**Real, Absolute**
- Variety
- Connectivity
- Convolution

**Perceived, Relative**
- Does not resolve easily into (Platonic) shapes
- f(familiarity)
- Shapes in clouds, fortunes in tea-leaves

**Nature’s complex, nonlinear systems:**
- Greater power densities, self-healing, auto adaptation, self-replication… etc.
- Use Nature’s examples to greatly improve man-made systems…
Complexity $\Rightarrow$ Life

Cambrian Life-form, c. 500MY BPE
For 4.5 billion years, Earth produced very simple life: bacteria; plankton; multi-cellular algae.

Then: 530 million years ago:
- Cambrian Explosion!!
- Extravagance of weird, bizarre, fractal life forms: sex!
- Evolution of eyes ⇒ Predator/Prey “arms” race
- All today’s body plans/architectures created…

Cambrian marked by c.3 mass extinctions, followed by continual resurgence of…

...Complexity ⇒ Continual Emergence of Life
Swimming animal is *anomalacaris, top predator*. The apparent “plants” are fractal animals – life too deep under the sea for photosynthesis…
Life, Order and Disorder…

• Evidently, *complexity auto-generates*…
• …Complexity $\Rightarrow$ order *and disorder*…
  – Big Bang $\Rightarrow$ stellar systems; galaxies; clusters; super-clusters… *Black Holes*
  – *Hymenoptera/Isoptera* $\Rightarrow$ hives; colonies; bivouacs… *swarms*
  – *Homo sapiens sapiens* $\Rightarrow$ families; societies; cultures; civilizations… hierarchies which eventually *collapse*, often spectacularly
Premise: Interconnected systems driven by an external energy source will tend to a cyclic progression in which:

- system variety is generated,
- dominance emerges to suppress the variety,
- the dominant mode decays or collapses, and
- survivors regenerate interconnected variety…
Unified Systems Hypothesis

• That open systems form, develop, sustain, collapse/decay and reform continually – “entropic cycling”

‘Law of Cyclic Progression: ’

“Open interacting systems’ entropy cycles continually at rates, and between levels, determined by available energy”

Unified Systems Hypothesis (HUSH)

- Basis for Cambrian Explosion?
- Endemic today?
USH Entropic Cycling Simulation

Dynamic Equilibrium

Dynamic Equilibrium

Dynamic Equilibrium

Collapse

Collapse

Collapse

Dynamic Equilibrium

Dynamic Equilibrium

Dynamic Equilibrium

Time
USH – Global Warming

• (Weather) Systems’ entropy will cycle continually at rates, and between levels, determined by available (increasing) energy.

• USH predicts that global warming will result in more extreme weather conditions, more frequently:
  • more severe storms,
  • more downpours, floods, BUT
  • more extended calms,
  • more extreme droughts
  • Weather systems are chaotic: impossible to predict individual events or locations
**USH “Use Cases”**

**USH is Universal, Scale-independent, understandable, useful**

- **Revolution**: Bolshevism; Stalinism; domino-collapse of Soviet Union

- **Politics**: left-wing; right wing; continual switching is stable… *dominant* leader who expels dissidents (‘wets’) from cabinet reduces *variety*, heralds own *collapse*

- International *economic* cycles (Kondratieff)

- *Bureaucracies* that “exist, like aircraft carriers, mainly to defend themselves” exemplify preferred patterns

- *Accountants* destroy companies by *shedding variety* to survive economic winter…

- Ancient Egypt ‘cycled’ through 3 unified ‘epochs,’ with ‘intermediate’ periods of relative disorder…

Each oval represents an epoch in the ancient Egyptian civilization

… and a rotating USH lifecycle map

- Each epoch built society slowly, established, then collapsed…
- Each new epoch built on the residues from its predecessor
- Entropic Cycling in social history? Faint echo of Cambrian Explosion?
Causal Loop Model – Demise of the Pyramid Age

Nome = “province”
Nomarch = provincial governor

Nome = “province”
Nomarch = provincial governor
• Unique approach to complex systems engineering –
  – natural, social and sociotechnical systems!
  – Mechanistic ⇐ Organic, “Biological” paradigm
  – Principles – holism – synthesis – organicism

• Anticipates continually changing environment

• Maintains/increases connected-variety to accommodate changing environments

• Promotes harmony through synthesis

• Continually refreshes connected-variety for homeostasis/dynamic equilibrium
Complexity – Levels of Organization

**Levels of Organization**

*Biology/Anatomy*  *Man-made Systems*

- Community  ↔  Company
- Population  ↔  Group
- Organism  5  Platform
- Organ System  4  System
- Organ  3  Subsystem
- Tissue  2  Composite
- Cell  1  Component

* Population - all the organisms that belong to the same species, in the same geographical area
** Community - a group of interacting living organisms sharing a populated environment
# Complexity – Levels of Organization

<table>
<thead>
<tr>
<th>Levels of Organization</th>
<th>Biology/Anatomy</th>
<th>Man-made Systems</th>
<th>SE Layer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nation</td>
<td>9</td>
<td>Nation</td>
<td>Socioeconomic/societal SE</td>
</tr>
<tr>
<td>Region</td>
<td>8</td>
<td>Organization</td>
<td>Industry Systems Engineering</td>
</tr>
<tr>
<td>Community</td>
<td>7</td>
<td>Company</td>
<td>Business Systems Engineering</td>
</tr>
<tr>
<td>Population</td>
<td>6</td>
<td>Group</td>
<td>Project Systems Engineering</td>
</tr>
<tr>
<td>Organism</td>
<td>5</td>
<td>Platform</td>
<td>Artefact Engineering</td>
</tr>
<tr>
<td>Organ System</td>
<td>4</td>
<td>System</td>
<td></td>
</tr>
<tr>
<td>Organ</td>
<td>3</td>
<td>Subsystem</td>
<td></td>
</tr>
<tr>
<td>Tissue</td>
<td>2</td>
<td>Composite</td>
<td></td>
</tr>
<tr>
<td>Cell</td>
<td>1</td>
<td>Component</td>
<td></td>
</tr>
</tbody>
</table>

* Population - all the organisms that belong to the same species, in the same geographical area

** Community - a group of interacting living organisms sharing a populated environment
The Social Genotype—Basis of Identity, Culture and Adaptive Social Behaviour

- Analogue/extension of DNA which expresses identity of *individual*.
- Social Genotype expresses identity/culture of *social group*.
- Rôles/groups and relationships form stable, palpable structures
  - Rôle more determined by relationships and interactions with other rôles, less by rôle-holder.
- Relationships mediated via common, shared *belief system*—shared attitudes, viewpoints/*weltanschauungen*, ethics, morals
  - which may be *very different* from those of the individual fulfilling the rôle! (Jung)
The Generic Reference Model

Thinking

Doing

Function Management
- Mission
- Viability
- Resources

Being

Systems Engineering:
• 3 elements seen in respective “environments”
• Viability provides platform for Mission Management
• Resources provide energy & materials for Viability and Mission Management
• Threats to Mission Management, & Resource Management
• Change challenges Homeostasis (resist) and Evolution (adapt)
GRM: Behaviour Management

- **Tacit knowledge**
- **World models**

**Cognition**
- **Interpretation**

**Nurture**
- **Experience**

**Belief System**
- **Evolution**
- **Selection**
- **Excitation**
- **Activation**
- **Behavioural Archetypes**

**Response Intent**
- **Beliefs**
- **Rôles**
- **Stereotypes**
- **Categories**
- **Values**
- **Ethics**
- **Morals**
- **Ideologies**
- **Training**

- **Collective Unconscious**
  - **Instinct**
  - **Archetypes**
  - **Libido**
    - **Aggression**
    - **Energy**
    - **Character**
    - **Emotion**

**Motivation**
- **Constraint**

**Environment**
- **Achievement**
- **Conformance**
Autonomous Peace Officer Functional Design Concept

Autonomous systems will behave ethically, morally and will need an integral belief system to accommodate uncertainty, and to make judgements.
Behavourial Archetypes - Ancient Egypt

Almost obsessional pairing

Tension of 'above' and 'below'

Horus and Seth

Red and White Crowns

King's placenta as twin in Beyond

Powerful Need for Duality—which must be reconciled

• Duat in the stars

Red and white—sacred colours
• blood vs. light?
• man vs. woman?
• opposites, perpetually destined to unite?

Upper and Lower Egypt

Amenability to:
• new ideas
• patterns of group behaviour
• forms
• customs
• beliefs
• social organization

Canons of belief

Canons of belief

Zoomorphs

King as Shepherd
• neolithic cattle farmer image

Emergence of Archetypes

Magus, the High Priest

The Healer

The Creator

Pyramid as perfect shape

Divine King

Idealism

Regression to contemporary norms

Extended group behaviour

Collective unconscious

Pharaoh as the self and individual of the people
Shepherds of their Flocks – Shepherd Archetype through the Ages

Crozier

Crook
Belief system

Straightforward believer's World Model

Reduction of psychological uncertainty

Interpretation of everyday events, situations

{ + }

Reinforcement

{ + }

Indoctrination/education in belief system

Icon establishment

Belief system

Rôle models of "good" and "bad" behaviour

Reward/punishment concepts

Co-operative social behaviour

Social cohesion

Power structures

Individual

Group

Maintaining/reinforcing the belief system—1
Belief system

Straightforward believer's World Model

Interpretation of everyday events, situations

Reducing psychological uncertainty

Reinforcement

Role models of "good" and "bad" behaviour

Reward/punishment concepts

Co-operative social behaviour

Social cohesion

Power structures

Icon establishment

Indoctrination/education in belief system

Fear reduction

Leadership & discipline

Training

Decision-making in Command and Control

Schwerpunkt?
GRM in Layered Virtual Machine Format

**Mission Management**
- Collect information
- Set/reset objectives
- Strategize & Plan
- Execute
- Co-operate with others

**Behaviour**
- Cognition
- Behaviour selection
- Stimulation
- Nurture
- Belief System
- Nature

**Form**
- Structure
- Influence
- Potential

**Resource Management**
- Acquire
- Store
- Distribute
- Convert
- Discard excess/waste

**Viability Management**
- Survival
- Synergy
- Homeostasis
- Evolution
- Maintenance

**Behavioural Influence**
- Collect information
- Set/reset objectives
- Strategize & Plan
- Execute
- Co-operate with others

**Belief System**
- Nature

**Structure**
- Influence
- Potential
One Level of Layered GRM Elaboration

Mission Management
- Collect information
- Set/reset objectives

Strategize & Plan
- Generate options in sequence
- Simulate mentally
- Generate all options
- Review all constraints
- Select preferred option

Decision mode

Execution
- Execute
- Co-operate with others

Behaviour Management
- Cognition
- Interpretation
- Behaviour selection
- Stimulation

Behavioural Influence
- World models
- Tacit knowledge
- Experience

Behaviour
- Stimulus

Stimulus

Belief system
- Ethics & morals
- Nature

Motivation
- Training
- Doctrine

Constraint

Evolution
- Homeostasis
- Viability Management

Resource management
- Acquire
- Store
- Distribute
- Convert
- Discard excess/waste

Form
- Structure
- Influence
- Potential

Environment

Recognition-primed decisions

Naive decisions
Causal Loop Model for Homo Sapiens Hair Growth

Homo Sapiens Transition from Arboreal Fruit Eater to Open-Plains Carnivore

- Search for Prey
- Female/child Domestication
- Pair Bonding
- Increased Sexual Activity / Availability
- Homo Sapiens Unique Hair Pattern

- Gaps Between Meals
- Male Hunting Cooperation
- Prey Pursuit Overheating (male)
- Subcutaneous Fat Development (Energy Storage)
- Need for Prolonged Pheromone Secretion
- Selective Pubic/Underarm Hair Retention

- Reduction in general Hair-Covering
- "causes"
Chaotic Phenomena

- Two main varieties:
  - Deterministic Chaos – exponential growth in uncertainty
  - Weak chaos – power law growth in uncertainty
    - shared with fractals and self-organizing criticality…
      - .. suggesting some phenomenological commonality

- Chaos is organized, structured, bounded –sic!!

Hénon Chaos

The Julia Set (fractal)
Deterministic Chaos – Poincaré (1887)

- French mathematician
  - 3-body celestial problem - how do ‘bodies’ behave in space?
- Poincaré won international maths competition: upper video clip:
  - regular, repeating, but incomplete. However...
  - .. different starting conditions give different result...
  - …corrected error only after winning!
- ‘Close-coupled’ behavior in lower video clip!
  - Never repeats
  - chaotic!
- Poincaré: ‘father’ of chaos

N.B. Apparently simple, Newtonian systems can exhibit complex behaviour!
Lorenz’s Weather – Deterministic Chaos

\[
\begin{align*}
\frac{dx}{dt} &= -10x + 10y \\
\frac{dy}{dt} &= 28x - y - xz \\
\frac{dz}{dt} &= -\frac{8z}{3} - xy
\end{align*}
\]

Lorenz’s Butterfly – “strange attractor”

-never repeats, never overwrites, never goes outside bounds – represents ‘climate’

–Signature of ‘pure’ deterministic chaos

Different starting conditions create different, but very similar, patterns
Coupling & Chaos

- Increased coupling between elements in 3-body problem caused *deterministic chaos*.
- Tight coupling between subsystems as parts of some whole may cause *deterministic chaos*, too.
- Shown in simulations…
- Beware:
  - .. of over-tight coupling between systems in systems *design* and in systems *integration*…
- .. “sailing close” to the ‘far edge of chaos’

*Video feedback:* TV camera pointed at screen showing picture from TV camera - ‘strike a light’ and – dynamic chaotic patterns…
“Simulated Chaos”

- The simple, 3-coupled reservoir model (c.f. 3-body problem) illustrates development of chaos...

- ...complex behaviour can emerge from simplest of systems – without designer/owner/user knowledge
The *Edge* of Chaos…

- Many real world systems may exist on the “edge of chaos:’ between order and disorder/chaos…
- Some view ‘complexity’ as between order and chaos
- Logistic/sigmoid *very common equation* in biology, engineering, population growth…

Logistic Bifurcation Diagram
(iterate $x_{n+1} = a \cdot x_n (1 - x_n)$)
Weak Chaos:

Self-Organized Criticality
Weak Chaos: Self-organized criticality

- 6 cm plate; drop grains of sand on plate; cone forms
- Cone $\rightarrow$ critical height
- Above critical height; avalanches reduce height
- Height varies above and below critical
- Measure number of grains falling off plate in each avalanche
- Many small avalanches; few large avalanches…
- Log (grains/avalanche) Vs. log (specific avalanche frequency) = straight line…  
  $\log y = \log x + C$

Investigating Earthquakes: Bak & Chen’s Sand Pile
Model based around Bak & Chen's sandpile concept, which they used to explore plate tectonic/earthquake patterns. Model gives reasonable facsimile of self-organized criticality. Graph could represent: Earth seismic readings, earthquakes; size and frequency of meteorites; stock market fluctuations; 1/f noise; crime statistics; deaths in conflicts; encephalographs; traffic movements; etc; etc.
The pattern derives from two distinct distributions: a random distribution representing the height buildup of the sandpile; and a Poisson distribution representing the number of entities in each avalanche...
Graph shows rarity of major slippage (result from 10+ runs). Implies that the occurrence of such rare events may not be predictable, but their frequency of occurrence is!

…c.f. Taleb’s notion of “Black Swan Events”
Lewis F Richardson's Diagram

Waiting Time

War Magnitude, M

Possible New Shape due to Nuclear Proliferation

World Population—Current and Near Future

5 min

1000 yr

100 yr

10 years

1 year

1 month

8 hours

Individual Killings

Data:— 1820 to 1945, extrapolated

1820 + 1000 = 2820

M = 5 means 10 killed

WWII

5 min

5 min
Weak Chaos…

- Bak & Chen’s sand pile
  - tectonic plate movement, earthquake patterns

- Weak chaos found widely
  - stock exchange price movements
  - 1/f ‘noise’ in conductors
    - ‘fixed’ ion grid, electron flow
  - distances between cars
  - asteroid size and frequency
  - crime statistics
  - Deaths in War
    - machine gun, tanks, gas, atomic bomb… do not cause deviation from straight line…!

Fractal Pattern/weak chaos arises *widely* in Nature, and in the “affairs of Man.”

Arises where ‘free’ flow is hampered or constricted.
‘Constricted Flow:’ Conceptual Model

- ‘Marble’ flow is constricted by ‘Golf-balls’
- ‘Marbles’ jostle, cluster upstream of ‘Golf-balls:’ cluster builds-up ‘pressure’
- Pressure forces release of ‘marbles’ as variously sized avalanches…
- Analogous behavior in many real-world situations
  - Criminals Vs Police
  - Turnstiles/checkouts
  - Economics
  - Turbulence
  - Production; etc., etc.

Compare with ‘sand-PILE’ model
BoB: on the Edge of Chaos?

- Top chart:
  - Daily aircraft losses
- Bottom chart:
  - Day-to-day variability in aircraft losses...
  - ...is there a hint of a butterfly shape?
- Was the BoB right on the Edge of Chaos?
Ancient SoC

• Is there a relationship between Deterministic Chaos and Self-organized Criticality?

• Ancient Egypt depended on annual Nile Inundation for good crops
  – Good inundation - good yield
  – Too high OR too low, poor yield…

• Inundation ‘driven’ by weather to South - deterministic chaos?

• Population rose during ‘good’ inundation

• Poor inundation ➔ famine ➔ population fell…
Self-organized Criticality

CHAOS

"Good" Inundation

"Poor" Inundation
Self-organized Criticality

“Signature” of self-organized criticality

Simple Attractor

‘Metaphor for the planet’s impending problems’

Stele showing effects of famine in the Nile Valley ⇒ Louvre
Summary

• Complexity gives life: is a fact of life!
• Systems science seeks to understand, manage, and exploit complexity – not to avoid it!
• Embracing complexity…
  – ..offers capability, intelligence, flex- adapt-ability
  – self-replication/healing/repair, power-density…
• “Nature’s systems engineering:” took 530My to evolve present efficient, intelligent organisms…
• Perhaps SE should adopt an evolutionary, biological paradigm, rather than its current mechanistic one…
  – but evolve solutions to problems rather more quickly!! We may not have much time left!