambers of gas

• open it to allow high velocity molecules into one chamber, but close it to low velocity molecules

• gradually accumulate high velocity (hot) molecules in one chamber and slow (cold) molecules in the other

• Is this possible? What would it take to implement it?
The Sorting Demon

cold gas

hot gas
Resolving the Paradox

- For almost 100 years, the sorting demon was thought to be paradoxical because it suggested that entropy could be decreased.

- We now know in principle how to implement the demon with sensors and a memory device.

  - But operating the demon requires energy.

  - And resetting the memory after each particle detection has an energy cost.

- This tells us that total entropy increases in the environment.
Open vs. Closed Systems

• An **open system** accepts inputs and outputs

• A **closed system** is **isolated** from its environment, so does not accept inputs or outputs

• But both these are **contradictory**:
  
  • a fully open system would **lose its identity**
  
  • a fully closed system is **impossible**

• so most systems are partially open, partially closed
Systems Principle #3

- There are no closed systems

- In Physics, this is known as the Third Law of Thermodynamics

- It’s usually expressed as “entropy tends to zero at absolute zero” or as “it’s impossible to reach absolute zero”

- In other words, you cannot isolate a system
Complex Systems
Non-Equilibrium Systems

• Most interesting real systems (e.g. plants, animals, machines, and planets) operate in a range of states which are far from equilibrium

• They take inputs of energy/matter from the environment in order to operate

• They produce outputs of waste energy/matter to the environment

• They have complex internal structure and may occur in large scale communities
Large Scale Behaviour

- Some **behaviour** of large scale systems can be predicted from low level properties, or described by simple laws e.g.
  
  - **Mass** of system = sum (masses of components) acting at centre of gravity
  
  - **Motion of rigid bodies** with a centre of gravity is described by Newton’s Law $s = vt + \frac{1}{2}at^2$
  
  - **Behaviour of a gas** is given by Boyle’s Law $PV = RT$
  
  - These predictions are only **valid** over **certain ranges**
Complex Systems

• Systems with many levels of nested components can exhibit complex behaviours, e.g. actuating mechanisms, moving around, sending messages, making things, etc.

• They can operate as functional processes, transforming specific inputs into specific outputs.

• They can also protect themselves against changes in the environment and exhibit resilience.

• They can repair themselves and reconfigure in response to external conditions.
Emergence

• Sometimes, large scale complex systems exhibit surprising and unexpected behaviour, e.g.

  • Phase change from gas to liquid or solid, crystallisation into geometric shapes, complex motion of water waves

  • Chemical processes, e.g. catalysis

  • Biological processes, e.g. life, consciousness

• We use multiple levels of description to document these emergent properties
The Problem of Emergence

- Higher level behaviour appears to show order. The basic problem is to explain how this arises from apparent disorder in large scale systems.

- Some, e.g. phase change, is due to micro-level interactions between atoms and molecules, as a substance is cooled.

- But some natural systems show self organisation, e.g. growth of living things. How does this happen?
Philosophical Explanations

- Philosophers traditionally use a number of approaches to explain complex behaviour
  - **Holism** => i.e. systems can **only be understood as a whole**
  - **Reductionism** => i.e. systems can be **fully understood from their basic parts**
  - **Vitalism** => living systems are made of **different stuff** from inorganic systems

- None of these explanations is satisfactory:
  - We **gain insight** by taking systems apart and understanding subsystems
  - We have **no evidence** for vitalism; living systems are made of the **same basic stuff** as simple systems
  - But can **all complex behaviours**, e.g. life, brains, consciousness, etc. be **understood** using just basic physics?
Emergence from Scale

- Experiments with *cellular automata*, e.g. Game of Life, have found self sustaining patterns, showing:
  
  - Simple *local rules* applied over a large scale can lead to *complex patterns* of behaviour
  
  - Some patterns include *gates* and *memory*, making them equivalent to a computer
  
  - Some natural processes appear to be exhibit *symmetry* and *computation*, e.g. crystal growth
Mechanism for Emergence

• What is the difference between a working system and a pile of components? or between a living creature and a dead one?

• Some patterns of behaviour are independent of the actual system components or even their type, e.g. motion of fluids. How can we explain that?

• The answer to these question appears to be information and computation, which enables the parts to be organised and specifies interactions
Models of Computation
Systems Principle # 4

- Complex systems use some form of computation

- Three classes of system provide models of computation:
  - Finite state machines (finite fixed memory)
  - Pushdown automata (finite stack memory)
  - Turing Machines (infinite two stack memory) and equivalents, e.g. CAs

- Turing showed that:
  - Finding the output of a TM is an undecidable problem
  - All TMs have equivalent capability, no matter how designed. We call this the Universality of Computation: any computer can do the same as any other
Finite State Machines

• A finite state machine (automaton) is an abstract system which can exist in a limited number of states, e.g. vending machine, lift

• The states provide a form of memory

• It can accept a defined set of input signals (often thought of as a string of symbols in some defined grammar) which cause transition from one defined state to another

• It provides a restricted model of computation, with less capability than a Turing machine - but then most real computers have finite memory
Computation in Nature

• Studies of one dimensional cellular automata suggest that some natural processes are equivalent to automata, e.g. turbulent fluids, weather systems

• We know that biological cells use a computing mechanism based on DNA

• Therefore, natural systems may perform computation and may exhibit universality

• Although we cannot predict their behaviour (through lack of information), we may be able to simulate it
Small Automata

• Margenstern studied Turing Machines with small numbers of symbols and states

• He asked what is the smallest automaton that exhibits universality?

• The answer is surprisingly small: a TM with 5 symbols and 5 states shows universality

• Studies of small Cellular Automata also show universality
Universality of TMs

TMs known to be universal

no. of symbols

no. of states
Complex Adaptive Systems
Complex Adaptive Systems

- **Real world** complex systems have a number of common features:
  - protective envelope, with input/output ports
  - static hierarchical structure of components with dynamic operational relationships
  - the capability to control their function in response to external conditions
  - the capability to exchange messages between components and with the external environment
  - the capability to model themselves and the external environment
  - and sometimes, the capability to replicate themselves
System Structure

• Static **hierarchical** nesting of components follows from the definition of a system. Can be represented by a **tree**

• Dynamic **networked** structure depends on how components “invoke” each other by passing messages. Can be represented by a **graph**

• Graphs can include **cycles** (loops) and **recursion**
Control Systems

• Control systems (e.g. thermostat, speed controller) can maintain some parameter at a constant value (steady state) via a **negative feedback loop**. Requires two data values plus an algorithm:

  • **Desired** value of parameter
  
  • **Actual** measured value of parameter
  
  • **Algorithm** for returning parameter to desired value

• Most complex systems and all living things include control systems
Modelling

• Most complex systems (e.g. computers, living things) exist within communities of similar systems

• Their environment is hazardous and competitive, but may offer rewards (e.g. food)

• To function successfully, they need to know about the environment by modelling it and monitoring it

• Information is encoded within the system and associated with algorithms for updating the model, responding to changes, and reacting externally
Self Modelling

• Complex systems also need to monitor and control themselves, to:

  • manage inputs, workload, etc.
  • maintain outputs with varying inputs
  • ensure correct operation of internal components
  • adapt to failures and external changes

• For this, they need a model of their own structure
Replication

• Because systems are fragile, the capability to adapt and respond will **degrade with time**. All systems become **defunct** eventually

• Longer term, only systems with the capability to **replicate** themselves will survive

• This means **copying all the internal and external model information** and creating a physical replica, as in the reproductive cycle of life

• Artificial hardware systems are rarely capable of self replication but **software often is**, e.g. viruses
Ecosystems

- Darwin recognised that animals and plants exist within competitive ecosystems, where there are many complex predator/prey relationships: “everything is connected to everything else”

- He also recognised that individual plants and animals are subject to natural variation

- And an ecosystem functions as a system which exerts selective pressure on individuals within it
Systems Principle # 5

• In a large scale ecosystem of variable systems, selective pressure will favour replication of the best adapted systems

• This is the **Theory of Evolution.** It describes a mechanism for **learning** about the ecosystem

• It also applies to economic markets, software releases, and other systems where each iteration incorporates **new adaptations**

• The selective pressure is **customer requirements!**
Conclusions
What have we Learnt?

• **All** systems are subject to known **scientific principles**

• Many natural systems show **aspects of computation**

• All **complex adaptive systems** are **computers**

• **Evolution** occurs in **systems with many similar components**, not in individual component systems

• **Systems development** is the iterative process of learning customer requirements